TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

JUNE TO DECEMBER, 1907

VOL. XXVI, PART II

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 WEST THIRTY-NINTH STREET
NEW YORK, N. Y., U. S. A
1908

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A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

THE PROPERTIES OF ELECTRONS

PRESIDENT'S ADDRESS

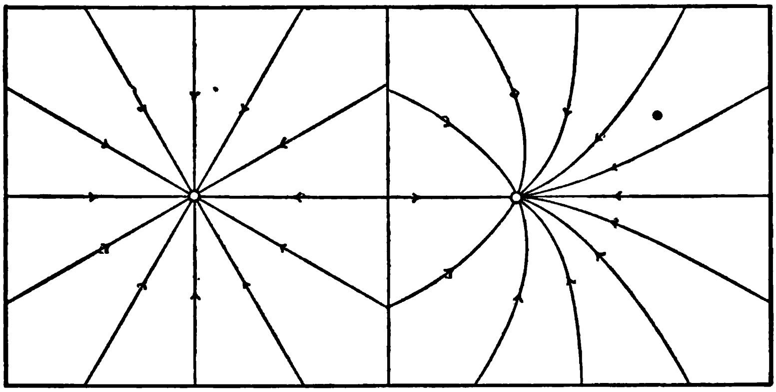
BY SAMUEL SHELDON

Introductory. The physical properties of electrons form the basis of electrical engineering, and a thorough understanding of them is essential for successful investigation in some departments of research. No specific treatment of the subject has appeared in the printed publications of the Institute. It is therefore hoped that what follows will be of service to the membership. No attempt has been made to treat of the conduction of electricity through gases, of the phenomena of radioactivity, or of electrolytic conduction, in all of which the electron plays an important part.

The Electron. Electrons, which are called corpuscles by some physicists, are the smallest particles of matter that have been isolated. They are considered by some (Larmor) to be constituted of ether. Their shape is unknown, but it is frequently assumed as spherical. At ordinary velocities the mass of an electron is 6.3×10^{-28} grams; at rest, its mass may be zero; and at velocities approaching closely to that of light it becomes nearly infinite. Each electron carries an invariable negative electric charge of $1.1\ 10^{-19}$ $[=e]$ coulombs, $= 1.1\ 10^{-20}$ $[=e_m]$ electromagnetic units, $= 3.4\ 10^{-10}$ $[=e_s]$ electrostatic units. Some writers use the term to designate particles carrying positive charges and having other properties. Such use is not common nor desirable.

Electrons in a free condition are present in metallic conductors, in gases, especially at low pressures, and to a limited degree in ordinary solid dielectrics. They are not present in free ether or space. Combined with other electrons and with an unknown something or condition, that gives under certain conditions evidences of positive electrification, electrons are present in all matter. Their properties are in nowise dependent upon the properties of the matter with which they are associated, and they are considered to be indestructible by any agent within the command of man. Every electron is in some manner entangled with the luminiferous ether.

The ether is a fluid plenum or continuum, endowed with the properties of inertia and rotational elasticity, and is the medium through which all forces are exerted. It fills all space between electrons and the bounds of the universe; it is supposed by some to penetrate the electrons, and (Lorentz) remains stagnant during the passage of electrons through it.



Stationary. Moving to the left.

FIG. 1.—Distribution of electric flux from an electron.

Each electron, when isolated and at rest, produces at every point in the ether an elementary electrostatic field, corresponding in direction and intensity to its charge. All electrostatic fields are due to the resultant superpositions of such elementary fields. The force exerted upon an electron in a field of intensity E, produced by a plurality of electrons, is Ee, dynes, both quantities being expressed in electrostatic units. An electron moving with uniform velocity in a straight line at a velocity v cm/sec produces at every point both an electric field and a magnetic field, and carries them with it. If the motion be in the direction of the Z axis of coördinates, and the velocity be small as compared with that of the propagation of ether disturbances, at a point whose coördinates are x, y, z, the electric field will be radially directed, and have a magnitude E, in electrostatic units, the same as when at rest. With the electron at the origin and with a medium of unit permeability, the equation for E is

$$E = \frac{e_s}{4\,\pi}\ \frac{1}{(x^2+y^2+z^2)}; \tag{1}$$

and the intensity components α, β, γ, of the magnetic field parallel to the X, Y, and Z axes, respectively, are given by the equations;[1]

$$\begin{aligned} \alpha &= e_m\, v \frac{y}{(x^2+y^2+z^2)^{\frac{3}{2}}} \\ \beta &= -e_m\, v\ \frac{x}{(x^2+y^2+z^2)^{\frac{3}{2}}} \\ \gamma &= 0 \end{aligned} \tag{2}$$

For large velocities, the velocity of light being c cm/sec,

$$E = \frac{e_s}{4\,\pi}\,\frac{c}{(c\ -\ v)^{\frac{1}{2}}}\ \left\{ \frac{x^2+y^2\ +z^2}{\left(x^2+y^2+\ \frac{c^2}{c^2-v^2}\,z^2\right)^3} \right\}^{\frac{1}{2}}$$

$$\alpha = \frac{e_m\, c\, v}{(c^2-\ v^2)^{\frac{1}{2}}}\ \frac{y}{\left(\ x^2+y^2\ +\ \frac{c^2}{c^2-v^2}z^2\right)^{\frac{3}{2}}} \tag{3}$$

$$\beta = \frac{e_m\ c\, v}{(c^2-v^2)^{\frac{1}{2}}}\ \frac{x}{\left(x^2+y^2\ +\ \ \frac{c^2}{c^2-v^2}z^2\right)^{\frac{3}{2}}}$$

$$\gamma = 0$$

An electron, with its charge e_m, moving with uniform velocity v cm/sec at an angle θ to the direction of a magnetic field of intensity H, is acted upon by the field with a force whose magnitude is

$$F = H\, e_m\, v \sin\theta \text{ dynes.} \tag{4}$$

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[1] Heaviside, Phil. Mag., p. 324, April, 1889; J. J. Thomson, Cond. of Elect. Through Gases, p. 531.

If an electron, moving with a velocity small compared with c cm./sec. that of light, suffer a change, either in the magnitude of its velocity or in its direction, a radiation of energy between it and the surrounding ether will take place whose magnitude is[2]

$$J = \tfrac{2}{3}\frac{e_m{}^2\ a^2}{c}\ \text{erg/sec} \tag{5}$$

where a is the acceleration in cm/sec^2

Charge of the Electron. J. J. Thomson[3] and others have determined the magnitude of the charge carried by a negative gaseous ion, which is the same as that carried by an electron. The method employed for measuring the charge depends upon the discovery[4] that if a dust-free ionized gas, saturated with water vapor, be adiabatically expanded so that the ultimate volume bears to the initial volume a ratio of 1.25, droplets of water will form about the negative ions, but condensation will not occur around the positive ions until this ratio reaches the value 1.31. when droplets will form about both ions. Using an expansion of ratio 1.25, the charge on a negative ion can be found from a determination of the number of droplets and of the total charge on all the droplets. The number of droplets is obtained from a determination of the size of each droplet and the weight of all of them. The total weight can be obtained from the known properties of gases that are saturated with water vapor. The size of the droplets can be obtained from the rate at which the cloud, that they form in the enclosing receiver, settles. According to Stokes' law, the terminal velocity u cm/sec of a sphere of radius r cm and excess of density d, falling through a gas of which the coefficient of viscosity is η, is expressed by the equation

$$u = \frac{2}{9}\ \frac{dgr^2}{\eta},$$

whence

$$r = \sqrt{\frac{9\eta u}{2gd}}, \tag{6}$$

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[2] Larmor, Æther and Matter, p. 227; Phil. Mag., Dec., 1897, p. 512.

[3] J. J. Thomson, Phil. Mag., Dec., 1898, Dec., 1899.

[4] C. T. R. Wilson, Phil. Trans., A., 1897, p. 265.

g cm/sec^2 being the acceleration due to gravity. From observation of u and a determination of η the value of r is obtained.

The droplets upon falling are allowed to collect in an insulated receptacle connected with an electrometer. H. A. Wilson[5] checked the determination of the size of the droplets by observing their rate of movement in a strong electric field arranged to act against or with gravity.

The total charge was determined by Thomson by impressing a small potential difference v volts upon two parallel horizontal electrodes so placed as to include between them all the ionized gas, and by measuring the current-density I ampere/cm^2 which flowed through the gas. Let N = total number of ions per cubic cm, positive as well as negative, e = charge on each ion in coulombs, u' = sum of velocities under a gradient of one volt/cm, of positive and negative ions (determined by a special method), and l the distance between the electrodes, then the charge on each ion is

$$e = \frac{l\,i}{N u' V} \text{ coulombs.} \qquad (7)$$

Thomson's latest value for e_s is 3.4 10^{-10}, using an expansion ratio of 1.31 and thereby obtaining the total number of positive and negative ions.

Mass of the Electron. Many determinations of the ratio of the charge on an electron to its mass m have been made, from which, knowing the charge, the mass can be obtained. One method, used by Thomson, was to pass a stream of electrons, projected from a cathode in a highly exhausted tube, through a magnetic field of uniform intensity H and perpendicular in direction to the path of the electrons. If the electrons be moving with a velocity v cm/sec, the field will exert a force $e_m\, v\, H$ dynes upon them, and they will move in a circular path whose radius can be determined from the observed deflection of the stream; and has a value, as in any case of centripetal acceleration, of

$$r = \frac{m v}{e_m H} \text{ cm}$$

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[5] H. A. Wilson, Phil. Mag., April, 1903.

whence
$$m = \frac{r\, e_m\, H}{v} \text{ grams.} \tag{8}$$

To obtain v the electrons must simultaneously be subjected to the influence of an electric field of intensity E in electrostatic units, whose direction is perpendicular to the lines of force of the magnetic field and also to the original path of the electrons. By adjusting the intensity and sign of the electric field until the force it exerts upon each electron, $E\, e_s$, is equal and opposite to that exerted by the magnetic field, it follows that

$$E\, e_s = H\, e_m\, v, \tag{9}$$

or
$$v = \frac{E\, e_s}{H\, e_m},$$

and
$$m = \frac{r\, e_m\, H^2}{E} \; \frac{e_m}{e_s} \text{ grams.} \tag{10}$$

Another method of obtaining an expression for v, involving m and measurable quantities, used by Thomson, was to allow the electrons to bombard the face of a thermopile whose rate of increase of temperature could be determined from the rate of increase of the thermoelectromotive force. If the face of the thermopile be bombarded by N electrons per second, moving with a velocity v cm/sec, heat will be communicated to it at such a rate dk/dt that

$$\mathbf{K} = dk/dt = \tfrac{1}{2} N\, m\, v^2. \tag{11}$$

If the charges of the electrons be allowed to pass to an insulated conducting system connected with an electrometer, the rate of increase of negative charge can be obtained, and is

$$\mathbf{e} = de/dt = N\, e.$$

Therefore
$$v = \sqrt{\frac{2\, e\, \mathbf{K}}{m\, \mathbf{e}}}, \tag{12}$$

and
$$m = \frac{r^2\, e\, H^2\, \mathbf{e}}{2\, \mathbf{K}}. \tag{13}$$

Another method of obtaining an expression for v, used by Kaufmann[6] and by Simon,[7] is based upon the assumption that all the kinetic energy of the electrons is represented by the energy that would be required to transfer their charges between two points having a difference of potential V equal to that existing between the cathode and the anode of the containing tube.

In this case
$$\tfrac{1}{2} N m v^2 = V N e, \tag{14}$$

and substituting the value of v in (8),

$$m = \frac{r^2 e H^2}{2 V}, \tag{15}$$

This method gives too large values because it does not take account of the energy lost in collisions, and that required to detach the electron from the cathode.

Many other methods of determining m have been employed; all yielding values of the same order of magnitude, but differing considerably from one another. The first determination of the ratio e_m/m was made by Zeeman in connection with his experiments on the influence of the magnetic field upon the spectra of gases. The values obtained by various methods, and upon electrons obtained in various ways are given in the following table[8] from Lorentz:

Method.	$\frac{e_m}{m} 10^{-7}$	v/c
Zeeman effect	1.6 to 3	0.1 to 0.3
Rotation of plane of polarized light	0.9 to 1.8	
Cathode rays (Simon)	1.86	
Cathode rays (other observers)	0.7 to 1.4	
Ultra violet rays on zinc	0.7	
Radium β rays	1.75	Small.

The differences between the values obtained are probably due to some of the electrons being loaded with matter, and to the various velocities with which they were moving.

The influence of velocity upon mass has been determined

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[6] Kaufmann, Wied. Ann., 61, p. 544; 62, p. 596; 65, p. 431.

[7] Simon, Wied. Ann., 69, p. 589.

[8] Lorentz, Electrotechnische Zeits., June 15, 1905, p. 558.

by Kaufmann in the case of electrons ejected from radium preparations in the form of β rays.

Suppose a charged electron to be moving in a curved path, and to be accelerating both tangentially and radially. Let the tangential acceleration be a_1 and the radial be a_2. Inasmuch as a moving electron produces a magnetic field, whose lines are circular and lie in a plane perpendicular to the direction of motion and whose intensity at any point is proportional to the velocity of the electron, the acceleration must be accompanied by an increasing strength of field. As this increase requires that work be performed upon the ether, part of the force which causes the acceleration must be used in performing this work.

Let m_1 and m_2 represent two coefficients, which, when multiplied, respectively, by the accelerations a_1 and a_2, give the forces required to perform this work represented by the increasing intensity of the two components of the magnetic field. Then, if m_0 be the mass as ordinarily understood, of the electron, the tangential and radial components of the force, respectively, will be

$$\left.\begin{aligned} f_t &= a_1\,(m_0+m_1) \\ f_r &= a_2\,(m_0+m_2) \end{aligned}\right\}\ \text{dynes} \tag{16}$$

The coefficients m_1 and m_2 appear, therefore, to represent, respectively, longitudinal and transverse electromagnetic masses of the electrons, which it is assumed have also a true mass m_0.

Now m_1 and m_2 are not constant, but depend upon the velocity of the electron, as shown in equations (2), (3) and (5). For small velocities, as compared with that of light, if the electron be assumed as spherical of radius R cm. and with its charge e_m spread uniformly over its surface, m_1 and m_2 each have the value;[9]

$$m_1 = m_2 = \tfrac{2}{3}\ \frac{e^2{}_m}{R} \tag{17}$$

For greater velocities these values increase, until at the velocity of light they become infinite. Using analytical results obtained by Abraham, Kaufmann concludes from his experiments upon the deflection of β rays that, within the limits of experimental errors, (m_0+m_2) varies with the velocity as m_2 should, and therefore $m_0 = 0$, that is, a stationary electron has

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[9] Thomson, Recent Researches in El. and Mag. 1893, p. 21.

no mass whatsoever, and all the mass of a moving electron is due to its entanglement with the ether. The values determined by Kaufmann and the percentage difference from theoretical values based upon the assumption $m_0 = 0$ are given in the following table:[10]

v/c	m_2/m Observed	Per cent. variation from theoretical
Small	1.	——
0.732	1.34	−1.5
0.752	1.37	−0.9
0.777	1.42	−0.6
0.801	1.47	+0.5
0.830	1.545	+0.5
0.860	1.65	0.
0.883	1.73	+2.8
0.933	2.05	−7.8 (?)
0.949	2.145	−1.2
0.963	2.42	+0.4

The following curve shows the relation which exists between

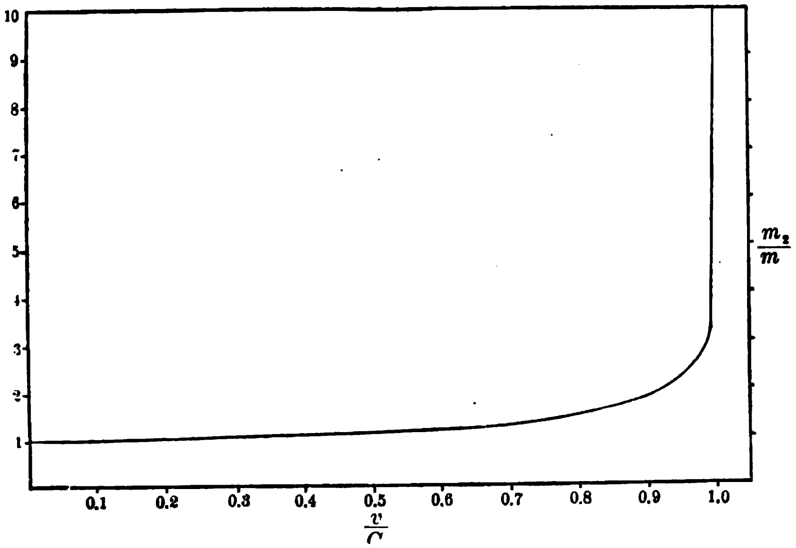

FIG. 2.

the mass of an electron, expressed in terms of its mass at low speeds, and its velocity expressed in terms of that of light.

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[10] Rutherford, Radio-Activity, p. 111.

The mass at small velocities is 6.3 10^{-28} grams. At a velocity equal to that of light, the magnetic flux surrounding an electron in a plane perpendicular to its path and passing through it, should become infinite; this follows from the substitution of $v=c$ and $z=0$ in equations (3). The electron thereby would acquire an infinite self-inductance. Consequently, an infinite force would need to be exerted upon it in order to produce a finite acceleration. The mass of the electron, therefore, at this hypothetical velocity would be infinitely large.

Size of the Electron. If it be assumed that the electron is spherical in shape, then, knowing its charge e_m and its apparent mass at low speeds m_1, its radius R can be obtained from equation (17)

$$R = \frac{2}{3} \frac{e^2_m}{m_1} = 1.3 \; 10^{-} \text{ cm} \tag{18}$$

which is much smaller than the diameter of atoms. Lorentz has been led to conclude, from the consideration of various phenomena appearing in moving systems of different kinds, that the electron is spherical when at rest, ellipsoidal at intermediate speeds, and a flat disc at the speed of light. Upon this assumption he obtains results, after a severe and complicated mathematical analysis, that are in accord with Kaufmann's experimental results, give larger masses for the same speed than those obtained by Abraham, give a mass of zero at rest, and are consistent with equation (17).

The Atom. On the supposition that the atom consists of a sphere of uniform positive electrification in which are contained a number of moving electrons. Thomson,[11] in 1904, endeavored to determine how electrons would arrange themselves in various atoms, and what properties would thereby be conferred upon the latter. Mathematical difficulties prevented a general solution for a spherical arrangement, but a solution for arrangements in rings was obtained. which has, by analogy, been applied to the spherical arrangement.

According to these results, it has been assumed that the atom consists of negatively charged electrons uniformly distributed over concentric spheres as a result of their mutual repulsion, and enclosed in a sphere of uniform positive electrification of such intensity that the electric field that would be

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[11] J. J. Thomson, Phil. Mag., March, 1904, p. 237.

produced outside the atom by the charges on the electrons is nullified.

Examination of the distribution necessary for equilibrium of such aggregates consisting of consecutive numbers of electrons, reveals the following facts:

1. The distribution of one aggregate may differ from that of another in having a greater number of electrons distributed upon one or more additional concentric shells. The first aggregate has as a nucleus the identical distribution of the second.

2. The equilibrium of the distributions of some aggregates may be very stable, while that of others is less so.

3. Some less stable aggregates will become more stable if one or a few electrons be added to it, thereby giving the atom which it represents a negative resultant charge.

4. Some less stable aggregates will become more stable if one or a few electrons be taken away from it, thereby giving the atom which it represents a positive resultant charge.

Assuming the atoms of the various chemical elements to be thus constituted, the equilibrium requirements will explain their physical and chemical differences and similarities. The different aggregates indicated in (1) would yield atoms of similar qualities, but different atomic weights, as lithium, sodium, and potassium. If an atom, consisting of an aggregate whose equilibrium would be rendered more stable by the losing of one electron, should be brought up to an atom requiring for stability an additional electron, a transfer of one electron would account for known facts. The first atom would afterwards have a resultant positive charge. The second atom would have a resultant negative charge, and the two would attract each other. The first atom would correspond to an electropositive atom, like that of sodium, and the second atom would be electro-negative like chlorine. After the change and resulting attraction, a molecule of sodium chloride is formed. Chemical affinity is thus considered to be due to electric attractions.

The number of electrons in an atom may vary from time to time, and the atom may therefore have a positive or negative electrification or may be neutral. The combination of two or more atoms, that are held together by electric attractions resulting from differences in the sign of their electrifications, constitute a molecule. The atoms may be of the same or different chemical elements.

If stable equilibrium is obtained by the loss of one and only one electron, the aggregate gives an atom that is univalent and electro-positive; if a single additional electron is required for stability the atom is univalent and electro-negative. The requirement of a loss or gain of two, three, or four electrons for complete stability characterizes the atoms as divalent, trivalent, and quadrivalent respectively.

More complex molecules, as for instance the various oxides of lead, result in some cases in an incomplete stability of the component atomic aggregates.

The electrons in the atom are supposed to be moving continuously in orbits, subject to displacement and distortion under certain circumstances. The large number of electrons and their entanglement with the ether has been offered as an explanation of the spectra characteristic of different substances, which are in some cases very complex.

Some aggregates are stable when the electrons move in their orbits with an angular velocity greater than a certain value and they become unstable when the velocity falls below this value. Electron velocities decrease very slowly as a result of the loss of energy which they radiate. When, however, the critical velocity is reached, an entirely new distribution may take place, and may be accompanied by ejection of some electrons from the atom. This is possibly what takes place in the case of radium.

As a consequence of the results obtained by Thomson,[12] in 1904, concerning the structure of the atom, many have concluded that an atom of hydrogen contains over a thousand electrons and that its mass is equal to the sum of the masses of the electrons. It, therefore, has no true mass, but merely an electromagnetic mass. They have also concluded that atoms of other atomic weights contain a proportionally larger number of electrons. Such an atomic structure would satisfactorily explain differences in the atomic weights and might lead to some conclusions explanatory of characteristic spectral complexities. Thomson, however. has more recently[13] concluded from experiments upon the dispersion of light in gases, upon the scattering of Röntgen radiation in gases, and upon the absorption of β rays from radium compounds that "the number of corpuscles (electrons) is not greatly different from their atomic weight." He finds from the dispersion due to hydrogen

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[12] Thomson, Phil. Mag., Vol. 7, No. 39, p. 237-265, March, 1904.

[13] Phil. Mag., p. 769, May, 1906.

that a hydrogen atom contains not far from one electron and that the mass of the carrier of positive electrical charge is large compared with that of the electron. From the scattering of Röntgen radiation in air he calculates that there are 25 electrons in a molecule of air.

The Ion. An important part is played in the phenomena of electrophysics by atomic aggregates of electrons that exhibit an external electrical field. When an aggregate or system of aggregates with an excess of positive or negative electrification is subjected to the influence of an auxiliary electric field, it tends to move in the same or opposite direction to that of the lines of force of this auxiliary field, according to the sign of its excess of electrification. It may then be termed an ion, positive or negative according to the sign of its excess of electrification. In the various physical states of matter are present the following:

NEGATIVE IONS

1. Isolated and free electrons.
2. One or more electrons acting as a nucleus for a cluster of molecules, the cluster roughly estimated, in some cases, as containing 30 molecules.
3. Atoms of electro-negative elements, the instability of whose aggregate has been reduced by the addition of one or more electrons.

POSITIVE IONS

1. Atoms of electro-positive elements, the instability of whose aggregate has been reduced by the subtraction of one or more electrons.
2. Molecular clusters from which an electron has been removed.

Negative ions may or may not be associated with ordinary matter. Positive ions are always found associated with it.

The lines of force of the electric field of an isolated ion are directed radially towards it as a center. In a molecule, while practically all the lines of force start from its electro-positive atoms and terminate upon its electro-negative atoms, thus being electrostatically nearly saturated, the field distribution is different for different planes passed through its molecular center. The molecule does not, therefore, suffer translation when placed in an auxiliary electric field, but rotates and orients itself. The orientation of a system of molecules produces a polarization of the substance containing the system.

Free electrons exist in gases at pressures under 10 mm. of mercury, especially when subjected to ionizing agencies; in conducting solids; in the β rays from radium; and in conducting flames.

Clusters exist in all conducting gases under pressures greater than 10 mm. of mercury; sometimes in gases at lower pressures, and possibly in liquids and solids.

Electronized or deelectronized atoms, or both, exist in all conducting gases at all pressures; both exist in liquid electrolytes, in solid conductors, and possibly in solid dielectrics.

The Production of Ions, or Ionization. In all gases at ordinary atmospheric pressures, spontaneous ionization is continually going on. This doubtless results from molecular collisions of an intensity much above the average. Recombination of positive and negative ions is also continually going on and will be discussed later. If an ionized gas of volume V cm^3 be enclosed in a receiver provided with two electrodes connected to the terminals of a source of electromotive force, an electric current can be made to flow through the gas and circuit. Under the influence of the electric field set up between the electrodes, the negative ions move towards the anode and the positive ions towards the cathode. A negative ion upon reaching the anode gives up to it an electron with its charge of $1.1\ 10^{-19}$ coulombs. The ion thus becomes transformed into an ordinary atom. What the anode does with the electron need not concern us at this point. In a like manner, the positive ion upon reaching the cathode receives from it an electron and itself becomes an ordinary atom. The double exchange is accompanied by what is generally understood as the conduction of $1.1\ 10^{-19}$ coulombs through the gas. It is also accompanied by the disappearance from the gas of one positive and one negative ion. If an increased voltage be employed, the velocity of the ions will increase, the current or rate of transference of electric quantity will increase, and the rate of disappearance will increase. The last can never be made to exceed the rate of production of ions. Therefore, a limiting saturation current is reached, which cannot be exceeded even though the voltage impressed upon the electrodes be increased so long as this increase does not of itself produce ionization. Spontaneous ionization of gases at ordinary atmospheric pressure will permit the passage of only about $3.3\ 10^{-18}$ amperes per cubic centimetre.[14]

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[14] Wilson, Proc. Camb. Phil. Soc. x; p. 32, 1900; Proc. Roy Soc. lxviii, p. 151, 1901.

Recombination of ions occurs in gases at a rate proportional to the square of the number present. If N ions per cm^3 be present at a given time, then the number n present after t seconds will be

$$n = \frac{N}{N\alpha t + 1} \tag{19}$$

where α is a coefficient of recombination, which equals[15] $1.1 \ 10^{-6}$ and has the same value for hydrogen, carbon dioxide, air, and probably other gases. Its value is independent of pressures above $\frac{1}{5}$ atmospheric, but decreases with decrease of pressures below this limit.

It has been determined by Townsend that an electron, moving in a rarefied gas along a free path whose terminal points differ in potential from each other by 20 volts, *i.e.*, 20/300 electrostatic units, acquires just sufficient energy to ionize a molecule with which it comes into collision. The energy required for the production of one negative and one positive ion from a gas molecule is therefore equal to the product of this potential drop by the charge on the electron, that is,

$$\frac{20}{300} \ 3.4 \ 10^{-10} = 2.3 \ 10^{-11} \text{ ergs.}$$

The velocity v acquired by the electron of mass m just before collision, is derived from the equation of energy $\frac{1}{2} m v^2 = 2.3 \ 10^{-11}$, and is

$$v = \sqrt{\frac{4.6 \ 10^{-11}}{m}} = 2.7 \ 10^{8} \text{ cm/sec} \tag{20}$$

This velocity is very great as compared with the mean molecular velocity of gases at ordinary temperatures. In weak electric fields, the electrons or negative ions, but not the positive ions, produce fresh ions by collision. In strong fields, both negative and positive ions produce them.

Salts introduced into the flame of a Bunsen burner are ionized and the flame becomes conducting Hot metals ionize the gas

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[15] Townsend, Phil. Trans A., 193, p. 129, 1900.

in contact with them and eject negative ions from themselves. A temperature of 200° cent. is sufficient to produce some ionization. Platinum[16] at 1500° cent. in a vacuum permits a maximum current towards it, by means of negative electrons which it throws off, amounting to one milliampere per square centimetre. Heated carbon filaments have been found to supply sufficient ions to allow of one ampere per square centimetre of surface.

Gaseous ions are also produced as a result of energy expended by radioactive substances, as by X-rays, by Lenard rays, by ultraviolet light, and likewise by chemical action.

Metallic Conduction of Electricity. Investigations concerning the nature of the process of electric conduction in metals have led to the conclusion that in the metals are to be found molecules and atoms of the metallic element, positive ions, and free electrons. The molecules and atoms are not free to migrate from one part of the metal to another, but have a limited freedom of movement about a mean position. The electrons are not constrained to any particular part of the metal, but are free to move from one part to another, such movement being accompanied by collisions and changes in the direction of movement, in a manner similar to that accompanying the movement of molecules in a gas, considered from the standpoint of the kinetic theory of gases. The positive ions have been supposed by some to change their positions, by others not. The number of free electrons per cubic centimetre of metal is very large, being of the order of a billion billions. The mean free path of an electron scarcely exceeds one millionth of a centimetre in any case. The number per cubic centimetre and the length of free path are different with different metals. In an ordinary metal at a uniform absolute temperature of T degrees, all the particles of the metal are in motion, collisions are constantly occurring, and the directions of the motion are such as result from chance. According to the doctrine of the equipartition of energy, the mean kinetic energies of the molecules, of the atoms, of the positive ions, and of the electrons, are equal to each other and dependent upon the absolute temperature. Inasmuch as the masses of the electrons are much smaller than those of the other particles, the velocities of the electrons must be much greater.

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[16] O. W. Richardson, Proc. Camb. Phil. Soc., xi, p. 286, 1902.

Following Drude,[17] assume a metallic conductor of unit cross-section, and length L cm's., containing N electrons per cubic cm. each of mass m and with a charge of e_s electrostatic units. If a difference of potential V in electrostatic measure be established between the ends of the conductor, the electrons will be subjected to the influence of an electric field of intensity $E = V/L$ and, during the interval of time τ between collisions, they will be subjected to a force in the direction of the length of the conductor such that

$$m \frac{d^2 L}{d \tau^2} = E\, e_s \text{ dynes.} \tag{21}$$

Integrating throughout the time τ and evaluating constants,

$$m L = \tfrac{1}{2} e_s E \tau^2 \tag{22}$$

The electrons, if the difference of potential be maintained, will in addition to their original undetermined velocities have a velocity component v_L in the direction of L such that

$$v_L = \tfrac{1}{2} e_s E \frac{\tau}{m} \tag{23}$$

A quantity of electricity will pass per second through a cross-section of the conductor, which constitutes a current I_S in electrostatic units, such that

$$I_s = e_s N v_L = \tfrac{1}{2} e_s^2 N \frac{\tau}{m} E = \tfrac{1}{2} e_s^2 N \frac{\tau}{m} \frac{V}{L} \tag{24}$$

The resistance per unit length, that is the resistivity of the metal, will, in electrostatic units, be

$$\rho = \frac{V}{L I_s} = 2 \frac{m}{e_s^2 N \tau} \tag{25}$$

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[17] Drude, Trans. Int. El. Cong., 1904, Vol. 1, p. 319.

The specific electric conductivity will equal the reciprocal of the expression or

$$\sigma = \tfrac{1}{2} e_s^2 N \frac{\tau}{m} \tag{26}$$

It is desirable to substitute for τ another expression, which takes into account the mean velocity, v, of the electron in the direction of its path and the average length λ of its free path. Since $v\tau = \lambda$

$$\sigma = \tfrac{1}{2} e_s^2 N \frac{\lambda}{v m} \tag{27}$$

Metallic Conduction of Heat. It is probable that the flow of heat in metal under maintained difference of temperature is due to the presence of electrons in the metal, they acting as carriers and distributors of energy which they possess in the kinetic form. According to the kinetic theory of gases, every molecule or particle possesses an average kinetic energy h at an absolute temperature of T such that

$$h = \alpha T, \tag{28}$$

where α is a universal constant which has a value of 1.6×10^{-16} ergs per absolute degree. If metals be ultimately constituted as has been assumed, then an electron, when uninfluenced by electric or magnetic forces, has the same energy as a gas molecule at the same temperature.

From the kinetic theory of gases, an expression for the heat conductivity of the metallic conductor, considered above, may be obtained. If one end of it be heated, the flow of energy or heat Q per second in the direction of its length and across any transverse cross-section of the conductor is given[18] by the equation

$$Q = \frac{v \lambda N}{3} \frac{dh}{dL} \text{ erg/sec.} \tag{29}$$

Substituting the value of h from (28),

$$Q = \tfrac{1}{3} \alpha v \lambda N \frac{dT}{dL} \tag{30}$$

The heat conductivity k of the metal in mechanical units, that

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[18] Drude, l. c., p. 321.

is, in ergs per square centimetre per absolute degree per centimetre, is obtained by reducing the temperature gradient dT/dL to unity. The expression is then

$$k = \tfrac{1}{3}\,\alpha\, v\, \lambda\, N \qquad (31)$$

It has long been known that with some exceptions the heat and electrical conductivities of pure metals, when at proper temperatures depending upon the metal, bear a constant ratio to each other. This is the law of Wiedemann and Franz. No satisfactory explanation for the constancy has been given except that which assumes that both electricity and heat are conveyed by electrons, the one under the influence of electromotive force and the other under the influence of thermomotive force. Dividing (31) by (27) and substituting $2\,\alpha\, T$ for $m\, v^2$

$$\frac{k}{\sigma} = \frac{4}{3}\left(\frac{\alpha}{e_s}\right)^2 T \qquad (32)$$

The following table of Jaeger and Disselhorst[19] gives the values of k/σ at 18° cent., at 100° cent., and the ratio of the latter to the former. In this table is also given the number of electrons N per cubic centimetre, calculated by Drude[20] from data concerning the optical behavior of metals, and the mean length λ of their free path.

Metal	$k/\sigma\ 10^{-8}$ (18°)	$k/\sigma\ 10^{-8}$ (100°)	$\frac{k/\sigma\ (100°)}{k/\sigma\ (18°)}$	$N\ 10^{-22}$	$\lambda\ 10^{6}$ cm
Aluminum......	636	844	1.32	14.	0.2
Copper.......	665	862	1.30	4.09	1.1
Silver........	686	881	1.28	6.35	0.9
Gold.........	727	925	1.27	4.36	0.9
Nickel........	699	906	1.30	9.21	0.08
Zinc.........	672	867	1.29	18.4	0.08
Cadmium.....	706	905	1.28	11.9	0.1
Lead.........	715	935	1.31	11.2	0.034
Tin..........	735	925	1.26	14.3	0.05
Platinum.....	753	1013	1.35	13.65	0.06
Palladium....	754	1017	1.35		
Iron.........	802	1061	1.32	14.6	0.05
Bismuth......	962	1077	1.12	10.8	0.007
Antimony....				26.	0.006

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[19] Jaeger and Disselhorst, Berliner Berichte, 38, 1899, p. 719.

[20] Drude, l. c., p. 327.

That k/σ is directly proportional to the absolute temperature is clearly indicated by the values given in the fourth column of the table. The coefficient $\frac{1}{273}$, common to gases, would give, for the temperature difference here employed, viz., $100^\circ - 18^\circ = 82^\circ$, the value 1.28.

The specific heats of metals are not so large as might be expected with such a large number of free electrons per unit volume.

To meet this difficulty, Thomson[21] assumes that the electrons are not free for a sufficiently long interval to acquire the energy corresponding to a given temperature. They suddenly shoot out from one atom into a neighboring one. On this basis, he calculates the values of k/σ and finds a difference of but about 12% from Drude's values.

Contact Electromotive Force. If two metals, having N_1 and N_2 free electrons, respectively, per cubic centimetre, be placed in contact with each other, and if $N_2 > N_1$, and the temperature be constant and uniform, then, according to the principles of the kinetic theory of gases, more electrons will pass from the latter into the former than in a reverse direction. This will give a negative charge to the former, and will thereby set up an electric field, whose lines of force will be perpendicular to the plane of separation; which will tend to reduce the velocity of the electrons entering the former and increase the velocity of those leaving it. An equilibrium will eventually result when as many electrons pass in one direction as in the other.

A contact difference of potential, of a value which can be predetermined if N_1 and N_2 be known, is established across the surface of separation. Drude[22] has derived an expression for this contact e.m.f., which at 18° cent. reduces to the form

$$E = 0.05 \log_\varepsilon \frac{N_2}{N_1} \text{ volts} \tag{33}$$

For other uniform temperatures, the value of E varies directly with the temperature expressed in absolute degrees. The complete expression for E is

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[21] Report of Lecture before I. E. E., Electrical Engineering, Feb. 28, 1907, p. 381.

[22] Drude, l. c., p. 323.

$$E = \frac{4}{3}\ \frac{\alpha}{e_m} T \log_\epsilon \frac{N_2}{N_1} 10^{-8} \text{ volts} \qquad 34)$$

where α is the thermodynamic constant, e_m the charge of an electron in electromagnetic units, and T is the absolute temperature.

Seebeck Thermal Electromotive Force. If a circuit be formed of two metals connected in series, and if the difference in temperature between its two junctions be $d\,T$ absolute degrees, then the thermal electromotive force $d\,E$ set up as a result, is obtained by differentiation of (34) and equals

$$d\,E = \frac{4}{3}\ \frac{\alpha}{e_m} d\,T \log_\epsilon \frac{N_2}{N_1} 10^{-8} \text{ volts,} \qquad (35)$$

from which the value of the thermoelectric power can be obtained. This expression assumes that N_2/N_1 does not vary with T, concerning which there is as yet not sufficient experimental evidence.

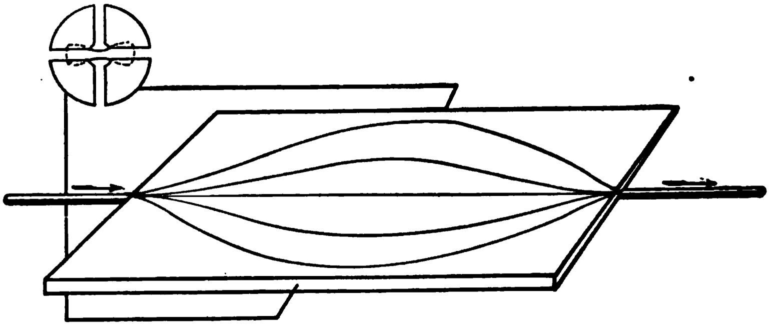
From equations (34) and (35), an expression is readily obtained for the rate of absorption or development of heat when a current I (amperes) flows in the circuit. This power P, which is a measure of the Peltier effect, is expressed as follows:

$$P = E\,I = \frac{4}{3}\ \frac{\alpha}{e_m} I\,T \log_\epsilon \frac{N_2}{N_1} 10^{-8} = I\,T \frac{d\,E}{d\,T} 10^{-8} \text{ watts.} \qquad (36)$$

Drude has also obtained an expression for the Thomson effect, that is, the development or absorption of heat as the result of a current that flows through a homogeneous circuit having local temperature differences.

Electromagnetically Induced Electromotive Force. The generation of electromotive force as a result of the relative motion between a conductor and the flux of a magnetic field is a direct consequence of the ether entanglement with the electron. A force acts directly on each electron whose direction is determined by the directions of the flux and of the motion, and whose magnitude depends upon the relative velocity and the flux-density.

The Hall Effect. Consider a rectangular piece of sheet metal with a current flowing along it. If the current enter by a terminal connected to the middle point of one edge of the rectangle and leave by a terminal connected to the middle point of the opposite edge, there will be a zero potential difference between two points located respectively at the centers of the remaining opposite edges. A galvanometer connected between these last two points would give no deflection. If now a magnetic flux be passed perpendicularly through the surface of the sheet, a current will flow through the galvanometer circuit, whose magnitude will be directly proportional to the strength of the original current and to the flux-density of the magnetic field, and whose direction will be reversed if the direction of



ɪɢ. 3.—Flow lines of current.

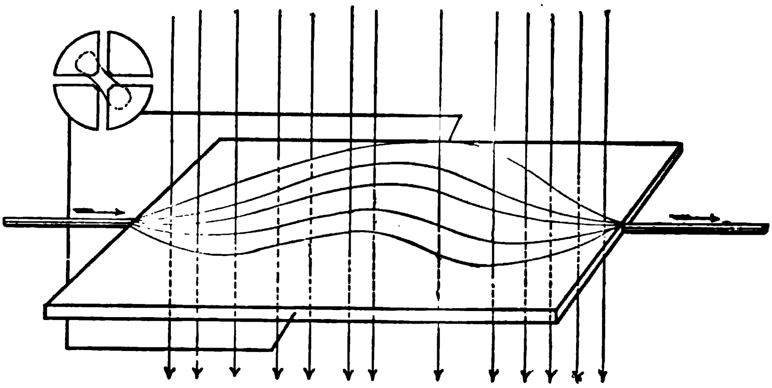


FIG. 4.—The Hall effect.

either the flux or of the original current be reversed. This phenomenon is known as the Hall effect. This effect is readily explained from the standpoint of the electron theory.

The electric current may be considered as accompanied by a procession of electrons moving in the sheet in a direction opposite to that of the current flow. Let the migration velocity of the electrons be v cm./sec., the charge of each be e_m electromagnetic units, and the magnetic flux-density be H, a transverse force F will be exerted upon each electron whose value will be $e_m v H$ dynes; and in consequence they will be forced towards one side of the sheet, and a flow of current through the galvanometer circuit will be necessary to maintain equilibrium. If no galvanometer circuit be present, a negative charge will appear at the side towards which the electrons move, and will grow until the transverse electric field which it occasions attains such an intensity E, in electromagnetic units, as to exert a force $e_m E$ dynes upon each of the electrons equal in magnitude and opposite in direction to that exerted by the magnetic field. Then

$$e_m E = e_m v H$$

Since e_m is known and E and H can readily be obtained by experiment, it is possible to obtain the average migration velocity v of an electron from the above formula, as

$$v = \frac{E}{H} \tag{37}$$

Boltzmann calculated v for various metals several years ago. The velocities are remarkably small for even very strong currents. Lorentz[23] gives the following values for one ampere flowing through a wire of one square millimetre cross-section: copper 0.005, nickel 0.2, and bismuth 90 cm./sec.

Some experimental results obtained in this field are not easily explained. The direction of the current in the galvanometer circuit, when an iron sheet is employed, is opposite to that which is to be expected. A thorough investigation of the Hall effect in ferromagnetic substances may shed some light upon the question of the cause of their large permeability. Thomson[24] explains the apparently inconsistent results by the

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[23] Lorentz, l. c., p. 588.

[24] Electrical Engineering, Feb. 28, '07.

assumption of a gyrostatic action of the molecule which causes the electrons to move in a different direction from that of the force exerted upon them by the magnetic field.

Solid Dielectrics. Solid dielectrics probably contain some free electrons, although the number per unit volume is small compared with that in metals. To free electrons is due the conductivity of solid insulators that remains after surface leakage has been prevented. Free atomic ions are probably absent, since conduction through their mediation would result in a transport of matter with accompanying differences in the chemical and physical character of the surface layers of the dielectric when kept between conductors having a maintained difference of potential. Such transport has not been observed. If the atomic ions of a dielectric are not possessed of freedom of migration, the maintenance of a mean position of equilibrium must be due to the attractions and repulsions of unlike and like charged particles. If a distinction is to be drawn between atomic ions devoid of freedom of migration and molecular aggregates of atoms, then the latter are probably also present.

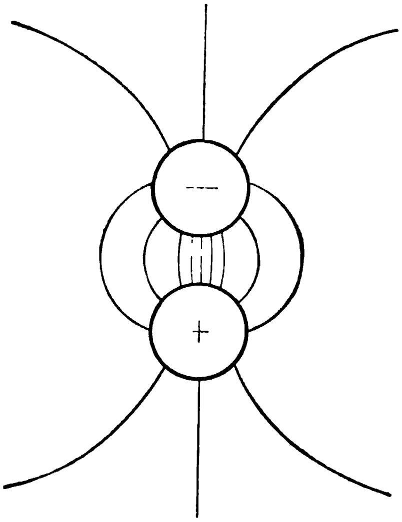

Fig. 5.—Dumb-bell molecule.

Consider a diatomic molecule in a solid dielectric. Although nothing is known of the shape of a molecule, and although in the treatment of the kinetic theory of gases it is frequently assumed to be spherical, it seems reasonable to assume, from the standpoint of the present discussion, that it is not spherical and that it may be shaped somewhat like a dumb-bell with an atom at each end connected by a sheaf of electrostatic flux lines. Such a molecule would behave in an electric field much as would a magnetic needle of the same shape in a magnetic field. Both would orient themselves, but would not suffer translation if the fields were uniform, and the molecule would have an electric moment similar to the magnetic moment of the needle. But, while the pole distance is rigidly maintained by the steel in the needle, this is not the case with the end atoms of the dumb-bell molecule. With a sufficiently large electrostatic flux-density, the molecule would be ruptured, its oppositely charged atoms being forced away from each other by the field. The rupturing of an assemblage of such molecules in a solid dielectric would, in such a field, manifest itself as a rupture of the dielectric. The molecular-magnet theory[25] of magnetic induction in iron, can, by analogy, be directly applied to solid dielectrics consisting of an aggregate of such dumb-bell molecules. The application of an electric field would orient the molecules to a greater or less extent, which would be evidenced as a residual polarization after the field was removed. Such polarization is a common occurrence. The flux due to the orientation would be superposed on the ether flux produced by the original source of the field, the dielectric thus exhibiting a larger dielectric constant than the free ether. That the dielectric constant of all solids is greater than unity is well known. Under the influence of alternating fields, the configuration of orientation would be different for the same values of increasing and decreasing intensities. This would result in a dielectric hysteresis of greater or less extent accompanied by an energy loss which would be dissipated in heat. This loss in ergs per cubic centimetre per cycle G has not only been observed, but its magnitude, as dependent upon the material and maximum electric flux-density E_{max}, is expressed by a formula[26] similar to Steinmetz's law for iron, the exponent n of E_{max} lying between 1.5 and 1.95, and corresponding to 1.6 in the Steinmetz formula. If α represent a constant dependent upon the character of the dielectric,

$$G = \alpha\, E^{n}{}_{max} \text{ ergs.} \qquad (38)$$

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[25] Ewing, Magnetic Induction in Iron and Other Metals, p. 382.

[26] R. Threlfall, Phys. Rev., 1897, iv, p. 457; v, p. 21.

A tendency to dielectric saturation, accompanied by a reduced specific inductive capacity corresponding to the saturation and reduced permeability in iron under increase of electric flux-density, has been observed in the case of crown glass, guttapercha, megohmit, and paraffined paper.[27]

The lack of rigidity of connection between the atoms of a dumb-bell molecule permits vibration of the atoms about a mean position relative to each other. There is a natural period for such vibrations. If now an alternating electric field of this natural period be impressed upon the molecule, an interatomic vibration would be started at the expense of energy supplied by the field. The natural frequency is very large, of the order of those due to light disturbances. The propagation of light disturbances is always accompanied by an alternating electric field of high frequency. If now light, of such color as to have a frequency synchronous with the natural frequency of vibration of the atoms of the dumb-bell molecule, be passed through a transparent dielectric containing such molecules, its velocity therein would be reduced below that which would exist for higher or lower frequencies, and a prismatic spectrum, produced by passing white light through a prism of such dielectric, would therefore show the colors in other than their usual order, that is, the prism would cause what is termed anomalous dispersion. The natural frequency of vibration of quartz molecules is such that radiations of wave-lengths much longer than those of red light ($\lambda = 56\ \mu$) are refracted by a quartz prism more than violet light.[28]

The argument outlined above applies equally well to molecules of greater atomicities and complexity. It is also applicable to the negatively charged electrons and positively charged remainders of atoms, if it be assumed that these can be separated under the action of an electric field. Such an assumption is made by J. J. Thomson.[29]

The Production of Light. Many efforts have been made to explain the characteristic spectra of the various chemical elements from the standpoint of the electron theory. For many reasons, such efforts can hardly be considered as successful, as clearly presented by Crew.[30] There is as yet too little knowl-

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[27] J. A. Fleming, Electric Wave Telegraphy, p. 137.

[28] Rubens and Aschkinass, Wied. Ann., 67, p. 459, 1899.

[29] J. J. Thomson, Phil. Mag., May, 1906.

[30] Henry Crew, Science, N. S., Vol. XXV, No. 627, p. 1-12, Jan. 4, 1907.

edge concerning the relations which exist between electrons and atoms as they occur in the various forms of matter. Furthermore, hardly anything is known about the positively electrified portion of matter or about positive electricity itself. This much, however, can be considered as established; that an electron with its negative charge e_m, when accelerating a cm/sec.^{2} the velocity of propagation of ether disturbances being c cm./sec., radiates energy into space whose value (see equation 5) is expressed as

$$J = \frac{2}{3} \frac{e_m^2 \, a^2}{c} = 2.7 \times 10^{-49} \, a^2 \text{ erg/sec} \qquad (39)$$

If by any means the sign of acceleration be changed periodically at a constant frequency having a value lying between 4×10^{14} and 8×10^{14}, then the radiant energy will consist wholly of monochromatic light radiation. Change in sign can be obtained either by reversing the direction of motion in a rectilinear path with accompanying changes in velocity (collision or impact), by merely changing the direction of the path (circle) leaving the velocity unchanged, or by both. If on the other hand the duration of the periods between reversals be variable within wide limits, then there will be non-luminous heat radiation, continuous spectrum luminous radiation, and ultraviolet radiation. In this case only a portion of the energy which is radiated is converted into light.

The acceleration which an electron may assume, varies over very wide limits. When it is considered that, within a vacuum tube of a few centimetres length, an electron can start from rest and attain a velocity of one-tenth that of light, that is, $3 \ 10^9$ cm/sec, its acceleration must have been at least $2 \ 10^{17}$ cm/sec The distribution of voltage in such tubes would indicate that its acceleration near the cathode would be many times greater than this. Assuming it to be five times as great; that is, $a^2 = 10^{36}$ cm/sec^2, this electron would radiate $2.7 \ 10^{-13}$ erg/sec or $2.7 \ 10^{-20}$ watt.

Black-Body Radiation. According to the Stefan-Boltzmann[31] law, a black body (one which absorbs all radiations falling on it and which neither reflects nor transmits any) at an absolute

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[31] Stefan, Ber. d. k. Akad. d. Wiss., 79B., 2 Abth., 1879, p. 391; Boltzmann, Wied. Ann., 22, p. 291, 1884.

temperature of T degrees, radiates from each square centimetre of its surface an amount of energy[32]

$$\begin{aligned} j &= 1.71\ 10^{-5}\ T^4 \text{ erg/sec} \qquad (40) \\ &= 1.71\ 10^{-12}\ T^4 \text{ watt} \end{aligned}$$

This radiation, at sufficiently high temperatures, consists of wave disturbances embodying all frequencies that are able to stimulate the optic nerves, besides a continuous series of frequencies in the infra-red and ultraviolet regions.

The portion, W, of the total radiation per cm^2 that is capable of stimulating the optic nerves so as to given a sensation of light is to be obtained from the equation[33]

$$W = C\left(\frac{T}{k}\right)^4 \lambda'^{-3}\ e^{-\frac{k}{\lambda' T}} \left\{\left(\frac{k}{T}\right) + 3\left(\frac{k}{T}\right)^2 \lambda' + 6\left(\frac{k}{T}\right)\lambda'^2 + 6\lambda'^3\right\}$$

$$-\,C\left(\frac{T}{k}\right)^4 \lambda''^{-3}\ e^{-\frac{k}{\lambda'' T}} \left\{\left(\frac{k}{T}\right)^3 + 3\left(\frac{k}{T}\right)^2 \lambda'' + 6\left(\frac{k}{T}\right)\lambda''^2 + 6\lambda''^3\right\}$$

erg/sec (41)

where $\lambda' = 0.000039$ = wave length at violet end of spectrum in cm.

$\lambda'' = 0.000075$ = wave length at red end of spectrum in cm.
$C = 1.24\ 10^{-5}$
$k = 1.4135$
$e = 2.718$ = Naperian logarithmic base.

The visible radiation efficiency at any temperature T is therefore

$$\varepsilon = \frac{W}{j} \qquad (42)$$

Carbon filaments are generally considered to yield approximately black-body radiation.

The radiated energy is not equally distributed among the various frequencies. Planck[34] has shown that the energy

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[32] F. Kurlbaum, Wied. Ann., 65, 1898, p. 746; Drude, Theory of Optics, p. 515.

[33] Mendelhall and Saunders, Astrophys. Journ., 1901, p. 46.

[34] Planck, Verh. d. Deutsch. Phys. Geo., 2, 1900, p. 202; Ber. d. k. Akad. d. Wiss., Berlin, 1901, p. 544.

radiated per cm² between wave-lengths λ and $\lambda+d\lambda$ can be represented by the equation

$$E = C\lambda^{-5}\frac{1}{e^{\frac{k}{\lambda T}}-1} \tag{43}$$

The physiological characteristics of the normal eye are such that for different wave-lengths different rates of energy are required to be received upon the retina in order to produce the same intensity of sensation. Therefore, while values of ϵ indicate the stimulative portions of radiation, they do not indicate the amounts of luminous sensation that thereby might be produced. Although the sense responsiveness of the eye for a given color varies and depends on the individual, on the portion of the retina stimulated, on visual fatigue, and on the rapidity of iris response to variations in intensity, an average sensation equivalent of W can be obtained by making use of Abney's[35] coefficients of luminosity for the normal eye. With wave-lengths as abscissas, values of E are plotted as ordinates. The values of E are each multiplied by the luminosity coefficient corresponding to the wave-length and used as ordinates in plotting a new curve. If the values of λ be limited to the visible spectrum, then the area included between the first curve and the axis of abscissas is proportional to W, while the area Z between the second curve and the axis is proportional to the sensation equivalent. The luminous efficiency of the radiation is then

$$\eta = \frac{Z}{j} \tag{44}$$

As the temperature of a black body rises not only does the power radiated increase but the predominating frequency rises, that is, the wave-length λ_m at which the intensity of radiation is the greatest, decreases. At an absolute temperature[36] T

$$\lambda_m = \frac{0.2887}{T}\text{ cm.} \tag{45}$$

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[35] Abney, Color Vision, 1895.

[36] Drude, Theory of Optics, 1902, p. 523; Wien. Berl. Ber., 1893, p. 55; Wied. Ann., 49, 1893, p. 633; 52, 1894, p. 132.

The intensity of the radiation at these wave-lengths also increases as the fifth power of the absolute temperatures.

If a black body, for example, a carbon filament, be considered as containing free electrons as well as atoms and molecules, then as its temperature is raised the mean kinetic energy of each electron would be increased. Inasmuch as the geometrical dimensions of the filament are not materially altered by the change of temperature, it is reasonable to assume that the length of free path is not increased. The increase of energy, causing an increase of electron velocities, will result, therefore, in an increased frequency of collisions and an increased rate of change of velocities. This accounts for the direction of the shifting of λ_m with rise of temperature, and for the accompanying increase of total radiation. Many of the collisions will occur oftener than at the preponderating frequency, and others will occur less often, which accounts for the character of the distribution of radiated energy over a wide range of frequencies. The accelerations which accompany collisions of the higher frequencies are of necessity greater than in the case of lower frequencies. The radiated energy is therefore greater in the former case than in the latter, and the curve of distribution of radiated energy over different frequencies is not symmetrical but deviates from the curve of probabilities.

Selective Radiation. No material radiates in accordance with the laws of black-body radiation. One of the first conclusions of Maxwell's electromagnetic theory is that good conductors of electricity cannot be transparent. Hagen and Rubens[37] have shown how the absorbing power and the emissive power of metals can be calculated from their electrical conductivities. Their experimental results for the longer heat-waves are very satisfactory. Kirchhöff's law, according to which the ratio between the emission and the absorption for all bodies has the same value, being a universal function of the absolute temperature and of the wave-length, has also been accounted for from the standpoint of the electron theory. Lorentz, using the expression for the electrical conductivity previously developed [see equation (29)] has calculated the value of this function. He then compares the amount of energy radiated from a metal within the limits of certain long wave-lengths with the experimental values obtained by Lummer and others, and finds that they are in accord.

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[37] Hagen and Rubens, Ann. der Phys., 11, p. 873, 1903.

Luminescence. At all temperatures above absolute zero, all bodies radiate energy. If the nature of the body be not changed by this radiation; that is, if it continues to radiate in the same manner, as long as its temperature is maintained constant by the addition of heat, the process is termed pure temperature radiation. If, on the other hand, the body changes because of the radiation, and does not continue indefinitely to yield the same radiation although its temperature is kept constant, the process is termed luminescence. The cause of some of the radiation in the latter case does not lie in the temperature of the system but in some other source of energy. According as the extra supplied energy accompanies either chemical transformations, exposure to light, or the passage of electric currents, the processes are respectively termed chemico-, photo-, and electro-luminescence. The total radiation from a body of this class is made up of two parts, that due to its temperature and that due to the extra energy. If the intensity of radiation of a body within any region of wave-lengths is greater than that of a black-body at the same temperature, luminescence must be present. This is frequently[38] taken as a criterion for the detection of luminescence. The frequencies of luminescent radiations are more or less restricted, being often evidenced by bright-line spectral distributions. The electrons which yield these radiations are supposed to vibrate harmonically under conditions that are not yet understood. That their movements are not governed simply by chance seems to follow from the character of the spectra. Although change in the character of the material as a consequence of its yielding luminescent radiation may not be capable of detection by chemical analysis, yet the atomic and molecular systems are nevertheless doubtless undergoing constant changes due to the loss or gain of electrons. The entrance of an electron into a system, or its ejection, must without doubt occasion complex harmonic disturbances of many or all the electrons in the system.

If luminescent radiation be confined chiefly to wave-lengths of the visible spectrum, the luminous efficiency of the body becomes high. Herein rests the economic significance of the efforts being made to advance the art of lighting by means of vacuum tube and flaming arc lamps.

A very interesting example of luminescent radiation is that

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[38] Drude, Theory of Optics, p. 528.

which is yielded by photogenic bacteria, which are frequently found in sea-water and upon meats and fish that have been directly or indirectly infected by sea-water. They are the sources of light known as the phosphorescence of the sea. Some cases of phosphorescence in animals and in plants are explained as an infection with them. Gorham[39] has shown that the light which they give is the result of chemical transformations accompanying metabolism inside the cells of their bodies. When fed with substances such as asparagin or glycocoll, they are able to grow and reproduce but not to give light. In Gorham's summary, occurs the following:

> We therefore conclude that for light production there must be present, over and above the requirements for growth, the oxygen of the air, *sodium or magnesium*, and certain organic acids, derived from the decomposition of the carbon and nitrogen constituent of the food.
>
> The chemical energy resulting from the union of the sodium or magnesium with these organic acids, in the presence of oxygen, or from the later combustion of the products of that union, is set free in the form of light.

The brightness of these bacteria considered as sources of light is very small. Lode's[40] measurements show an intensity of emission of 0.00069 candles per square meter. This is too small to stimulate the color sense. The *bacillus lucifer* of Molisch,[41] however, is much brighter, gives a continuous spectrum in the green, blue, and violet, and is able to stimulate the color sense.

Conclusion. Although much is known concerning the size and mass of the electron, its electric and magnetic effects when in motion, and its radiation effects during acceleration, little more is known concerning its structure than that:[42]

> It is the intrinsic strain-form alone that constitutes the electron; and it is a fundamental postulate that the form can move from one portion to another of the stagnant ether somewhat after the manner that a knot can slip along a cord.

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[39] F. P. Gorham, The Photogenic Bacteria, Doctor's Thesis, Harvard Univ., May 1, 1903.

[40] Lode, Zentralbl. für. Bakt., I 35, Bd., p. 524.

[41] Molisch, Leuchtende Pflanzen, 1904, p. 133.

[42] Larmor, Æther and Matter, 1900, p. 335.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

THE HEATING OF COPPER WIRES BY ELECTRIC CURRENTS

BY A. E. KENNELLY AND E. R. SHEPARD

In August 1889, a report was made by one of the present writers[1] to the Edison Electric Light Co., on " The Heating of Conductors by Electric Currents." The report was published in the minutes of the convention of the Association of Edison Illuminating Companies, at Niagara Falls, August, 1889. It contained a large number of measurements of the temperature elevations of active conductors supported in wooden moulding, and in free air, within doors and without. A further report was made in 1893[2] upon the temperature elevations of electric-light cables. The research reported in the present paper has been undertaken to extend the scope of the above measurements, and also to increase the precision of the results previously obtained. In the measurements of 1889 and 1893, above referred to, the temperature-coefficient of resistivity of copper wires was taken as 0.388 per cent. per degree centigrade of temperature elevation; whereas it is now taken by the American Institute of Electrical Engineers as 0.42 per cent. per degree centigrade from and at 0° cent.[3] Again, the law of thermal radiation employed was that of Dulong and Petit;[4] whereas the law of radiation generally adopted at this time is that of Stefan.[5]

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[1] The Heating of Conductors by Electric Currents, by A. E. Kennelly, *The Electrician*, Dec. 13th, 1889, Vol. XXIV, p. 142; *The Electrical World*, Vol. XIV, No. 21, p. 336, Nov. 23, 1891.

[2] The Carrying Capacity of Electric Cables, Submerged, Buried or Suspended in Air, by A. E. Kennelly, Minutes of the Ninth Annual Meeting Association of Edison Illuminating Companies, 1893, p. 79.

[3] Trans. Am. Inst. Elect. Engineers, Vol. XIX, p 1082, June, 1902. Standardization Report.

[4] Annals de Chemie et de Physique, 1817, Vol. VII.

[5] **Wien. Akad. Ber., 1879, LXXIX, pp. 391–428.**

Although these changes in physical data and constants do not greatly affect, from an engineering standpoint, the results previously obtained; yet it seemed desirable to make a new series of measurements[6] and deduce their results with the aid of the most recent data. It is the object of this paper to describe the new measurements, so far as they relate to wires in water, soil, or wooden moulding, leaving the measurements on wires in air to some future occasion.

Method of Determining Temperature Elevations. The copper conductor under test had a length of from 2 to 6 metres (6.56 to 19.69 feet). Pressure wires were soldered to it near its ends. The resistance of the conductor between these pressure wires was determined; first, when cool, *i.e.*, at the temperature of the surrounding air, and second after having been heated by an electric current of measured strength. The increase in the resistance of the conductor enabled its increase in temperature to be determined by the formula:

$$R_t = R_0 (1+0.0042\,t) \qquad \text{ohms} \qquad (1)$$

where R_0 is the resistance of the conductor at 0° C., and R_t its resistance at t° C.

Method of Measuring the Resistance of the Copper Conductors. The resistances of the copper conductors under test were measured by a differential galvanometer; *i.e.*, by connecting one coil of a differential galvanometer to the pressure wires on the tested conductor, and the other coil to the terminal of a german-silver constant resistance of determined amount in circuit with the tested conductor. Extra resistance was inserted in the circuit of the coil of preponderating current until the galvanometer deflection was zero, or the two currents differentially balanced. Under these conditions, the resistance of the tested conductor became known in terms of the constant german-silver resistance. As the tested conductor increased in temperature, its changes of resistance could readily be observed and followed, by noting the change in the balancing resistance.

The electrical connections employed are indicated diagrammatically in Fig. 1. A separate motor-driven low-voltage direct-current dynamo Y, of 3-kw. capacity (300 amperes at

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[6] The research was carried on at Pierce Hall, Harvard University, and a report thereon formed the subject of a thesis for the degree of A.M. by E. R. Shepard, entitled : "The Heating of Copper Wires by Electric Currents." 1906.

10 volts), was connected by stout leads to the conductor $C\,C$, under test, in another room, through a grid resistance D of german-silver wires and a regulating resistance R. The current strength in the circuit was measured by the Weston ammeter A, and adjusted partly by varying the resistance R and partly by varying the shunt field rheostat F. The differential galvanometer G has one coil connected to pressure wires on the standard grid resistance D, and the other coil to pressure wires on the tested conductor $C\,C$. An adjustable resistance r was inserted in one or the other of the two galvanometer circuits as occasion required, in order to secure a differential balance. Switches in the main circuit and in the galvanometer circuits have been omitted from the diagram.

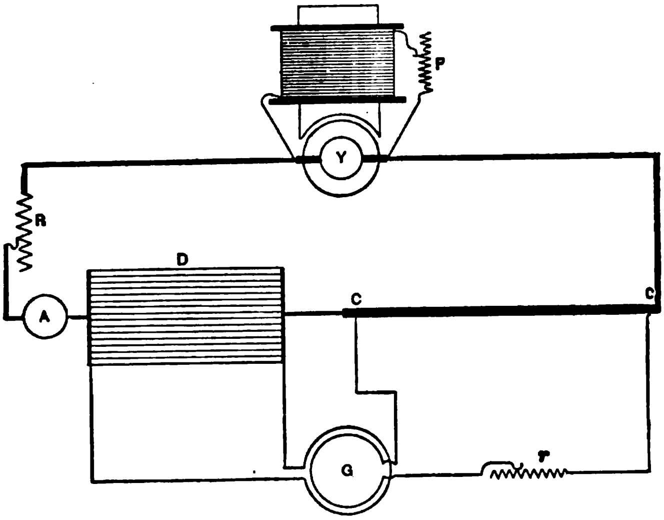

Fig. 1—Electrical connections in tests

The German-silver Wire Grid. The grid was made up in such a manner as to carry the strongest testing currents used with a relatively small rise of temperature, and was made of metal having a relatively small temperature-coefficient of resistivity, so as to maintain a practically constant resistance during the tests. It consisted of an open wooden frame about 2 metres long (6.56 feet) by 1 metre broad (3.28 feet), containing 65 parallel wires of german-silver supported freely in air, each 0.129 cm. (0.0503 in.) in diameter, and 183 cm. (6 feet) in length. These wires were divided into three permanently connected groups of 25, 20, and 20 wires respectively, in such a manner that the groups could be connected either in series or in parallel for different resistances and current-carrying capacities. When the three groups were connected in series, the total resistance of the grid between pressure wires was 0.0441 international ohm. When the three groups were connected in parallel, the resistance of the grid between pressure wires was 0.0044 international ohm. Intermediate series-parallel groupings and corresponding resistances were also used in some of the tests.

The resistance of the grid was frequently measured and checked. One such check measurement was ordinarily made with each successive conductor test. The grid resistance was measured by using the same connections as are shown in Fig. 1, but with a standard platinoid strip resistance substituted for the conductor *C C*. Two such standard strips were employed, with resistances of 0.015125 and 0.03053 international ohms respectively. These standard resistances were in their turn checked and calibrated by comparison with a standard 0.01 international ohm loaned by the Jefferson Physical Laboratory. All the measurements of resistance stated in this paper are in terms of the international ohm, and are ultimately referred to this 0.01 ohm standard.

The Differential Galvanometer. The galvanometer employed was of the Edelmann type, having a steel split-bell suspended magnet, swinging in a copper well, and two separate coils of silk-covered wire placed on opposite sides of the suspended magnet. These coils were wound specially for these tests with silk-covered copper wire, each coil having a resistance of about 1800 ohms. The resistances of the coils, being subject to change with variation of room temperature, were frequently measured during extended tests. The differential condition was also frequently checked.

The sensitiveness of the galvanometer as used in the tests was 0.143 microampere for 1 mm. scale deflection at the range used of 140 cm. Referred to a range of 1 metre, this would be 0.20 microamperes per mm. scale-reading deflection, or the current sent by 1 volt through 5 megohms, including both coils.

The periodic time of the galvanometer swing was 5.17 seconds. The damping ratio of successive opposite elongations was 2.465, or the Naperian logarithmic decrement of successive opposite elongations 0.9027. Four complete swings, executed in 20.7 seconds, sufficed to reduce the deflection to $\frac{1}{1310}$ part, or, for practical purposes, to rest.

When balance is obtained on the differential galvanometer G in Fig. 1, we have

$$x = R_{\text{D}} \frac{G_{\text{C}}+r}{G_{\text{D}}} \qquad \text{international ohms} \qquad (2)$$

where R_{D} is the resistance of the grid, G_{C} and G_{D} the resistances of the two galvanometer coils respectively, including leads, and r the resistance added to the circuit of the conductor $C\,C$, whose resistance is x ohms. In all the experiments, G and r were measured by a B.A.-unit Wheatstone bridge, in B.A. ohms. As, however, only the ratio $\frac{G_{\text{C}}+r}{G_{\text{D}}}$ appears in formula (2) this does not affect the evaluation of x in international ohms.

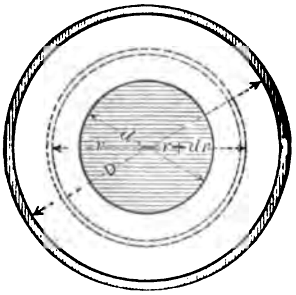

FIG. 2—Diagrammatic cross-section of lead-covered insulated wire

Theory of the Temperature Elevation of an Active Conductor Cooled Entirely by Thermal Conduction. The simplest case of the heating of an active electric conductor is that of a uniform cylindrical wire carrying a steady direct current, and covered with a uniform concentric coating of rubber or other insulator, the external surface of which, either with or without a leaden sheath, is kept at a uniform known temperature by being immersed in a tank of running water.

In Fig. 2, the wire of diameter d cm, is covered by insulating material to a total diameter of D cm. The external sheath of lead is so good a thermal conductor that, for all practical purposes, its temperature is t° C. at all points The internal wire of copper is likewise so good a thermal conductor that its temperature at all points is $t+\theta$ degrees centigrade. This means that, after a sufficiently long application of a direct current through the wire to establish a steady thermal condition, there is a difference of temperature of θ° C. between the internal and external surfaces of the insulating cylinder.

If we consider one unit length or linear centimetre of the conductor, the thermal resistance, to the radial flow of heat, offered by any cylindrical element of the insulator between the radii r and $r+dr$ centimetres will be

$$d\mathcal{R} = \frac{dr}{2\pi r}\sigma \qquad \text{thermal ohms} \quad (3)$$

where σ is the thermal resistivity of the insulator at its working temperature, and is numerically equal to the thermal resistance of a cubic centimetre of the substance between any pair of opposed faces, dr is the thickness of the elementary cylinder, and $2\pi r$ the surface area of this cylinder in unit length. The total thermal resistance between wire and sheath will be the sum of all the resistances of the elementary cylinders between the internal diameter d and the external diameter D; or

$$\mathcal{R} = \frac{\sigma}{2\pi}\log_\epsilon\frac{D}{d} \qquad \text{thermal ohms} \quad (4)$$

in a linear centimetre of the insulator.

If ρ_t is the electric resistivity of the wire at the initial temperature t° C., which is also the temperature of the external surface, the electric resistance of the wire per linear cm. is

$$R_t = \frac{4\rho_t}{\pi d^2} \qquad \text{ohms at } t^\circ \text{ C.} \quad (5)$$

and at the temperature finally reached by the wire $(t+\theta)^\circ$ C.. the resistance is

$$R_{t+\theta} = \frac{4\rho_t(1+a\theta)}{\pi d^2} \qquad \text{ohms} \quad (6).$$

where a is the temperature coefficient of resistivity of the wire for the initial temperature t° C., and[7] is equal to $\frac{1}{238.1+t}$.

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[7] The Resistivity Temperature-Coefficient of Copper. *Electrical World*, June 30, 1906.

The total flow of heat, or thermal current, passing radially through a linear centimetre of the insulator in the steady state, with a current of I amperes in the wire, is

$$\mathcal{J} = I^2 R_{t+\theta} \qquad \text{watts per cm.} \quad (7)$$

This thermal energy current follows a law similar to Ohm's law, or

$$\mathcal{J} = \frac{\theta}{\mathcal{R}} \qquad \text{watts per cm.} \quad (8)$$

and by (4)

$$\mathcal{J} = \frac{\theta}{\frac{\sigma}{2\pi} \log_\varepsilon \frac{D}{d}} \qquad \text{watts per cm.} \quad (9)$$

and by (6)

$$\frac{4 I^2 \rho_t (1 + a\theta)}{\pi d^2} = \frac{\theta}{\frac{\sigma}{2\pi} \log_\varepsilon \frac{D}{d}} \qquad \text{watts per cm.} \quad (10)$$

Consequently

$$\frac{\theta}{1 + a\theta} = \frac{2\sigma\rho_t \log_\varepsilon \frac{D}{d}}{\pi^2 d^2} I^2 \qquad \text{degrees C.} \quad (11)$$

or

$$\frac{\theta}{1 + a\theta} = K I^2 \qquad \text{degrees C.} \quad (12)$$

where K is a constant for a conductor of given dimensions, if the thermal resistivity σ may be taken as constant. We know that σ may vary with temperature in many substances, but there is evidence in this report to show that it is substantially constant in various insulating substances, between the limits of 0° C. and 100° C.

Equations (11) and (12) express the relation between the final temperature of any wire carrying a continuous current, under the conditions of Fig. 2. Equation (12) must apply to any uniform wire carrying a continuous current in the steady state, no matter how many successive layers of insulator there may be, provided only that the heat escapes by conduction, as distinguished from radiation and convection, and also provided that the thermal resistivities of the successive insulators may be taken as constant within the range of their working temperatures. Formula (12) applies, therefore, to all buried continuous-current cables, and also to insulated wires in water. It also applies fairly well to insulated wires in wooden moulding. It is the fundamental equation of electric heating of concealed wires, carrying continuous currents, from the temperature t° C. of surrounding objects to the final temperature $(t+\theta)^\circ$ C., when the temperature elevation θ does not exceed, say, 100° C.

The temperature coefficient a varies with the initial temperature t° C.

For an initial temperature $t = 12^\circ$ C. $a = 0.004$
" " " " $t = 18^\circ$ C. $a = 0.0039$
" " " " $t = 25^\circ$ C. $a = 0.0038$

If we take $t = 18^\circ$ C., as an average initial temperature in practice, equation (12) becomes:

$$\frac{\theta}{1+0.0039\,\theta} = K I^2 \qquad \text{degrees C.} \qquad (13)$$

This means that the final temperature elevation θ of a wire carrying a continuous current I amperes, increases somewhat more rapidly than the square of the current, and the deviation from the square is greater, the greater the temperature elevation. This relation may also be rendered evident in a graphical way as follows: Logarizing both sides of (13), we have

$$\log \theta - \log\,(1+0.0039\,\theta) = 2 \log I + k \qquad (14)$$

where $k = \log K$, and is a constant for a given size of wire and succession of insulating coatings.

If we plot $\log I$ (Fig. 3) against $\log \theta$, we draw the straight line $e\,f$, making with $e\,x$ an angle 63° 26′ whose tangent is 2. This represents the locus of $\log \theta$. We then lay off a curved line $A\,B\,C\,D$, such that its distance from the straight line $E\,F$ is everywhere $\frac{1}{2} \log\,(1+0.0039\,\theta)$. By deducting these distances from $e\,f$, we obtain the final curve $a\,b\,c\,d$, which, by (14), is the graph of $\log \theta$ in relation to $\log I$. Joining the points a and d by the broken straight line $a\,d$, we find that this is inclined to the $e\,x$ axis by an angle whose tangent is 2.289; so that the final temperature elevations of 10° and 100° C., in accordance with (13), represent an increase of temperature in the ratio of $I^{2.289}$, or the exponent of 2.289 for the currents.

In other words, judging from these two observations alone, it would appear that the temperature increased as the 2.289th power of the current. If, however, we consider the points *a* and *c* on the curve, corresponding to the temperature elevations 10° and 50° C. respectively, the dotted straight line *a c* makes with *e x* an angle whose tangent is 2.19. This represents an increase of temperature elevation according to $I^{2.19}$, so far as concerns these particular points.

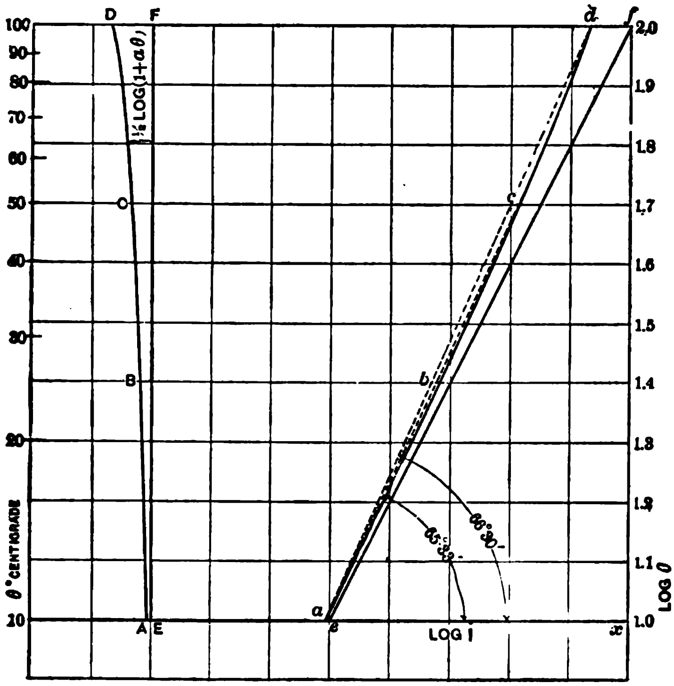

FIG. 3—Diagram indicating the graphical relation between current and temperature elevation when plotted on logarithm paper

If then we plot log θ against log I, in accordance with (13) and (14), the graph will be a flat curve commencing at an angle $\tan^{-1} 2$, and bending slowly upward in such a way that, on the 10°–50° range, θ varies approximately as $I^{2.2}$; whereas taking the 10°–100° range, θ varies approximately as $I^{2.3}$. The exact value of the exponent will depend both on t and on θ If we limit our enquiry to temperature elevations of 50° C., we may expect to find the observations on logarithm paper fall nearly on a straight line, making an angle $\tan^{-1} 2.2$ with the axis of abscissas. If, however, we extend the range of observation to $\theta = 100°$ C., the mean straight line on logarithm paper will be somewhat steeper, and approach the angle $\tan^{-1} 2.3$.

Thus if $t = 6°$ C. $\theta \propto I^{2.304}$ between $\theta = 10$ and $100°$ C.
if $t = 12°$ C. $\theta \propto I^{2.296}$ “ “ = “ “ “
if $t = 18°$ C. $\theta \propto I^{2.289}$ “ “ = “ “ “
if $t = 25°$ C. $\theta \propto I^{2.282}$ “ “ = “ “ “

For practical purposes, therefore, with temperature elevations averaging about 50° C., we may regard the theoretical graph of temperature elevation against current strength on logarithm paper as conforming fairly well with a straight line making an angle $\tan^{-1} 2.2$, or 65° 33′, with the axis of abscissas, or

$$\log \theta = 2.2 \log I + k \qquad (15)$$

corresponding to

$$\theta = K I^{2.2} \qquad \text{deg. C.} \qquad (16)$$

Measurements of Temperature Elevation in Rubber-Covered Wires. Five sizes of new rubber-covered and braided code wire, all from the same factory, were used in these tests, immersed in running water. The dimensions of these wires are given in the following table:

TABLE I.
Dimensions of Rubber-Covered and Braided Code Wires

Size of Wire A. W. G.	Diameter of Copper Wire		Diameter over Rubber		Diameter over Braid	
	cm.	Inch	cm.	Inch	cm.	Inch
8	0.3263	0.1285	0.6348	0.25	0.7365	0.290
10	0.2552	0.1005	0.4952	0.195	0.6223	0.245
12	0.2032	0 0800	0.432	0.170	0.5715	0 225
14	0.1626	0.064	0.3987	0.157	0.482	0.190
16	0.1296	0.051	0.2895	0.114	0.381	0.150

A length of about 5 metres of each of the above wires had pressure wires soldered to the conductor, and was then immersed in running water during the test. The time required to attain a practically steady temperature after the application of a continuous current was only about 5 minutes under these conditions. Table II gives the recorded observations in the case

TABLE II.

TESTS OF NO. 16 A. W. G. RUBBER COVERED AND BRAIDED WIRE IMMERSED IN RUNNING WATER AT 5° C. DISTANCE BETWEEN PRESSURE WIRES 550 CM.

Time from Start, min.	Current Strength, amp.	Res. of Galvr. Coils B.A.U.		Res. added to wire B.A.U.	Ratio of Increase	Res. of wire Int. ohms.	θ Temp. Elevation of wire, ° C.	Res. of Standard Grid Int. ohms	$R_{t+\theta}$ Res of wire per cm. Int. microhms	I watts per cm. $I^2 R_{t+\theta}$	θ/I Thermal Res. of linear cm.	t Temp of water ° C.
		C	D									
0	3	1776	1853	1200	1.	0.07081		0.04409	128.7			5
7	30	"	"	1292	1.031	0.07300	7.54	"	132.7	0.1194	63.15	"
15	35	"	"	1330	1.0435	0.07390	10.58	"	134.3	0.1645	64.31	"
22	40	"	"	1370	1.0570	0.07486	13.86	"	136.0	0.2176	63.69	"
26	45	"	"	1420	1.0738	0.07604	17.94	"	138.2	0.2799	64.09	"
33	50	"	"	1477	1.0930	0.07740	22.61	"	140.7	0.3517	64.27	"
										Mean =	63.9	

of the No. 16 wire, and is a fair example of the measurements taken collectively. The second column gives the current strength steadily applied. The initial balance was obtained by a brief application of a current of 3 amperes. A current of 30 amperes was then applied at the start and the balance again observed after 7 minutes. The current was then increased to 35 amperes for 8 minutes, and so on.

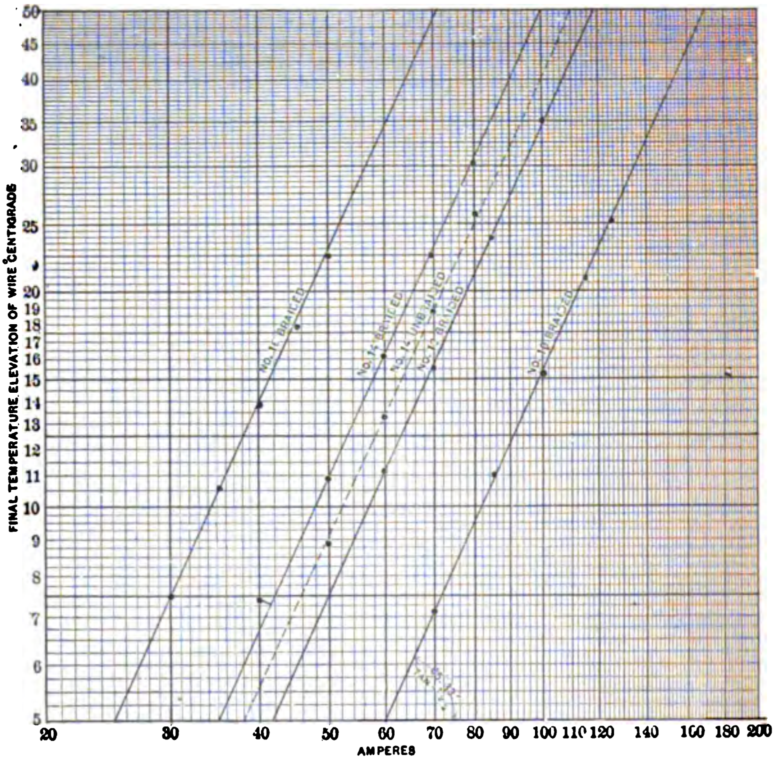

FIG. 4—Observed temperature elevations of different sizes of code rubber-covered wires in water

The last column but one gives the thermal resistance of a linear centimetre of dielectric and braid. Its mean value is 63.9 thermal-ohm-cm.

The temperature elevations θ in the above table are plotted as black circles in Fig. 4 on logarithm paper. The straight line, marked No. 16 braided, is drawn through the 30-ampere point to make an angle of 65° 33′, or $\tan^{-1} 2.2$, with the axis of abscissas. This straight line corresponds, therefore, to formulas (15) and (16) derived from the theory already outlined. The agreement of the observation points with the theoretical straight line is seen to be satisfactory.

Table III contains all the final temperature elevations computed from the measurements made on the samples of wire scheduled in Table I, and also contains the corresponding thermal resistances in one linear centimetre. The final temperature elevations are all plotted in Fig. 4 as ordinates, against currents as abscissas, to logarithmic scales, the straight lines being drawn parallel to each other according to formulas (15) and (16). With the exception of one doubtful observation on the No. 14 braided wire, all the points are in satisfactory conformity with these parallel straight lines, thus confirming the theory already outlined, as expressed in formulas (11), (12), (13), and (14).

TABLE III

TEMPERATURE ELEVATIONS OF DIFFERENT SIZES OF RUBBER-COVERED WIRES IN WATER

Current Amp.	I No. 16 Braided $t=5^\circ$		II No. 14 Braided $t=5.5^\circ$		III No. 14 Unbraided $t=5^\circ$		IV No. 12 Braided $t=4.5^\circ$		V No 10 Braided $t=4.5^\circ$	
	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.
30	7.54	63.15								
35	10.58	64.31								
40	13.86	63.69	7.4							
45	17.94	64.09								
50	22.61	64.27	10.91	52.88	8.8	42.93				
60			16.22	53.47	13.3	44.31	11.16	59.45		
70			22.46	53.12	18.6	44.56	15.43	59.37	7.16	45.8
80			30.32	53.17	25.86	46.15				
85							23.77	60.11	11.11	47.46
100							35.16	61.59	15.26	46.32
115									20.86	46.87
125									25.13	47.03
Means		63.90		53.21		44.50		60.13		46.70

A comparison of columns II and III in Table III, or of the corresponding lines in Fig. 4, shows that the addition of a coating of cotton braid about 0.4 mm. (1/64 inch) increased the temperature of the No. 14 wire about 2° C. with 50 amperes, and about 4.5° C. with 80 amperes, the wire being immersed in water in each case. The braid also added 8.7 thermal-ohm-cm. (3.76 thermal-ohm-inches) to the linear thermal resistance of the covering of this particular wire.

Taking the internal and external diameters of the braiding of No. 14 wire from Table I as 0.3987 cm. (0.157 in.) and 0.482 cm. (0.190 in.) respectively, we obtain by formula (4) the thermal resistivity $\sigma = 287.1$ thermal-ohm-cm., when soaked in water at 5° C.

With this thermal resistivity for the soaked braid, the thermal resistivity of the rubber covering on the wires was deduced, as in the following table:

TABLE IV.
THERMAL RESISTANCES AND RESISTIVITIES OF WIRE COVERINGS

Size Wire A. W. G.	Thermal Resistance of Wire in a linear centimetre			Thermal resistivity	
	rubber + braid	braid	rubber	braid	rubber
	ohms-cm.	ohms-cm.	ohms-cm.	ohms-cm.	ohms-cm.
10	46.7	10.47	36.23	287.1	343.5
12	60.13	12.82	47.31	"	394.4
14	53.21	8.71	44.50		311.6
16	63.90	12.51	51.39	"	401.5
				Mean =	387.8

The mean resistivity of the " rubber " covering of these wires was therefore 387.8 thermal-ohm-cm.; but, since this material in code rubber-covered wires is largely composed of filling material other than rubber, different compositions are likely to vary considerably in thermal resistivity.

The thermal resistance $\mathcal{R}$ in a linear centimetre of any size of such braided and rubber-covered wire is readily determinable from the dimensions of the wire and the above mean thermal resistivities by the aid of formula (4), and the probable temperature elevation for a given current strength then follows from formula (8). If the wire is buried in the ground, the additional thermal resistance of the ground must be added, taking into account the heat that may be liberated by any active wires buried in the same trench or conduit.

Heating of Code Rubber-Covered Wires in Wooden Moulding. When rubber-covered wires are laid in wooden moulding, the heat generated by continuous currents in each wire has to pass in succession through the rubber, dry braiding, air-space, wooden moulding, and finally through wall, ceiling or air. Owing to the complex geometrical relations of these successive thermal resistances, they are not easy to compute, even when the thermal resistivities of the respective substances are correctly stated. The best plan is, therefore, to measure the thermal resistance of the series combinations under different conditions such as occur in practice, and then to tabulate the safe carrying capacity of such wires from the measurements directly, as in the report of 1889, above referred to.

The moulding used in the tests here reported was of pine wood, of the cross-section shown in Fig. 5. Its length was 3.86 metres (12.67 feet) and its weight was 720 gm. per metre (0.48 lb. per foot). It was lightly nailed down flat upon the wooden floor of the testing room. The wire to be tested was laid in a loop along the moulding so as to occupy the two outside grooves, as indicated in the figure, leaving the middle groove vacant. Pressure wires were connected to the test wire at points about 5 metres apart. The temperature elevation became substantially constant thirty minutes after the application of each testing current strength. The initial temperature t° C. varied from 19.0° C. to 21.0° C. in the different series of tests. The results of the measurements are recorded in Table V in terms of the final temperature elevation and of the linear thermal resistance for each size of wire.

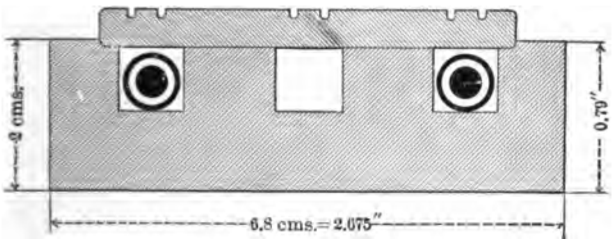

FIG. 5—Cross-section of wooden moulding

It is to be observed that the temperature elevations of these wires, whose dimensions were substantially the same as those appearing in Table I for the lengths tested in water, are more than ten times greater than those for the corresponding steady current strengths in Table III.

The linear thermal resistance of the rubber, as above deduced, is deducted in Table V from the mean linear thermal resistance of each moulded wire. The balance is the inferred linear thermal resistance in series of dry braid, air, wood, and external air. This extra linear thermal resistance steadily diminished from 466.6 thermal-ohms in one linear centimetre (183.5 thermal-ohm-inches), with No. 16 wire, to 343.9 thermal-ohm-cm. (135.3 thermal-ohm-inches) with No. 8 wire. This reduction in linear thermal resistance may be accounted for by the reduction in the thickness of the air-space between braid and wooden-moulding walls, as the size of the wire was increased. With these particular sizes of wire, composition of " rubber," size and quality of moulding, the linear thermal resistance of the entire series was about ten times as great as that of the rubber alone, and consequently for a given linear thermal current I, or linear $I^2 R$ heat loss in the wire, the $\mathscr{I}\mathcal{R}$ drop, or temperature elevation θ, would be correspondingly increased about ten times. But at the higher temperature thus attained, the linear copper resistance R would be greater for a given electric current strength; so that in relation to electric current, the temperature elevation would be increased more than ten times by taking the wires out of the water and placing them dry in this wooden moulding.

TABLE V

TEMPERATURE ELEVATIONS AND THERMAL RESISTANCES OF WIRES IN MOULDING

	No. 16 A. W. G. $t = 21.1°$ C.		No. 14 A. W. G. $t = 19.1°$ C.		No. 12 A. W. G. $t = 19.9°$ C.		No. 10 A. W. G. $t = 19°$ C.		No. 8 A. W. G. $t = 19°$ C.	
	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.
15	17.4	543.4								
20			17.6	479.9						
30	83.3	523.3	47.3	517.6	23.7	455.1	14.2	461.3		
40	173.7	437.5	93.2	498.3	51.7	507.3				
45							31.6	434.0	16.9	381.5
50			102.1	463.5	85.1	482.6				
60							61.0	427.8		
65									41.2	409.
75							106.4	417.9		
85									72.5	381.
100									105.2	363.2
	Mean	518.		490.		481.7		435.		385.
	Rubber	51.4		44.5		47.3		36.2		41.1
Braid, Air & Wood		466.6		445.5		434.4		398.8		343.9

The observed temperature elevations below 110° C. in Table V are plotted on logarithm paper in Fig. 6. The parallel straight lines there shown, fairly connecting the various series of observation points, are drawn to make an angle of 66° 25′ or the antitangent of 2.29. It has been pointed out that over a range of 100° C. the temperature elevation θ, above $t = 18°$ C., increases theoretically as $I^{2.280}$; whereas over a range of 50° C., as in Fig. 4, the temperature elevation θ increases as $I^{2.2}$. While the agreement between theory and observation is not so good

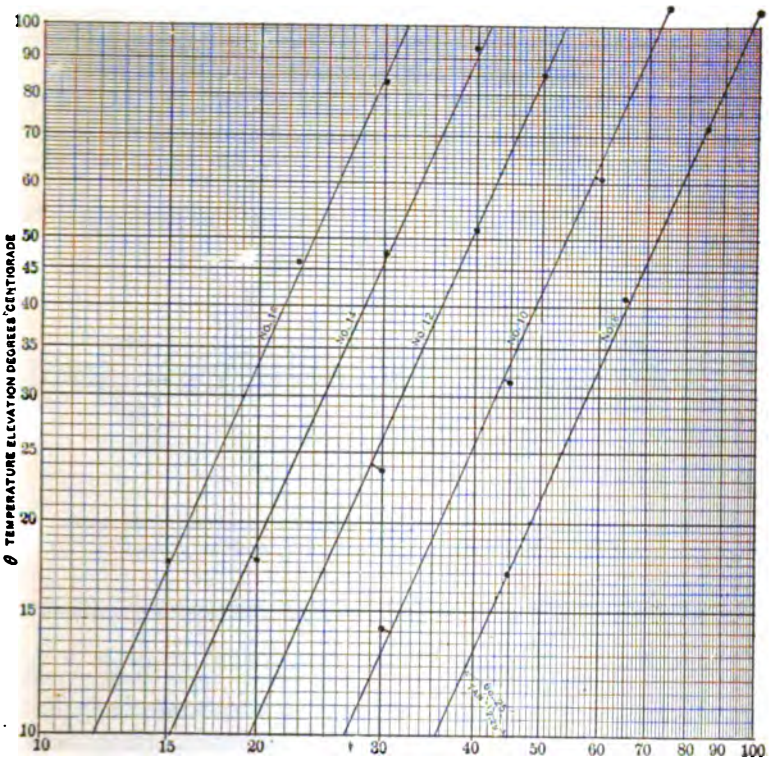

FIG. 6—Final temperature elevations of wires in moulding

in Fig. 6 as in Fig. 4, yet it may be regarded as practically satisfactory. By comparing Figs. 4 and 6, it is evident that these braided wires would carry with a given final temperature elevation some three times more current in water than in this moulding. With the braiding removed, they would carry in water nearly 3.3 times more current than when braided and in this dry wooden moulding, with the same temperature elevation. In all cases of wires cooled entirely by thermal conduction, the electric current strength I amperes which will produce a given final temperature elevation θ, above a given initial temperature t° C., must, by formulas (11) and (12), vary as $1/\sqrt{\mathcal{R}}$, or inversely as the square root of the linear thermal resistance, assuming that the thermal resistivities in the series are substantially constant throughout their working range of temperature. Thus in Table V. the mean linear thermal resistance $\mathcal{R}$ of the rubber covering alone is shown to be 47.3 thermal-ohm-cms. (18.7 thermal-ohm-inches) for No. 12 wire, which would be the total linear thermal resistance of this size of wire in running water, unbraided. But in moulding, the mean linear thermal resistance of this braided wire increased to 481.7 thermal-ohm-cm. (190 thermal-ohm-inches). The ratio of increase in linear thermal resistance in the two cases would be $\frac{481.7}{47.3} = 10.2$ and the steady electric current strength, which the wire could carry with an assigned temperature elevation θ° C., would be changed in the proportion $\frac{1}{\sqrt{10.2}} = \frac{1}{3.2}$ times; *i.e.*, 3.2 times more current in the water than in the moulding.

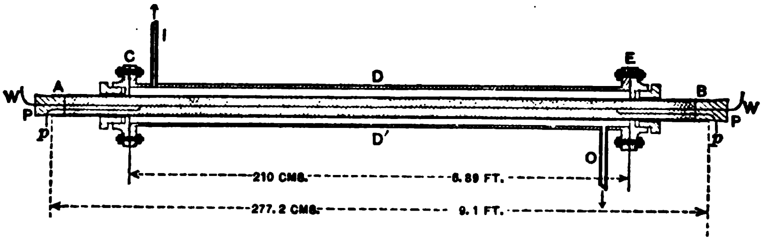

Fig. 7—Longitudinal section of water-jacketed pipe containing a test wire packed in sand, soil, or gravel

Measurements with Bare Wires Surrounded by Sand, Soil or Gravel. The heating of underground wires and cables depends, as is already known, upon the depth below the surface at which the wires are laid, and upon the thermal resistivity of the soil; as well as upon the dimensions of the wires and the currents they carry.[8] The measurement of the thermal resistivity of

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[8] "The Carrying Capacity of Electric Cables, Submerged, Buried, or Suspended in Air," by A. E. Kennelly. Minutes of the Ninth Annual Meeting, Association of Edison Illuminating Companies, 1893, p. 79. "Die Berechnung Elektrischer Leitungsnetze" Herzog-Feldmann, Vol II, p. 130.

the soil presents some difficulty. A series of observations was made on the thermal resistivity of several varieties of sand, gravel, and plaster of paris.

For the above purpose, an iron pipe *A B*, Fig. 7, 277.2 cm. (9.1 ft.) long and 8.92 cm. (3.5 in.) in external diameter, was provided with a water-jacket external cast-iron pipe *C D E*, 210 cm. (6.89 ft.) long and 15.24 cm. (6 in.) inside diameter, as indicated in Fig. 8. A steady stream of tap water was allowed to flow through the water-jacket during each test, the water entering at the inlet *I* and issuing at the outlet *O*. The internal diameter of the pipe *A B* was measured both by calipers, and by finding the mass of water held by the pipe between the wooden end-plugs *P P*. This mean internal diameter was 7.77 cm. (8.06 in.).

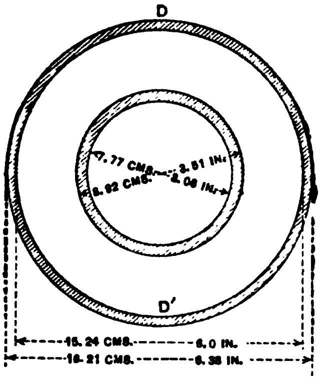

Fig. 8—Enlarged cross-section of water-jacketed pipe through *DD* Fig 7.

The copper wire *W W* under test was held at or near the axis of the tube, and smaller pressure wires *p p* were soldered to it at points 2 metres apart (78.74 in.). The mean diameter of the wire was 0.3256 cm. (0.1282 in. or No. 8 A.W.G.). Other sizes of wire were also used.

The first substance tested was a yellow sand, of moderately fine grain, obtained from a pit in a field near the Pierce Hall laboratory and may be taken as a fair sample of sandy soil. This sand was carefully dried and packed, while still warm, into the pipe *A B*, Fig. 7, around the bare wire *W W*. A steady current of water was then allowed to flow through the water-jacket for some hours, so as to bring the temperature of the apparatus substantially to 16° C., the temperature of the tap water. A strong current was then passed through the wire *W W* with the connections of Fig. 1, and steadily maintained until the resistance of this wire, between pressure taps, showed that the final temperature had been very nearly attained. Observations of resistance were obtained at frequent intervals. Table VI gives a particular series of observations obtained with a current of 128.2 amperes kept steadily flowing through the test-wire, the initial resistance balance being secured with 15 amperes. Column I gives the clock time of each observation, column II the elapsed time from the closing of the circuit, column III the balancing resistance *r*, Fig. 1, column IV the side to which that resistance was added, columns V and VI show the respective resistances of the two galvanometer circuits, column VII gives the resistance of the 2 metres of test wire. column VIII gives the inferred temperature of the test wire, and the last column, the inferred rise of temperature.

TABLE VI.

Observations with 128.2 Amperes Passing through Copper Wire of Diam. 3.26 mm., in Dry Sand, Water-Jacket Maintained at 16° C.

I			II	III	IV	V	VI	VII	VIII	IX
Time			Time from start	Res. *r*	added to	Resistance		Res. of test wire Int.	Temp. of test wire	Temp. rise of test wire
h.	m.	s.	seconds	B. A. U.		C side B. A. U.	D side B. A. U.	microhms	$t+\theta$° C.	θ° C.
11	30	00	0	30	grid D	850	985	4141	16.	0.°
	30	15	15	0	—	"	955	4271	24.	8.
	31	00	60	50	wire C	900	"	4522	39.4	23.4
	31	15	75	70	"	920	"	4623	45.6	29.6
	31	55	115	90	"	940	"	4723	51.7	35.7
	34	15	255	130	"	980	"	4924	64.1	48.1
	35	35	335	144	"	904	"	4995	68.4	52.4
	37	00	420	153	"	1003	"	5040	71.2	55.2
	38	40	520	100	"	1010	"	5076	73.4	57.4
	43	00	780	174	"	1024	"	5146	77.7	61.7
	46	00	960	183	"	1033	"	5191	80.4	64.4
	51	40	1360	192	"	1042	"	5236	83.2	67.2
	54	00	1440	195	"	1045	"	5251	84.1	68.1
12	01	30	1890	204	"	1054	"	5296	86.9	70.9
	5	30	2130	207	"	1057	"	5312	87.9	71.9
	12	12	2532	210	"	1060	"	5327	88.8	72.8
	22	30	3150	213	"	1063	"	5336	89.4	73.4
	27	00	3420	215	"	1065	"	5351	90.3	74.3
	36	00	3960	218	"	1068	"	5366	91.2	75.2
	46	00	4560	220	"	1070	"	5377	91.8	75.8
13	27	00	7020	229	"	1079	"	5422	94.6	78.6
	36	00	7560	229	"	1079	"	5422	94 6	78.6
	50	00	8400	229	"	1079	"	5422	94 6	78.6

The resistance of the standard german-silver grid *D*, Fig. 1, in the above series of measurements was 4799 int. microhms.

Fig. 9 shows at *A* the graph of the observations in the above table. The curves *B*, *C*, and *D* are the corresponding graphs of similar series of measurements with 100, 77.2 and 50 amperes respectively. These four curves show the rise of temperature

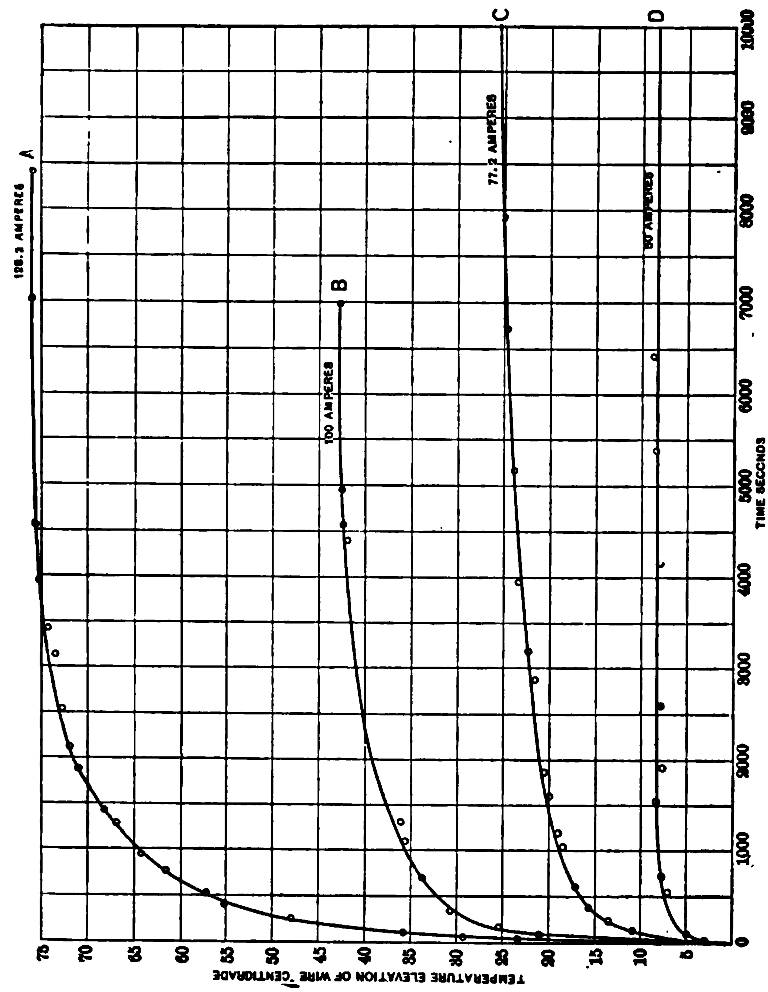

Fig. 9—Heating of wire in sand and pipe.

in the wire during the first 7,000 seconds of steady electric current flow. About half of the final temperature elevation was reached by the wire in 150 seconds. The initial rate of temperature elevation with 128.2 amperes was about 0.5° C. per second. After 100 seconds, this rate fell to 0.1° C. per second, and after 1000 seconds to 0.01° C. per second.

In Fig. 10, the curves indicate the temperature elevation of another copper wire No. 10 A. W. G. (diam. 0.256 cm. or 0.1008 in.) in relation to time, after applying a steady current of 90 amperes, and also after interrupting the current. In the practically steady state, with a temperature of 6° C. in the water circulating through the water-jacket and a temperature in the wire of 78.1° C. or 72.1° C. temperature elevation, the linear thermal current

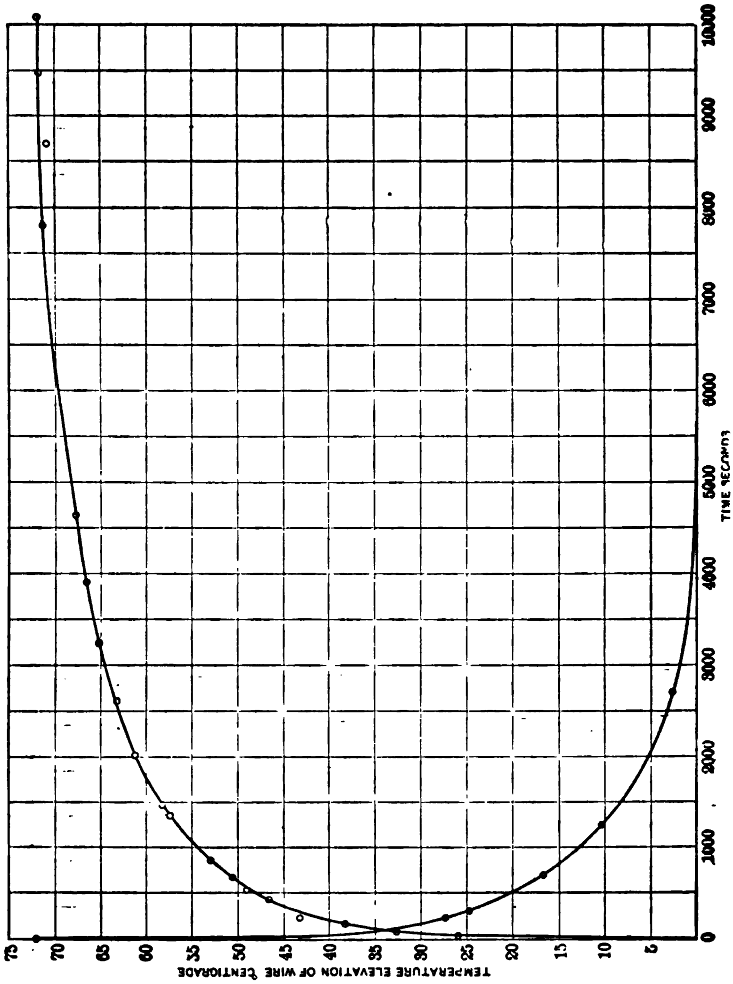

Fig. 10—Heating and cooling curves, of No. 10 A.W G. bare copper wire in dry white sand. 90 amperes.

was 0.3354 watts per cm. (0.852 watts per inch) and the linear thermal resistance 215 thermal-ohm-cm. (84.6 thermal-ohm-inches). By the use of formula (4), taking d = 0.256 cm. and D = 7.77 cm., the thermal resistivity of the sand was 805.9 thermal-ohm-cm.

The curves of heating and cooling for a No. 17 A.W.G. copper

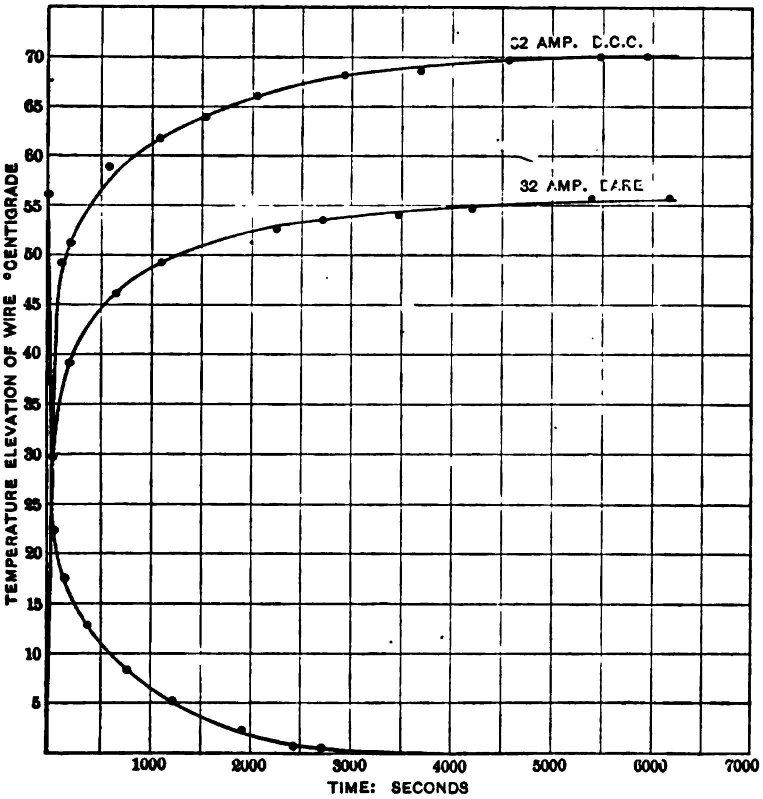

FIG. 11—Curves showing the heating and cooling of No. 17 A.W.G. wire double-cotton covered and bare in fine quartz sand.

wire of diameter 0.1132 cm. (0.0445 in.) double-cotton-covered to 0.1346 cm. (0.053 in.) are given in Fig. 11. The heating current in each case was held at 32 amperes. The upper curve shows the rise of temperature elevation with the wire when cotton-covered and packed in fine dry white quartz sand. The lower curve gives the corresponding temperature elevation rise, after the cotton covering had been removed from the wire and the same replaced in the pipe with the same quartz packing. The descending curve gives the cooling in the latter condition. It will be observed that, both in this figure and in Fig. 10, the cooling occurs more rapidly than the heating. That is, the cooling falls to 1° C. remaining temperature elevation in about half the time that the heating process requires to attain within 1° C. of the final temperature elevation.

The thermal resistivity of the dry cotton covering on the wire appears to have been 2373 thermal-ohm-cm., the highest resistivity of any of the substances tested.

The accompanying table gives a collection of all the measurements of thermal resistivity made with the water-jacketed pipe.

Column I in the above table describes the material employed in packing the pipe, or the nature of the thermal insulator tested. The size of the square aperture in a wire screen sieve through which the bulk of the material would pass is also given. Column II states the condition of the material as to dryness. The additions of liquid referred to are in percentages of volume. Column V gives the strength of the continuous current used in each test, and column VI, the temperature elevation θ° C., thereby finally produced, with water usually at or near 5° C. circulating in the cooling jacket. The diameter of the bare copper wire used is given in column VII.

Column VIII shows the computed thermal resistivity σ of the material, as deduced from the temperature elevation θ, and the linear thermal current in watts per cm. Column IX gives the thermal resistivity σ', as deduced from the linear thermal current when expressed in lesser calories, or water-gram-deg.-cent. per linear cm. The thermal resistivity of a substance expressed in calorie measure is 4.186 times greater than when expressed in watt measure, 1 gram-calorie per second being taken as 4.186 watts. Column X contains the thermal conductivity of the substances in watt measure, or the reciprocal of σ in column VIII. Column XI contains the thermal conductivity of the substances in calorie measure, or the reciprocal of σ' in column IX.

It will be observed that the thermal resistivity varied between 161.4 thermal-ohm-cm. for quartz sand with 20% water and 761.7 thermal-ohm-cm. for dry powdered plaster of paris. The dry cotton covering of the wire whose heating is shown in Fig. 11, had, however, a resistivity of 2373 thermal-ohm-cm.,

Yellow sand
and other
0.4 mm...

Fine white q

Average mesh

Crushed quart

Same crushed

Fine gravel

Fine sandy soil

Powdered pla

which corresponds to a thermal conductivity of 4.214×10^{-4} thermal-mhos-per-cm. in watt measure, or 1.007×10^{-4} thermal-mhos-per-cm. in gram-calorie measure. This agrees with the value for cotton wool given by Peclet.[9]

Fig. 12 shows the relation of the observations with the temperature elevation of wires in the water-jacketed pipe to the steady current strength when plotted on logarithmic paper. The parallel straight lines are drawn to make an angle of 66° 30′ or the anti-tangent of 2.3, to cover a range of 100° C. temperature elevation from an initial temperature of 6° C., in accordance with formula (15) adapted to 100° C. instead of 50° C. The agreement between the observation points and these straight lines of average exponent 2.3 is fairly satisfactory from an engineering standpoint.

The following conclusions may be drawn from the observations here reported:

(1) The fundamental formula for the direct-current final heating of a wire that cools by conduction is (12)

$$\frac{\theta}{1+a\,\theta} = K\,I^2$$

where K is a constant for the wire determined by the total linear thermal resistance. This formula applies to concealed wires, *i.e.*, to insulated wires in water, in the ground, or in wooden moulding.

(2) The thermal resistivities of the various substances tested with different temperature elevations, including rubber composition, braiding, moulding, and various soils, may, for practical purposes, be regarded as constant, *i.e.*, not appreciably affected by temperatures up to 100° C.

(3) Wet braiding on a No. 14 rubber-covered wire added a linear thermal resistance of 8.7 thermal-ohm-cm. (2.46 thermal-ohm-inches) and raised the final temperature of the wire immersed in water by about 2° C. with 50 amperes.

(4) The linear thermal resistance of the rubber-covered wires in dry wooden moulding was about 10 times greater than when immersed in water, thus increasing their temperature elevations more than 10 times with a given current or reducing their current-carrying capacity more than 3 times for a given temperature elevation.

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[9] " C. G. S. System of Units," by Everett—Heat Conduction of Woolly Substances, p. 128. London, 1891.

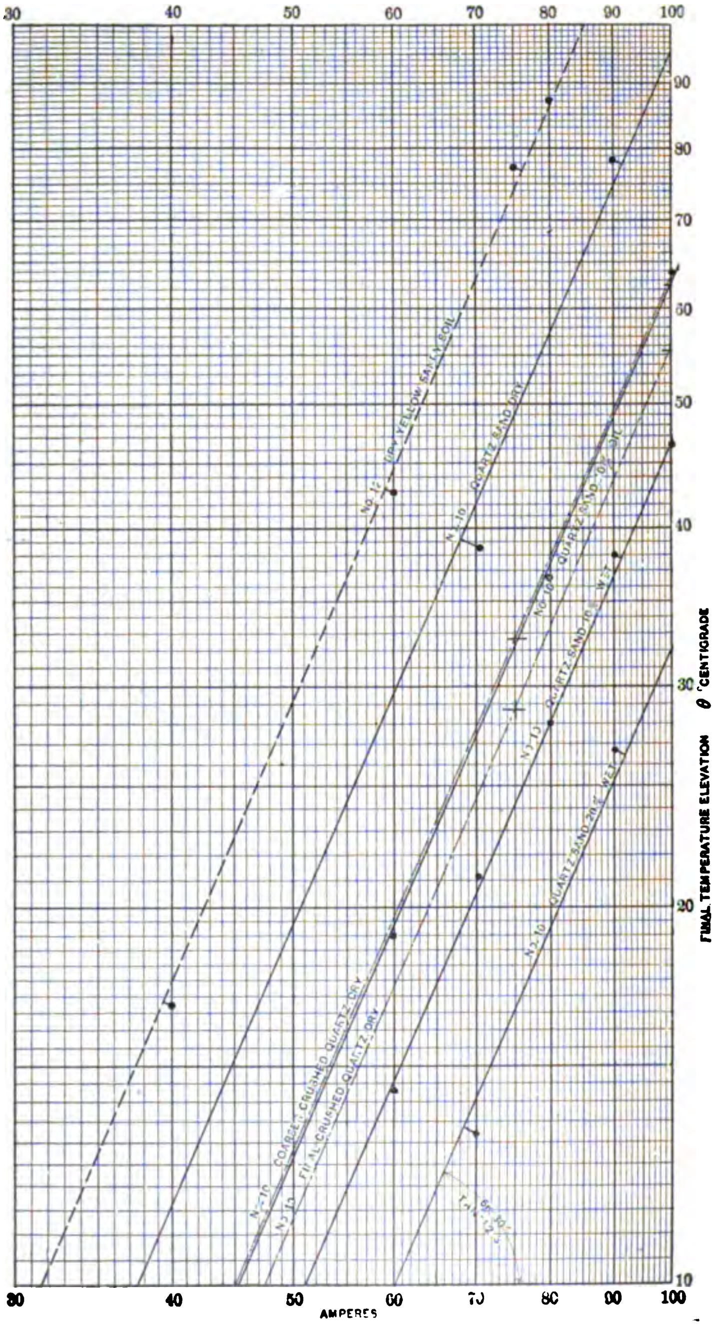


Fig. 12—Final temperature elevations of bare wires in water-jacketed pipe, with different packings.

(5) When plotted on logarithm paper, the final temperature elevation of a wire in relation to steady current strength is nearly a straight line of inclination $\tan^{-1} 2.2$ (Fig. 4) for temperature elevations not exceeding 50° C., and not far from a straight line of inclination $\tan^{-1} 2.3$ for temperature elevations not exceeding 100° C. (Figs. 6 and 12).

(6) A No. 12 A.W.G. copper wire, rubber-covered, and immersed in water substantially attained its final temperature elevation in 300 seconds, or 5 minutes, after applying a steady current. The same wire in dry wooden moulding took 1800 seconds, or 30 minutes, and the same wire, bared but packed in sand within a water-jacketed pipe of 7.77 cm. (3.06 in.) internal diameter, took about 7800 seconds, or 130 minutes, to reach a similar approximation to final temperature elevation.

(7) The wires in the water-jacketed pipe cooled more quickly than they heated.

(8) Changing the size of the wire in the water-jacketed pipe from No. 8 (0.326 cm.) to No. 12 (0.205 cm.) did not appreciably affect the thermal resistivity of sandy soil as measured with these wires (351 thermal-ohm-cm.) Similarly, changing the size from No. 10 (0.256 cm.) to No. 17 (0.113 cm.) did not appreciably affect the thermal resistivity of dry quartz sand as measured by those wires (400 thermal-ohm-cm.).

(9) The thermal resistivity of the sandy soils tested was greatest when those soils were dry, and diminished with the addition of water or oil to them.

(10) The thermal resistivity of a sample of crushed quartz was greater with the material in a coarse condition. Crushing the particles of quartz to about half their previous linear dimensions reduced the thermal resistivity of the material about 10%.

(11) The lowest thermal resistivity observed was that of quartz sand with 20% of water added by volume (161.4 thermal-ohm-cms) the highest was that of the white dry double cotton covering of a wire (2373 thermal-ohm-cm.), both in watt measure.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

POWER-FACTOR, ALTERNATING-CURRENT INDUCTIVE CAPACITY, CHEMICAL, AND OTHER TESTS OF RUBBER-COVERED WIRES OF DIFFERENT MANUFACTURERS

BY HENRY W. FISHER

Probably no form of insulating material for wires has been so frequently discussed as india rubber and its component ingredients, known commercially as "rubber." Very many tests have been devised to determine the percentage of rubber and other materials, and especially the amount of fine para.

In a compound containing both pure para and other grades of rubber, it will probably never be possible to tell the relative percentages of each. If the amount of inferior grades of rubber is considerable, an indication of the fact can be obtained from some of the various tests now used.

Specifications have been devised with a view to securing, by the application of certain well defined tests, an absolutely certain percentage of pure para. In some of these cases, the manufacturer could have furnished a better compound containing wax or similar solid hydrocarbons mixed with the dry mineral filler, but the presence of such materials would make it impossible to tell how much of the rubber was fine para.

In view of these rather complicated conditions, several of the manufacturers of rubber-covered wire framed a set of specifications which would ensure 30% para and give at the same time latitude to the manufacturer to use such other ingredients as in his experience would make a compound having toughness, elasticity, resistance against high voltages, and other desirable qualities. These specifications were brought to the attention of the Institute in a paper by Mr. Wallace Clark, read in New York on April 27, 1906.

The object of the present paper is to give the results of certain tests which, while not strictly new, have not been applied commercially to rubber-covered wires. One reason for conducting this investigation was to see if power-factor tests would not live an insight into the qualities of different makes of rubber-insulated wire.

The definition of power-factor, as here used, is the ratio of the power absorbed in the rubber compound to the apparent loss as found by multiplying the charging current by the applied volts. Practically speaking, it may be considered as an indicator of the loss in the dielectric around the wire and therefore a low power-factor is desirable.

A considerable amount of work has been done by various experimenters to determine how the losses in condensers and cables vary with the applied volts, frequency, capacity, etc. One of the most recent investigations of this sort was given in the paper of Dr. Paul Humann which appeared in the " Elektrische Bahnen U. Betriebe" from August 24 to September 24, 1906.

Dr. Humann's formula for the loss in the dielectric of paper-insulated cables is as follows:

$$W = K E^2 n C \qquad (1)$$

Where W = the loss in watts,

K = a constant varying with different insulating compounds,

E = the effective pressure in volts,

n = the frequency of the alternating current,

C = the inductive capacity of the cable.

The proof of the above formula is as follows:

$$\text{power-factor} = p.f. = \frac{W}{I\ E} \qquad (2)$$

$$I = \text{the charging current} = \frac{2\pi\, n\, C\ E}{10^6} \qquad (3)$$

Substituting and transposing,

$$W = \frac{(p.\,f.)\ 2\pi}{10^6} E^2 n\, C = K\, E^2 n\, C \qquad (4)$$

where $K = \frac{(p.f.)\ 2\pi}{10^6}$. The loss is in watts and it varies in direct proportion to the frequency, capacity and power-factor and to the square of the electromotive force.

The methods adapted by Dr. Humann were somewhat involved and complicated, but nevertheless ingenious. In order to get true readings he had to expurgate the harmonics of the alternating-current voltage, producing thereby a true sine-wave electromotive force.

The writer is much indebted to Dr. Rosa, of the Bureau of Standards, for outlining some extremely simple methods to determine power-factors, capacities, inductances, etc. This led to the design of a special form of bridge having non-inductive resistances ~~with~~ minimum inductive capacities, and suitable binding-posts for the various apparatus employed. The rest of the outfit consisted of a vibration galvanometer, and a motor-generator the speed of which was kept absolutely constant by an electrically driven tuning-fork. The rate of vibration of the tuning-fork could be varied by the application of weights near the end of the forks.

By careful adjustment of both the tuning-fork and galvanometer they could be brought into synchronism, when the latter becomes a most sensitive instrument for indicating minute alternating currents. Moreover, as the galvanometer needle responds only to the fundamental period of the alternating-current circuit, and is not at all affected by existing harmonics, it is unnecessary to employ a sine-wave electromotive force for measurements of capacity, inductance, and power-factor.

The method employed in these researches is based on the fact that a cable or condenser, the absorption and leakage of which is not zero, is equivalent to a cable or condenser with zero absorption in series with a resistance, called the " equivalent resistance," such that the angle of lead between the electromotive force and current shall be $90°-\theta$.

With a perfect condenser $\theta = o$. The power-factor $= \cos (90-\theta) = \sin \theta$. (5)

Fig. 1 shows the diagram of the connections and arrangement of the various instruments.

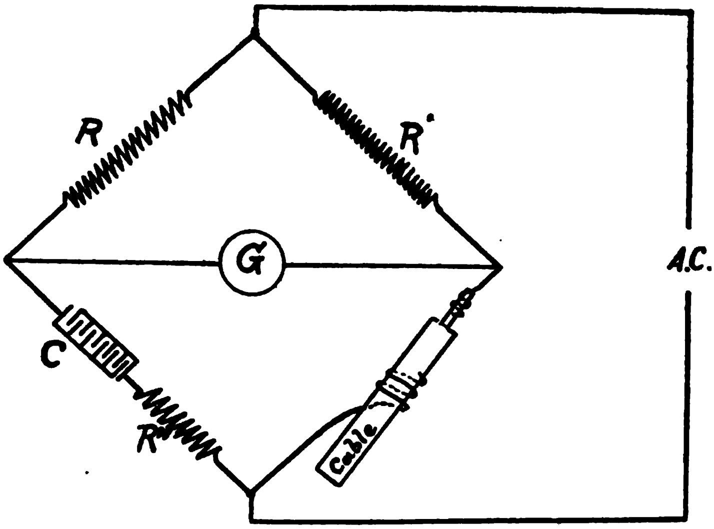
R and R' are the ratio arms of the bridge; R'' is the resistance which is placed in series with the standard condenser C; $A. C.$ is the alternating-current source; and G is the vibration galvanometer. The plan of procedure is first to vary R or R' until a partial balance is obtained, then adjust R'' and R until the galvanometer mirror ceases to vibrate, when the power-factor of the cable =

$$\text{Power-factor of condenser} + \frac{2\pi n R'' C}{10^6} \qquad (6)$$

and capacity of cable $= \frac{R}{R'} \times C$

Where n = the cycles per second and C = the capacity of the standard condenser.

Fig. 1.



The reflection from the galvanometer mirror of a lamp filament was used until a balance was practically obtained, then the reflection of a scale was observed, and the resistances varied until the scale divisions were sharp and well-defined.

This method is so extremely sensitive that in making tests of cables it was generally impossible to adjust the bridge for any length of time so that the galvanometer mirror did not vibrate. There is apt to be a continual slight variation in capacity and power-factor. With perfect standard condensers, capacities can be compared to within one point in 5000.

Owing to some peculiar factory vibration which affected the vibration galvanometer, it was impossible to make the tests at a frequency of 60 cycles per second as originally intended, and

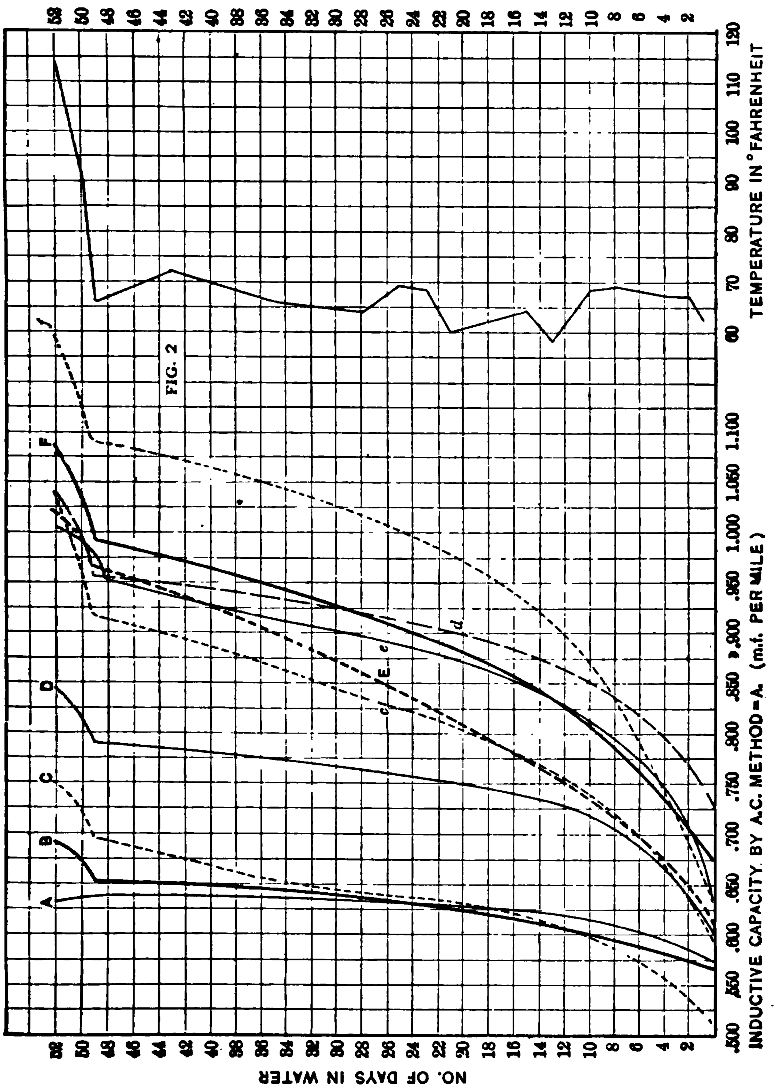


FIG. 2

hence after considerable adjustment a frequency of 53.5 cycles was employed throughout the tests.

Coils of rubber-covered wire of various manufacturers were purchased in different cities. These were cut into lengths of 210 ft. and placed in a metallic tank which was afterwards filled with a strong saline solution. Each curve represents therefore the results of tests on two or more coils of wire.

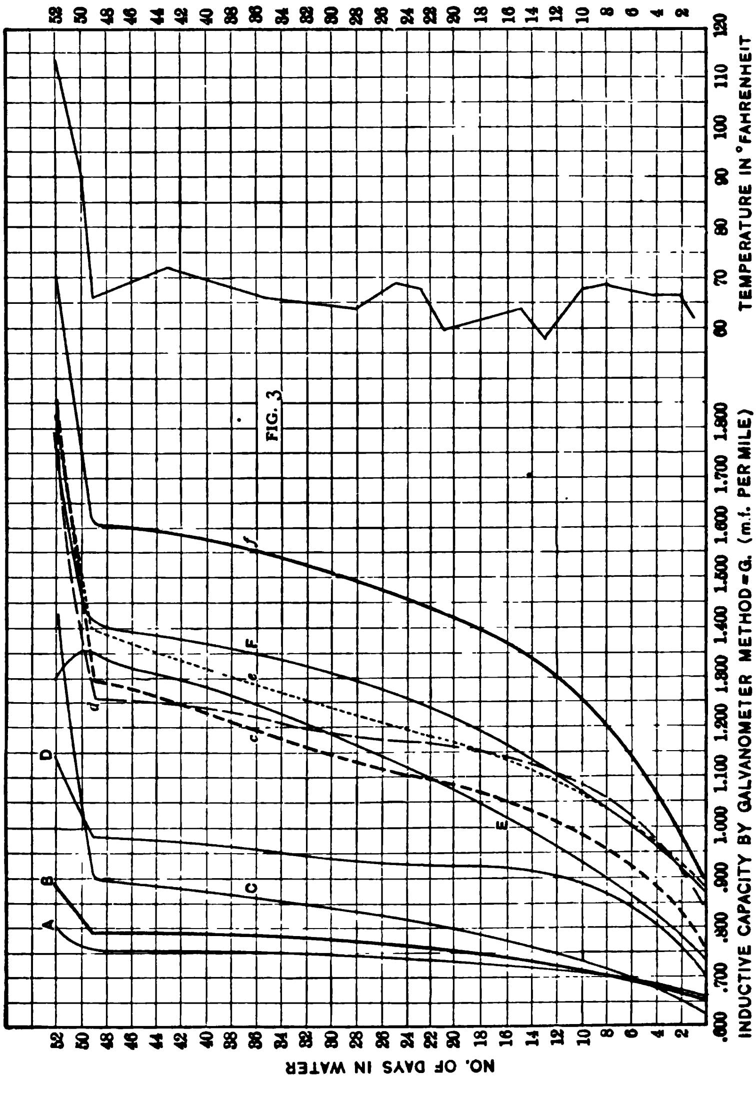


FIG. 3

The voltage tests were made on four samples of each original coil. The samples were four feet long, three feet of which was under water for 24 hours before the test was applied. Samples of each coil were reserved for chemical analysis, but owing to the time required for this work returns were not received from all coils. Sufficient tests were made, however, to permit of a general comparison between most of the samples.

Table I gives the general dimensions of the rubber-covered wire and the average break-down voltage tests.

Table II gives the results of the chemical analysis. The different samples are represented by letters, and the different materials by numbers.

TABLE NO. I.
DIMENSIONS AND BREAK-DOWN VOLTAGES OF SAMPLES.

Sample Letter	Size of Wire B. and S. G.	Diameter in mils over		Thickness of Rubber	Break-down Voltage
		Braid	Rubber		
A	10	323	209	53.5	22860
B	10	280	204	51	23100
C	10	293	209	53.5	15960
c	10	302	202	50	14450
D	10	303	213	55.5	16750
d	10	292	205	51.5	16300
E	10	285	194.5	46	13600
e	10	303	201	49.5	16770
F	10	300	209	53.5	22040
f	10	306	209	53.5	15120
G	10	245	195	46.5	23600
H	10	249.5	193.5	45.75	18355
h	10	246	197	47.5	12825
I	10	252.5	199	48.5	17775
i	10	257	201	49.5	18650
J	12		235	77	23035
K	12		234	76.5	22500

Chemical tests of rubber are difficult to make, and owing to the fact that several of the ingredients are slightly soluble in solvents other than those particularly used for each; there is a possibility of slight errors in the amount reported. No. 2 is the acetone extract and No. 3 the pyridine extract. The tests were most carefully made each in the same manner and by a person the accuracy of whose analysis had previously been checked by his reports of samples having known ingredients.

In designating the wire of any one manufacturer the large character represents the higher priced wire and the small character

TABLE II

Specific Gravity and Composition of Rubber

Material Number.	Name of Material	Sample Letter and % of Material																		
		A	B	C	*c*	D	*d*	E	*e*	F	*f*	G	H	*h*	I	*i*	J	K
	Specific Gravity.........	1.75		1.76	1.86	1.86	1.97	1.66	1.81	1.91	2.02	1.75	1.79		1.74	1.77		
1	Rubber (H_{16} C_{18}).......	26.84		23.32	22.42	20.64	15.52	16.67	16.72	20.12	17.20	27.32	21.85		23.33	22.43	28.30	27.96
2	Free oils, Resins, Waxes Solid Hydro-carbons.....	4.71		9.92	9.75	5.80	7.17	17.99	10.90	4.69	3.61	3.49	6.10		7.04	7.45	3.70	2.99
3	Pitch, Tar, Bituminous Substances...	2.16		1.54	1.29	2.86	2.90	3.41	3.59	1.80	2.62	1.79	2.22		2.98	1.99	0.375	0.375
4	Ether Extract...........	0.300		0.915	0.97	1.22	0.64	0.34	0.27	0.35	0.47	0.51	0.35		0.50	0.73	0.55	0.28
5	Blown oils Fatty Matters...........	0.81		0.66	1 02	1.15	1.85	2.02	0.83	0.90	0.44	0.18	0.60		0.18	0.74	0.32	0.00
6	Combined Sulphur.......	2.41		3.41	5.08	3.83	4.26	5.47	3.48	4.45	3.01	3.01	3.37		3.64	3.65	2.50	2.62
7	Free Sulphur............	0.23		0.56	0.46	0.20	0.20	0.44	0.71	0.20	0.27	0.24	0.32		0.25	0.25	0.32	0.40
8	Organic Matter.......... (soluble in water)	0.38		0.67	0.97	0.43	0.67	0.90	0.78	0.68	0.64	0.43	0.78		0.66	0.75	—	—
9	Moisture.................	0.14		0.24	0.46	0.30	0.210	0.25	0.57	0.21	0.15	0.34	0.34		0.20	0.43	0.41	0.310
10	Mineral Matter..........	62.03		58.77	57.58	63.60	66.61	52.53	62.16	66.62	71.61	62.71	64.08		61.22	61.60	63.53	65.38

of the same letter the lower priced wire of the same manufacturer.

The measurements made, which are represented by curves, were as follows.

A, the inductive capacity by alternating-current method;

G, the inductive capacity by the ballistic-galvanometer method;

The insulation resistance after one minute's electrification, by direct deflection method;

P. F., the power-factor;

W, the total loss at a frequency of 53.5 cycles and electromotive force = 75 volts.

For convenience in comparison the loss *W* is multiplied by 50, making it equal to that of 50 miles of wire, when the lowest loss is about one watt.

Owing to the time required to complete these tests, it was necessary to make two sets of measurements on two different lots of wires and hence the reason for two sets of curves. On account of the great variation in insulation resistances, two sheets with different scales had to be used. These are given in Fig. 4 and 5, and to get a relative comparison between the two sets of curves the insulation resistance of wire *e* is shown in both figures.

On the right-hand side of each set of curves is given the variation of temperature with time. It was impracticable to keep the temperature at the same point throughout the tests, but the variation in temperature would make little difference in all the various tests, except possibly those of insulation resistance. As the variation of temperature was alike with all coils, the relative average results may be considered sufficiently correct for the purposes of this paper, which deals with comparisons rather than with absolute values. The last two tests were taken at temperatures of about 90° and 115° fahr., thus affording a chance of comparing the various temperature coefficients.

Some explanation of the curves represented by the term A/G is here necessary. This is the ratio of the inductive capacity measured by the alternating-current method to that measured by the usual galvanometer method. In a paper by the writer, read two years ago at the Asheville convention, the statement was made that the dielectric loss in a cable seems to increase as the above ratio becomes smaller. This appears to be generally true here, too.

Inductive capacities are usually measured by the ballistic galvanometer method and A/G is the factor by which said capacities must be multiplied in order to get the true alternating current capacity.

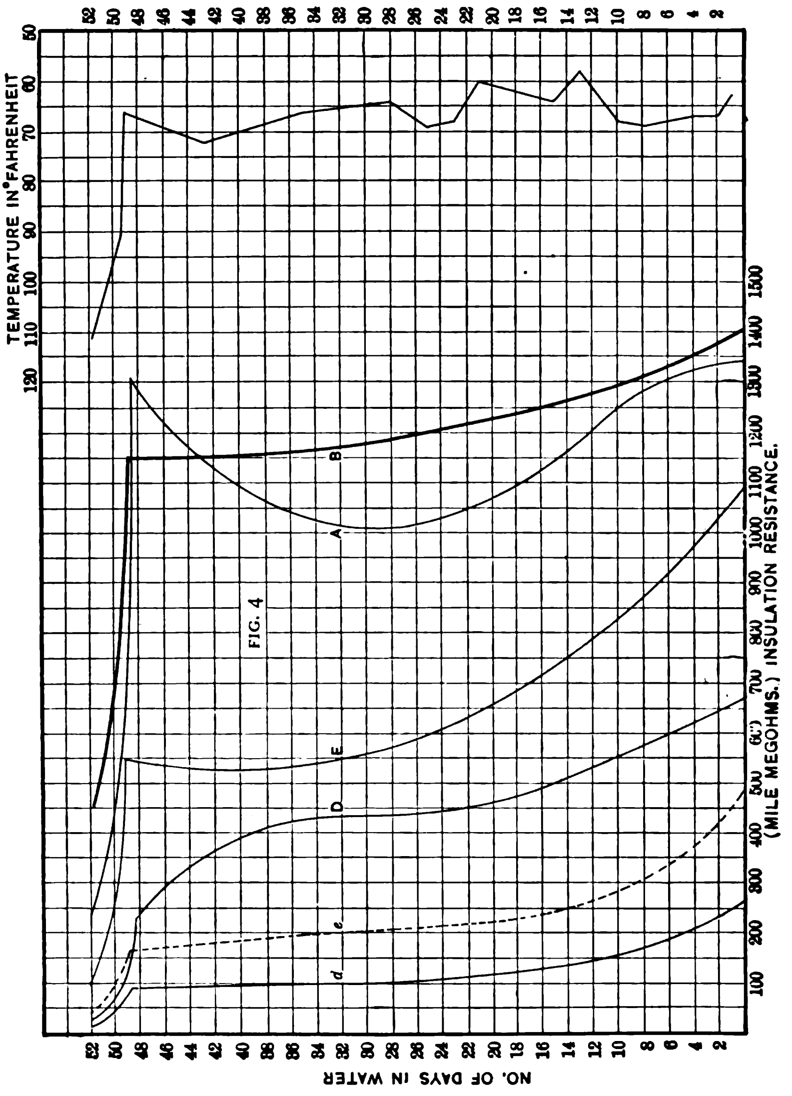


FIG. 4

In a paper of this kind which deals with so many different tests, perhaps the most difficult undertaking is the attempt to make correct deductions and comparisons. For the present confining our remarks to Fig. 2 to 8 inclusive, it is at once noticeable that the insulation resistance, power factor, and A/G decrease with the time of immersion in water, and the others increase

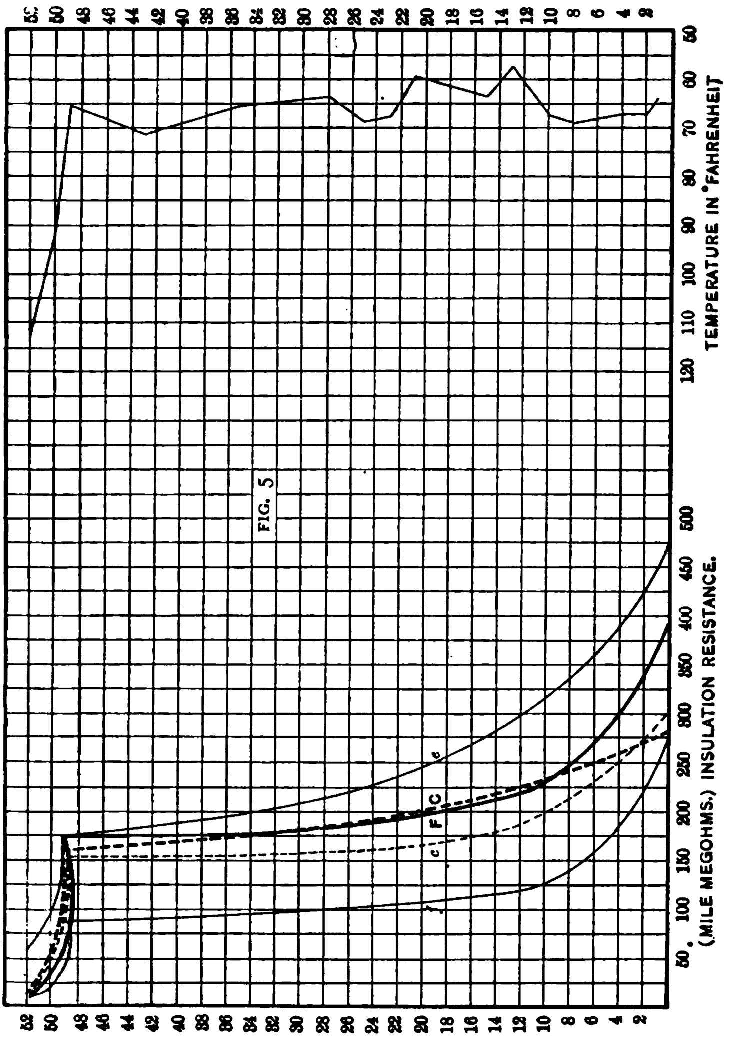


FIG. 5

with the time of immersion. This is what one would naturally expect, because all the samples were braided and therefore the water would take some time to fill all the interstices around the rubber.

It is also evident that the rate of change is generally less where the percentage of rubber is high, as with samples *A*, *B*, *C*, and *D*. *B* was not analyzed, but it evidently contained a large percentage of rubber.

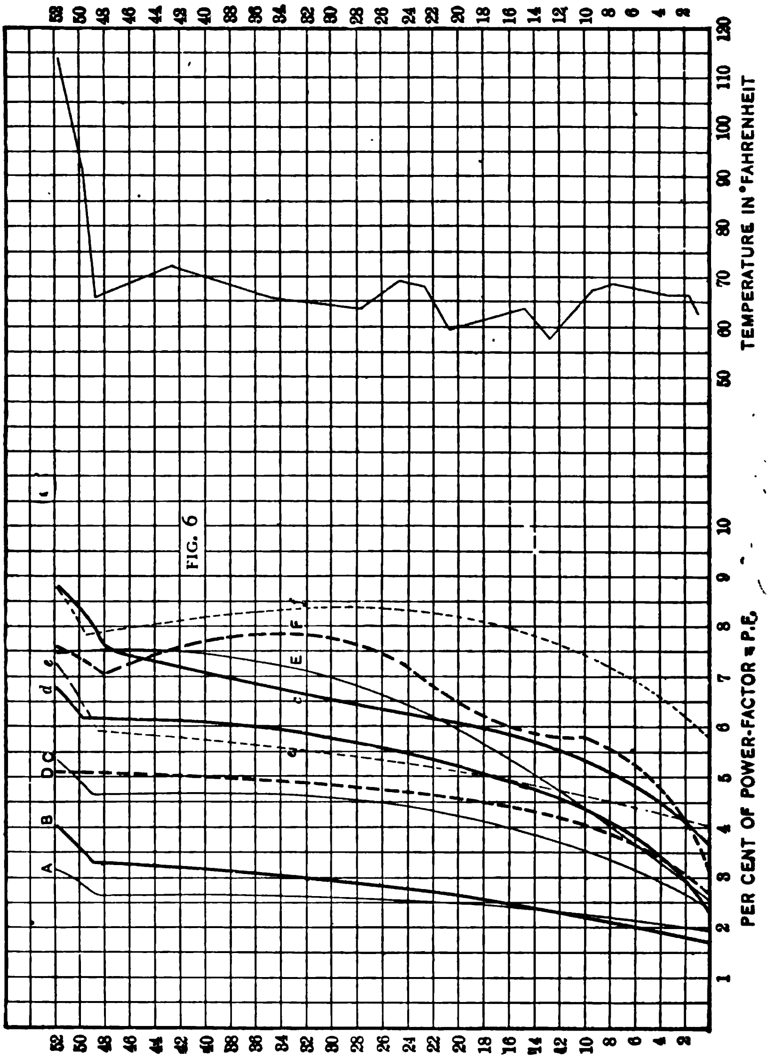


FIG. 6

It will also be seen that while the curves do not always follow in the same order, yet there is a certain amount of regularity among them; for instance, *A* and *B* are at one extreme and *f* at the other. The general tendency is for the insulation resistance to vary inversely as the capacity. There are, however, some notable exceptions which will be considered in due time.

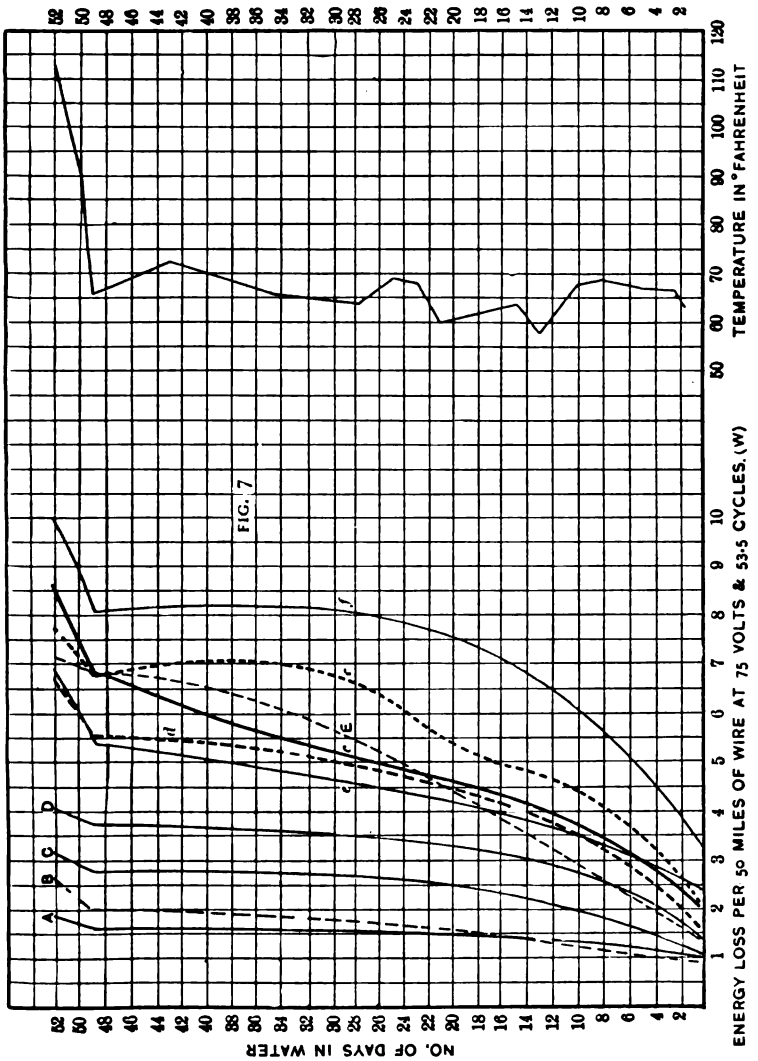


FIG. 7

We may here ask the pertinent question; what are the desirable qualities of a rubber insulating compound? This might be answered as follows: 1, good materials and uniformity of structure; 2, great electrical strength; 3, good lasting properties. Insulation and capacity tests give us some idea of the first, high-voltage tests of the second, and while long-time tests are essential for the third, yet power-factor or loss-tests

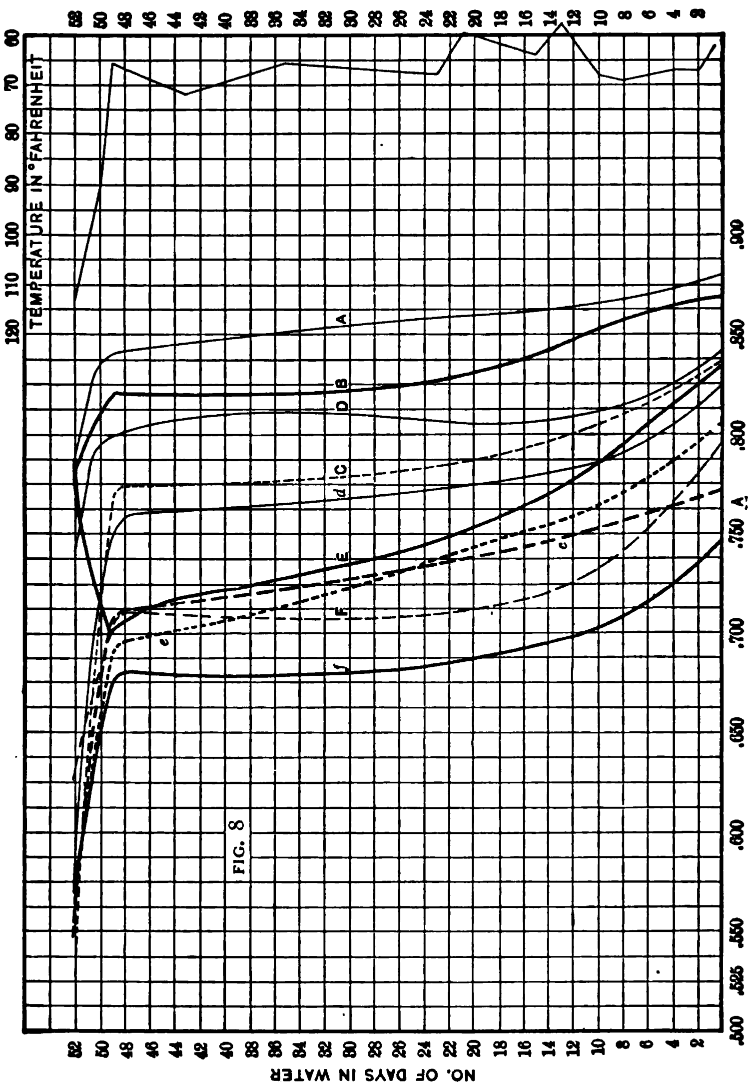


FIG. 8

covering a shorter period of time may indicate any tendency to gradual disintegration.

Now, making some general comparisons, we find that *A* and *B* have high insulation resistance, high resistance to voltage, small

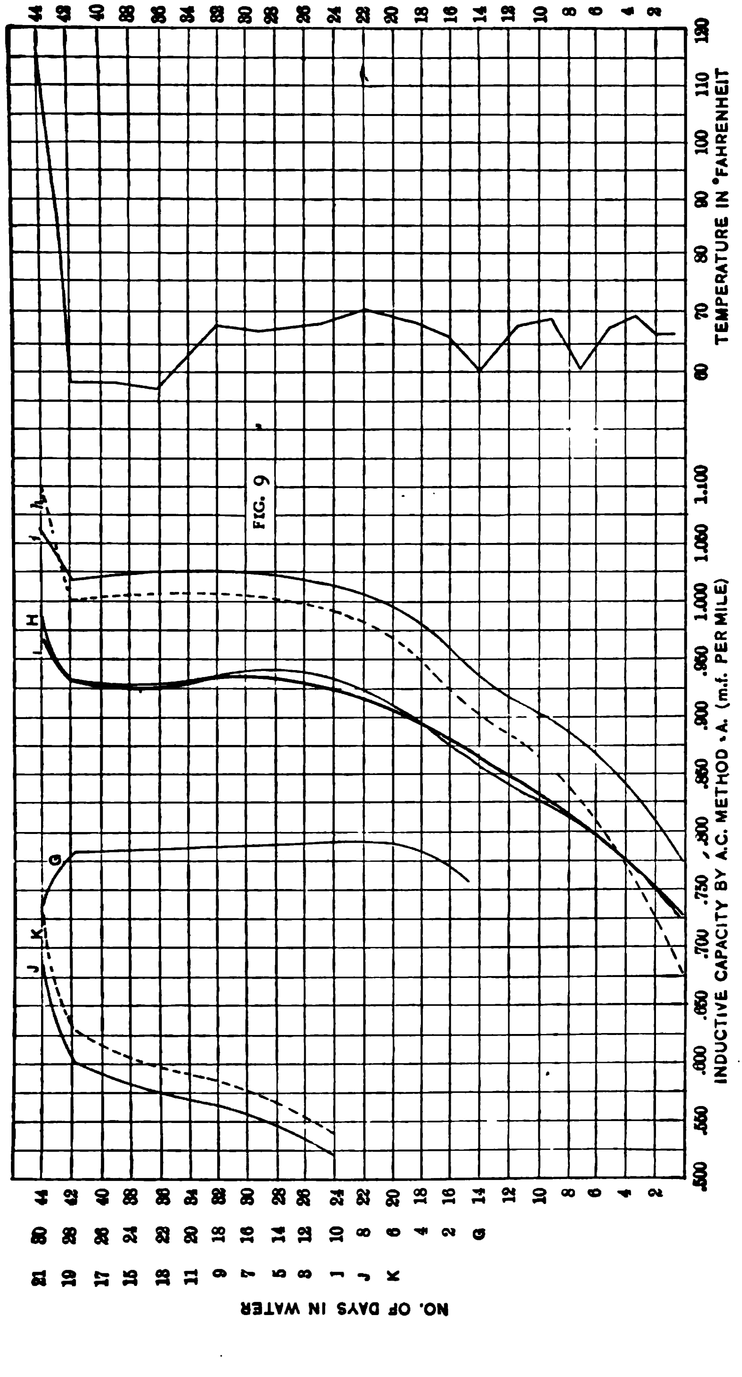

TEMPERATURE IN °FAHRENHEIT
60
70
80
90
100
110
120
INDUCTIVE CAPACITY BY A.C. METHOD A. (m.f. PER MILE)
.500
.550
.600
.650
.700
.750
.800
.850
.900
.950
1.000
1.050
1.100
NO. OF DAYS IN WATER
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
21 19 17 15 13 11 9 7 5 3 1 J K
G
H
I
J
K
h

FIG. 9

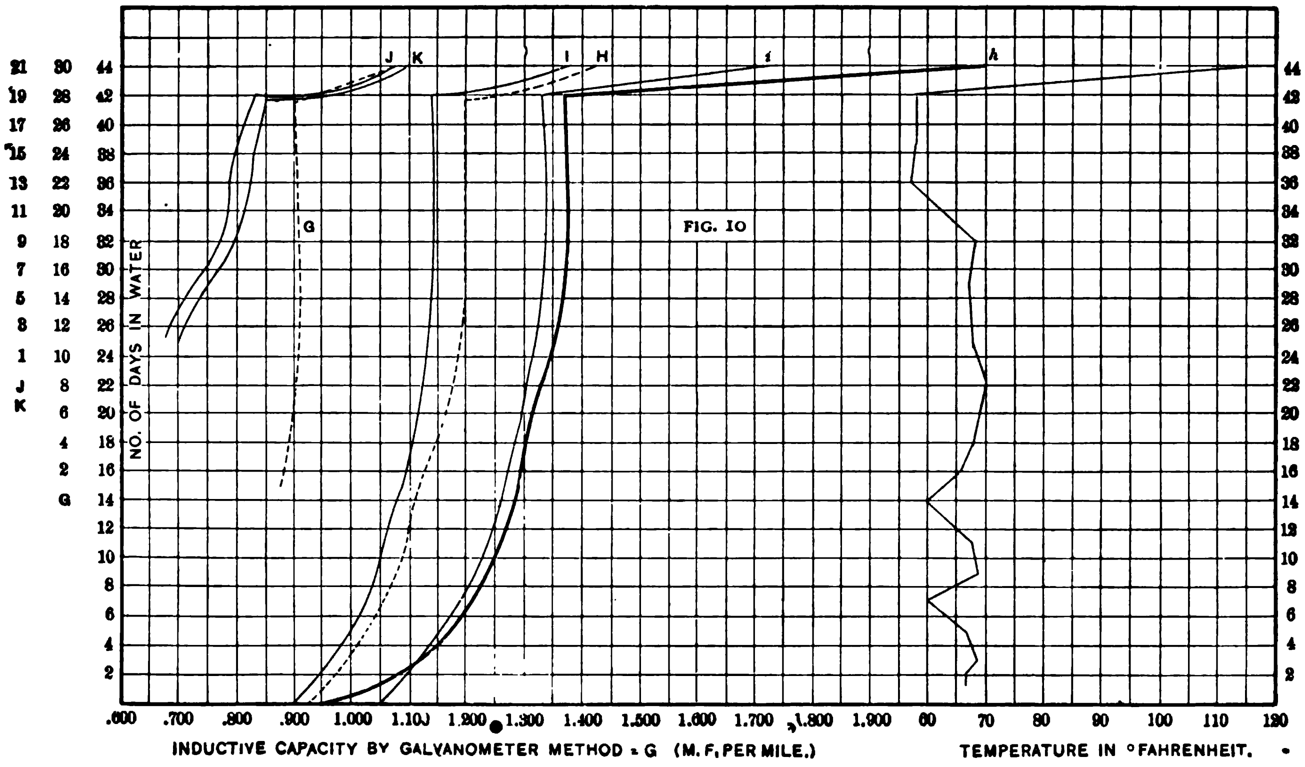

J
K
I
H
i
h
G
NO. OF DAYS IN WATER
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
21 19 17 15 13 11 9 7 5 3 1 J K
.600 .700 .800 .900 1.000 1.100 1.200 1.300 1.400 1.500 1.600 1.700 1.800 1.900
60 70 80 90 100 110 120
INDUCTIVE CAPACITY BY GALVANOMETER METHOD = G (M. F. PER MILE.)
TEMPERATURE IN °FAHRENHEIT.

FIG. 10

energy loss, and *A* shows a higher percentage of rubber. *F*, on the contrary, while having about equally good resistance to voltage, has much less rubber, much less insulation resistance, and greater energy loss. The percentage of rubber in *C* lies about midway between *A* and *F* and yet *C* withstands much less voltage, has an insulation resistance about equal to *F*, but the energy loss is nearer that of *A* than that of *F*. In trying to account for this, we see that *A* and *F* have about the same combined amount of materials 2 and 3, while *C* has almost 4% more of those materials. It therefore seems that the addition of too much waxes, pitches, etc. is not beneficial.

The most notable cases of excessive amounts of materials 2 and 3 are *E* and *e*. *E* withstood the lowest voltage test but this may be entirely due to its thinner rubber wall, and yet its insulation resistance was third from the highest. This shows that the insulation resistance does not depend entirely on the amount of rubber. *C* had 23% rubber and *E* about 17%, and yet the insulation resistance of the latter was best. The energy loss of *E*, however, was much greater than that of *C*. The writer fully realizes that some of these differences may be partly due to the quality of the rubber employed.

Through an oversight, the letters *E* and *e* were reversed, *e* being the higher priced compound and *E* the cheaper grade. In all the figures except those giving power-factor and energy loss, *e*, the better grade, is further from *A* than *E*.; *e* withstood a higher voltage than *E*, and hence with these wires the energy test and voltage test were the true indications of quality.

D and *d* are consistent throughout the whole series of curves, and yet the break-down voltage of *D* is not as high apparently as one would expect.

The writer can give no definite reason why *F* and *f* should almost invariably test worse than the other samples. In break-down voltage tests, they were practically as good or better than first and second grades of other wires. The use of an inferior grade of rubber might partly account for it, but, because of the high dielectric strength of *F*, the writer is of the opinion that the materials 2, 3, and 5 employed, had properties which made the insulation resistance low, the capacity high, and the energy-loss and power-factor high. The writer is fully aware of the fact that insulation, resistance, and capacity are affected by the conditions and time of vulcanization, which might be the cause of some of these discrepancies. It is hardly likely, however, that

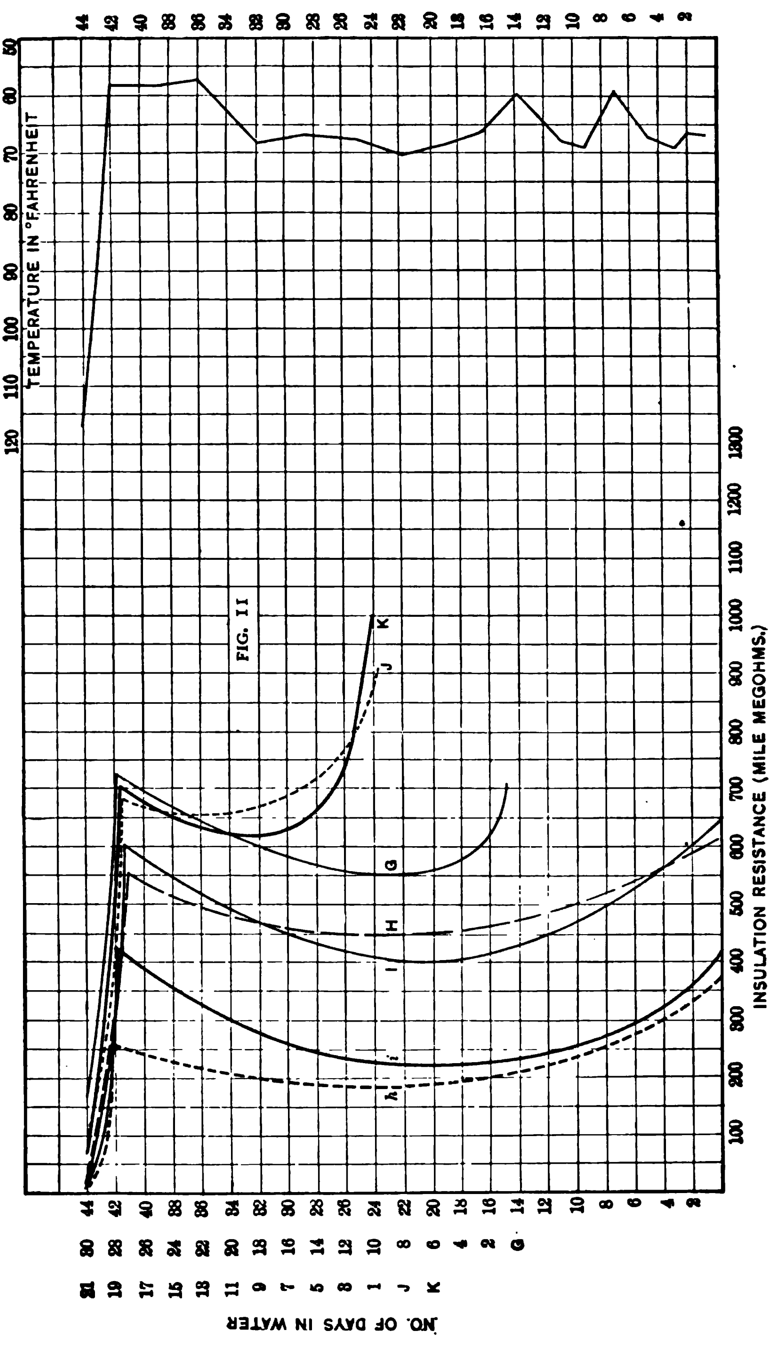

TEMPERATURE IN °FAHRENHEIT
50
60
70
80
90
100
110
120
INSULATION RESISTANCE (MILE MEGOHMS.)
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
K
J
G
H
I
i
h
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
G
31
19
17
15
13
11
9
7
5
3
1
J
K
NO. OF DAYS IN WATER

FIG. II

F and *f* were vulcanized at the same time, and hence the theory of slightly defective material is probably the nearest correct.

It is interesting to note the peculiar change of insulation resistance of sample *A*. There was first a gradual decrease and then an increase to the time when heat was applied, when the insulation again became less. After rubber covered wire is vulcanized, there seems to be a tendency for the insulation resistance to increase and the capacity to decrease. This probably accounts for the above effect. There are other samples which show this tendency to improvement after the lapse of time, but in a less marked degree.

Referring once more to the break-down voltages, it is well to bear in mind the fact that long coils of wire will not withstand anything like the break-down voltages which punctured the four-foot samples. In a few cases, some of the four-foot samples broke down at a much lower voltage than the average of the others made by the same manufacturer.

The second lot of samples are designated as follows: *G*, *H*, *h*, *I*, *i*, *J* and *K*. The curves representing tests made on these are found in Figs. 9, 10, 11, 12, 13, and 14.

Samples *H*, *h*, and *I*, *i* were tested for 14 days when two samples, the average of which is given by the *G* curves, were put in the same tank. At the end of 23 days, the samples *K*, *L* were put in the tank. There are, therefore, three sets of time figures, but under two of these are placed the letters of the samples to which they refer, and the third set must be used for *H*, *h*, *I*, *i*.

The sample *G* seems, from the chemical analysis, to be reasonably close to 30% rubber. The thickness of rubber is the smallest, and yet the break-down voltage was the largest.

All the curves of *G* show but a slight tendency to variation after the lapse of a few days, and there is a general indication of a gradual improvement with time.

The insulation resistance of *G* is not so high as that of *A* and *B*. This difference is partly accounted for by the difference in the rubber wall, and partly by the amounts and kind of materials 2 and 3. The power-factor and the energy-loss of *G* are also greater than those of *A* and *B*, but this is probably partly due to the smaller amount of materials 2 and 3. (See remarks later on about *J* and *K*.)

All the insulation resistances given in Fig. 11 become better near the end of the tests, this is partly due to a drop in temperature which occurred for the two tests prior to increasing the

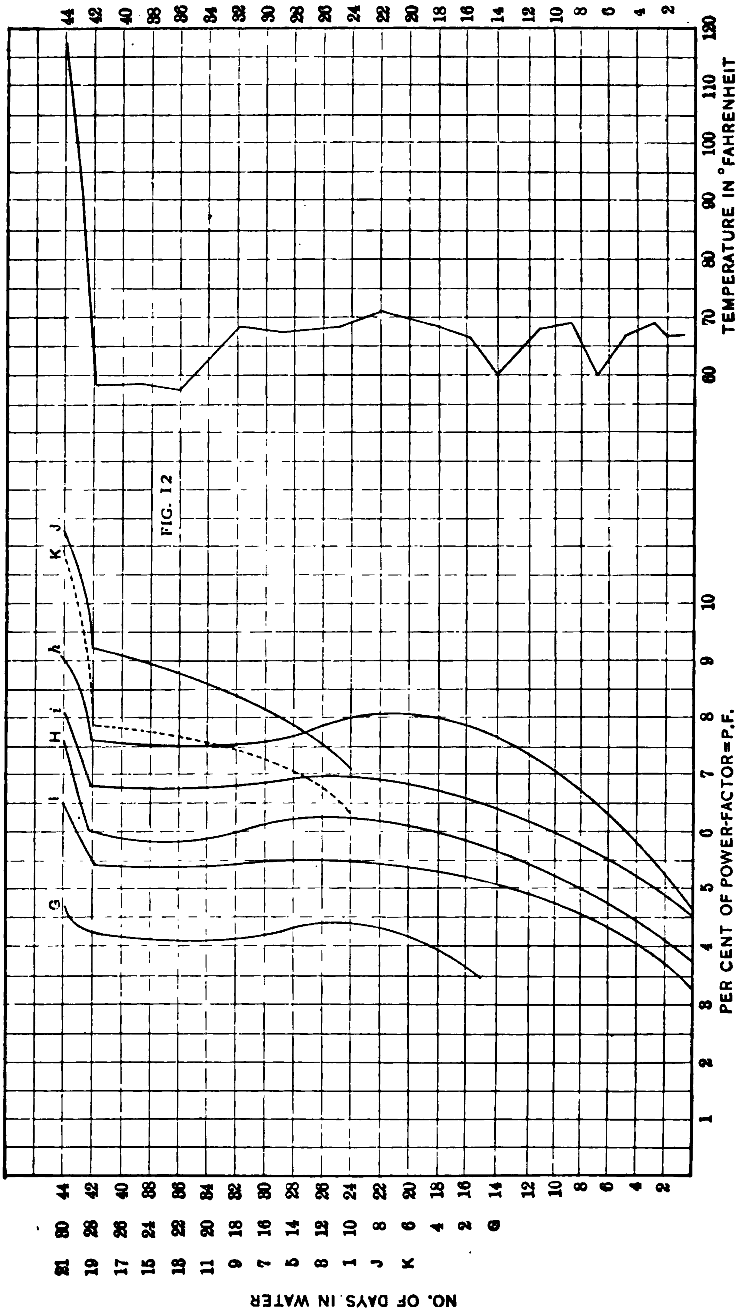
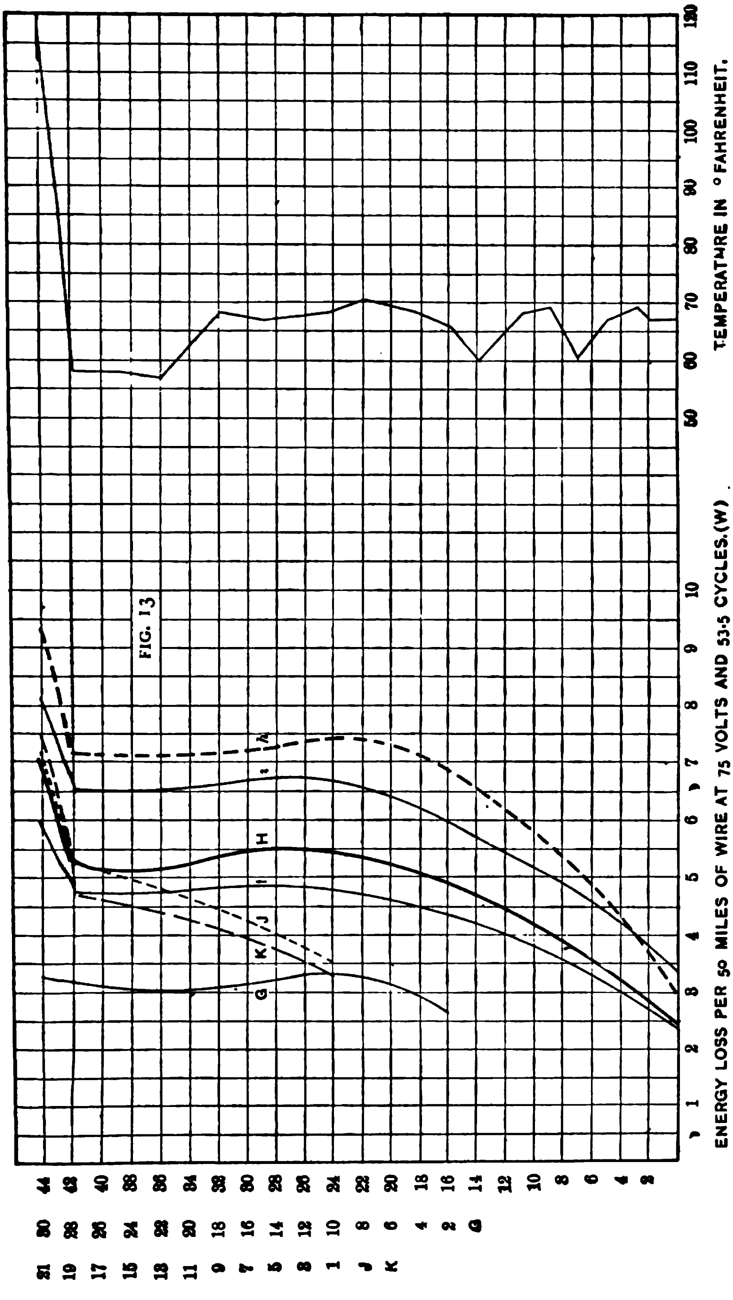

TEMPERATURE IN °FAHRENHEIT
60
70
80
90
100
110
120
PER CENT OF POWER-FACTOR=P.F.
1
2
3
4
5
6
7
8
9
10
G
I
H
i
h
K
J
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0
21 19 17 15 13 11 9 7 5 3 1 J K
NO. OF DAYS IN WATER

FIG. 12



TEMPERATURE IN °FAHRENHEIT.
50
60
70
80
90
100
110
120
ENERGY LOSS PER 50 MILES OF WIRE AT 75 VOLTS AND 53·5 CYCLES.(W)
0
1
2
3
4
5
6
7
8
9
10
G
K
J
I
H
h
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
21 19 17 15 13 11 9 7 5 3 1 J K

FIG. 13

temperature at the end of the series. There is sufficient evidence, however, to show that before the above happened, the insulation resistance of all these samples had ceased to drop, and, in fact, was slightly improving. This is probably because all the samples analyzed had over 20% of rubber. Some of the insulation resistance curves are odd in appearance, but this may to some extent be due to errors or surface leakage. In measuring the insulation resistance of only about 200 ft. of wire, a high degree of accuracy cannot be expected.

" *I*," contained slightly more rubber than *H*, and in most cases the former tests best. In like manner, *i* is better than *h* in the larger number of curves: *h* was white-core and this may partly account for its low break-down voltage.

c, *d* and *f* were also white-core rubber, and the break-down voltages of these were also among the lowest. The white-core part of the insulation was not analyzed, the reported ingredients being those contained in the black-rubber portion.

And now, we come to curves *J* and *K* which are perhaps the most interesting of the series. *J* was made of 15% fine para rubber and 15% african rubber. *K* had 30% fine para. The rest of the materials in both samples was about 1% wax and dry mineral matter. The analysis does not show quite 30% rubber, but this is partly due to the extractive matter contained in the rubber. On all sheets, curves *J* and *K* are reasonably close to each other.

The power-factor and energy loss of *K* are less than those of *J*. Several of the curves are, however, erratic in appearance, showing a tendency to an unstable condition.

In two prominent points, break-down voltage, and power-factor and energy-loss, these samples are inferior to *A*, *B* and *G*.

1. *Break-down voltage.* The thickness of rubber on the samples *J* and *K* was about 50% more than that of the other wires, and yet the break-down voltage of *J* and *K* was about the same as those of *A*, *B* and *G*.

Thinking that this might be partly due to the greater electric density around the smaller wire (No. 12) which formed the conductor of *J* and *K*, the writer tested several samples of No. 14 wire with 51 mils rubber wall, containing about 22% rubber; the average break-down voltage was 19,000 volts, which agrees closely with the other sample containing about the same amount of rubber.

2. *Power-factor and energy loss.* The tests of *J* and *K* were

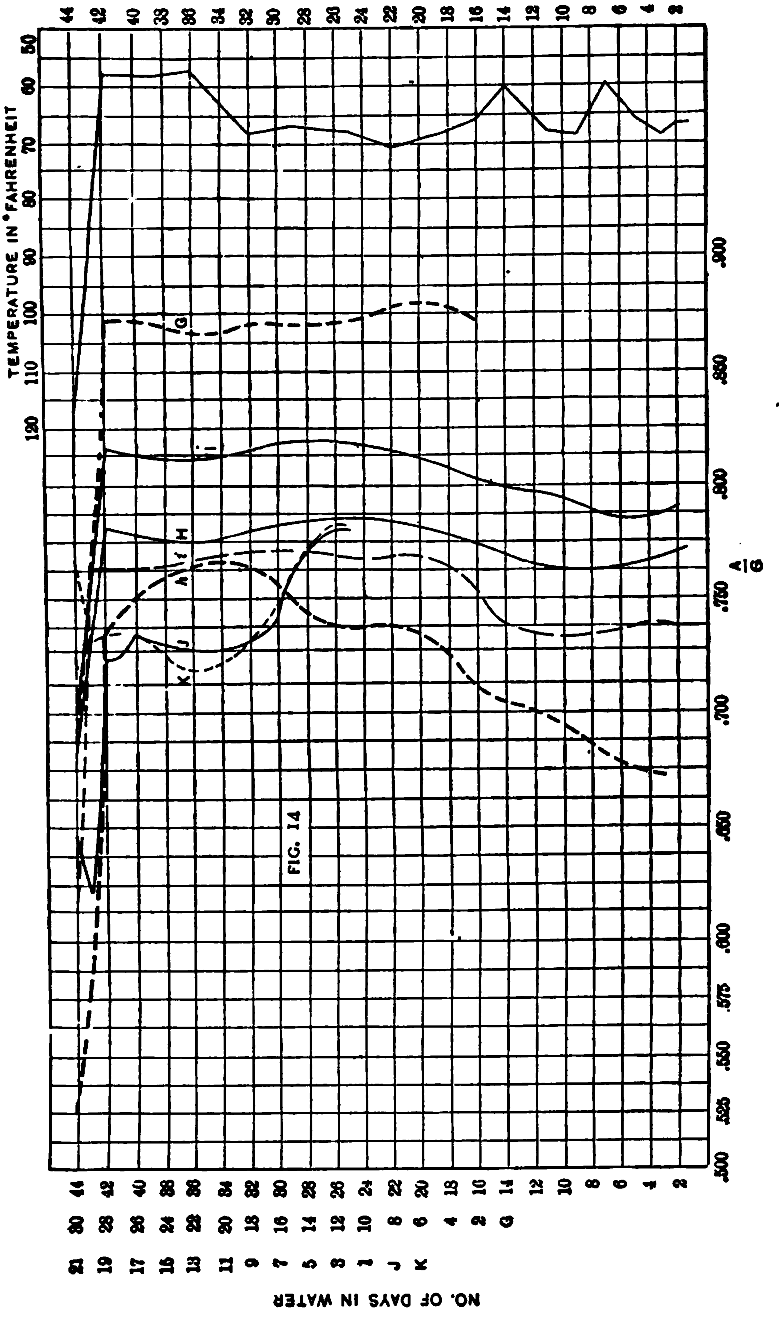

TEMPERATURE IN °FAHRENHEIT
50
60
70
80
90
100
110
120
A/G
.500
.525
.550
.575
.600
.650
.700
.750
.800
.850
.900
G
H
I
J
K
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
21 19 17 15 13 11 9 7 5 3 1 J K
NO. OF DAYS IN WATER

FIG. 14

not carried on for so long a time as those of the others, and yet the power-factors were greater at the end of the series than those of any of the others, and there was a marked indication of still further increase.

The energy-loss of *J* and *K* is not so great as that of some other wires; this is due to the fact that the capacity of *J* and *K* is much smaller on account of their greater thickness of rubber. No doubt, if these samples had a thickness of rubber of about 50 mils, they would have tested worse in most respects than any of the samples of the series.

It therefore appears that the addition of certain materials to a rubber-insulating compound (containing say 30% of rubber), which upon chemical analysis will show a high percentage of extractive matter, may result in a much better quality of rubber-insulating material than one composed of 30% para and showing but a low percentage of extractive matter.

This paper has been prepared in great haste and therefore matters of importance may have been overlooked or omitted. In conclusion, the writer wishes to express his appreciation of the ample facilities afforded him for this investigation, by the Standard Underground Cable Co. He also wishes to acknowledge the valuable assistance rendered by the following persons: Messrs. H. D. Shakarian, T. D. Waring, H. Barbour and G. D. Eustachio.

DISCUSSION ON "POWER-FACTOR, ALTERNATING-CURRENT INDUCTIVE CAPACITY, CHEMICAL AND OTHER TESTS OF RUBBER-COVERED WIRES OF DIFFERENT MANUFACTURERS," AT NIAGARA FALLS, JUNE 25, 1907

Henry W. Fisher: In presenting this paper to the Institute I wish it to be clearly understood that no attempt has been made to say anything or do anything that would be discourteous to the manufacturers of rubber-covered wire. The main object of the paper is to compare a large variety of rubber-covered wires, especially with reference to power-factor and dielectric loss. So far as I know these tests have not been applied commercially to any extent here.

A careful examination of the results given in the paper will show that power-factor tests are valuable in helping to determine the quality of rubber-covered wires, but that they cannot be relied upon to indicate the amount of fine Para. All the tests given are essential, especially the chemical, voltage, and insulation resistance tests.

Chas. P. Steinmetz: This paper is interesting in giving what may lead to an advance in our method of judging cables. It proposes to investigate the character of cables by measuring the energy loss in the cable as represented by the power-factor. The energy loss in the cable appears to me a very important quantity. However, I do not believe it would be safe to judge cables merely by this energy loss. What is important in a cable or any condenser is 1: the disrupted strength; that is, that the cable stands the operating voltage with a sufficiently high limit of safety, and 2: the deterioration, that the cable does not deteriorate at the operating voltage within a reasonable time. Deterioration is the effect of energy consumed in the dielectric of the cable, Therefore, if one could imagine a cable which has no energy loss whatever in the dielectric or zero power-factor, such cable would not deteriorate. This shows the importance of the energy loss in the cable. However, the deterioration is not necessarily, and probably in general is not proportional to this energy loss.

We do not know much, to tell the truth, of this energy loss in the dielectric in the alternating field. We suppose there is some kind of a dielectric molecular friction similar to the molecular magnetic friction of iron; that is, a conversion of electric energy into heat during cyclic changes of static stress. This dielectric hysteresis is harmless, regarding deterioration, because it is a conversion of the energy into heat and merely raises the temperature of the cable slightly, just as the current existing in a conductor raises it, and, if we keep the temperature of the cable sufficiently low, no deterioration will take place owing to this heat. So the production of this additional heat by dielectric hysteresis, must be taken in consideration in designing a cable system.

There is, however, a phenomenon, no analogy of which exists in the magnetic field; that is, a conversion of energy not directly into heat, but into chemical action, and that probably is what leads to the deterioration, the destruction of the dielectric. It is a chemical action exerted upon the dielectric proper, or upon gases included in the dielectric, either absorbed or as air bubbles, etc. If we could separate the energy converted into chemical action from the energy converted directly into heat, we could draw conclusions, the former may give us a clue to the probable life of the cable or condenser. But even then it may not give a direct estimate of the life, because the distribution of the destructive energy is all important. We may have cases in which the energy converted into chemical action, that is destructive energy, is moderately high but uniformly distributed over the whole cable, and the cable so has a good life, while in other cable in which much less energy is acting destructively, may rapidly go to pieces, because the total chemical action, although less is concentrated in a few spots, some air bubbles there weaken the dielectric, rapid oxidation of the rubber etc., takes place, and so disruption. That latter feature is well known to any one who has attempted to build electrostatic condensers for very high voltage. There the chemical energy is localized at some few spots where air bubbles have remained in the dielectric, and destroys it.

While we do not yet know much concerning the laws of energy loss in dielectrics, we know that a part of it, the dielectric hysteresis proper, probably does not vary proportionately to the square of the voltage, and so does not give a constant power-factor independent of the voltage, but a power-factor which probably decreases with increase of voltage, while from other observations and theoretical reasons it appears probable that the chemical destructive action at higher voltages increases more rapidly than the square of the voltage; that is, the power-factor increases with increasing voltage, and it appears to me, any conclusion which could be drawn from measurement of the power-factor of the cable could be drawn only if the power-factor is measured at the operating voltage, at which the cable is to be run, and that is the main objection I have to the paper, although in general I agree with the trend of it. I think that power-factor and energy measurement are made at 75 volts, if I am not mistaken. I believe they should be made at the voltage at which the cable is supposed to operate.

I wish to call attention to the statement that the condenser with the internal energy loss can be represented by a perfect condenser in series with a non-inductive resistance. I do not think that is quite correct. I think an imperfect condenser can be represented by a perfect condenser, shunted by a high resistance. If we consider the extreme case, where there is a very high loss, a series resistance would mean the wattless component of voltage is reduced thereby, which is hardly probable. In the present case it makes no difference because the non-inductive resistance is very small, compared with the remaining wattless effect, but, where there is a very considerable energy loss, I think the safer way is to put it that the imperfect condenser is represented by a perfect condenser shunted by a non-inductive conductance.

The paper certainly refers to a feature that has not always been given proper attention; that is, the importance of the energy loss in the cable, not for the sake of the efficiency of the plant, but for the sake of its possible effect on the life of the cable. One great difficulty in this matter is the method of measuring the loss, which the paper says is difficult and complicated, and not very easy to do under usual factory conditions.

E. W. Stevenson: In the early part of the paper Mr. Fisher mentions something about the change of dielectric with the temperature. I would ask him if it is an admitted fact that the smaller change of dielectric resistance due to temperature shows a higher percentage of pure para? The reason I ask this is because recently I read a specification that called for a very small change of dielectric resistance per degree of increase or decrease in temperature. That is the first time such a requirement has been called for. There has been considerable argument upon it, whether it is so or not.

Henry W. Fisher: The temperature coefficients vary with the ingredients mixed with the rubber, and probably also with the steam temperature and pressure and time of vulcanization. The coefficients are generally less the higher the percentage of fine Para rubber. The coefficients are not uniform throughout a considerable difference of temperature. In some cases the curves representing the coefficients in terms of temperature are of double curvature and sometimes single curvature. I presented curves showing these peculiarities at the Asheville meeting two years ago.

Henry G. Stott: This is a subject in which I take a great deal of interest. It seems to me that the paper starts in from the wrong point of view. A number of different types of wire are taken and analyzed as closely as possible, and then the results of various tests are given to show just how the various characteristics varied with a change in composition. I think we could get a great deal more information if the manufacturers would start out with a definite composition and increase just one ingredient at a time, and follow that up so that we could get a complete curve of variation due to various percentages of that ingredient and so on, following through with the percentage of para, various extracts, mineral matter, etc. But if we could start on a definite basis and build up first one characteristic and then another, I think we would arrive at something very definite upon which specifications could be based.

The paper on specifications for rubber-covered wires by Mr. Langan, read a little over a year ago, assumed to give such specifications. On trying to carry out the specifications enumerated, stretching tests and others, I found that the same results could be duplicated by entirely different compounds, African rubbers, mixtures of various sorts, reclaimed rubber could be made to give practically the same characteristics as 30 per cent. or 40 per cent. para rubber, and based on that I published a series of tests made on different types of compound to show how impossible it was to depend on anything at the present time except on the manufacturer's word, as to what the wire contained. Chemists all agree that it is extremely difficult, if not impossible, in any analysis to say exactly what the constitutents are in any given rubber compound.

Henry W. Fisher: I am interested in Dr. Steinmetz's remarks and fully agree with him that tests of this sort should be conducted at higher voltages. However, at the time these tests were made the apparatus available was designed for low voltages, and the wires tested were those used generally on 100-volt lines.

It is my intention, however, soon to use higher voltages, in connection with which special apparatus like condensers, transformers, etc., will have to be designed. Probably the apparatus most difficult to obtain would be a good mica condenser of low power-factor and high capacity to operate continuously at from 6,000 to 10,000 volts.

Answering Dr. Steinmetz's criticism relative to the method of connecting the resistance in the standard condenser circuit—in getting the power-factor it is immaterial whether the resistance is in multiple or series, so long as the right formula for each case is employed. This formula for series connection was obtained from Dr. Rosa, of the Bureau of Standards and undoubtedly is correct. The resistance is used in series with the standard condenser to make the phases of the currents in the two branches of the bridge the same.

I will ask Dr. Steinmetz if he has treated this problem analytically to see if the series resistance method is incorrect, or whether he reasons from analogy that the resistance should be in multiple with the condenser?

Chas. P. Steinmetz: In the magnetic circuit, the resistance which represents the equivalent of the loss of power in the magnetic cycle, is in shunt to the circuit. In the electrostatic field we do not know enough to say whether there is a series component, but the assumption is justified that there is an electrostatic hysteresis similar to the magnetic hysteresis, and, in this case, the wattless component and the energy component should be shunted to each other, as in the case of the magnetic circuit.

I may say that, as the formula was worked out by Prof. Rosa, it was undoubtedly worked out for a case like this, where the energy quantity is very small, and where, therefore, in the first approximation, it is immaterial whether you put the resistance in series or in shunt. The question would become of importance when the energy component is considerable compared with the wattless component.

E. W. Stevenson (by letter): At the end of Mr. Fisher's paper he lays particular stress on the low breakdown voltage of the white core samples. This is a very interesting fact, especially as it comes from such an authority as Mr. Fisher. I certainly admire his courage in making the statement. I have always been strongly of the opinion that white core is nothing more than a fad. Of course it is generally understood that the white core does not contain sulphur, and therefore is used for the purpose of preventing the sulphur of vulcanization attacking the copper of the conductor. But of course all copper in rubber-covered wire is tinned, and this tinning, as everybody knows, is merely for the purpose of preventing this action, therefore if the tinning is done properly what is the use of complicating the covering process by putting on a white core?

The British navy requirements call for a pure para next to the conductor, a second covering, called a filler, in which there is no sulphur, and a third covering of vulcanized rubber on the outside, thus making three separate covers. This forces the manufacturer to use strip method of covering which, as many of us know, is not the best for all cases.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

INTERACTION OF SYNCHRONOUS MACHINES

A GRAPHICAL SOLUTION BY MEANS OF A NEW CIRCLE DIAGRAM

BY MORGAN BROOKS

When two synchronous machines are in operation as generator and motor, the amount of power demanded of the motor causes it to assume a definite phase relation to the generator, somewhat dependent also upon their relative excitation and upon the impedance of the circuit including the two machines. When such machines are operating in parallel, there is theoretically no power to be transferred, but this ideal condition can only exist when the excitation and phase relation of the machines are identical; if these differ, even by a small amount, transfer of power must take place between generator and motor. The power required by the motor causes a certain vector difference; conversely, the presence of a vector difference points to a definite transfer of power from one machine to the other.

The object of this paper is to present a new circle diagram showing the physical relation of the quantities and conditions involved, to derive and interpret the fundamental equations, and to develop simple loci for solving graphically or numerically the problems of synchronous operation. While based upon strict mathematical analysis, it is hoped that the simplified diagram here shown will be found so direct and rational as to make the analytical method more easily understood and generally serviceable.

The elementary theory of synchronous alternating machines assumes that successive instantaneous values of electromotive force and current follow one another in a manner strictly harmonic. Oscillograph records from normal alternators so closely approximate sine-wave forms as to justify the theory. Irregularities, if considerable, indicate an unsatisfactory machine, one not amenable to simple calculations; but if slight they may usually be neglected, or the irregular wave be replaced for the purposes of calculation, where circuits have small reactance, by what is known as its " equivalent sine wave," having the same effective value.

A true sine wave is determined by the projection upon a fixed axis, usually vertical, of a uniformly rotating vector, whose length gives the value and whose period is the frequency of the harmonic quantity represented. Such a rotating vector could not be seen by the eye, and in order to make use of it an imaginary snap-shot is taken of it, giving the position of the vector at a certain instant.. A picture or diagram of this sort, showing the relation of two or more machines as they exist at a given instant, illustrates the interaction of synchronous machines, and may even allow us to make satisfactory calculations as to operating conditions.

In Fig. 1 let the line *O A*, or briefly *A*, represent the electromotive force (preferably the measured or effective rather than the maximum value) of a single-phase alternator, and let *O B*, or briefly *B*, represent the value and relative position of the electromotive force of another alternator. If the machines so represented are running separately, their vectors may assume any angular relation and need not be of the same length, since the machines may not be equally excited or driven at precisely the same speed. Such a diagram would be understood to mean merely that the machines are adapted to operate together, and are running at approximately the same speed and excitation. For convenience, our snap-shot will always be taken when machine vector *A* is vertical, so that the relative difference of vector position is confined to *B*. If the two machines represented in Fig. 1 are about to be connected in parallel, it is understood that the vectors should be found nearly coincident before the paralleling switch is closed, after which the machines should continue to run with vectors coincident, or nearly so. If hunting should exist, its vector representation would be in the oscillating position of the two vectors, now one ahead slightly, now the other, their possible separation indicating the greatest amplitude of the hunting action. The position of *B* with reference to *A* in Fig. 1 might represent either an extreme position of hunting, or a limiting position for switching into parallel. If two machines, equally excited, were thrown into parallel when their vectors were coincident connection being understood both at *O* and at *A B*, no current would flow in the local circuit; but if the machine vectors were

Fig. 1

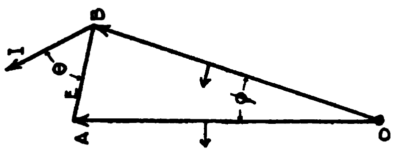


FIG. 1—Vector diagram

Fig. 2

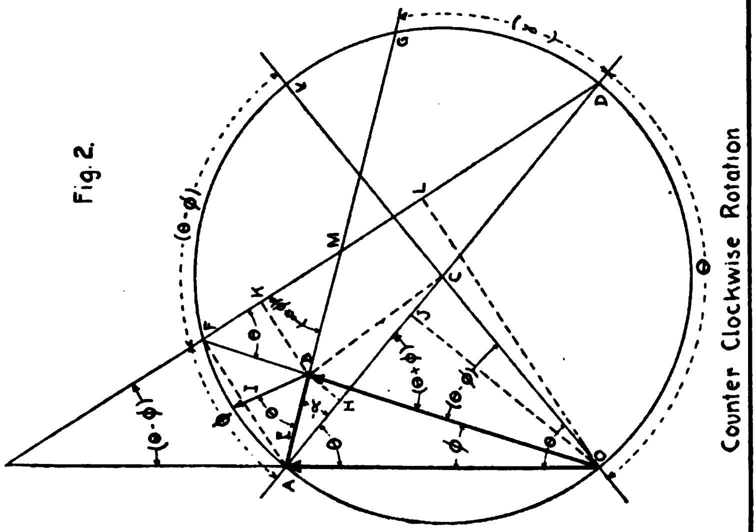


FIG. 2—Circle diagram

a little out of exact coincidence, as *A* and *B* in Fig. 1, then a current would flow between the machines, owing to the vector-difference voltage, *A B*, existing in the local circuit, since it is possible to take *A-B* to represent the vector difference of the voltage *O-A* of machine *A*, and voltage *O-B* of machine *B*. *A-B* represents the only electromotive force acting and we may use *E* in place of *A-B*. The current, *I*, that *E* will drive through the circuit, depends upon the impedance, *Z*, of the local circuit, which includes both machines as well as the line connecting them. Since the impedance of a synchronous machine is of such a value as to allow full-load current to flow on applying about one-third normal voltage, when two machines are coupled directly together in one circuit about two-thirds of the normal voltage of one machine is required to produce full-load current. When *E*, or *A-B*, is equal to two-thirds of *O-A*, which occurs when angle *A-O-B* = 39°, approximately full-load current will flow. This " circulating current " acts to diminish the angle between the vectors; that is, to bring the machines more nearly into phase, and normally the two machines operating in parallel will be maintained closely in phase, since much less than full-load current is required to compel proper phase relation. It is to be noted, however, that there is no compelling action whatever when phase coincidence exists with equal excitation. The current prevents a separation but does not hold the machines firmly together as often supposed.

Assuming counter-clockwise or trigonometrical rotation of our machine vectors, *A* and *B*, the machine whose position is in advance; that is, *A* in Fig. 1, is a generator, and is retarded by reason of giving out power; while the machine whose position is behind; that is, *B* in Fig. 1, is a motor, and is accelerated by the power received. The tendency is to bring the machines into step. If the action should be strong enough to drive *B* ahead of *A*, the circulation of current is reversed; *B* would be retarded by becoming a generator, while *A* would be accelerated as a motor. It is easy to see that hunting might occur from excessive action and reaction. Synchronous machines operating in parallel are then held together by a sort of elastic band, not under tension when the machines are in step, but preventing them from pulling far out of step by a rapidly increasing force, a force that may prove unnecessarily strong, causing a hunting action.

The value of the synchronizing force under working conditions may be calculated, as will be shown. When two machines are operating together under light load, if one loses its driving power it will fall behind its normal parallel vector position only just far enough to enable it to receive current to maintain it in step. No noticeable change in running occurs. It is often supposed that when a generator becomes a motor it falls behind 180 electrical degrees, while in fact it falls behind a very small angle, perhaps 10°. When two machines are transmitting power in the relation of generator and motor, the current flowing between the machines is no longer called circulating current. The motor takes a vector position sufficiently behind the generator to produce the vector difference, E, required to drive the current corresponding to the power demanded of the motor. In parallel operation the machines are usually contiguous, and the current which may "circulate" has in general only the impedance of the machines to limit it; while in generator-motor operation a transmission line with transformers and potential regulators is commonly included, producing a condition as to impedance quite different from parallel connection.

A number of synchronous machines may be operated together, some as generators and some as motors, and the machines may vary greatly in size. To simplify the problem two identical single-phase machines, A acting as generator and B acting as motor, will be considered as connected in a single circuit, so that any current generated in A must pass through the armature of B. The problem commonly provides that the terminal potential of the generator shall be maintained constant, while the excitation of the motor shall be under control. Constant frequency or speed is assumed. The line is assumed to have its resistance, r, and its reactance, x, $[= 2\pi f L$ neglecting capacity effects] constant, and the motor resistance and reactance are also assumed as constant. To include the capacity reactance of a transmission line would change the assumption that all the current generated must pass through the motor, since the capacity of the line acts as an alternative path. The capacity or line-charging current being nearly wattless, the power determinations of the problem are not greatly affected by their omission under load conditions of operation. A correction may be made to obtain the total current required of the generator. The assumption of constant impedance for the synchronous motor, while not precisely true, is akin to the assumption of constant friction loss in engine operation. Except for abnormal conditions, it is believed that no great error is thus introduced. This gives the ratio of R to Z $[R/Z = \cos\theta]$, or the power-factor of the circuit as a known constant, and enables a simple diagram to be plotted.

The regular equations of synchronous operation will now be developed by means of Fig. 2, which differs from Fig. 1 only in the drawing of a circle, whose diameter is $A/\cos\theta$, so centered as to make A a chord, in the extension of vectors B and E to intersect the reference circle at F and G, and in projection of the electromotive-force vectors, A B, and E upon the circle's diameter $A\,D$ and upon the chord $F\,D$, the utility of which projections will presently appear.

NOTATION

A, short for $O\,A$, a vector representing generator terminal voltage, assumed to be kept constant. Vertical position chosen for convenience.

B, short for $O\,B$, a vector representing the induced motor voltage, variable both as to length and direction. Position shown in Fig. 2 indicates any position whatever in its relation to A.

E, or $A\,B$, a vector representing the vector difference of A and B, or the net voltage acting in the circuit which includes the motor.

I, the current produced by E. $I = E/Z$.

R, the resistance of the motor and circuit.

X, $[= 2\pi f L]$ the reactance of the motor and circuit.

$Z = \sqrt{R^2 + X^2}$ the impedance of the motor and circuit.

θ, the angle between E and I. It is a constant determined by the condition,

$\cos\theta = R/Z$, the power-factor of the circuit, often confused with $\cos\alpha$, below.

θ appears in Fig. 2 as the angle made by the lines $A\,C$ and $O\,C$ with vector A; the reference circle is determined by having their intersection C as its center.

ϕ, the angle between A and B, a variable, assumed positive when B lags behind A as shown, the usual condition of operation, when B is a motor.

$\theta + \phi$, the angle between B and $A\,C$, since θ is the angle between $A\,C$ and A, and ϕ that between A and B.

$\theta - \phi$, the angle between A and the chord $F\,D$, which lags behind $A\,C\,D$ by the angle ϕ.

α, the angle between A and I, a variable, considered positive when I lags behind A due to B being under-excited.

$\cos\alpha$, the generator power-factor, sometimes confused with $\cos\theta$ above.

The angle α, appears on the reference diagram as the angle B A C, or the angle between $A\ C$ and E. A lags $\theta°$ behind $A\ C$ by construction. I lags $\theta°$ behind E by definition, hence it is seen that angle B A C is also the zero angle of I to A. Normal excitation reduces this angle to O, and $\cos a = 1$.

$\alpha - \phi$. the angle between B and I, since B lags $\phi°$ behind A. This angle is usually negative, as α is normally small, that is, I usually leads B.

The angle $\alpha - \phi$ appears on the reference diagram as $A\ M\ F$, or the angle between E and chord $F\ D$.

$\cos (\alpha - \phi) = \cos (\phi - \alpha)$ might be called the motor power-factor.

These angles are conveniently measured by half the intercepted arcs, as indicated in the diagram, Fig. 2.

P', the power output of the generator $= A\ I \cos \alpha$.
P'', the power intake of the motor $= B\ I \cos (\alpha - \phi)$.

The diagrams are calculated for values as follows:

$A = 1000$ volts, and
$R = 1$ ohm.

Where $\theta = 45°$, $X = 1$ ohm also, and $Z = 1.41$ ohm
" $\theta = 60°$, $X = 1.73$ ohm, and $Z = 2$ ohms.
" $\theta = 75°$, $X = 3.73$ ohms, and $Z = 3.86$ ohms.

With the above data, the power figures in Figs. 4b and 6 are in kilowatts.

From the projections of A, B and E on diameter $A\ D$, Fig. 2, it is evident that $A\ J - H\ J = A\ H$, or as

$$A \cos \theta - B \cos (\theta + \phi) = E \cos \alpha \tag{1}$$

multiplying by A/Z,

$$\frac{A^2 \cos \theta - A\ B \cos (\theta + \phi)}{Z} = A \frac{E}{Z} \cos \alpha = A\ I \cos \alpha = P' \tag{2}$$

the generator output.

From the projections of A. B and E upon the chord $F\ D$, it is evident that

$$F\ L - K\ L = F\ K, \text{ or}$$

$$A \cos (\theta - \phi) - B \cos \theta = E \cos (\alpha - \phi). \tag{3}$$

Multiplying by B/Z,

$$\frac{A\,B\cos(\theta-\phi)-B^2\cos\theta}{Z}=B\frac{E}{Z}\cos(\alpha-\phi)$$

$$=B\,I\cos(\alpha-\phi)=P'' \qquad (4)$$

the motor intake.

The difference between generator output and motor intake is lost in heat, as with direct-current machines; this is shown in equations (2) and (4):

$$P'-P''=\frac{A^2\cos\theta+B^2\cos\theta-2\,A\,B\cos\theta\cos\phi}{Z}$$

$$=\frac{R}{Z^2}[A^2+B^2-2\,A\,B\cos\phi]=\frac{R\,E^2}{Z^2}=R\,I^2 \qquad (5)$$

Equations (2), (4) and (5) above, are the well-known fundamental equations of synchronous machine operation, and, while derived from the relation of two machines operating as generator and motor, they apply to two machines in parallel operation, provided the current be now understood as circulating current only.*

Power Output.—

Interpretation of equation (2) above,

$$P'=A\frac{E}{Z}\cos\alpha$$

or,

$$E\cos\alpha=\frac{P'Z}{A},$$

a constant for any given value of generator output, P'. Hence, for constant P', $E\cos\alpha$, the projection of E on diameter $A\,D$, is constant, or the locus of B lies in a line perpendicular to $A\,D$, such as $N\,Q$, Fig. 3. The equation is the regular polar equation of a straight line. The power output of generator P' is directly proportional to the length of the projection on $A\,C$, and hence measured thereby. Parallel lines drawn at equal distances

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*Compare Franklin & Williamson, Alternating Currents, page 189. Second Edition.

apart, serve as a chart for reading the value of P' when the position of B is known.

With $P' = O$, the locus becomes the tangent to the reference circle at A. For positive values of P', that is, generator action, the parallels are to the right of this tangent; for negative values of P'', that is, for motor action, reversing the ordinary conditions of the problem, parallels may be drawn to the left of the tangent, shown in dotted lines in Fig. 3. For such positions of B making A a motor, it is evident that machine B must become the generator, as will be demonstrated under power intake. Mathematically there is no limit to the possible values of P', either positive or negative. Operating values are limited by the possible excitation of B, and normal operating values of P' would not ordinarily exceed corresponding values of P'', the motor intake, by more than 25%, the condition for 80% efficiency. Excessive values of P' will exist momentarily in synchronizing two machines if the switch be closed at an unfavorable vector position.

Power Intake.

Interpretation of equation (4),

$$P'' = \frac{A\,B\cos(\theta-\phi) - B^2\cos\theta}{Z}$$

transposing,

$$B^2 - B\frac{A}{\cos\theta}\cos(\theta-\phi) = -\frac{P''Z}{\cos\theta} \qquad (6)$$

a constant for given intake, P''. This equation is the polar equation of a circle, as may readily be seen from Fig. 2 as follows:

Substituting for $A/\cos\theta$ its value, $2\,(O\,C)$, adding $(O\,C)^2$ to both members, and writing $(O\,B)$ for B,

$$(O\,C)^2 + (O\,B)^2 - 2\,(O\,C)\,(O\,B)\cos(\theta-\phi) = (O\,C)^2 - \frac{P''Z}{\cos\theta}$$

The first member evidently gives the remaining side of the triangle O C B, and we have

$$(C\,B)^2 = (O\,C)^2 - \frac{P''Z}{\cos\theta} \text{ or } (C\,B) = \sqrt{(O\,C)^2 - \frac{P''Z}{\cos\theta}} \qquad (7)$$

The second member is constant for constant load on motor, hence, for such load, the locus of B lies in a circle centered at C and of radius determined by the radical.

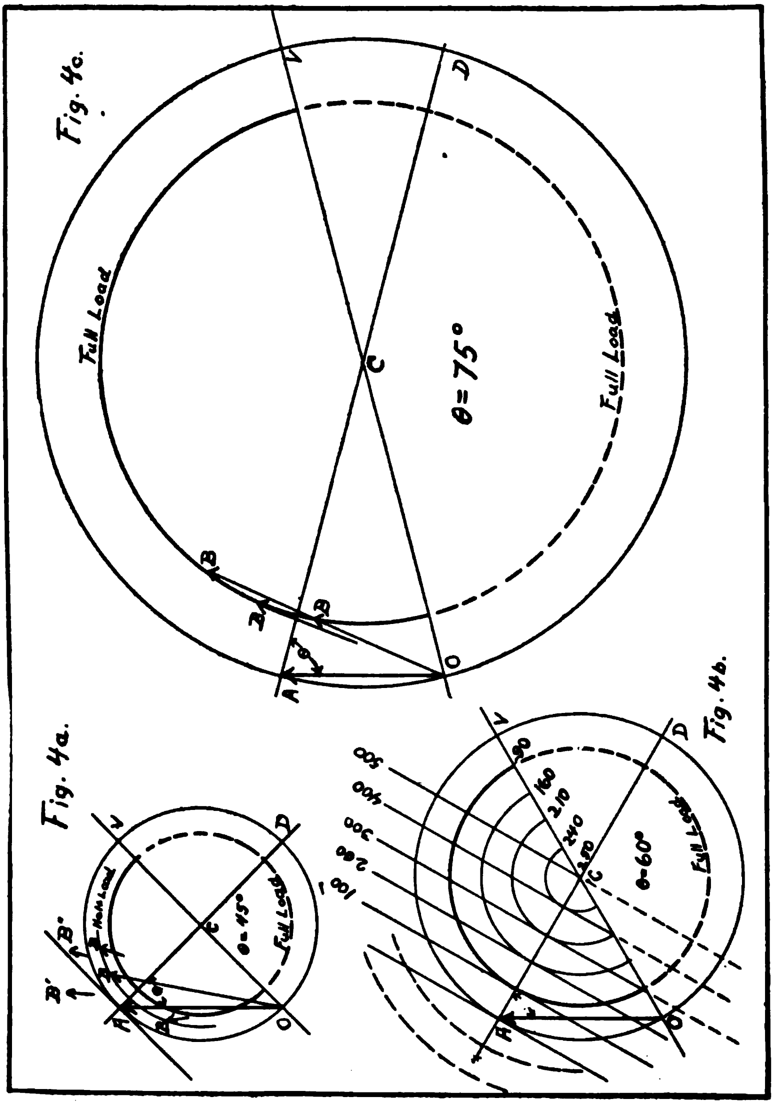

FIG. 4a—Locus of B for constant motor intake. FIG. 4b—Same for $\theta = 60°$. FIG. 4c—Same for $\theta = 75°$

For $P'' = O$, B lies in the circumference of the reference circle, which has C for its center, and $O\,C$ for radius. This is evident since I lags 90° behind B for any point in the circumference. There may be a large current, and the $R I^2$ losses are supplied by the generated power P'.

Negative values of P'', meaning that machine B has its function reversed and acts as a generator, bring B necessarily outside the reference circle, as at B' and B'', Fig. 4*a*. There is no mathematical limit for such external values. If the position of B is also to the left of the tangent ST, as at B', the function of machine A is also reversed, being a motor, while, if the position lies to the right of the tangent, $S\,T$, but outside the circle, as at B'', A remains a generator, and both machines act as generators to supply the large $R I^2$ losses of such a position.

Positive values of P'', that is, normal motor action, give loci for B within the reference circle, the value of $C\,B$ diminishing with increasing load, as can be seen from equation (7). The locus for any given load is a definite circle, whose radius is readily determined. Loci differing by equal amounts, as loci for 50, 100, 150, and 200 kilowatts, will be separated in such manner as to have equal areas in the rings included between successive loci. In equation (7), if $\frac{P''\,Z}{\cos\theta}$ exceeds the value of $O\,C^2$, the value of $C\,B$ is an imaginary quantity; that is, the motor must fall out of step when such an excessive load is applied.

$$\frac{P''\,Z}{\cos\theta} = (O\,C)^2$$

is the limiting case, the maximum load which the motor will theoretically carry. $C\,B = 0$; that is, the point C is the locus of B for this load, which is several times full load. At this point $B = O\,C$, and $P'' = \frac{B^2\cos\theta}{Z}$. Equation (2) gives the generator power for the same point as follows:

$$P' = A\cdot\cos\alpha\,\frac{E}{Z} = \frac{A\,B}{Z} = 2\ B^2\frac{\cos\theta}{Z}$$

It will be noted that this is just twice the value of P'', showing 50% efficiency, as with direct-current motors at maximum load. Loci for normal loads are circles but little smaller than the reference circle.

Efficiency.

Interpretation of equation (5),

$$P' - P'' = \frac{R E^2}{Z^2}$$

Dividing by P', which by equation (2) $= A\ E/Z \cos \alpha$

$$1 - \frac{P''}{P'} = \frac{E\,R}{Z\,A \cos \alpha} = \frac{E \cos \theta}{A \cos \alpha}.$$

Transposing,

$$\frac{A}{\cos \theta}\left(1 - \frac{P''}{P'}\right) = \frac{E}{\cos \alpha} \qquad (8)$$

For a given value of efficiency, P''/P', the first member becomes constant, and the equation is the polar equation of a circle. For different efficiencies, circles of different diameters are found, but all pass through the common point A, which is common to all positions of E; they are all tangent to S T at A.

For efficiency $= 1$ the locus of B is reduced to the point A.

For efficiency $= 0.9$ the locus of B lies in a circle whose diameter is $0.1\ A/\cos \alpha$.

For efficiency $= 0.8$ the locus of B lies in a circle whose diameter is $0.2\ A/\cos \alpha$.

For efficiency $= 0.5$ the locus of B lies in a circle whose diameter is $0.5\ A/\cos \alpha$.

For efficiency $= 0$ the locus of B lies in a circle whose diameter is $1.\ A/\cos \alpha$.

These loci are sufficient to indicate any desired efficiency. For zero efficiency the locus coincides with the reference circle, which is also the locus of zero intake of machine B. Fig. 5 shows loci for given efficiencies as marked.

Heat Loss. Equation (5), $P' - P'' = R\ I^2$, shows that the machine A not only furnishes the power P'' to machine B, but also supplies the heat losses $R\ I^2$ of the circuit. These losses should include the core losses of transformer and motor, and for better interpretation the second member might read $R\ I^2 + H$, meaning by H the core losses, which are approximately constant and independent of current. It is seen that the $R\ I^2$ losses proper, or copper losses, assuming R as constant, depend upon I^2, hence

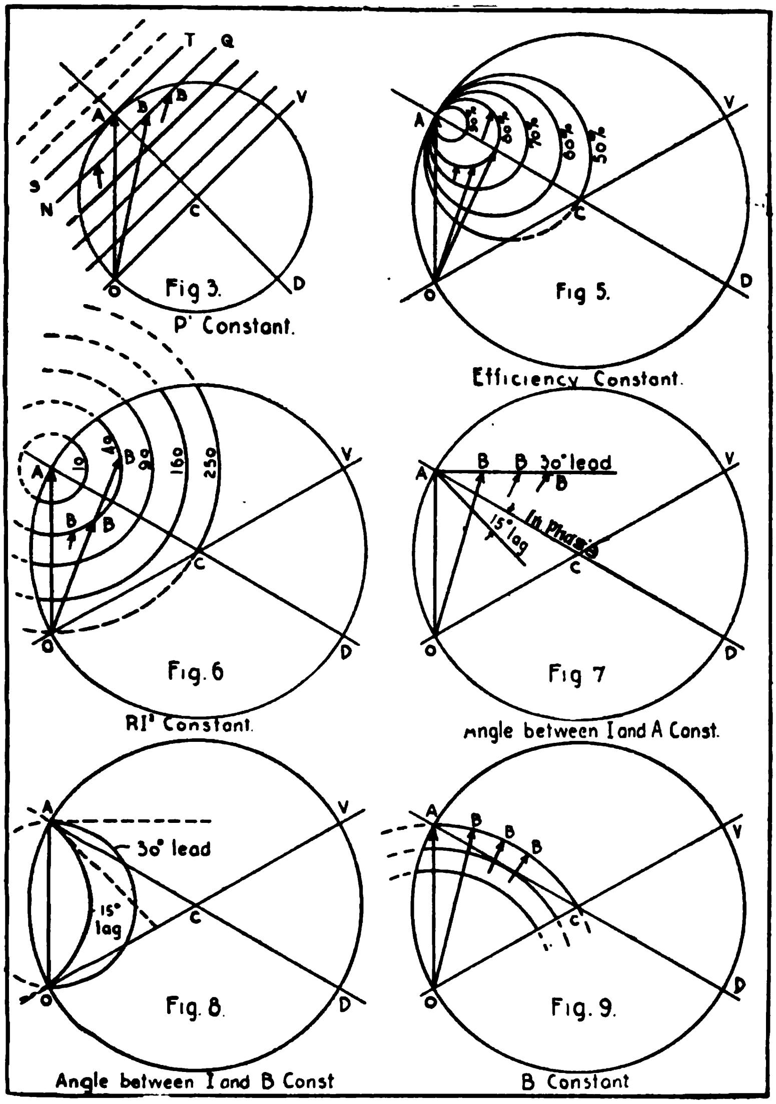

FIG. 3—Locus of B for constant generator output

FIG. 5—Locus of B for constant efficiency

FIG. 6.—Locus of B for constant I^2R loss

FIG. 7—Locus of B for given current angle referred to generator

FIG. 8—Locus of B for current referred to motor

FIG. 9—Locus of B, when of constant value.

upon I, and upon E, which produces I. For any given loss, whether or not including core losses, the locus of B will be at a constant distance from A, that is, a circle centered at A and readily determined; see Fig. 6.

Power Loci. It is easier to calculate values of P'' from considerations of efficiency, than from equation (7). What constitutes full load for a given motor is a matter of engineering judgment, commonly called "rating." For normal power transmission an average of copper losses may be taken at 10%, whence the efficiency, as here defined, is 90%. This does not include losses in the generator. In Fig. 5, the efficiency locus for 90% is shown. At the point where this efficiency circle cuts the line $A\ C$, a line marked 100, parallel to $S\ T$, marks the locus of P', while the circle marked 90 marks the locus of P''. The power ratings will be in the ratio of 100 to 90 to produce an efficiency of 90%. The 90 circle may fairly represent full load on the motor. The next parallel, marked 200, is the locus of P', and the circle touching it, marked 160, is the locus of motor intake, 160 being 80% of 200. In the same way parallels 300, 400 and 500, and the circles 210, 240 and the point 250 are determined. The maximum of P'' in every case is at the point C. The maximum intake of the motor on this basis is $250/90 = 2.8$ times the full-load rating. The current flowing is just five times that required for full load. By a different rating of the motor, other ratios would be found.

Lag and Lead. Combinations of two or more sets of loci give many other interesting facts. For any given power, the locus in general has two intersections with a given efficiency circle, showing that there are two positions of B for the same efficiency of load. A point between can be found where more power is transmitted at higher efficiency. Where an efficiency circle touches a power circle is the highest efficiency for that power. All such points of tangency lie in the line $A\ C$, the locus of B, to bring current in phase with A, the generator e.m.f. Here angle α is zero. With angle α positive, B lies below or to the left of the line $A\ C$, indicating that current lags behind the vector A; with angle α negative, B lies above or to the right of $A\ C$, causing current to lead vector A. The locus for any required lag or lead is easily drawn by merely passing a line through A, making the desired angle with $A\ C$, the normal line. Such loci are shown in Fig. 7.

The loci for current in phase with B, or at any desired angle with B, are drawn almost as easily. They are arcs of circles passing through A and O, and tangent to the corresponding straight loci for same angles with respect to current and A, as shown in Fig. 8.

B Constant. Loci for given values of excitation of B are simply circles with radius centered at O, Fig. 9. If the two synchronous machines are operating as generator and motor, it is evident that the intersection of such locus of B, representing given excitation with the locus of the load P'' of the motor, will show the vector position of B for the conditions given. If the load be increased, the intersection must be with a smaller power circle representing the increased load. The machine B falls back slightly until this intersection is reached. Since in general falling behind places the motor in a region of greater power intake, the action is stable. If, however, the load is increased so much that the vector does not intersect the required load circle until it has come into line with the diameter $O\ C\ V$, running is unstable, because the slightest falling behind brings less power to the motor, and it necessarily falls out of step.

The diameter $O\ V$ appears as a definite boundary for stable running, but as armature reaction is not taken into account in the analysis, it is not to be entirely relied upon. From Fig. 4a it would appear that a demagnetizing armature reaction would bring the vector B, if equal to A, more nearly to the point C, the locus for greatest intake of power; while in Fig. 4c demagnetizing reaction would carry the vector B further away from that point. Currents that are in phase with A, meaning normal positions of B for maximum efficiency along the line $A\ C$, are demagnetizing for B. Since the action of the current is normally demagnetizing upon the motor, a satisfactory operating angle for θ is somewhat less than 60°, a condition fairly well shown in Fig. 2. If B exceeds $A/\cos\theta$, the diameter of reference circle, the machine B is incapable of operating as a motor, since B must then fall outside all possible loci of power intake.

Reactors. The use of a reactance coil increases the angle θ. For long lines, where owing to resistance θ may be small, its use is justified. For proper operation it is easy to use too powerful a regulator, as seen from Fig. 4c where $\theta = 75°$. Here it is only possible to obtain the large values of motor intake by exciting the motor greatly beyond the value of A. Hence if only moderately excited, the motor would fall out of step too easily. Effort should be made to make θ about 55° to avoid manipulation of field rheostats. Where the transmission line is short, the angle will probably exceed this, but to reduce the angle by the introduction of resistance would of course be very objectionable, as it would decrease the efficiency. It might be possible to select a machine with lower inductance than usual for such short line conditions, as for operation in parallel.

Condenser Action. The above paragraph must not be confused with the question of over-excitation to produce the so-called "condenser effect," giving a leading current in respect to A. Over-excitation makes the angle α negative; that is, it is excitation carrying vector B beyond the line $A\,C$, the normal excitation locus. It is seen that this is not a constant excitation, but depends upon the other conditions of the circuit, load, etc. With θ greater than 60°, over-excitation means as a rule, excitation of B greater than that of A; while with θ less than 60°, B may be over-excited, and yet be less excited than A. Under-excitation is less than normal, making the current lag. due to a positive angle α. It is possible to have under-excitation, and yet an excitation greater than that of the generator. This may be the case at heavy loads with a large angle θ. It may be remarked that "condenser effect" is not a true capacity action, since such effect would not tend to increase the triple-frequency component of current, as would be the case with true capacity.

Converters. Synchronous converters may be compound-wound, and so operate successfully on circuits where the angle θ is considerably more than 60°. For short lines, where θ is large, the converter series-winding should be cumulatively connected, to increase the excitation when loaded. This will be the proper condition for such a machine serving lighting circuits, where over-compounding is desired. For long lines powerful reactors may be required to make the use of compound-wound converters feasible. For railway service, where precision of direct-current voltage is less important, it may be satisfactory in the case of a low value of angle θ to reverse the series-winding, making it differential. Operation at least would be more satisfactory. A shunt-wound converter is often preferred, and should act well on moderately long lines. Diagrams for large and small angles θ show why there has been a spirited discussion of the relative advantages of cumulative and differential connection of the series-winding in converters, the difference in action being due to external conditions.

Synchronizing. The constants determining the diagram for showing the behavior of synchronous machines in operation, even under the abnormal condition of falling out of step, are not applicable in making a diagram to predict the initial circulating current upon connecting the same machines in parallel. If two machines are pulled out of step without opening the circuit, it is unusual for any damage to the machines to result, although they pass through all possible phase relations. Yet experience proves that it is unsafe to close a paralleling switch except at or near coincidence of phase. The reactance of an inductive circuit upon first closing the switch depends upon the coil-winding, as if it were without iron, while as soon as the core becomes synchronized full " synchronous reactance " takes effect. The initial current is several times that which would flow at corresponding unfavorable phase position under operating conditions and lasts long enough to produce electrical and mechanical strains which sometimes result in disaster. By using a value for Z, the impedance, perhaps only 15 to 25 per cent. of normal, and a correspondingly small angle θ, a diagram may be constructed that will properly indicate the dangers of imperfect synchronizing.

For safe and effective synchronizing, the circuit may be first closed through a coreless reactance coil of moderate dimensions, as explained in a paper entitled " The Self-synchronizing of Alternators," presented by Mr. M. K. Akers and myself before the Institute in May, 1906. The diagram for showing self-synchronizing employs a value for Z about twice the normal and a large angle θ, and shows that shocks may be eliminated without reducing the useful synchronizing power in the same degree.

Synchronizing Power. The synchronizing power, tending to bring two machines into phase, may be derived from equations (2) and (4).

Equation (2)

$$P' = 1/Z\,[A^2 \cos\theta - A\,B\,(\cos\theta\cos\phi - \sin\theta\sin\phi)]$$

P' positive shows that the load upon machine A tends to retard it.

Equation (4)

$$P'' = 1/Z\,[A\,B\,(\cos\theta\cos\phi + \sin\theta\sin\phi) - B^2\cos\theta]$$

P'' positive shows that the driving upon machine B tends to accelerate it. With P' and P'' both positive, or both negative, the machines are forced together with a power found by adding the two equations:

$$P' + P'' = 1/Z\,[(A^2 - B^2)\cos\theta + 2\,A\,B \sin\theta \sin\phi] \qquad (9)$$

The first term of the second member appears to be negligible, not only because B is usually about equal to A, but also because $\cos\theta$ is small. The synchronizing power is often taken as

$$1/Z\,[2\,A\,B \sin\theta \sin\phi] \qquad (10)$$

If ϕ, the angle between the machine vectors, is the only variable, the value of (10) varies with $\sin\phi$. There is no power acting to hold the machines together, but only to prevent them from moving apart. The effect is a maximum at $\phi = 90°$, and diminishes up to the unstable position of 180°, where it is again zero. The effect, apparently negative beyond 180°, means that the action is to increase the angle toward 360° or 0°.

The above discussion concerns itself only with synchronizing forces. The first term of equation (8) appears negligible, yet its derivation from equation (2) and (4) shows that $1/Z\,[A^2\cos\theta]$ and $1/Z\,[-B^2\cos\theta]$ represent powers acting in the same sense, that is, to retard both machines, A and B.

With angle θ large, as in normal operation, the retarding powers are small, but with Z and angle θ both small, the condition which exists momentarily at the instant of switch-closing, both machines may be so suddenly retarded as to wreck them, since under the condition of small value of θ the braking effect is at its maximum, and the "$A\ B$" terms of equations (2) and (4) are a minimum. When coreless reactors are used, it is impossible for Z and θ to be small, even momentarily, and the shock to the machines is prevented. No synchronizing effect is obtained without some reactance. The effect is a maximum for large angles of θ. Introducing reactance to increase the angle θ means also an increase in the value of Z, which might result in limiting the current too much. A satisfactory compromise may be effected by trial, but the diagram will indicate readily the proper value of reactance to employ.

There should be a distinction drawn between paralleling alternators, and synchronizing a motor or converter with a distant generator. To bring into action an additional generator, especially when the object is to relieve an overload on the machines in operation, care should be taken not to close the switch with the incoming machine in motor, or " B "-vector, position. This will be best accomplished by having the incoming machine running slightly above synchronous speed, and closing the switch not too early. For placing a converter in service, on the other hand, the incoming motor is to receive power, and should not be switched in as a generator or in " A "-vector position. This is best accomplished by having the machine running slightly below synchronous speed, and closing the switch not too early.

Comparison with " V-Curves." The loci of B for various powers as shown in Figs. 4a, 4b, and 4c correspond precisely with the irregular shaped curves called " phase characteristics " or more commonly " V-curves." In the circle diagram, excitation and current are measured by proper scales radially from O and from A (a double polar diagram). In the usual form of V-curves, the plotting is by rectilinear coördinates. The circle diagram may be rapidly constructed by ruler and compasses, while the V-curves have to be calculated and then carefully plotted. That they are identical will be evident to anyone comparing the diagrams. If the curves are derived from experiment, two observations at given load will suffice to determine the circle with considerable accuracy, while a multitude of observations are needed to prepare a good V-curve. Of course not all observations will fall accurately in an exact circle, but the moderate deviation of normal power loci shows the essential reliability of the circles. It seems possible that a few observations carefully plotted in a circle diagram will serve to determine the " constants " of a transmission line, or of a machine, even better than the usual " synchronous impedance " tests. The method has the advantage of making the measurements under operating conditions.

The use of the circle diagram is not confined to two synchronous machines of single phase. Two or three phases may be represented. Moreover, the diagram may be applied to a non-motor load, such as a transformer with any sort of load on the secondary. It suggests a method of graphically estimating the angular phase difference between the secondaries of transformers used for different services, or between the primary and secondary of a single transformer, and at all loads. In the case of a transformer, the angle θ changes greatly with the load, and several diagrams might be required where one would suffice in synchronous machine operation. Indeed the use of previously prepared diagrams, or charts, outlined for different values of θ would make the rapid graphical solution of synchronous problems a pleasure instead of a task. The calculations and diagrams assume pure sine curves of electromotive force and current, and some allowance may be required where these curves are distorted.

That the vector relations shown by the circle diagram actually exist, at least approximately, has been recently shown by a mechanical phase indicator attached to two machines running in parallel. The problems involved in the operation of alternating-current machines are often obscure, since the real forces are not subject to direct measurement, and it is hoped that this presentation of the circle diagram will serve a useful purpose in the interpretation of the interaction of synchronous machines.

DISCUSSION ON "INTERACTION OF SYNCHRONOUS MACHINES", AT NIAGARA FALLS, N. Y., JUNE 25, 1907.

E. J. Berg: Any paper which tells in a simple way how to calculate the characteristics of two machines in parallel is valuable, especially when the equations or diagrams give the synchronizing power. From this we can determine the stability and the natural period of the machine, in other words we can predict something about its hunting tendencies. I doubt, however, if this paper will give this information and I ask Professor Brooks for some explanations. Professor Brooks uses the reactance and the resistance in the total circuit. It must be remembered that machines having the same synchronous impedance, which means substantially the same synchronous reactance, have widely different characteristics. For instance, a machine of definite pole construction and a given synchronous impedance may have an angular displacement of the armature at full load of 15 degrees, whereas another machine of the wound rotor type having substantially uniform magnetic reluctance may have 30 degrees displacement with the same impedance. It is obvious therefore, that any calculations based upon the reactance are of little value in determining its characteristics.

I hope that I am mistaken in thus interpreting the paper and that Professor Brooks can explain that he has taken into consideration not only the true reactance of the armature, but the armature reaction, that is the demagnetizing or magnetizing effect of the armature current on the field.

Chas. P. Steinmetz: I agree with Mr. Berg that these diagrams, and also the original diagram of mine that has been referred to, apply not to existing but to ideal machines. To illustrate; with change of field excitation the current rises—on one side leading, on the other side lagging; but they are not suitable to predetermine exact values, because they apply to a machine in which the reactance is constant, the armature reaction constant, the magnetic inductance, as brought out by Mr. Berg, constant in all directions. Such machines do not exist. Try experimentally to reproduce the diagrams I gave in my paper many years ago and you find near the non-inductive load, near the minimum point, you get about the same shape, but toward much lower or higher excitation you get values which may not be exactly the same as calculated.

For higher values of excitation, the experimental curve more and more deviates from the calculated, due to magnetic saturation. For low values of excitation, the curve should bend back before reaching the zero line of voltage. Instead of this, the experimental curve can sometimes be made to cross the zero line. If at constant impressed voltage you gradually lower the field excitation from that corresponding to minimum current down to zero, and then reverse the field, the machine keeps in step and you may bring up the field in opposite direction, until you have a very high reversed field excitation, and still the machine runs in the same step, with the armature reaction producing the field against the opposing magnetomotive force of the field circuit, until suddenly the machine slips one pole back and with the same field excitation, everything remaining the same, the current drops down to the value which corresponds to the positive value of excitation. Now, that no diagram shows because it is the effect of the asymmetrical magnetic structure, that is the magnetic flux is not in line with the resultant magnetomotive force, but differs therefrom by a certain angle, being closer to the center line of the field pole, and this feature throws any simple calculation out, and requires a much more complicated system of diagrams in which you have to consider the two separate components of magnetic inductance, and of armature reaction. The reactance is not a constant, but a function of the position, has different values in two directions at right angles to each other and the magnetic reluctance of the circuit also has two values. You must divide the system into two components, which can be done, but makes it a little more complicated.

Comfort A. Adams (by letter): Without wishing to subtract in any way from the credit due Professor Brooks for his very interesting paper on " The Interaction of Synchronous Machines ", it is only fair to state that the principle diagrams there described were published by Professor Blondel in 1895 in " L'Industrie Electrique ", and later in his book on " Synchronous Motors ". The writer has used the Blondel diagram for the last twelve years in his classes and has found it a great aid in making clear the operation of synchronous machinery. He therefore appreciates most highly the interesting additions to this diagram made by Professor Brooks.

The quantitative relations between the armature resistance and reactance shown in this paper lead one to assume that the *leakage reactance* was chosen in place of the *synchronons reactance* which should have been employed.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

PROTECTIVE APPARATUS ENGINEERING

BY E. E. F. CREIGHTON

The main object of this paper is to describe the methods which have been in use in the development of lightning apparatus, so that some or all of these methods may be adopted or recommended as standard in the investigation of the value of any particular apparatus. As an introduction, it is pertinent to point out the differences and identities in the operation of the arrester in test as compared with its operation in actual service. Generators, motors, arc lights, practically all electrical apparatus except lightning-arresters—are tested under the conditions; under which they are to operate. The lightning-arrester in service comes into action only intermittently, with long intervals between operations, and each operation is under conditions more or less different from the previous ones. It protects, fails, or is destroyed according to its adaptation to meet the imposed conditions. The arrester may operate for years before it encounters conditions which it is incapable of meeting. The conditions which caused the failure are usually unknown, therefore little or no progress can be made in the design without studying the actual conditions which caused the failure of the arrester. Since this cannot be done at present with cloud lightning, we must experiment with artificial lightning in the laboratory until this condition causing failure is found. Simply noting whether an arrester fails and then making an adjustment, elimination, or addition of parts of the arrester is a cut-and-try method and has already been carried to the limit of its efficacy in the development of protective apparatus.

In making a plea for the recognition of the value of laboratory tests, it is pertinent to look at the subject from several viewpoints. Lightning-arresters are but auxiliary devices to the large expensive machines of electrical transmission systems and the receipts therefrom to the manufacturer are small in proportion. The successful and continuous operation of electrical systems, however, depends greatly upon the efficiency of the protective devices. Great expenditures have been made in the development of protective apparatus, not on account of the intrinsic commercial value of the arrester business, but on account of the broader scope it gives to the electrical industries. Station managers should realize that to them has been given each year the very best apparatus that could be developed, and that the manufacturer of large apparatus is even more desirous than they to install an arrester which operates perfectly. Failures of arresters are comparatively infrequent, and in order to eliminate these last faults the intelligent coöperation of many station managers is desirable. In a short time, instructions and apparatus for studying the operation of lightning arresters in service will be ready to send to managers, and conscientious efforts of many will show the rare instances where the arrester fails and will indicate the complete solution of the problem. If the insulation of electrical apparatus has been seriously deteriorated by overheating, a manager should make an effort to ascertain this fact and not befog the problem by laying the fault to the arrester. Furthermore, there is always a necessity for engineering in the choice and location of arresters to give the best conditions of protection.

Up to the present, the design of electrical transmission apparatus and that of protective apparatus have gone hand in hand. For example, when the arrester was adjusted to its maximum permissible sensitiveness and failed to protect the end-turns of a transformer, the transformer designer came to the rescue by adding extra insulation to the end-turns. At present, the designers of protective apparatus are endeavoring to design arresters for each potential, that will limit the rise to 150% of normal. That arresters have been faulty is conceded, but the designer has too often to meet the condition of weak insulation and the occurrence of rare lightning phenomena. The problem is further complicated by the varied demands of protection at different voltages of transmissions.

A brief survey of the relation of line voltage to the problem of protection is herewith given.

Line potential and the problem of protection. As a thunder-cloud approaches a transmission line, each lightning discharge increases the severity of the induced stroke on the line. In this wide range of intensity, it is easy to imagine that there is an average value of potential, due to discharges to the earth within a mile of the line, and yet not actually striking the line, which occurs frequently. Its value is unknown, but, judging from the fact that it does not jump over the insulators, it is less than the spark-potential of the insulator and therefore, in general, less than 200 kilovolts. The indications are, however, that it is probably not less than 100 kilovolts.

The thunder-cloud takes no account of the potential of the line, so that a 500-volt trolley wire will get the same induced lightning stroke as a 60-kilovolt transmission in the same location. 100 kilovolts would be harmless to the insulation of the 60-kilovolt line, but an arrester must operate instantly and rapidly on a low-voltage line to bring this potential down to a safe value before the relatively weak insulation is damaged. On high-potential lines, furthermore, the brush discharge potential of the line conductor is not much above the line potential, so abnormal potentials may lose an appreciable part of their dangerous peak values through the energy thus lost in the atmosphere. There is one compensating condition in the protection of low-voltage systems, in the greater factor of safety in the insulation customarily used in the construction. It is not unusual to find a 2,000-volt transformer with a factor of safety of 5 to 10 and a lightning-arrester with a spark potential of twice normal, whereas a 60-kilovolt transformer may have a factor of safety little greater than two, and the arrester must be adjusted within this limit.

Effect of location of circuits on the problem of protection. There is another compensating condition favoring the design of arresters for low-potential circuits; namely in the shorter lengths and favorable locations, both due to natural engineering requirements. For example, 2300-volt circuits are usually short and confined to the streets of a city where the houses and overhanging trees protect the lines from lightning charges induced by the storm clouds. Trolley wires are often overhung with feeders and have an additional compensation in leaky insulators. The numerous supports of the trolley wire each with a low-insulated, leaky-surfaced insulator help to discharge the static electricity to ground at the point where it is freed. Unfortunately, 2300-volt circuits and trolley lines are not confined to shady avenues and city streets, but are often carried into the open country. This is the part of the circuit which needs special care and protection against cloud lightning. A striking illustration of this necessity was shown last summer at a coast city The city trolley was connected with a beach line. A storm passed over the city, disabling more than a dozen cars on the beach but none of the cars on the city streets. All these cars carried arresters of antiquated design. Another trolley circuit, an interurban, in a lightning storm district passes along miles of road with many large trees on each side. In consequence, with the ordinary protective apparatus, burn-outs of motors from lightning are so infrequent as to cause no disturbing increase in the repair expense.

Factor of damaged insulation. In the matter of satisfactory protection, a factor enters which is beyond the control of the lightning-arrester designer. This is the effect of the abuse of the insulation of electrical apparatus. These abuses are usually confined to overheating and wetting the insulation. Overheating produces a gradual weakening which will finally cause a short-circuit even at normal voltages. This final catastrophy, if due to normal voltages, will not be affected by the presence of the lightning-arrester, but the arrester, according to its efficiency, will lengthen the time during which the insulation can withstand abnormally high potentials.

Guarantees. Because of the necessity for the insertion of a conditional clause stating that the insulation has not deteriorated, no form of useful guarantee that the arrester will protect the insulation can be given by the manufacturer, even when an absolutely perfect and universally applicable lightning-arrester is in commercial service. A guarantee that an arrester will not be destroyed within a given time, say one year of service, could be given, but it would put a premium on making the arrester safe, even at the expense of the apparatus, and is therefore objectionable.

Regarding service tests. The final criterion of success of an arrester is infallible protection under every condition of service. Perfect operation in one location does not prove the success of an arrester unless it can be shown that the lightning in that location was severe and of widely variable nature. There is an element of luck with storm-centers away from the line; specially high factors of safety of insulation, favorable location of lines, and freedom from resonant conditions must be taken into account. A considerable expenditure of money and time must be made before any conclusion can be drawn from a service test The information from a laboratory test, while not final in its conclusions, gives immediate results and brings an earlier solution.

Trouble inspection. Furthermore, the service test alone gives no information regarding improvement of design. If the arrester is destroyed, the designer is often called in to inspect and investigate the cause of the trouble. There are perhaps a few pieces of fused metal, arc holes, broken chunks of porcelain, burned insulation of the leads, and a disgruntled manager. The results are visible. The cause of the trouble disappeared as rapidly as the air vibration of explanation. One goes over a series of possible causes like the presence of bugs, bad condition of the arrester due to previous operation and lack of inspection, collection of dirt on the bushings, grounded phase, direct stroke, line-to-line surge or line-to-ground surge, standing wave, and faulty design. On the other hand, if the failure of the arrester was the failure to protect the apparatus, speculations are made on the nature of the stroke of lightning, its natural frequency, duration, quantity of electricity, standing wave, and resonance. If the puncture was internal, there is sometimes the question of abnormally weak insulation due to poor workmanship, or abuse in the form of overheating, wetting or mechanical injury. Possibly the arrester was not at fault. If the trouble was a standing wave, it might have been in a poor location to protect. The earth connection may have been bad, and so on.

If the insulation was punctured at the bushing, or the spark jumped through the air, there is seldom a question of damaged insulation and the fault must be laid to the arrester circuit. There are at least four leading questions of interest to the engineer.

1. Subject of quantity and frequency. Was the arrester resistance too high?

2. Subject of frequency. Was the equivalent needle-gap too high at the particular natural frequency of the discharge? (Some arresters vary in equivalent needle-gap with a variation in natural frequency of the lightning surge.)

3. Subject of earth connection. Was the resistance of the earth connection abnormally high, or was the distance between the earth connection and arrester abnormally long?

4. Subject of resonance. Was there a standing wave with a node at or near the arrester and an anti-node or peak at the point of puncture?

The first three subjects are matters of design. The fourth subject is a matter of the location of arrester and choke-coils. Unless the trouble inspector enters the field with predetermined knowledge of the action of an arrester under the strains of different kinds of lightning strokes, the inspection is fruitless. Such a knowledge can be obtained only through laboratory tests with artificial lightning.

Example of interpretation from inspections. As an example of interpretation from an inspection, the following is given. Arresters of special design, set very close to line potential, were installed on a long system operating at 13,000 volts. Near the generating station, the arresters were arranged to give less possibility of short-circuit under heavy lightning than in the sub-stations. During the entire winter the line superintendent conscientiously examined and removed tell-tale papers in the arrester gaps. About the only information gained during all this time was that the arresters were sufficiently sensitive to operate from the internal lightning caused by switching and other accidental disturbances. A short time ago a lightning storm occurred. The tell-tale papers at one sub-station showed discharges through the arrester. At another sub-station two current transformers were punctured, but the tell-tale papers in the arresters at the cable terminal house near the sub-station, and in the arresters in the sub-station itself, showed no discharge. In other words, the discharge passed two sets of lightning-arresters adjusted close to normal line potential and punctured the two transformers. Why did the arresters fail? What kind of lightning stroke was it?

To answer these questions, the predetermined fact is known that these arresters are not sensitive to the first half-cycle of the lightning discharge and therefore not sensitive to low-frequency high-potential surges. When these arresters were installed, the designer knew nothing of the fact nor how to overcome it. It is also known that these arresters are exceedingly sensitive to high-frequency discharges.

A probable explanation is that high-frequency cloud-lightning caused a discharge over the entire arrester, cutting out all resistance. A low-frequency surge followed which passed the other arresters and damaged the current transformers, the weakest insulation in the sub-station. There is one other possible explanation; there may have been a standing wave with the nodes at the arresters. This seems improbable, however, because there were two arresters, and, furthermore, the same phenomenon has been observed in several other cases where the insensibility of this type of arrester to low frequency seems to be the fault.

In another paper, the method of correcting the design of the arrester considered above is given. If a manager of a transmission system assumes the untenable position that the manufacturer has sold a piece of apparatus which will not take care of all lightning conditions and is responsible for replacement of arresters, an embarassing commercial situation arises which cuts off free intercourse between the engineers and consequently impedes progress. Perhaps a manager has decided that the arresters are an unnecessary evil and has taken them all off the system. With good luck, such a system may run several months without trouble from lightning, but each high-potential surge which enters the station will do a definite amount of irreparable damage to such insulation as is not self-repairing. Sooner or later, enough strokes of high potential occur at one point to cause a puncture, and all other points weakened by overstraining are likely to give way under the secondary strains of the energy surges of dynamic potential coming from the initial short-circuit.

Unless the cause of the failure of the arrester can be traced to something specific, little improvement of design is possible. We have already come to the stage where accurate measurement is the life of further progress. It is necessary to produce artificial lightning of varying potential, quantity, frequency, and duration in the laboratory, and to study with it the characteristic behavior of a lightning-arrester. By applying considerable dynamic energy to the arrester at the same time, the secondary effects of dynamic current discharge and the endurance of the arrester may be determined. Knowing the characteristic behavior of an arrester under varying conditions, it is often possible to make a very plausible surmise of the nature of the cause of the failure. The engineer who advances the argument, as has been done, that " it is only a laboratory test and does not prove the value of the arrester " loses the proper viewpoint. The object of the laboratory test, aside from the educational experience it gives, is to prove the converse condition regarding an arrester; that is to say, if the arrester will not withstand reasonable laboratory tests in conjunction with the insulation which it is designed to protect, it is sure to fail sooner or later on the line. If the laboratory test shows the arrester weak in some particular point, and that point only, it does not necessarily condemn the arrester, for it may be due to a condition which may be taken care of by some other kind of arrester or one that may not occur on the circuit in years. But, if such an arrester fails, it often seems permissible to attribute the cause to this weakness. With such knowledge, it is possible to employ to great advantage a particular type of arrester on certain kinds of circuits or in certain locations.

An analysis preliminary to standardization recommendations. Before attempting to write standardization rules, it is pertinent to review the necessities of the situation.

First of all is the selection of names for the apparatus and the general terminology as a means of common intercourse.

The second consideration is the nature of the lightning so far as known, and the strain which must be relieved by the protective apparatus.

The third consideration is the nature and characteristics of the insulation to be protected.

The fourth consideration is the characteristics of the protective apparatus.

The fifth consideration is the nature of the test with artificial lightning, which will demonstrate the characteristics of the protective apparatus.

1. TERMINOLOGY

Lightning. Lightning is a general term to express surges of potential anywhere of dangerously abnormal value. The subdivisions of lightning are external and internal. Cloud lightning is external lightning. Dangerous surges due to switching, etc., are internal lightning.

Protective apparatus. There is required a general term to cover all devices which give protection. Protective apparatus is suggestive, clear, and brief.

Lightning-arresters. A name is required for devices connected not only between lines but also between lines and ground. So far, " lightning-arresters " is the commonly used term, and it seems desirable to retain this to avoid confusion.

Internal-surge protectors. Another device, which may be of the same form as a lightning-arrester, is connected only between line and line, not to ground directly. There are a great many of these devices installed at the present time, and it is desirable to have a convenient special term to distinguish them from lightning-arresters. The term " static protector " has been frequently used. The term is not suggestive of the nature of the device, and may be confused with the apparatus known for a long time as a " static discharger." " Static " means specifically the displacement in a dielectric medium. There are static strains which may be distinguished from one another. There is the normal static strain of potential between line and line, which varies every instant with the wave of electromotive force of the generator. There is also the excessive static strain between line and ground due to cloud-lightning strokes. There is, still further, the excessive static strain between line and line, due to the stoppage of a dynamic flow of electricity in a number of ways; and there is, finally, the excessive static strain between line and ground, due to the gradually accumulated static electricity from wind, rain, etc., coming in contact with the transmission line. This last form of static will not be released at all by the static protector, so there seems to be no reason for standardizing this false nomenclature. Devices for carrying off the gradually accumulated static usually have low current-carrying strength and have been known for years as " static dischargers." Since this form of static is directly generated in the line and the word " static " is suggestive of rest, it seems desirable to retain this term " static discharger " for the discharges of gradually accumulated static electricity. Conversely, since the other static stresses are indirectly generated from electromagnetic stresses, and, furthermore, since this electrostatic stress is continually being transformed into electromagnetic stress and back again in the form of surges, it seems desirable to adopt a term like " internal-surge protector." It lacks brevity but there is no doubt of its meaning.

A lightning-arrester is always more or less of an internal surge protector according to its design, and it may have auxiliary devices which make a static discharger of it also. On the other hand, an operator should not deceive himself into a sense of security because a static discharger has been sold to him under the misnomer of a lightning-arrester. Again, an operator cannot expect an internal-surge protector to protect against surges of an external origin, as, for example, cloud-lightning.

Earths (connections, resistances, etc). The word " earths " is used here specifically to mean the connection between the conductor and the earth in which it is buried. On overhead lines, it is usually the only " ground " connection. (See below, " *Grounds*.")

. Length of the earth connection of an arrester is the distance from the arrester to the conducting stratum of the earth.

The earth resistance of a lightning-arrester is the ohmic resistance from the arrester to the conducting stratum of earth. Its value may be obtained by measurement between three earthed conductors.

Grounds. " Grounds " is a more general term than earths. A phase may become grounded without being earthed; for example, a cable having its armor insulated from the earth may become " grounded " by having one of its conductors connected with the armor. The armor may be " earthed " by connecting it with a conductor buried in conducting earth; in this case, we may still speak of the phase as grounded. If the transmission system is a mixed cable and overhead system, "earthing" the armor may make a considerable change in the surges through the system.

Sparks. An electric spark is the phenomenon of conduction of electricity by a luminous gas.

Arc. An arc is the phenomenon of conduction of electricity by the heated vapor or vapors of the electrode.

Dielectric-spark lag. Is the time elapsing between the application of the sparking potential and the complete formation of a spark.

Natural or proper frequency of a circuit is the number of oscillations per second of potential or current which will take place if the circuit is allowed to discharge without interference from excessive damping or extraneous power. Such a circuit involves the presence of both capacity and inductance.

Continuous and continual, as applied to the electrical terms, retain their defined sense. A continuous oscillation is one which appears without a break. Continual oscillations are successive sets of oscillations with more or less interval between the sets. A generator furnishes continuous alternations, a Tesla transformer produces continual oscillations. Continuous lightning is sometimes produced by one phase of a generator when another phase is short-circuited. Continual lightning is produced on a non-grounded neutral system when one phase is connected to ground through an arc. Both continuous and continual lightning may be temporary, but should be distinguished from transitory lightning.

Recurrent surges is a term synonymous with continual surges.

Surges. Electrical surges is a term having a sense a little more general than lightning. Any unusual rush of current or potential is a surge. If the surge potential reaches a dangerous value, it is lightning.

Transitory. Transitory, as applied to electrical terms, retains its defined sense. Cloud-lightning gives transitory lightning on a transmission line. Many lightning-arresters are designed for transitory lightning but not for continual lightning.

Equivalent spark-gap. This is a general term to express the puncture-potential equivalent of a piece of apparatus or insulation. The gap is in parallel with the device and of such value as to cause at least 90% of the spark discharges to pass through the device, and not more than 10% across the gap. The equivalent spark-gap is the only means of directly indicating the potential of a transitory charge. The specific terms are equivalent needle-gap and equivalent sphere-gap.

Equivalent needle-gap. Is the gap of the value explained above when the electrodes of the gap are needles.

Equivalent sphere-gap. Is the gap of the value explained above when the electrodes are spheres. It is necessary to state the diameter of the spheres; for example, equivalent 2-inch sphere-gap.

Equivalent spark-gap characteristic curve. This is the relation of the applied potentials as represented by gap-lengths (abscissas) to the equivalent spark-gap (ordinates). In this expression, the specific words " needle " or " sphere " may be substituted for " spark."

Dynamic. Used as an adjective to the words current, voltage, wattage, energy, etc., designates the current, voltage etc., which come directly from the dynamos or generators, as distinguished from the current, voltage, etc., which come from static charges, electromagnetism, cloud-lightning, etc. on a line. The latter is of relatively small energy. There is no general term to express all the discharges that are not dynamic. "Static" is a word used in this sense a number of times, " lightning " is another; but they are both specific and not general. For example, the internal lightning from one phase of a generator when another phase is short-circuited is really dynamic potential, dynamic current, dynamic energy, etc. It is true that before a discharge takes place there is always a storage of energy in the static stress, in spite of the fact that the source of this static stress may have been due to the aforementioned condition, or to the sudden interruption of a dynamic current, and, therefore, static comes the nearest to expressing the general sense. Non-dynamic would be a general adjective covering the phenomena not directly derived from the generator.

Static. This term was originally applied to the stationary charges of electricity on rubbed glass, wax, etc. The use of the term has been extended until it covers all forms of electric displacement in a dielectric. This electric displacement may be changing its value at every instant, and the electric charge is therefore not stationary. The variation in dielectric displacement gives the static current or condenser current.

Non-dynamic. Is an adjective applied to the electrical terms to cover all effects which do not have their source directly in the generators.

Accumulated static charge. This term applies to the charges of electricity which accumulate on a transmission line due to wind, rain, etc. and represents an electric displacement in the dielectric between line and earth.

End-gap static. Discharges of a multigap arrester. On high-potential circuits, a few of the series gaps at each line connection are bridged by tiny sparks which give out a buzzing sound. The number of gaps bridged by the sparks depends on several factors—applied potential, relative capacity of each cylinder to its adjacent cylinder and ground, and leakage through or over the surface of the supporting porcelain.

Grounded neutral system, and *non-grounded neutral system* as applied to a transmission circuit are terms which are self-explanatory. A three-phase delta circuit may have an artificial neutral made by the connection of auxiliary apparatus in *Y* relation, and this neutral may be grounded. The word neutral cannot be omitted in this expression without confusion with the continual lightning condition of an accidentally grounded phase.

Forced oscillations. Forced electrical oscillations are oscillations impressed on a circuit regardless of the free, natural, or proper oscillations of the circuit. Alternations from a generator on a line are forced alternations.

Resonance. If the forced oscillations have the same frequency as the natural oscillations of the circuit there is perfect resonance, or tuning, and both the current and potential will assume abnormal values.

Standing wave. A standing wave is to be distinguished from a traveling wave. A standing wave is caused by traveling waves moving in opposite directions and so timed that they pass each other always in the same relative position. The result will be nodes at certain points and anti-nodes at points midway between. The nodes remain at zero or normal potential, and the anti-nodes vary in potential from double the potential of a single wave in the positive sense to the same potential value in the negative sense.

Rate of discharge is the current, $I = \frac{dQ}{dt}$. The rate of discharge is an important factor in connection with the resistance of a lightning-arrester.

Acceleration of discharge. Is the rate of change of current. Acceleration $= \frac{dI}{dt} = \frac{d^2Q}{dt^2} = \frac{E}{L}$. The acceleration of discharge is an important factor in connection with the inductance of a lightning-arrester circuit.

Recurrence. Recurrence is a convenient word to use to avoid confusion with the word frequency in a technical sense. The frequency (natural) of lightning may be about a million cycles per second, but the frequency of recurrence of lightning stroke may be expressed in minutes or months.

Oscillogram. The tracings of wave-forms taken with an oscillograph.

Multigap. Multigap expresses the condition of a number of gaps between conductors in series.

Multipath. Multipath expresses the condition of a number of gaps or circuits in parallel.

Multiplex connection. On a lightning-arrester, this commercial term means that there are certain cross-connections between phases of the arrester above the earth connection. These cross-connections may or may not have an appreciable resistance.

No-gap aluminum arrester. An aluminum arrester composed of a series of aluminum electrolytic cells connected directly to the lines without the intervention of any gaps.

Gap aluminum arrester. Is the same as above except there is a gap between each phase wire and the cells to prevent the natural capacity current of the cell from flowing continuously.

Graded resistance arrester. A trade term to express the form of multigap arrester according to the 1907 design. A number of resistance circuits of variable ohmic value are thrown in parallel across the simple multigaps. These resistance circuits have a common connection at one end and tap in at different points on the multigaps.

Nature of lightning. In the A. I. E. E. PROCEEDINGS, May, 1906, the writer gave a brief outline of lightning effects as a basis for a laboratory study of methods of measurements. Dr. C. P. Steinmetz has given a very complete classification of lightning on transmission lines* from the broad standpoint of the analyst of the phenomena. While it is necessary to keep in mind the classification according to the phenomena, it is more direct for the designer of protective apparatus to analyze according to the effect of the lightning on the insulation and the lightning-arresters. Regardless of the cause of the lightning, the arrester and insulation take into account in the two kinds of lightning, transitory and continual, only the three factors—the frequency, the duration, and the potential of the stroke.

The nature of lightning on electrical transmission has been very little studied by direct measurements, on account of the lack of specific instruments with which to make the measurements, the erratic appearance, the transitory duration, and the danger involved.

Frequency. By a study of artificial lightning, it can be demonstrated that a transmission line may be subjected to any frequency of electrical oscillation ranging from one-half cycle per hour (gradually accumulated static electricity) to about a billion cycles per second. On many particular lines, the frequencies of oscillations will exist probably in groups of harmonics. The first and lowest group starts with the generator frequency and runs up in odd multiples thereof to all the higher harmonics. On account of the impossibility of getting very abrupt changes of

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*PROCEEDINGS of A. I. E. E., March 1907.

magnetism in a generator (due to the relative permeability of iron and air) the upper harmonics from the generator wave very quickly become negligible.

It is usual to assume that the fundamental wave of the generator will not attain an abnormally dangerous value on account of the limitation of the exciter voltage, but, under the special condition of a short-circuited phase on a multiphase generator, the voltage of the phases not short-circuited may rise to a very dangerous value. Several years ago Mr. L. Robinson, at the suggestion of Dr. C. P. Steinmetz, took oscillograms of this condition of operation in some large generators and found a rise of 250%. This surge requires special attention in the application of lightning-arresters.

The second group of oscillations starts with the natural period of the electrical circuit, including in its factors the inductance and capacity (static) of transformers, cables, overhead lines, choke-coils, and translating devices of any kind in the common circuit. There are also the upper harmonics of this group. The first group may overlap the second group. If any frequency of the first group coincides with that of the second group, then that particular oscillation of the second group is in resonance (or in tune) with the particular wave of the first group, and its free oscillation will be magnified until the natural energy losses of the oscillation are equal to the energy derived from the harmonic of the generator wave.

The third group of oscillations includes those starting with the fundamental frequency of the transmission line or cable (not including the apparatus.) The line or cable may oscillate as one segment or any odd multiple thereof, giving thereby all the upper harmonics.

The fourth group of oscillations may be designated as miscellaneous. In this group are such oscillations as those between the system and an isolated conductor. An example of this kind of oscillation is found in the multigap arrester. Usually, about a half-dozen gaps next to the line connection will have a spark-discharge across them continually. Each time the second cylinder is connected to the first, an oscillation is set up on the line, the results of which have been experimentally measured.

The fifth group of oscillations comes from external sources and will oscillate independently of the line. In this group are the forced oscillations on the line derived from cloud-lightning.

The natural frequency of cloud-lightning, not yet having be measured, is presumably determined by the static capacity the part of the cloud that is discharged and the inductance the discharge path between cloud and earth. Since both t inductance and capacity vary, the natural frequency of tl cloud-lightning will also vary over a limited range. In th group come also the oscillations on a line from wireless tel graphic signals and induction from adjacent transmission lines If any of the oscillations of the previous groups are in tune o resonance with one of the fifth group, then such an oscillatio may be enormously magnified. It is useless to speculate o whether or not cloud-lightning has any upper harmonics.

Following is a summary of the five groups.

First group. Generator frequency and harmonics.

Second group. Natural frequency of the main circuit and harmonics.

Third group. Natural frequency of the line circuit and harmonics.

Fourth group. Miscellaneous oscillations.

Fifth Group. Forced oscillations from an external source.

Comments on the five groups. The generator and cloud-lightning are both sources of energy. The generator frequency is below any of the natural periods of the lines and therefore its fundamental wave is impressed on the line from end to end with only relatively slight modifications of form by inductance and capacity; the cloud-lightning frequency is unknown, but there is reason to believe that it may be of the order of 100,000 to 1,000,000 and consequently agrees with some of the possible oscillations of the other groups. The oscillations on a line due to cloud-lightning are of a double nature; there are, first, the forced oscillations due to the natural frequency of the cloud discharge, and, secondly, the free oscillations of the charge left on the line.

1. These forced oscillations may be more or less magnified or nullified by interference. Unlike the generator forced wave, the cloud-lightning forced wave may be far above the natural frequency of the line, and the whole line cannot rise and fall simultaneously with the cloud-lightning oscillations. There will be a succession of waves which will be partly reflected from the ends of the lines, and the reflected wave traveling in the opposite direction will combine algebraically with the waves it meets. If the line is an odd multiple of

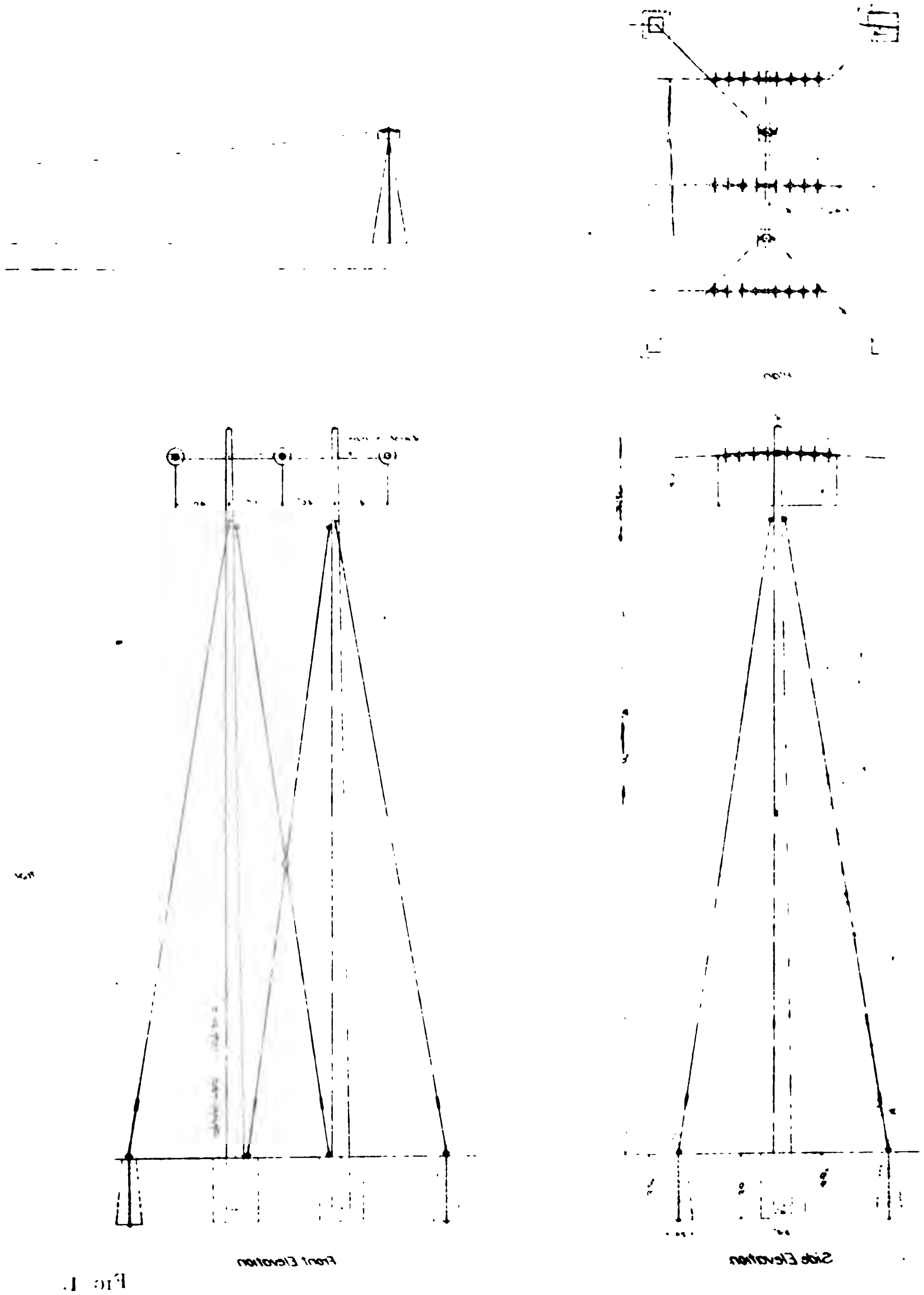

FIG. 1.

a quarter wave-length, two waves traveling in the opposite direction will meet at a certain point on the line and will neutralize each other; the succeeding wave will do the same at the same point; consequently this point of the line will remain at constant potential. At a quarter wave-length in either direction on the line, the potential is changing its value at every instant as the waves cross each other. The result is that the potential will vary gradually and harmonically from zero to twice the original height of the traveling wave. This effect has been called a standing wave. It is variable in value of potential at every instant, but is fixed in its position on the line. Three positions of such a wave are illustrated in Fig. 1. *A* and *B* are two points on the transmission line. The dotted curve represents the reflected wave, and the broken curve the standing wave. The point *A* is zero for all positions of the waves and is therefore the node. The point *B* is zero in the top curves, 150% in the middle curves, and 200% of the traveling wave in the lower curve.

If the length of the line is not an odd multiple of the quarter wave-length, then the reflected waves cause a jumble without definite form.

If the induction from the clouds is electromagnetic (horizontal lightning stroke parallel to the line), there is no resultant quantity of electricity on the line and the surges set up will die out gradually by loss of the initially imparted energy; but, if the induction from the cloud is electrostatic, there will be a definite charge of electricity set free and left on the line.

2. The free oscillation. When a thunder-cloud over a line discharges, it may set free a charge distributed over the line according to the area of the liberated charge on the cloud and its position relative to the line. The length of charged line may be perhaps of the order of 1000 ft. to 5000 ft. If the line had sufficiently high resistance, this charge, when liberated, would spread over the line as a bucket of water flows when thrown into an empty trough. The line resistance in reality is almost negligible, consequently the energy of the charge will be transformed into electromagnetic energy and back, continuing to oscillate until the waves are damped out. Neglecting leakage to ground, this charge will finally have changed its position from the occupancy of the capacity of a short length of the line, to the occupancy of the total capacity of the line, and in consequence its potential will have decreased proportionally. Mean-

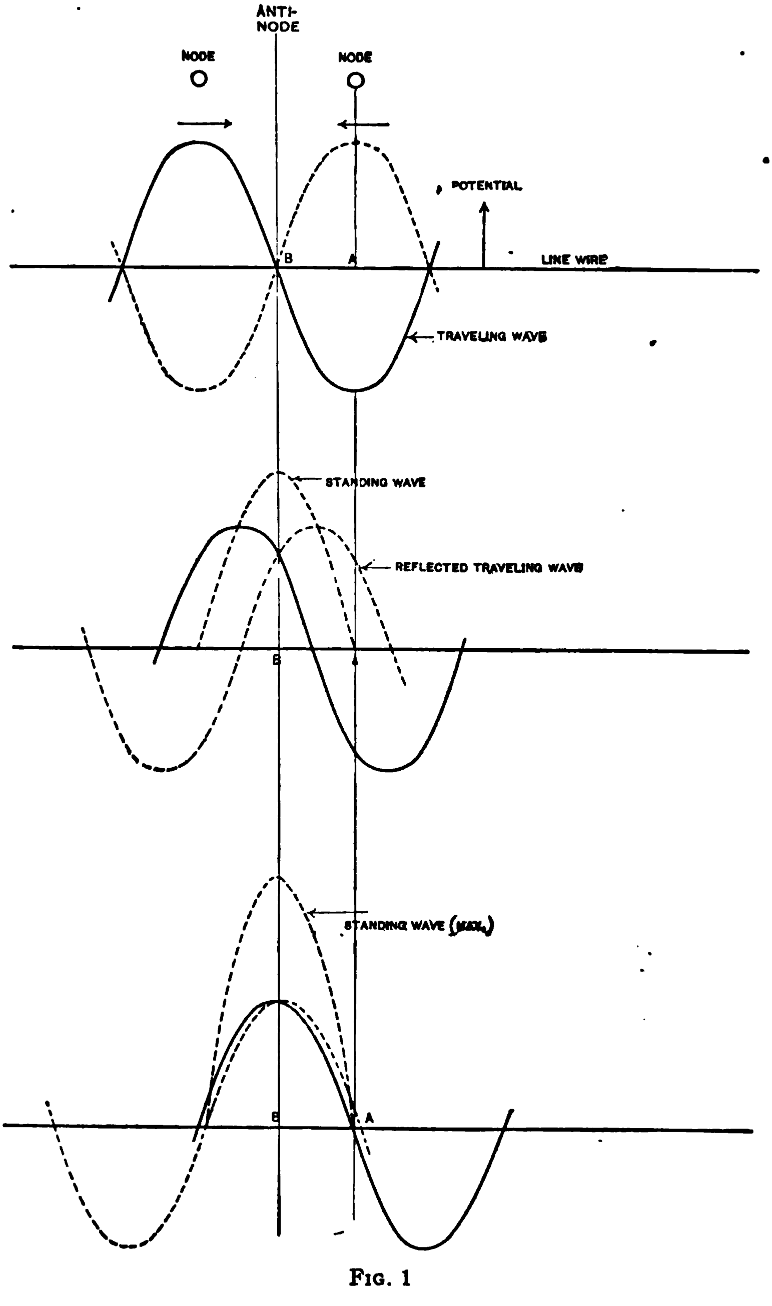
ANTI-NODE
NODE
NODE
POTENTIAL
LINE WIRE
B
A
TRAVELING WAVE
STANDING WAVE
REFLECTED TRAVELING WAVE
B
A
STANDING WAVE (MAX.)
B
A

FIG. 1

while, the waves have traveled in both directions on the line, giving the possibility of a standing wave.

We can examine the condition giving a standing wave by assuming a fictitious line 100,000 ft. long and the length of the line covered by the induced charge at 2000 ft. The quarter wave-length then is 1000 ft. If the line is divided into imaginary 1000-ft. sections, and, if the liberated charge should so occur as to cover exactly two of these sections, the reflected waves would be so timed as to cause standing waves. If the charge were liberated in any fractional position of the 1000-ft. section, the standing wave would be more or less destroyed.

Following out this line of reasoning, it is evident that a standing wave is a matter of chance not only in the relative location of the liberated charge on the line, but also in the relative length of the charge to the length of the line. If this theory is true, strokes of equal potential may vary greatly in their resultant effects.

There is an important condition of surge, involving probably all the first three groups mentioned above. This has been mentioned elsewhere as the grounded-phase condition. In this, the generator is the source of energy, but it does not force the oscillation into the system. Owing to the grounded-phase condition of capacity, the generator produces a static charge which is set free to vibrate by the making and breaking of the arc between the faulty phase and ground. The phenomenon is somewhat analogous to putting a spring under tension and suddenly releasing it. As with the spring, the electrical oscillations die out, but may be renewed a number of times during a half-cycle of the generating wave. An oscillogram of this condition is shown in Figs. *P*, *S*, and *T*, " Methods of Testing Protective Apparatus," PROCEEDINGS, American Institute of Electrical Engineers, May, 1906.

Duration of lightning. Nearly all lightning oscillations are individually of short duration. There is one notable exception; namely, the continuous surges set up on one line from a parallel line (*e. g.*, telephone circuit under a power circuit). All the transitory surges have a logarithmic decrement of potential and current. The rate of decrease of the peaks of the lightning potential depends upon well-known laws; it is proportional to the rate of dissipation of the energy of the stroke. The energy of this electrical charge is dissipated in at least three ways; radiation, heat, and chemical transformations.

Hertz has shown that an open circuit is a good radiator of energy (wireless telegraphic waves) and therefore a poor oscillator. On the contrary, a closed circuit is a poor radiator, but it will oscillate for probably several hundred cycles, provided the energy is not absorbed in resistance and arcs in the circuit. Hertzian waves are radiated only at extremely high frequencies. Lower frequencies radiate in the form of brush discharge only There is an analogy to the hertzian waves in sound vibration. If the air is not struck with a quick blow, it slips around the vibrating material and does not send out a sound wave. A transmission circuit may oscillate as either a closed circuit or an open circuit. Line-to-line oscillations are examples of the former; line-to-ground oscillations of the latter.

The line wires, as closed circuit oscillators, have a very low ohmic resistance and therefore, as far as this factor is concerned, a small decrement of voltage. If the oscillation is low enough in frequency to pass through transformers, the hysteresis and eddy losses in the iron will very quickly destroy the free oscillations. In each of these cases the energy of the electrical discharge is transformed into heat.

In arcs, especially the liquid-electrode types, and when the oscillating current is passed through electrolytes, such as the aluminum-cell type, more or less energy is absorbed in chemical dissociation.

Decrement. What is the best value of decrement? This question is open to discussion. The shorter the duration of the oscillation, the less will be the liability of damage to the insulation; or the quicker the lightning-arrester operates after the potential rises, the less the likelihood of damage to the insulation.

Without going into mathematical refinements, the duration of lightning, as affected by logarithmic decrement, can be demonstrated by simple curves. The subject of oscillating current is thoroughly treated in a number of text-books, but there are certain specific conditions concerning lightning which make some of the general statements regarding the surges inapplicable to lightning on transmission lines. As an example, the general statement is made that with a fixed inductance, capacity, and quantity of electricity, the time of quickest discharge exists when the value of resistance in series is equal to the critical value $R = \sqrt{\frac{4L}{C}}$. This is not true for lightning on a transmission line without lightning-arresters, and it is further from the truth for the lightning-arrester circuit itself. The duration of lightning on a transmission line without arresters will be shorter if the resistance (or its equivalent in other energy-absorbing power, as brush-discharge, electrochemical energy, etc.) is less than the critical value. The arrester is placed directly in shunt with the transmission apparatus, and, although the surges on the line may continue for a longer time with negligible resistance in the arrester, the potential across the arrester is reduced quickly to a safe value in spite of the longer duration of current. The duration of lightning is the time required for the potential to reduce to the safe value. The relations are shown graphically in Figs 2, 3, and 4. Fig. 2 shows two curves of a potential discharge when the only variable is the initial lightning potential. The resistance has a value above the critical value. The higher the initial lightning potential in this case, the longer will be the duration of the lightning. This corresponds to the discharge of lightning through an arrester or static discharger containing high series resistance.

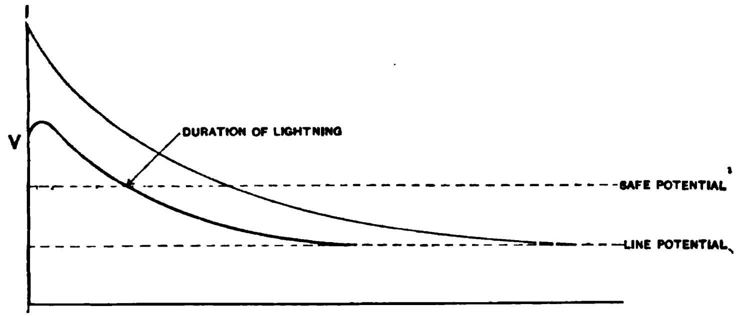

Fig. 2

Fig. 3 shows two discharges, one non-oscillatory and the other oscillatory; for simplicity, these are given the same decrement. The resistance in the case of the oscillatory discharge is less than the critical value, and the duration of lightning is about the same as for the value of resistance above the critical value.

Fig. 4 shows the condition of most rapid discharge of lightning. The resistance lies between the two values of Fig. 3, but the rate of energy-loss is greater. The second half-cycle brings the potential to the safe value. If the energy is absorbed in electrochemical action, as in the aluminum cell, the energy loss is proportional to the quantity of electricity, and the resistance may be zero without affecting the result. Furthermore, the critical lightning potential of the aluminum and liquid-electrode arresters will prevent the potential from rising above the safe value on the first half-wave. To obtain the same result at the multigap arrester terminals, it must be possible to cut out all series resistance if the viciousness of the discharge demands it. The above discussion is made without reference to the dielectric spark-lag.

Continual lightning. Recurrent surges. Although each lightning surge is transient, in general there may be a succession of free oscillations with normal value of potential between them.

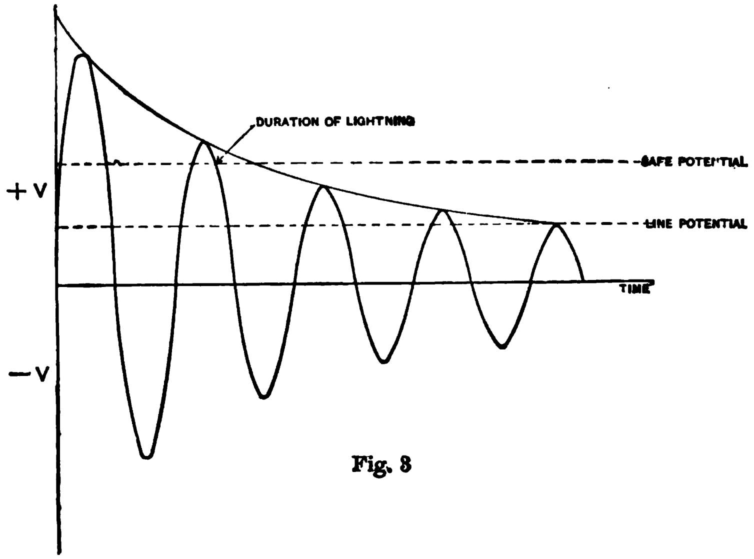

Fig. 8

These recurrent surges result invariably; for example, from a grounded phase on an insulated Y or delta system and from a loose contact on an alternating-current trolley system. As a rule, the duration of each surge cannot even be guessed, but the total duration of the successive surges is limited only by the removal of the condition which caused them.

Potential of the surge. This subject is best treated under the two heads of transitory oscillations and continuous oscillations.

In the case of free or natural oscillations, there is always a loss of energy and a consequent decrement in the successive peaks of potential. The only method of measuring potential in this case is by the equivalent spark-gap. If the oscillations are sufficiently low so that a quarter-cycle is not greater than the dielectric spark-lag of the gap, the gap may be expected to be proportional to the potential. On the other hand, if the frequency is exceedingly high, or the drop of potential is rapid, then the gap will no longer measure the peak value of potential, but some lesser value of potential depending on the two factors, spark-lag and logarithmic decrement of discharge. An illustration of this was given in a paper by the writer, (PROCEEDINGS of the American Institute of Electrical Engineers, May, 1906.) As a result of this condition, the maximum potential cannot be determined and the nearest expression is to state the equivalent spark-gap. This dielectric spark-lag, with some

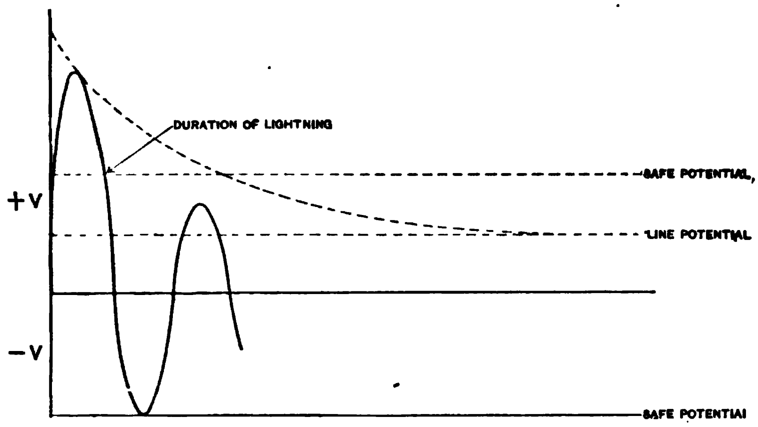

Fig. 4

types of apparatus, has a bearing on the problem of protection. The insulation to be protected has also a dielectric spark-lag, and, while it may not puncture before the arrester releases the strain, it may nevertheless receive an injurious blow. If the insulation has the property of " self-repairing " the injury is transient.

Continuous oscillations must be distinguished from recurrent oscillations. The needle-gap in parallel will apparently measure the potential in this case, but, continuous oscillations occur very seldom in lightning-arrester work. If recurrent surges follow each other in very rapid succession, it seems reasonable to assume that the equivalent needle-gap is a close measure of the potential, but this condition of " very rapid succession " is too indefinite to be relied upon. In consequence we shall necessarily be limited in this case also to expressing the potential, not in volts, but in equivalent spark-gap.

Nature and characteristics of the insulation to be protected. Tests of dielectric strength have been made for years on insulations with continuously applied potentials, applications ranging in time from one second up. Much of this information is available in published form. Tests of insulation with transiently applied potentials are meager.

Under transiently applied potentials the three types of insulation—solid, liquid, and gaseous—have properties not shown by the tests of continuously applied potential. This difference results from both the dielectric spark-lag and the property of self-repair. Solid liquid, and gaseous insulations differ in degree in these two characteristics. When the disruptive potential applied to the oil insulation is removed, the injury inflicted is gradually repaired, provided a slight circulation at least of the oil is possible. Oil has also a comparatively high dielectric spark-lag. Air has the property of self-repair, but its dielectric spark-lag is much less than that of oil. Solids, in general, have no self-repairing property but have a dielectric spark-lag lying between the values for liquids and gases. The characteristics of any insulation are studied by the same methods as lightning-arresters. These methods are given farther on.

The spots most vulnerable to lightning in electrical apparatus are the bushings of the leads, the end-turns, and the space between phases. Briefly stated, there are just two factors concerning lightning and insulation that should be known; namely, the potential, and the duration of its application at abnormal values.

4. *Characteristics of lightning-arresters.* After what has preceded, the qualities which an arrester must possess to protect insulation are fairly evident. The questions to be answered are:

A. Is the equivalent needle-gap affected by the natural frequency of the oscillation?

B. By the rate and acceleration of discharge?

C. By the quantity of discharge?

D. What is the nature of the dynamic current suppressing device?

E. What is the endurance $\left\{\begin{array}{l}\text{to single strokes?}\\\text{to recurrent surges?}\end{array}\right.$

F. Is there a dielectric spark-lag?

Before attempting to answer these questions by the designation of tests, a review is made of the simpler tests described by the writer in the Proceedings of the American Institute of Electrical Engineers, May, 1906. To these tests some additions have been made.

First test. Test of static discharger. This test is of less importance than those following. The source of energy, in Fig. 5, is a static machine. The equivalent spark-gap is the value of the gap *G* which causes the discharge to pass through the arrester. The spark-gap is necessarily a sphere-gap because the needle-gap will carry off the current of a small static machine in brush-discharge as rapidly as it is generated, and thus limit the potential to a small value. The condensers are sometimes used as a convenience in observing the spark-distance. The report from the condenser-discharge cannot be confused with any brush-discharge.

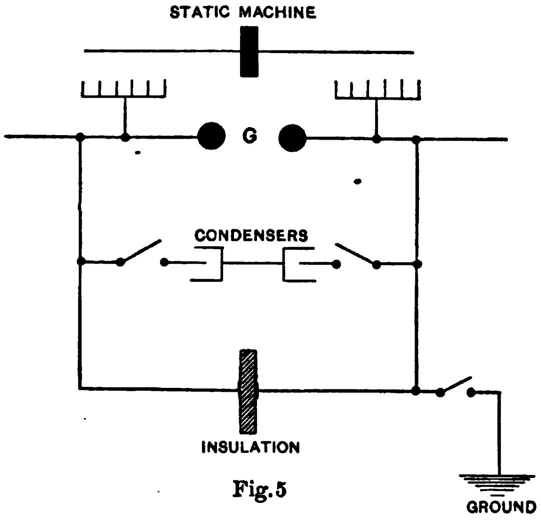

Fig. 5

If the static-discharge has a high frequency, the measurement of the ohmic resistance will permit a calculation of the current flow at double the normal potential of the system. Double potential is here chosen, as in other similar cases to follow, with a specific object in view. For the present at least, it seems necessary to design the insulation of electrical apparatus with a minimum factor of safety of 2. Therefore, 200% gives the discharge current at the limiting value of potential. There is a more important reason for choosing 200% potential for the calculations. Some types of arresters, especially the electrolytic types, have a small current discharge at normal potentials, but have a critical value of limiting potential above which the current flows freely. Choosing 200% normal potential for the purpose of calculation brings out the desirable characteristics of these arresters.

Second test. Equivalent needle-gap at commercial frequency by step-up transformer. Fig. 6 shows the recommended connections of the transformer, arrester, and needle-gap. The presence of

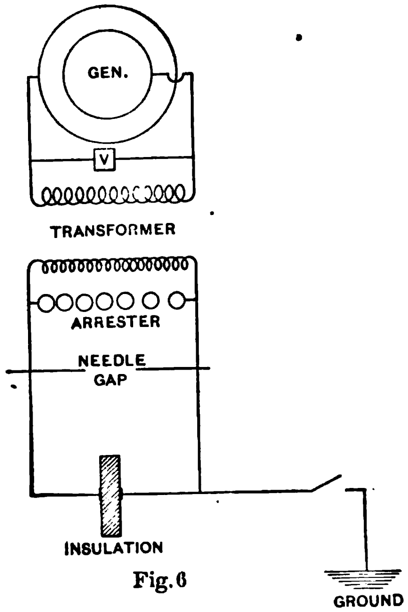

Fig. 6

nsulation is not necessary, although it is sometimes desirable. The thickness and nature of the insulation, when used, is the same as the arrester is designed to protect.

Two equivalent needle-gaps differing somewhat in value are obtained from this test. They are:

a. Equivalent needle-gap (e.n.-g.) by transformation.
b. Equivalent needle-gap (e.n.-g.) by needle-gap.

The equivalent needle-gap by transformation gives the potential of the fundamental wave, and the value by needle-gap gives approximately the peak of the superposed surges derived from the various local oscillations of the high-potential circuit.

There are three tests to be made, making six equivalent needle-gaps in all.

First condition, no grounded phase; switch S open.

Second condition, grounded phase; switch S closed.

Third condition, arcing ground; switch S arcing to maximum length of arc.

Third test. Disruptive-stroke test. There are two simple forms of circuits which are recommended for this test. The principal difference between the two, lies in the use of a static machine as a source of potential in one case and a transformer in the other; see Figs. 7 and 8.

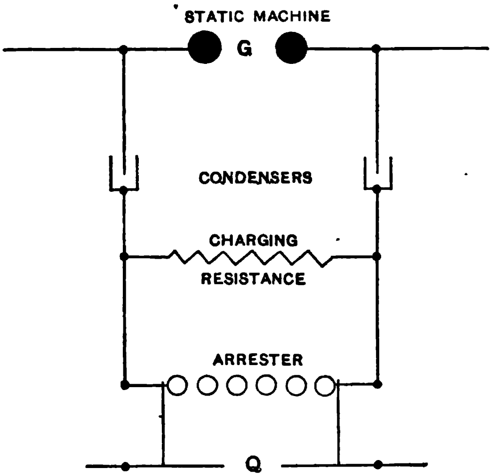

Fig. 7

In Fig. 7, the potential corresponding to the gap G is apparently the same as the spark potential obtained from tests with a transformer, and not the values corresponding to the direct-current potential.

Fig. 8 is a modification of the circuit used by Mr. Percy Thomas a number of years ago for starting the dynamic current across the arresters. The modification results from the different desideratum. The quantity sought is the equivalent spark-gap. It was found that the two gaps, corresponding to the gap G and insulating the arrester from the transformer until the spark jumped both gaps, caused variations in the equivalent spark-gap according to the relative lengths of the two gaps. Some details of the tests which led to the adoption of this simpler circuit (Fig. 8) are given elsewhere in this paper.

Method of disruptive stroke test with the static machine as source, Fig. 7.

Choose a charging resistance of the order of a megohm and state its value if known.

Before connecting the arrester to the circuit, make the equivalent spark-gap characteristic-curve of the charging resistance. This curve shows the limitations of the testing apparatus.

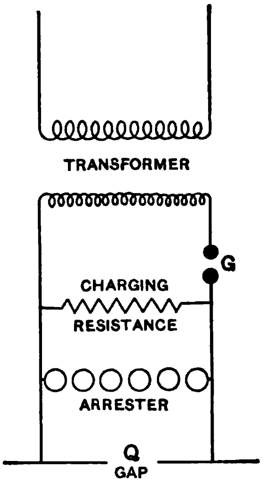

Fig. 8

The abscissas of this curve are the lengths of the setting of the gap *G*, and the ordinates are the corresponding values of the needle-gap or sphere-gap *Q*, which will allow not more than one in ten of the strokes at *G* to pass over the *Q* gap. This curve, once made, is good for all subsequent tests.

Place the arrester in position, and take the equivalent spark-gap-characteristic-curve in the same way as for the charging resistance.

The value of capacity to use in this test need not be standardized. There is a certain minimum value of capacity which gives a discharge of sufficient energy to puncture the insulation which the arrester was designed to protect. The maximum value of capacity which may be used is determined entirely by the size of the static machine. When the leakage through the condenser equals the current generated by the static machine, it becomes impossible to raise the potential across the gap *G* to the spark value. For most of the tests, the writer has found four one-gallon Leyden jars (two on each side) sufficient, and an upper limit of the gap *G* of 5 to 7 in. This apparatus will send a spark over about 200 of the 1/32 in. multigaps under the usual conditions of installation, and the number of multigaps may be greatly increased by using antennae wires near the row of gaps.

The terminals of the spark-gap *Q* should invariably be connected to the terminals of the arrester. The natural frequency of the oscillation will be of the order of a million, and consequently a few inches of wire added to the arrester length will, in many cases, add very materially to the value of the equivalent spark-gap.

There are a number of variations of the circuit of Fig. 7 which have been used in research work, but such variations would complicate the methods of test without a corresponding gain in the knowledge of the operation of the arrester. Some of the results of these variations are given elsewhere by the writer. The variations consist in making such changes as replacing the charging resistance by a charging reactance of a high value, and the introduction of reactance-coils in the circuit at different points.

Method of disruptive-stroke test with a transformer as source of potential. Fig. 8. The figure makes a description unnecessary. The same charging resistance and condensers may be used, and also the same gap *G* in the new location.

The procedure is to set the gap *G*, and then increase the excitation of the generator (preferably of smooth wave-form) until *G* sparks and opens an automatic circuit-breaker. The excitation should then be slightly increased to overcome the effect of the dielectric spark-lag which gives a gradual breakdown of the air in the gaps when the voltage barely reaches the spark voltage. The excitation-circuit, resistance, and voltage are then held constant. The excitation-switch is then opened until the circuit-breaker is closed and then closed again—and so on for each discharge.

The equivalent spark-gap-characteristic-curve is made in this case as in the preceding one. The other precautions are the same.

The upper limit of the capacity of the condensers which may be used, is determined solely by the size of the generating apparatus. The capacity of the condensers should be stated in the report.

The two methods using the same condensers, charging resistance, and values of *G* gap give somewhat different values of equivalent spark-gap. The method of Fig. 5, using the transformers, gives the higher value. A plausible explanation of this may be found in the ionization of the needle-gap by the applied potential previous to the passage of the spark across the gap *G*. This does not occur in the circuit shown in Fig. 7. Since the spark at the gap *G* (Fig. 8) always takes place at peak values, the gap *Q* is always ionized, whereas in transmission practice the generator potential may be at zero potential when the lightning stroke occurs. This feature is unfavorable to the use of the method of test, but the employment of a transformer with its greater energy capacity and availability will often offset the disadvantage. On the other hand, the equivalent needle-gap

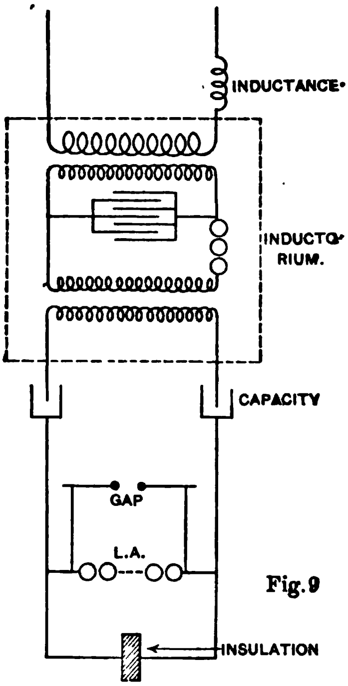

Fig. 9

so found will be at its highest value, since the needle-gap, when it sparks, is ionized to a lightning-potential corresponding to at least two or three times the normal line potential of the arrester. The arrester gaps are also somewhat ionized by the potential.

Fourth test. The Tesla transformer test, Fig. 9.

The natural frequency of this oscillation transformer is usually of the order of 100,000 cycles per second and the continual discharges are good imitations of continual lightning or resonant surges.

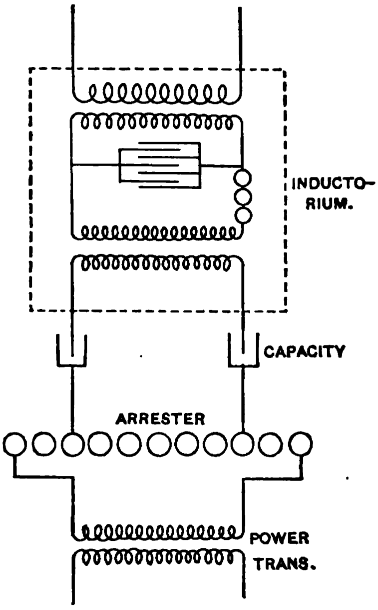

Fig.10

If it is desired to measure the equivalent sphere-gap by this method, the connections of Fig. 9 seem to be the most desirable. The procedure is to close the switch S and then elongate the gap at G until the arrester takes all the discharge. A needle-gap cannot very well be used at G, on account of the energy lost in brush-discharge from the points.

The Tesla transformer is specially adapted to give the effect of continual lightning. The method of connection to the dynamic circuit is shown in Fig. 10. Condensers are used between the Tesla transformer and the arrester to prevent the short-circuiting of the dynamic-current through the high-potential coil of the transformer. The high frequency passes through these condensers as easily as through a straight wire, but the current at generator frequency is comparatively insignificant. The discharge circuit is arranged so that the current passes in opposite directions, thus lessening the tendency to choose the path through the power transformer. This tendency is still further minimized by connecting the condensers to points on the arrester somewhat away from the ends. These points of connection are determined by trial, the desideratum being to get a uniform continual discharge through the entire arrester.

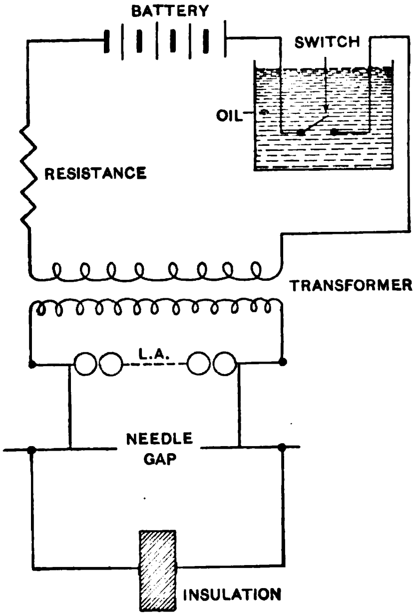

Fig. 11

Fifth test. Half-wave test (Fig. 11). This test for equivalent spark-gap is of great importance as it brings out the sensitiveness of the arrester to the first impulse. An " induction-coil " gives the same kind of discharge in rapid succession and may be used up to the limit of its capacity, instead of the power transformer of Fig. 11. The energy in the induction-coil is limited to a small value, and the observer must assure himself that the energy is sufficient to give the correct value of equivalent spark-gap. The variations of equivalent spark-gap are demonstrated in the tests given in the appendix of this paper, and are made evident by varying the value of direct current in the primary.

In making this test the record should contain statements of the kilowatt capacity of the transformer, the ratio of transformation, and the nature of the primary circuit (battery or dynamo, and the total resistance of the primary circuit). Care should be taken to hold the switch in the primary closed long enough to allow the direct current to rise to its full value.

If a spark occurs at the needle-gap on " make," a flaring arc is formed, which with the 50-kw transformer has sufficient energy to melt the points of the needles. The " break " gives a higher potential and forms only a spark; consequently, it is more convenient to use.

Equivalent spark-gaps of resistances and closed-circuit apparatus cannot in general be obtained by this method, since the presence of such a closed connection on the secondary prevents the rise of potential to high values.

Sixth test. Endurance test.. The endurance of an arrester depends on the nature of the dynamic current-suppressing device. There are two factors concerning this device to be determined The first is the action due to transitory lightning. What is the nature of the suppressing device; the time required to suppress the dynamic, and the maximum current discharge?

The second factor is the action due to continual lightning when the current-suppressing device is brought into continual action. Is this suppressing ability diminished by the passage of the dynamic current?

Oscillograms of the current and voltage during discharge will give, with most types of arrester, enough information to make a fair answer to the questions of the previous paragraph. The oscillograms will show:

a. The duration of the dynamic current, and the point of extinction when the instant of starting the current is varied.

b. The voltage across different parts of the arrester.

c. The maximum value of current of the test.

d. If the arrester did not drop the potential of the circuit, a generator of infinite kilowatt capacity could not have done more. If the arrester did drop the potential of the circuit, oscillograms will show where the potential was absorbed, and variations of the current of the test will show the law of relation of current to impressed voltage. From this information the current flow for any size of generator may be determined. If the arrester is designed for transitory lightning only, the endurance is determined by sending discharges at intervals of 10 to 20 seconds until the arrester is seriously damaged or inoperative.

If the arrester is designed for continual lightning, the endurance is determined by sending a continual discharge from some auxiliary device, like the Tesla transformer, over the arrester until serious damage to the arrester or short-circuit to the apparatus results.

An attempt is made below to outline the methods of test which will give answer to the questions at the beginning of the section marked " 4th consideration "

A. *Natural frequency.* The effect of a variation in the natural frequency of the oscillation on the equivalent needle-gap may be demonstrated, in general, by a comparison of the values obtained from tests numbers 1, 2, 3, and 5. The first test with high-potential direct-current is not always available. Static machines furnish a very small current; the leak over most arresters is sufficient to absorb the charge on the static-machine plates as rapidly as it is generated, and consequently prevents the rise of potential across the terminals of the machine. A sphere-gap must be used instead of the needle-gap, on account of the line discharge from the latter. Where mercury rectifiers are obtainable, high-potential direct-current may be obtained in greater values. This test is usually not necessary as the second, third, and fifth tests give sufficient data, as a rule, to demonstrate the characteristics of the arrester. Applications of potentials at alternator frequencies of 16 to 60 cycles (test No. 2) give the actual spark potential both by transformation and by equivalent needle-gap. The third test gives natural frequencies, easily regulated to values of a million per second or more. The equivalent needle-gap will usually differ from the values obtained in test No. 2.

In both tests, No. 2 and No. 3, the potential is applied during several cycles of the oscillations. It has been found that some arresters do not discharge easily during the first half-cycle of the oscillation. Through considerations of the dielectric spark-lag and frequency, this characteristic affects the protective value of the arrester. Test No. 5 (half-wave test) brings out this characteristic. By inductive reasoning, it can be shown that an arrester which has a half-wave equivalent spark-gap much greater than the disruptive-stroke equivalent spark-gap is not a good protector for low-frequency strokes. If the arrester does not spark over its gaps during the first half-wave, the insulation in parallel will be punctured unless the time of the first half-cycle of oscillation is less than the dielectric spark-lag of the insulation. In other words, such an arrester may give good protection at exceedingly high frequencies but decreases in protective value as the frequency of the lightning surge happens to be lower.

Summarizing, we have for the study of frequency effects on the arrester that:

Test No. 1 (direct-current static) is usually unavailable and unnecessary.

Test No. 2. Alternator gives two equivalent needle-gaps.

a. The needle-gap corresponding to the voltage by transformation (no arrester connected to the terminals).

b. The equivalent needle-gap as actually measured in parallel with the arrester.

Test No. 3 (disruptive stroke) gives two equivalent spark-gaps, one for each test.

c. The equivalent needle-gap of suddenly applied potential (alternator as source), arrester energized previous to stroke.

d. The equivalent needle-gap of suddenly applied potential (static machine as source), arrester not energized previous to stroke.

The form of the equivalent needle-gap characteristic curves will usually give information concerning the effect of frequency by inductive reasoning.

Test No. 5 (half-wave test) gives one equivalent spark-gap.

e. Equivalent needle-gap which shows the sensitiveness during the early part of any surge.

B. Effect of rate and acceleration of discharge on the equivalent needle-gap. The rate of discharge is the value of the current carrying off the quantity of electricity which causes the strain on the insulation. Mathematically, it is expressed as

$$I = \frac{dQ}{dt} = C\frac{dv}{dt}$$

It is the rate of decrease in the quantity of electricity, or it is the rate of decrease of potential. It is evident that the higher the rate of discharge, the less will be the liability of damage to the insulation. The rate of discharge (that is, the current) varies inversely as the resistance in the circuit. The effect of the rate of discharge, as affected by resistance, is shown by the equivalent needle-gap characteristic-curve of the resistance of the arrester, especially using the disruptive-stroke test.

Before an arrester can have a rate of discharge (current) there must be an increase of current from zero, or normal, to the value considered. The rate of this increase is the acceleration of the discharge. Even if the final rate of discharge is high, it will be of little avail if it requires a relatively long time to reach the condition of rapid relief. The aceleration of discharge is the rate of increase of current. Mathematically it is expressed as $\frac{dI}{dt} = \frac{V}{L}$ when V is the potential of the lightning and L the inductance of the arrester in the path of the lightning. Since the potential of a lightning stroke on a line cannot be controlled or limited in any way except by overhead grounded wires or materials, the factor of inductance of the arrester must be reduced to its minimum possible value. Since the inductance of an arrester is normally very low, it will cause no appreciable voltage effect except at very high frequency, therefore the high-frequency disruptive test (No. 3) should be used to measure the inductance. In order to eliminate the other involved factors, viz., dielectric spark-lag and rate of discharge, a wire of good conductivity may be carried over the contour of the arrester circuit and the equivalent spark-gap of this inductance taken. This equivalent spark-gap is inversely proportional to the acceleration. In general, arresters have negligible inductance as compared with the inductance of the earth connection.

C. *Effect of the quantity of lightning discharge on the equivalent spark-gap.* It should be noted that in this the quantity of dynamic electricity is not included. The quantity of dynamic electricity which follows the lightning stroke produces an effect on the endurance and arc-extinguishing power, and should be considered under a different head. If the dynamic discharge causes the lightning surge, the quantity of electricity involved in the excess potential comes under this head.

The effect of quantity of electricity was incidently involved and discussed under rate and acceleration of discharge.

There are three means of increasing the quantity of lightning electricity:

1. By keeping the capacity constant and increasing the potential.

2. By keeping the potential constant and increasing the capacity.

3. By maintaining a current at high potential and allowing it to flow for a time. $Q = I\,t$.

If the increased quantity of electricity is obtained by an increase of potential, the duration of abnormal potential will be extended, since the logarithmic decrement remains the same. If the increased quantity of electricity is due to increased capacity, the natural frequency of the oscillations will be lowered inversely, proportionally to the square root of the capacity.

Increased quantity by increase of time requires the application of continuous power.

The quantity of lightning electricity which may be generated in a laboratory is usually small as compared with the induced stroke on a transmission circuit, but not always. The usual criticisms of laboratory tests are based on this fact. This condition is unfortunate, but does not prevent reasonable deductions from laboratory tests. For example, if increasing quantities of electricity up to the laboratory limit are used, and the equivalent needle-gap of arrester (X) continues to rise with the increasing values, it seems safe to conclude that any greater quantity on the line will give a still higher equivalent needle-gap. If the equivalent needle-gap of an arrester (Y) remains constant for all available values of quantity in the laboratory, the conditions on the line discharge will be more favorable to Y than to X, to say the least.

The equivalent spark-gap characteristic-curve taken with either the disruptive stroke test (No. 3) or the half-wave test (No. 5) will show effects of the increase in quantity of electricity. In test No. 3, the quantity may be increased by an increase in potential obtained by drawing out the G gap, or it may be increased by using larger condensers. In the second case, the potential may be left constant, but the natural frequency of the discharge is somewhat lowered, according to the formula

$$n = \frac{1}{2\pi\sqrt{LC}}.$$

The quantity of electricity in the half-wave test depends on the electromagnetic circuit, dimensions, and on the value of current in the primary. Greater quantity, then, may be obtained by choosing a larger transformer or by increasing the value of the direct current.

The only known way of reducing the quantity of cloud-lightning charge on a line is by means of an overhead grounded wire or other overhanging material.

D. *What is the nature of the dynamic current-suppressing device?* To make this definite, some of the known devices are herewith enumerated.

1. Arc suppressed by rectifying quality of zinc; example, multigap arrester.

2. Arc suppressed by elongation of the arc to extinction; example, horn gap, magnetic blow-out, and movable plunger or electrode.

3. Arc suppressed by increase of resistance; example, conglomerate materials, analogous to coherers.

4. Arc suppressed by counter electromotive force; example, liquid electrode.

5. Arc suppressed by fuses in series.

6. No arc to suppress; dynamic limited by condenser effect. Example, aluminum cell without series-gaps.

There are at least three features about the dynamic current-suppressing device which should be determined experimentally.

a. Does the device for the dynamic current also restrict the flow of the lightning current in any way?

b How long does the device require to extinguish the dynamic current?

c. Does the extinguishment of the dynamic current set up secondary lightning surges on the system?

To answer question (*a*), the equivalent spark-gap should be taken under the widest range of conditions possible in the laboratory.

To answer question (*b*), a study of the oscillograms of the discharge is necessary.

To answer question (*c*), some knowledge may be gained by arcing in connection with inductances and capacities of variable proportions. Even line tests are feasible, using protected needle-gaps at different points to measure the rise of potential. Oscillograms will sometimes give an indication of surges, or possible surges under more favorable conditions, in the form of a sudden decrease of current.

E. *Endurance of the arrester.* Two conditions of endurance corresponding with the service conditions should be recognized.

1. Endurance to transitory lightning strokes at stated intervals.

2. Endurance to recurrent surges.

From observations of a number of thunder storms, the general conclusion has been reached that two strokes of cloud-lightning follow each other either in rapid succession, one setting off the other, or only after an interval which may be reckoned in several seconds or minutes. The time between strokes will vary with the storms, but an interval of three to ten minutes was usual in one locality.

Starting discharges over an arrester in a laboratory test at intervals as great as three minutes, would make an endurance run of inconveniently great length. An arrester recovers from a stroke of lightning quickly, and it is necessary to give sufficient time only between strokes to dissipate the energy loss in the arrester. In most cases, an interval of 10 sec. is sufficient to dissipate the heat, but in a number of cases the writer has used ¼ sec. with a total endurance of 10,000 strokes.

If the arrester is intended only for intermittent lightning strokes, the only rule that can be adopted is to make the interval sufficient to avoid damaging the arrester by carrying the effect of one stroke over to the succeeding one; such an arrester should be capable of successful operation also when the strokes come in pairs, the interval between the two strokes of each pair being in the range of one to ten cycles of the generator frequency. In the test record, the interval should be noted.

If the arrester is designed for recurrent surges, its endurance is expressed in the number of minutes it will carry the continual train of discharges until the arrester no longer protects or is inoperative. Going out of operation may be the result of total destruction, destruction of some essential part, or increase of equivalent needle-gap to a dangerously high value.

F. *The dielectric spark-lag.* Although there are no commercial methods of measuring the dielectric spark-lag sufficiently developed to present at this writing, the subject is too important in lightning protection to leave without mention. Progress in the development of protective apparatus requires a recognition of its existence, and a further study of the cases where the dielectric spark-lag of an arrester involves a danger to the insulation. Any arrester involving the use of a gap in series has a dielectric spark-lag. Thus, eliminating other defects, dielectric spark-lag is dangerous wherever it is possible to injure normal insulation placed in parallel with the arrester by subjecting both simultaneously to any kind of a lightning discharge. The converse of this statement, that the failure is due to the dielectric spark-lag only, is evidently not true. Each case must be discussed on its own merits based on the previously mentioned tests. The use of one or more series gaps necessarily involves a value of dielectric spark-lag. In reporting on the lightning-arrester, it is necessary, for the present at least, simply to state whether the arrester has or has not series gaps; the use of series gaps does not condemn the arrester, although it is a distinguishing feature.

As a brief summary, recommendation of tests of lightning arresters should include at least the following:

1. The equivalent spark-gap characteristic-curve by the disruptive-discharge test.
2. The equivalent spark-gap at generator frequency.
3. The maximum discharge current at normal voltage and at double normal voltage.
4. The half-wave equivalent spark-gap.
5. The endurance of the device.

The principal protective apparatus to be considered are as follows:

1. Lightning-arresters.

The choice of arresters will usually lie among the four following types:

a. Multigap arrester.
b. Aluminum arrester (no-gap type and gap-type).
c. Liquid-electrode arrester.
d. Magnetic-blow-out arrester.

2. Lightning-arrester choke-coils or reactances.
3. Overhead grounded wires, one or more, with or without lightning-rods.
4. Overload switches, either single-phase or multiphase.
5. Insulator protectors, horns or gaps, with or without fuses.
6. Static dischargers.
7. Earth connections.
8. Horn arresters with resistance.

The classifications of the circuits to be protected are as follows:

1. Constant-potential alternating-current overhead systems $\begin{cases}\text{grounded neutral}\\ \text{non-grounded neutral.}\end{cases}$
2. Constant-potential alternating-current cable system $\begin{cases}\text{grounded neutral}\\ \text{non-grounded neutral.}\end{cases}$

3. Constant potential direct-current systems.
4. Constant-current systems.

Comments on the protective apparatus. *a.* The multigap arrester has been used for years, and has been described and discussed elsewhere down to the latest designs. Its excellent qualities for discharging transitory lightning are well known.

b. The aluminum arresters are particularly well adapted to discharging continual lightning. They do not replace the multigap arrester, but complete the protection of a system by taking care of lightning which endangers the multigap arresters. Nearly all cases of destruction of the multigap arresters of the old design have been due to continual lightning. Every constant-potential system should have at least one installation of aluminum-cell arresters. This arrester is preferably installed on the bus-bars so as to take care of all feeders, and the multigap arrester on the feeders outside the switches for protection of the particular feeders. The aluminum arrester is a winter and summer arrester, as continual lightning is not directly due to cloud-lightning. The two types of aluminum arresters are the no-gap and gap types. The gap type is the cheaper and has a less maintenance expense, but the no-gap type is more effective.

c. The liquid-electrode arrester is recommended for potentials above 35 kilovolts, where the design of a multigap arrester is difficult.

d. The magnetic-blow-out arrester has been used for several years. It is adapted to constant-potential direct-current systems.

2. Lightning-arrester choke-coils or reactances have the function of retarding high-frequency lightning traveling toward the station. This retardation gives the lightning-arresters time to relieve the lightning potential before it strikes the apparatus. This high-frequency lightning seems to come invariably from cloud-lightning, therefore the installation of choke-coils on the cable systems is unnecessary and not to be recommended. In many cases, the installation of good lightning-arresters both inside and outside choke-coils is to be recommended.

3. Overhead ground wires. If a wire be placed underground, it is protected from the static charge of cloud lightning. If the insulated wire is simply placed in a metallic sheath and hung overhead, it is still protected from electrostatic charges from the clouds. Both these methods are often impossible of employ-

ment on account of the unjustifiable expense involved. The next best thing to do is to put the ground over the line wire. The farther above the line wire the grounded wire is placed, the better is the partial protection. Dr. Steinmetz recommends that an overhead grounded wire be so placed that two imaginary lines drawn from this wire 45° down from the horizontal will include all line wires between them. Each additional overhead ground wire, properly placed, gives some additional protection against induced static electricity from the clouds. The investment is the controlling factor in the choice.

The overhead grounded wire also has the function of protecting wooden poles from shattering by direct stroke of cloud-lightning. It also has the possibility of carrying a direct stroke of cloud-lightning to ground past the line wires without shattering the insulators or causing a short-circuit. More data regarding this point are needed.

Lightning-rods at each pole add a slight probability that a direct stroke will strike at the pole and not between poles.

If the overhead grounded wire is earthed at every pole, direct strokes of lightning are likely to find a more direct path to earth. The wave-front of a direct stroke is usually so steep that the charge finds the natural inductance of the horizontal wire a great impedance, and consequently it is likely to side-flash to other lines and also over insulators to its natural terminus, the earth. If the earth connection is made at every third pole, there are of course more chances that a direct stroke will hit a midway point and have a greater distance to travel parallel to the line wire before it reaches the earth. The parallel movement of the charge gives electromagnetic induction on the power wires. Practically all reports of damages to lines by direct strokes confine the line damage to about seven successive poles. This fact is suggestive.

4. Overload switches are a part of the protective apparatus, especially on grounded neutral systems. Multiphase switches are usually installed and are to be recommended on all systems, like a cable circuit, where a short-circuit between phases follows quickly after a short-circuit from phase to neutral. On overhead grounded neutral systems, phase-to-phase short-circuits are less likely to occur, and consequently, if three single-pole switches are used, the phase short-circuited may be opened automatically; and the load, if not excessive, may be carried on the remaining two wires with a ground return for a time.

5. Insulator protectors. An insulator protector is a single gap or horn gap placed beside the insulators and set with a gap-length such that a spark will just prefer to jump the gap to arcing around the insulator. The insulator should be in its wet condition. The use of this protector is based on the principle that if the arc must take place at the insulator, due to any high potential, it will guide the flames so that the insulator will not be cracked by the heat. The arc is then interrupted either by a fuse or by automatic trip-switches in the station. If no damage is done to the generator or transformers, the line can be immediately put back into service. Otherwise, the line is out of service until the linemen locate and repair the damaged insulator. On most alternating-current railway circuits, a momentary interruption of service is not very objectionable.

There are some evident objections to the use of the insulator protector.

In general, every electrical system should have some lightning protection. There is a certain minimum of protection below which it is not advisable to go. The amount of protective apparatus above this minimum will depend primarily on the value of the transmission apparatus and the value of continuity of service. Since there is a uniformity in these values in the various installations throughout the country, there is consequently a general uniformity of practice. There are, however, many special cases which require the careful consideration of every device described above. Such examples are found in large factories and industries depending entirely on continuity of electrical power, also in large lighting plants in cities. Thoroughly efficient protection is not much more expensive than partial protection, and is cheaper than carrying duplicate plants and apparatus, in addition to the repair bill and almost inevitable interruption of service when apparatus is destroyed. Arresters are of the nature of insurance. A reasonable percentage of the cost of the apparatus, cables, lines, etc., with the factor of the cost of repair of each kept in view, should be added to the monetary value of continuity of service. The sum thus found should be the limit up to which it is justifiable to make expenditures for protection and inspection.

Recommendations for protection of electrical plants in general. These recommendations will vary with the class of circuit to be protected.

1, Constant-potential, alternating current, overhead systems.

The first consideration is the question of connecting up grounded neutral or non-grounded neutral (this includes straight delta connection). The answer is somewhat influenced by the kilowatt capacity of the generating apparatus and the multiplicity of the circuits. In general, it may be stated that the distinguishing troubles on a non-grounded neutral system are primarily potential or internal-lightning troubles; these may finally result in a short-circuit which becomes a current trouble. On the other hand, in the grounded neutral system the initial trouble is usually a short-circuit which may become an internal-lightning surge when the abnormal current is suppressed. Until the advent of the aluminum arrester, there was no way of taking care of the continual lightning on a non-grounded neutral system, due to a phase becoming accidentally grounded, and consequently practice has been favoring the grounded neutral connection. It seems safe to predict that the non-grounded neutral connection will now become more favored on account of the possibility of operating for an indefinitely long time with a grounded phase.

Insulators often fail one at a time, and such failure causes a short-circuit in the grounded neutral connection. The subject of overload-switches has already been discussed above.

On a non-grounded neutral system, the aluminum arrester is absolutely essential. On a non-grounded neutral system, it is advisable to use an aluminum arrester to take care of the preliminary continual oscillations which sometimes precede a short-circuit, and afterwards to take care of the low-frequency energy surge that sometimes results from the interruption of the short-circuit current. In the case of multiple circuits, an aluminum arrester in a station may be used, connected directly to the bus-bars. Multigap or other arresters for transitory lightning should be installed on each line or feeder, and lightning choke-coils should be used in each phase between the arrester and bus-bars. Line arresters should be used on the line at high altitudes, exposed lengths, fractional multiples of the line length to catch standing waves, and in the usual path of thunder storms. Transitory-lightning-arresters should be installed on all incoming and outgoing lines in conjunction with choke-coils in every sub-station. An aluminum arrester is probably unnecessary, in general, in each sub-station, but in some cases it will be advisable to install another arrester at the extreme end of the line.

When low-potential systems are fed from high-potential systems, special precaution should be taken to prevent the destruction of the arrester, and then of the low-voltage apparatus over the entire system by the accidental impression of the high voltage on the low-voltage system. This may happen either through electrostatic induction or direct connection of the two systems. Continual and continuous lightning are produced on the low-voltage system. The multigap arrester without series resistance will short-circuit by welding the cylinders and thus save the apparatus. An aluminum cell will take care of this condition without interrupting the service, but the arrester must be of special design, as it may have to operate continuously at its critical voltage until the fault is removed. If it is only electrostatic induction through the step-down transformers, the design is easy, but, if it is a direct connection between one phase of the high-potential system and the low-potential system, the aluminum cell must be capable of carrying the condenser current of the high-potential line until the fault is removed.

One substantial overhead wire well-grounded is a justifiable investment on nearly all overhead systems. Two driven iron pipes as earth connections are recommended, or one pipe and the usual wire to the bottom of the wooden post. Using large copper plates buried in the earth is as a rule unnecessary.

Earths. Make an earth connection as near the arrester as possible, even if it must be a relatively poor earth, then extend the earth connection to two good earths. It is advisable to measure the ground resistance each year before the thunder storms appear and to be assured that it is low.

Constant-potential cable systems. The choice of grounded or non-grounded neutral is again up for choice, as the conditions in a cable system are quite different from those of an overhead system. From a protecting standpoint, the difference lies in the fact that the phases are as a rule throughly isolated from one another in the overhead system, and an arc fed by the capacity current of the line can play from one phase to ground without affecting the insulation between phases, but in the cable the capacity currents are much greater, and an arc from phase to ground quickly melts and burns away the insulation between phases. In the usual multiple-feeder system, there is not time in this short interval to locate and disconnect the faulty feeder. Since a short-circuit is to result anyway, and open the circuit-breaker, practice has favored the use of the grounded neutral connection. This avoids most of the continual surges due to a grounded phase on a non-grounded neutral. The aluminum arrester will protect against the continual surges, and, if there are only a few feeders, some evident advantage may be gained by using the non-grounded neutral connection.

The circuit should be broken as quickly as possible after an arc starts, or the heat from the flame will cause widespread damage to adjacent cables and wires. This is especially true on large, high-current systems where even normal current could quickly burn up considerable cable. The engineer should take note of the effect of the heat of an accidental arc, and use non-inflammable separations for the cable. Asbestos covering or brick barriers are to be recommended in manholes or at terminal bells.

Unless there is some special reason for not doing so, the cable sheath should be thoroughly and frequently earthed. It is undesirable to make the sheath carry currents of fusing values, or to allow even a small arc to play upon the sheath to the earth in any spot, especially where inaccessible.

Except the transitory lightning due to switching, all surges on a cable system are continual. Therefore, the multigap, or any other arrester involving an arc in the discharge, is not so well suited for this system as the no-gap aluminum arrester. No choke-coils need be used on a cable system.

Mixed cable and overhead system The only addition to what has been said of each system is the statement of the advisability of installing arresters at the junction point of the two systems.

4. Constant-potential direct-current systems have been satisfactorily protected by the single-gap arrester, notably the magnetic blow-out type. In the future, it is probable that the no-gap aluminum arrester will find an application where cloud lightning is especially severe and where the conditions warrant the extra expense.

5. On constant-current systems, the peculiar conditions permit the use of a simple horn gap with a suitable series resistance.

Although this paper has been carried to an unusual length, not all the salient features of each subject treated have been discussed. It is hoped, however, that enough has been said to assist in bringing the practice in protective apparatus out from the somewhat indefinite speculative stage and to establish the foundation of methods and tests which will place the engineering on the same reasonable basis as that of other electrical branches.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907

PRACTICAL TESTING OF COMMERCIAL LIGHTNING-ARRESTERS

BY PERCY H. THOMAS

Introductory. The question as to what tests for commercial lightning-arresters might be properly incorporated in the standardization rules of the American Institute of Electrical Engineers has lately been considered by the Standardization Committee. The committee finally decided not to adopt any lightning-arrester tests in the new edition of the rules adopted June 21, 1907. However, the sub-committee on lightning-arresters hopes to get a full consideration of the subject for the benefit of a later Standardization Committee. The present paper, together with another paper on the same subject by Mr. E. E. F. Creighton, is prepared at the request of the sub-committee to serve as a basis for discussion. As no lightning-arrester tests have ever been included in the standardization rules, the initial treatment should now receive especially careful attention.

Some idea of what constitutes suitable subject-matter for the standardization rules of the Institute must be assumed at the outset. It is the opinion of the writer that the purpose of the standardization rules should be to give such directions and information for the comparison and test of commercial lightning-arresters as may be likely to be of general practical use, and which are of such a character as to be generally agreed to and accepted by engineers having experience with the use or design of lightning-arresters. This subject-matter need not be limited to specific tests or specifications, but may properly include general considerations, suggestions of forms of making tests, of apparatus, etc. Individual personal opinions, as to the superiority of particular designs of arresters, specific tests about the value of which there is not a general agreement, untried tests, and, in general, purely theoretical considerations should be omitted.

Research work, covering the effects of various conditions on the performance of lightning-arresters, the investigation of really new types, for example, electrolytic arresters, and the best conditions for determining the detail of designs, etc., is of great importance and should be actively encouraged. But such matter properly finds no place in the standardization rules.

All information and tests embodied in the standardization rules must be sufficiently general to be applicable under all conditions within their terms; for example, a test applicable only to high-voltage alternating-current arresters should not be recommended in such broad terms as to be applied to direct-current railway arresters.

This matter must be capable of being readily understood by any electrical engineer having experience with plants, likely to require the lightning-arresters under consideration. No such person should be expected to have to make a special investigation of new types of apparatus or new methods of test to carry out the rules. All rules should be such as not to favor any particular manufacturer's apparatus.

Tests may be made to determine:

1. The condition of individual arresters.
2. The effectiveness of a particular design.
3. The characteristics of different types.

In general, there will be little occasion for testing the condition of individual arresters, since inspection will usually reveal any defects in the materials or construction. The relative advantages of the different broad types of arresters will in most cases be determined by general considerations and consensus of opinion, rather than by definite tests. It is therefore with individual designs that practical tests on commercial arresters will be found most useful, and here such tests will be of very great benefit. For example, from time to time new commercial arresters appear, advocated by comparatively irresponsible persons. These arresters very often have little protective value. Such arresters, especially on lower voltages, although they are by no means confined to such voltages, find a ready sale entirely independent of their merits, and the more frequently, since engineers of low-voltage plants are often not at all familiar with the lightning-arrester problem. If a standard test generally accepted and capable of easy application can be determined, the detection of such practically worthless arresters will be a comparatively easy matter. Similarly, the necessity of commercial trials on a large scale of special forms of high-tension arresters which have a very limited protective power, may be eliminated by suitable comparative tests. Again, if generally accepted tests were at hand for the criticism of commercial arresters, the designs of many of these arresters would undoubtedly be overhauled and perfected so as to appear to advantage under such tests. If the tests were wisely chosen, a distinct advance in the art would follow.

In testing the effectiveness of individual designs, one of the most important features to be determined is the insulation strength of the apparatus to resist the static strains existing during actual discharge.

Tests should undoubtedly be made to cover auxiliary apparatus as well as arresters proper, for example, line choke-coils.

Conditions of actual operation. A recital of the various ways in which lightning and other static disturbances can affect an exposed commercial circuit has been often made. Practically all result in the equivalent of the production of a sudden rush of electricity, or wave, or surge along a line wire. Such a surge usually passes both ways in the wire until it is discharged, dissipated, or reflected. There is obviously no upper limit to the electromotive force which may be applied to a line wire by lightning, and the wave or surge may be theoretically of any frequency. As a matter of fact, however, since extremely high frequency—for example, 100,000,000 million cycles—must necessarily be associated with extremely small electrostatic capacities, in the writer's opinion such very high frequency disturbances need not be here considered. (See appendix I.)

The distinctive characteristics of the static surge or wave are its abnormal frequency and the fact that it is not directly supported by the power of the generator. It should, of course, be remembered that these surges not only produce strains to ground and between line wires, but they frequently cause concentration of potential between turns of windings in coils, especially near the terminals.

Resonance, being usually supported directly by the power of the generator, will not be cared for by lightning-arresters and is here omitted from consideration.

There is another possible source of potential rise of a static character; namely, the sudden interruption of a current flowing through inductance, such as the inductance of a transmission line. It is evident that a short-circuit including the whole or a portion of the transmission system, will store a relatively large amount of energy in the inductance thereof if by any means such a short-circuit current be abruptly interrupted, a very high potential will result, being limited only by the electrostatic capacity of the lines and their insulation strength. It is the opinion of the writer, however, that this condition never occurs where large currents are involved, since the condition predicated for producing the short-circuit provides also a discharge path for any voltage rise, and since the very energy stored in the choke-coil will tend to maintain the current uninterrupted until the major portion of this energy is dissipated. When, however, in the case of the opening of such a short-circuit as in an open-air arc, the extension of the length of the arc proper has reduced the current to a value where it becomes relatively unstable, there will be a tendency for the arc to go out suddenly, causing the ***remnant*** of the energy, originally remaining stored in the inductance, to produce a rising potential. This residue will, however, never be more than a small portion of the maximum energy stored. A great many direct tests of the opening of circuits through enclosed fuses and circuit-breakers, where conditions have been definitely known to be as assumed, have shown practicably negligible rises of potential. The fact that high voltages have appeared in electric accidents coincidentally with short-circuits and arcs is no proof that these high voltages have resulted from the sudden interruption of heavy short-circuit currents.

The severity and general range of the static disturbances actually materializing within an electric system is definitely limited in certain ways.

A. The maximum voltage of a surge passing along a line must be limited to the voltage which will cause a discharge to earth over the line poles. That this is an effective limitation is shown by the great number of transmission poles which have been shattered by lightning. It is natural to suppose that on this account, transmission lines having steel poles will not make as heavy demands on the terminal protective apparatus as lines having wooden poles, since the discharge to earth can presumably occur much more readily on the former. It remains to be seen, however, whether the added annoyance of grounds and cracked insulators where the steel poles are used, does not more than offset the advantage of the discharge from the wire over insulator to ground.

B. Disturbances of very small energy, and hence very high frequency discharges, can be neglected, since the electrostatic capacity of the terminal line wiring and apparatus will be such as to absorb their energy without serious rise of potential.

In general, then, it is the opinion of the writer that we are safe in concluding that we have to deal only with static waves, or surges of potential not over a few times line potential, on extra high-tension circuits; namely, high enough to discharge to ground over the insulators, such surges having frequencies usually very high with regard to normal frequency, but not what is generally understood by extremely high frequency; for example, practically never reaching fifty million cycles a second.

Lightning-arresters should discharge without serious rise of potential and without otherwise disturbing the system, this specific type of " static,"—not static disturbances in general, nor all kinds or forms of that can be devised or produced under laboratory conditions,—but merely static discharges actually occurring under the limitations imposed by commercial plants.

Choke-coils, static interrupters, or reinforced insulation must serve to protect windings from local concentration of potential under the same limitations as to the character of the static disturbances as above.

It should be stated in this connection that to enable an arrester to exert its protective function properly; it is necessary that all the insulation of the system, including the apparatus and the lines shall be high, and especially that it be high against *static disturbances*. Bushings and surfaces are often broken down much more easily by static than by normal frequency strains. It is by the strengthening of the insulation of the system that immunity from lightning has been in the past most readily obtained and will in the future be most effectively increased.

TESTS

Discussion and specification. The discussion in this paper will be confined to lightning-arresters for electric lighting and power circuits, alternating and direct current. Such arresters may be of many types having radically different characteristics and structures. For the sake of clearness, it will be well to enumerate the principal of these types:

Multigap arresters, with series or shunt resistances or both. These arresters are used practically only on alternating-current, constant potential. The multigap feature is, of course, introduced on account of its non-arcing power.

Arresters relying for the suppression of the generator arc upon the blowing of a fuse or upon the opening of a circuit-breaker.

So-called horn arresters.

Magnetic-blow-out arresters.

Electrolytic arresters.

Many special types, including such arresters as the water-jet, the Gola, the Wurts railway arrester, and many others relying on special materials or special forms for their non-arcing power or discharge characteristics.

The features of arrester apparatus most susceptible of satisfactory tests are perhaps:

A. The initial break-down voltage.
B. The static equivalent during discharge.
C. The circuit-opening power.
D. The insulation strength.
E. The ability to stand repeated discharges.
F. The choking power and insulation strength of choke-coils and equivalent apparatus.

Holding Normal Voltage

General considerations. The determination of the voltage necessary to cause an arrester to discharge is of importance; first, as ascertaining the minimum voltage at which protection begins; secondly, the margin of safety which the arrester has in order to secure itself against continuous break-down. The second consideration is of special importance in the high-tension arresters, especially voltages of 30,000 and above.

On very high-tension circuits, the power of multigap lightning-arresters to hold the normal line voltage is very greatly affected by attendant conditions; for example, the electrostatic capacity of the intermediate unconnected cylinders forming the gaps causes a break-down to occur at a much lower voltage on high frequency than on low frequency. This subject has been fully discussed before the Institute, for example, in connection with the following papers:

"Methods of Testing Protective Apparatus" by E. E. F. Creighton; see discussion by Chas. P. Steinmetz, TRANSACTIONS, Vol.

XXV, 1906; " Protection against Lightning, and the Multigap Arrester," by D. B. Rushmore and D. Dubois. TRANSACTIONS, Vol. XXVI, 1907, and "Multigap Lightning Arresters with Ground Shields," R. B. Ingram, *Electric Journal*, April, 1907.

Since the capacity of these gap cylinders is increased by the nearness of grounded objects, the placing of arresters near a wire or transformer case or similar object, or more particularly in the neighborhood of other arresters or line wires on another leg of the circuit, tends very greatly to increase this effect. The effect is so marked that an arrester entirely capable of holding the line voltage with a good margin of safety, if installed apart from other objects, will be utterly unable to hold normal voltage, if installed in close proximity to another arrester connected to a different leg of the line. From this, it follows that tests to determine the power of an arrester to hold normal voltage must be made under conditions equivalent to those under which that individual arrester is to serve. The writer suggests that, on voltages of 40,000 volts or higher, an excess of air-gaps may be provided, and the exact number required to give a proper margin over line voltage be determined by trial after final installation.

Too sensitive an adjustment of the series-gaps of an arrester on very high tension circuits will be the cause of the greatest annoyance, and probably will result in the destruction of the arrester. The resulting frequent discharges of the arrester will oftentimes be laid to abnormal static, due to some unknown cause, when as a matter of fact the only difficulty is the ease with which the arrester discharges on slight impulses of high frequency or even fluctuations of abnormal voltage. This condition has in the past, often been a source of great annoyance in commercial plants where it has frequently not been recognized; it should always be carefully borne in mind.

Description of test. The actual measurement of the breakdown voltage of an arrester can best be made at normal frequency. In making this measurement, the primary object is to determine the margin of safety in the arrester over the normal line voltage as read on a voltmeter. Thus in this particular instance the use of the needle-point spark-gap for measuring the voltage as provided in the standardization rules, though always of value, is not as directly the criterion sought as the voltage determined by the voltmeter. In making such a measurement, all the conditions provided in the standardization rules under " Insulation Tests " should be followed, where applicable. The writer suggests that, where practicable, the determination of the breaking down voltage of arresters on 40,000 volts or over be made from the main generator of the system with the arresters and neighboring apparatus in final position.

It is true that high-tension multigap arresters will break down at a much lower voltage on high-frequency electromotive force than on normal frequency; but, in the opinion of the writer, since this phenomenon is in the direction of safety, and, since it has been established by actual experience on high-tension plants that this fact does not cause discharges on arresters frequently enough to be troublesome, this may be accepted as a favorable characteristic of such arresters. This matter is, however, properly a subject for investigation and research.

MAXIMUM IMPEDANCE OFFERED TO A DISCHARGE—NEEDLE-GAP EQUIVALENT

General considerations. The maximum impedance offered to a discharge determines the protective power of an arrester, and is therefore of the greatest importance. On the other hand, since so little can be definitely determined as to the type of discharges actually to be met, and so much depends upon the characteristics of the circuit and apparatus being protected, it is impracticable at the present time to devise *absolute* tests of a general character which are not likely to be uncertain or misleading. It is of course easy to choose condensers and circuits, and apply static to arresters under a great variety of conditions with presumably considerable variation in results, but in the opinion of the writer such tests, except where they can be shown to be reasonably within the conditions existing in a transmission line, should not be specified for the testing of commercial arresters, but should be considered as proper subjects for investigation and research. However, comparative tests between arresters may be often made to great advantage.

If an arrester be subjected to a high-frequency discharge from a condenser, and its static equivalent measured by the equivalent needle-gap method, the numerical result will depend upon the character and method of operation of the testing apparatus; for example, it will depend on the electrostatic capacity of the condenser, the inductance through which it discharges, the voltage to which it is charged, the auxiliary circuits providing for the charging of the condenser, and the disposition of the arrester itself. Since it is manifestly impossible to determine upon any reasonable number of definitive conditions as representing the transmission line under all conditions, no general absolute test should be attempted as such; that is, no attempt should be made to treat each arrester as having so many units of protecting power irrespective of conditions of service and of test.

The study of arresters through the agency of condenser discharges has been an absolute necessity in the progress of recent years. This progress has been notable. Tests with any reasonable form of condenser discharges, as distinguished from applications of normal frequency, will show practically the same characteristic results, although numerically different frequencies and different circuit arrangements, etc. will show variations. Consequently, to get what advantage is practicable out of such tests, the natural course would seem to be to use some condition, or conditions, of condenser capacity, etc., known to be reasonably well within the conditions of actual operation and reasonably easy of realization, and then to make comparative tests for what they may be worth. By this means, a large part of the value of a complete range of static tests will be obtained. Any further data that might be found by multiplying the tests under different conditions, would probably produce only small changes in the actual conclusions; such additional tests are more properly subjects for investigation and research than for practical tests of commercial arresters.

Taking up these tests more in detail, the various types of arresters will be separately considered, since their needle-gap equivalents are controlled by radically different features.

1. *Arresters offering no impedance to the discharge.* Such arresters rely on special features for suppressing the generator arc. Examples are the fuse type, the horn type, and the magnetic blow-out type. If a horn arrester has also a series resistance, it is no longer properly a horn arrester but a series resistance arrester. It is obvious that the maximum impedance offered to a discharge by this type is practically equal to the initial discharge voltage, and no further test is required than has been already indicated under the head of holding normal voltage. This type of arrester is especially effective in discharging the line.

In connection with these arresters, the question must be raised, however, that it is theoretically possible for the device relied on for interrupting the generator current to introduce a rise of potential. This question can be determined finally only by experience. The definite data available at the present time, derived from direct tests, have, as far as the writer is aware, failed to indicate any serious rise of potential from the operation of fuses, horn, or magnetic blow-out arresters. The question is, however, somewhat a matter of controversy.

2. *Arresters with series resistance.* Series resistance must necessarily offer some impedance to a static discharge. The amount of this impedance will depend upon the value of the resistance, on its inductance and its capacity, on the abruptness of the application of the charge, and upon the inductance through which such charge must pass. Any inductance in the series resistance will tend to impede the discharge; any capacity, however, either internal or with other objects, will tend to facilitate the discharge. The higher the frequency, that is, the greater the abruptness of the discharge, the greater will be the relative importance of the inductance and capacity in the series resistance in comparison with the ohmic resistance.

It is evident that the danger to apparatus introduced by the series resistance will be negligible if the discharge be small enough, or may theoretically be dangerous with the lowest resistance if the discharge be abrupt and heavy enough. Since both the magnitude and abruptness of the discharges which can be produced in a commercial system are limited by certain maximum conditions, it becomes an open question just how much danger will result in practical operation from a definite series resistance.

Series resistances for lightning-arresters have been designed on two principles; first, sufficient to cut down the generator current following a discharge, to render the device easily non-arcing, and to prevent all burning of cylinders; secondly, usually with multi-gap arresters, to allow as free a discharge as possible while still maintaining the non-arcing quality. In the latter case the shunt resistance has ordinarily been used as well, and helps decidedly in cutting down the minimum allowable series resistance. Experience shows that the first mentioned high series resistance does seriously impede the static discharge on commercial lines and it has been practically abandoned as a means of principal protection, though somewhat used to carry off the so-called slowly accumulated charge. The low series resistance is much used on all types of alternating-current circuits except those of lower voltages; it can hardly be considered at present as finally determined, whether or not the present " minimum value " series resistances offer serious opposition to actual discharges on commercial systems. In most cases they do not.

The determination by test of the impedance offered by a series resistance arrester to a static discharge is hardly practicable, since such resistance will ordinarily constitute practically the major portion of the resistance in the test circuit, so that, whatever the discharge voltage may be, it will of necessity be impressed upon the series resistance. The needle-gap equivalent would then be merely a measurement of the voltage and quantity of current in this particular test, and not any inherent characteristic of the arrester. Some idea of the relative value of two arresters may be obtained by connecting them in series, passing a discharge through, and measuring the needle-gap equivalent of each arrester. As far as the writer knows, this particular form of test has rarely been made. Obviously, a comparison of the ohmic value of the series resistances of two arresters, generally similar, will give a good idea of their relative effectiveness. Where the types of series resistance are, however, entirely different, a comparative test by putting the two in series and subjecting them to the same discharge, or some equivalent test would be necessary for forming a trustworthy judgment.

3. *Special forms of arresters.* Under this head are included, as above, arresters relying on special forms and special materials for their non-arcing power, and arresters having an unknown construction. Here will be classified many new types of arresters, especially low-voltage forms which appear from time to time, but are not founded on well-recognized principles and are presumably of doubtful utility.

These types are generally found to be intermediate in their characteristics between groups 1 and 2, above. They are not like group 1, in which the maximum impedance to a discharge is practically independent of the character or strength of the discharge, nor are they quite like group 2, in which the needle-gap equivalent is more or less directly proportional to the severity and abruptness of the discharge; their equivalent is usually found to increase slowly with increasing severity of discharge. It is in these special groups that direct tests by discharge of condenser through the arrester are of the most service. Such tests may be made to give a measure of the impedance offered to the discharge, as compared with that offered by some standard well-known arrester, thus giving data for the judgment of their effectiveness where inspection and the results of commercial service are insufficient to determine the merits of the arresters.

In view of the compactness of construction of most lightning-arresters, there is always an opportunity for a discharge to break down insulation or jump an air-space, short-circuiting a portion of its normal path. Such action is of course likely to destroy the arrester and shut down the system, since the non-arcing features are ordinarily be thereby crippled. The test with a severe condenser discharge may be made to serve the function of testing the insulation of the arrester. This is one of the tests most needed and most easily made, and should be strongly recommended. In actual practice, a great many arresters have failed on both high-tension and low-tension circuits from discharges jumping between parts or to ground, and allowing the generator current to follow. When these tests are made without the power lines being connected to the arrester, care must be taken to detect the occurrence of internal sparks, as they may not otherwise be noticed.

Description of test. The test to determine the impedance offered to a discharge may be best made by discharging a condenser directly through the apparatus to be tested, and measuring the maximum voltage across this apparatus by a needle-point spark-gap. The measuring spark-gap may either be so set as to take the discharge half the time, while the apparatus takes it the other half, or it may be so set as just to fail to take any discharges. The former condition is presumably the better one, since to make a spark-gap take all the discharges when connected in parallel with an arrester, it is sometimes necessary to increase the gap a very considerable percentage. This percentage will depend upon all sorts of conditions not definable or controllable, so that a very considerable source of variation will be introduced into the measurements, if the method of entirely suppressing the spark in the measuring gap be adopted. The needle-point gap taking half of the discharges will be the comparative measure of the impedance voltage offered to the discharge.

Spark-gap. The condenser should always discharge over a spark-gap to reach the apparatus to be tested. This is the element which introduces the high frequency. This spark-gap should preferably be large enough to cause a voltage to be impressed upon the arrester very much higher than the normal voltage of the circuit upon which it is to be used; where possible perhaps three times normal voltage. The tests will of course be of value even if a considerably lower discharge potential be used.

Condenser. The electrostatic capacity of the condenser should preferably be considerable, because it is intended to reproduce to some extent the more severe conditions of practical experience. A pair of high- or low-tension line wires will ordinarily have a capacity in the neighborhood of one hundredth of a microfarad per mile. It is thus seen that where several lines are connected to the same bus-bars near the arrester, a considerable capacity may discharge over the arrester. It is difficult to tell just what portion of a line wire near the discharge point should be considered to discharge directly through the arrester, since the inductance of the line becomes very considerable and tends to delay the discharge of the more remote parts, allowing the arresters more time to pass off the excess. (See Appendix II). It is suggested as a compromise value that where practicable a few hundredths of a microfarad be tried. This figure is admittedly open to discussion. Capacity can be most easily measured by determining the charging current taken on a *true sine* electromotive force at a known frequency and voltage; one microfarad takes three-eighths of an ampere approximately at 60 cycles and 1,000 volts.

It may further be added, that it seems practically very unlikely that any considerable length of transmission line can be raised at one time to an excessively high potential by any static disturbance. The total length of line simultaneously affected could hardly exceed a few miles at most. Where so much capacity as here recommended is not available, since all such tests must be relative, a considerably smaller condenser will give valuable results. High voltage rather than extremely large electrostatic capacity is recommended.

Abruptness. The condition of extreme abruptness in a test, which is one of the severe conditions, is obtained by having no impedance, other than the arrester directly, in the discharge path of the condenser and by limiting the length of the connecting wires in such path to a few feet. The initial abruptness of the discharge (though not the frequency of oscillation) depends solely upon the inductance and resistance in the discharge path; it is not lessened but rather increased by enlarging the capacity of the condenser. It is of much more importance in making the discharge sudden, that the inductance in the discharge path of the condenser be eliminated, than that the electrostatic capacity of the condenser be large. The character of a discharge is indicated by the sound. The " crack " should be extremely sharp and loud.

Circuits. In providing means for charging the condenser conveniently (except where using a static machine), it will usually be necessary to prevent the current supported by the charging apparatus from being maintained through the lightning-arrester after a discharge. This might oftentimes burn out a resistance.

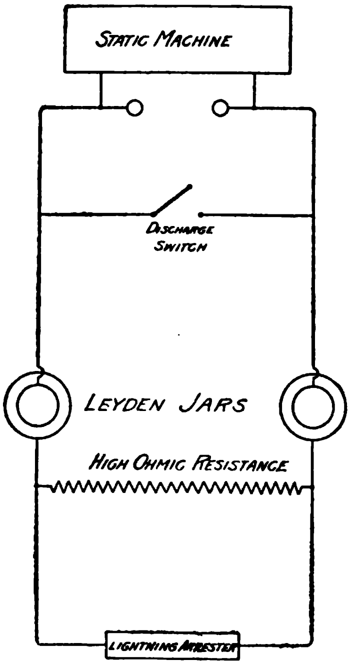

Fig. 1—Diagram of circuits for testing impedance offered by lightning-arrester to a discharge—static machine and leyden jars

A variety of connections may be utilized for these tests, two of which are shown in Figs. 1 and 2. Others may be devised.

Where laboratory apparatus and laboratory skill are available and the voltage is not too high, the arrangement in Fig. 1, utilizing a frictional or static generator, will be found convenient and compact. Under other conditions, however, static machines are often not available; they are very troublesome except in the hands of persons especially expert, and in general will be found less satisfactory than the connections in Fig. 2. The arrangement shown in Fig. 1 is substantially that described by Mr. Creighton in a paper before the annual convention of this Institute in 1906, Vol. XXV of the TRANSACTIONS.

It is, of course, possible to utilize the circuits of Fig. 1, substituting for the static machine a step-up transformer connected to an alternating-current main. A switch will then be used across the high-tension leads of the transformer to start the discharge. There must usually be some current-limiting device in connection with the transformer, to prevent too much current flow on the closing of the switch. This arrangement should give a satisfactory source of static discharge.

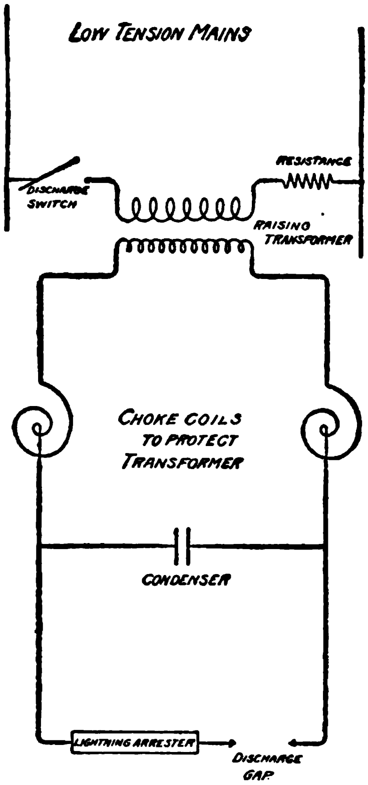

FIG. 2—Diagram of circuits for testing the impedance offered by a lightning-arrester to a discharge—alternating-current mains and step-up transformer

In Fig. 2, alternating-current is used to charge the condenser through a step-up transformer and the discharge is produced by the closing of a switch, as shown. This switch must ordinarily be opened rapidly, to prevent the generator current from following a discharge over the series-gap through the arrester. The resistance or inductance in series with the primary of the transformer also serves to limit the generator current. Such a switch may easily be made by mounting a contact on the end of a pole some feet in length, arranged to swing past a coöperating contact point; this will close and open the circuit rapidly enough to get a single discharge over the series-gap with each closing.

By using a very high ratio in the step-up transformer and suitable values of the inductance or resistance in the primary, it is often possible, by leaving the switch closed, to produce a rapid succession of practically pure static discharges over the series-gap through the arrester. Apparently under these conditions the condenser charges and discharges each alternation, and all generator current is suppressed by the inductance or resistance. This continuous spark method should be used with great care, and only when the actual suppression of the generator current in the arrester has been demonstrated. This condition is favorable for making a very large number of discharges in a short time, but is very hard on the arrester; as, for example, in case of a puncture of insulation. It can be more readily obtained when, instead of a generator of considerable power and choke-coils or resistance in the low-tension side of the transformer, a small generator is used having its field weakened very much below normal value, and a transformer ratio chosen much greater than necessary to break down the discharge gap. In this case, the field reaction kills the generator voltage as soon as the condenser discharges over the series-gap. This is a very effective arrangement but is not always available, as it requires a special generator.

Construction of condensers. Condensers may be conveniently made up in a number of ways.

Leyden jars in sufficient quantity are satisfactory, though the writer has not found them nearly as convenient as other forms. The capacity of a leyden jar having 50 square inches of foil coating inside, and having a glass wall approximately three thirty-seconds of an inch thick is somewhere near 0.0005 microfarads.

Glass plates with tin-foil cemented on them, and placed in a rack, are effective but easily broken.

Sheets of metal between sheets of solid insulating material such as oiled cambric or oiled paper, either in or out of oil are quite satisfactory.* This type of condenser, though inferior in point of dielectric loss, is extremely compact, is easily constructed of materials readily obtained, and is quite robust. The leads are preferably brought out from each condenser plate separately, so that the capacity and insulation strength may be varied by connecting the plates in different combinations.

Tests of choke-coils. Although lightning-arrester choke-coils, and other forms of auxiliary apparatus accomplishing the same purpose, do not serve the same function as lightning-arresters, yet the impedance offered to the discharges from the line is of importance, since it is the function of the choke-coil to offer as large an impedance as practicable to such surges as may pass an arrester. Comparative tests of the impedance values of choke-coils are especially desirable at the present time, since there is very little data on the relative choking power of the more usual designs of such coils, and their relative merits are not easily determined otherwise. These tests do not involve very much difficulty in the making, and when made as comparative tests serve an important function.

The same apparatus and method of tests as described for testing the impedance of arresters to discharge, may be utilized in connection with two or more such coils in a series, one being a standard for purposes of comparison. The needle-gap should be taken on each of the two coils under the same or similar conditions, and a comparison of results will show the relative power of these coils. By this same means the insulation strength of the coil and the spacing of its leads can be tested.

POWER TO SUPPRESS THE GENERATOR ARC

General considerations. This all-essential feature of an arrester is unfortunately extremely hard to test and determine in the general case, since the difficulty of suppressing a generator arc increases with larger and larger currents and is multiplied many times when the generator circuit includes much inductance. With many arresters, tests made on anything less

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*The capacity of a plate condenser may be calculated fairly closely from the formula: Capacity in microfarads = the area of one plate in square inches divided by the thickness of dielectric in inches $\times 2.25 \times$ the specific inductive capacity $\times 10^{-7}$. The specific inductive capacity of air is 1 and of solid dielectrics from 3.5 to 6.

than a full-size plant cannot give a safe guide for judging the non-arcing power of an arrester, since only on such plants can the maximum generator current be obtained. Designs behaving perfectly satisfactorily in many laboratory tests on medium-size machines, or on large machines with limiting resistances, may very likely fail utterly to suppress the arc when placed upon regular commercial circuits. In a paper, presented concurrently herewith and supplementary to a paper by the writer read at the annual convention of the American Institute of Electrical Engineers in 1902 on the " Function of Shunt and Series Resistance in Lightning-Arresters," are shown some curves of the non-arcing power of multigap arresters on alternating-current circuits, which are the result of actual tests and show this fact in a very marked manner.

This condition is not of an imaginative nature, since this very difficulty has occurred a great many times. It is very seldom that conditions are favorable for making such tests, as they require, except with an arrester inherently limiting the generator current, practically the exclusive use of a large generating plant; and, because short-circuits may be produced frequently, there is great danger of damage to the generating apparatus. It is of course true that lightning-arresters, themselves limiting the flow of current from the generator, need be tested on circuits only just large enough to supply, without material drop of potential, the current naturally taken by the arrester. In all cases it should be definitely determined that no more current would be supplied during the discharge were the generating capacity infinitely large, otherwise the test would not be trustworthy. Also, it is important that, where necessary, special inductance should be introduced into the circuit to represent any inductance which might be found in an actual power system; as, for example, the inductance of a transmission line. The presence of such inductance markedly increases the difficulty of suppressing the generator arc.

Speaking broadly, it may often be determined from general considerations whether an arrester will be non-arcing or not, in which case tests will be unnecessary. In practically all free-discharge, non-arcing arresters, the tests of non-arcing quality will cause destruction of the arrester and usually of several arresters. Considering more particularly the bearing of the various arrester types on tests of non-arcing power, the following should be noted:

a. A number of arresters utilize a free discharge path to earth, with means brought into action after the passage of the discharge for suppressing the arc. Such are the fuse-type arrester, the horn arrester, the magnetic-blow-out arrester, etc. The horn type is sometimes used in connection with series resistance or with a fuse, in which case it should not be classed as a horn arrester but as a resistance or fuse arrester.

The ability of these arresters to suppress the generator current then becomes a question of the ability of the fuse, the horn form, or the magnetic field to open the circuit. There seems to be no doubt of the ability of a properly constructed fuse, usually of an enclosed or explosive type, to open any circuit. Numerous tests have been made on this subject. There is a good deal of question as to the ability of horn arresters to open promptly very heavy currents. Magnetic-blow-out arresters are used only on low voltages where they have a very decided arc-opening power.

b. Arresters of the series resistance type. When the series resistance is very large, the maximum generator current will be low, and there will be no question as to the non-arcing character of the arrester.

When the series resistance is made as small as possible, as is usually the case in connection with the multigap shunt resistance arresters which are much used for high alternating pressures, the design of the arrester is usually somewhere near the lower limit of non-arcing power and tests will be of value. The factors determining the non-arcing power of multigap arresters, with or without shunt resistance, have been pretty thoroughly investigated. As a matter of fact, with a given inductance in the circuit, the number of gaps required to suppress the generator arc with a high-tension alternating-current circuit increases at a rate between the first and second power of the current. With increase in inductance in the circuit, it also rapidly increases with a given current.

c. The types of special material or special form arresters already referred to, including arresters of unknown method of operation, will be found generally to have characteristics intermediate between those of the two classes above mentioned, and very little can be inferred as to their non-arcing power aside from tests, unless the results of actual experience have been sufficient. Unfortunately, with special forms on high voltages, for reasons already explained, it is often very difficult to make adequate tests. For low voltages, alternating and direct-current, however, it is relatively easy to make tests, and they are often to be recommended, especially where claims are made for some unknown arrester which has not been widely and publicly used.

Description of test. The tests of non-arcing power are made by reproducing operating conditions; that is, connecting an arrester across a powerful supply circuit and passing a static discharge across the whole or a part of the arrester to initiate the generator arc. The generator capacity should in all cases be sufficient to supply, without material drop in voltage, all the current which the characteristics of the arrester will allow it to take. On this account, tests on horn and fuse-type arresters and other types not limiting the flow of generator current on discharge are rarely practicable. When made on smaller machines, or by limiting the current flow by resistance or otherwise, they are of little value.

The *inductance* corresponding to the maximum inductance to be expected in service, should be included in the generator circuit.

Source of static discharge. It is a very troublesome matter to obtain a satisfactory source of the static discharge. Where a Holtz or frictional machine is available, and the voltage is not too high for this machine to cause a discharge, it may be satisfactorily used. In most cases, however, it will be found more satisfactory to get the high-tension discharge from a transformer. An arrangement similar to that already described for testing the impedance offered to discharges by arresters, may be here utilized. In this case, a much smaller condenser may be used than for the above test, and the voltage need be only just high enough to cause the discharge. It is essential in such a test to avoid synchronism, that the source of discharge be not taken from the same supply as the generator, since, if the static waves have always the same relation to the waves of the generator, all conditions of practice would not be obtained. If special pains should be taken to adjust phase relations to give the discharge at the most severe point of the wave, the same source might be used, but this method is difficult and uncertain.

Evidently, in order to get the most unfavorable condition for suppressing the generator arc, the discharge should be passed over the arresters in the early part of the cycle of the generator wave, since this allows maximum of heating or other activity in the arrester before the first zero point.

The actual severity of the exciting static discharge seems to be unimportant in this work; a comparatively slight spark is entirely sufficient.

Protection of apparatus. It is necessary in practically all cases to protect the generator, by powerful choke-coils or static interrupters, from the strains produced by the static discharge utilized to jump the arrester. It is desirable as well, unless otherwise provided for, to protect the high-tension side of the charging transformer, by means of choke-coils or other apparatus, from a short-circuit due to the condenser discharge across its leads.

Timing the discharge. The production of the exciting spark at the proper time of the cycle may be accomplished by a small synchronous motor driven from the supply and arranged to close the circuit at the proper time, as described in papers by E. E. F. Creighton on " New Principles in the Design of Lightning-Arresters," read at the March meeting, 1907, and " Methods of Testing Protective Apparatus," read at the annual convention, 1906, or it may be accomplished by the swing-switch method already described, in which case a number of trials must be made with each setting of the apparatus to ensure the reaching of the worst condition, since the point within the cycle at which the discharge occurs is largely a matter of accident. From 20 to 50 trials should be made under each condition. This method is preferable to the synchronous-switch method, as so much dependence need not necessarily be placed on the accuracy of the operating mechanism. Oscillograph curves are here, of course, a great safeguard.

Auxiliary Apparatus. It is very desirable in tests of this sort to have an adjustable resistance controlling the flow of current from the generator, which can be cut out gradually until the maximum condition is reached. Such a resistance must be of a very robust and well-insulated character. It is also necessary to have in circuit an entirely reliable circuit-opener of some sort, such as an oil-switch or a fine-wire enclosed fuse. Either arrangement may be made satisfactory.

It is, of course, of interest and value to have oscillograph records of the currents and voltages of the tests, but as this involves a great deal of work in setting up the apparatus and is not wholly necessary, the oscillograms will often be omitted.

It should be noted in testing alternating-current multigap arresters utilizing shunt resistance, that, if when the static discharge is produced at the early part of the cycle, no current follows into shunted gaps; the discharge should be produced at a somewhat later point of the alternation, as this will be more favorable for the initial starting of current in the shunted gaps.

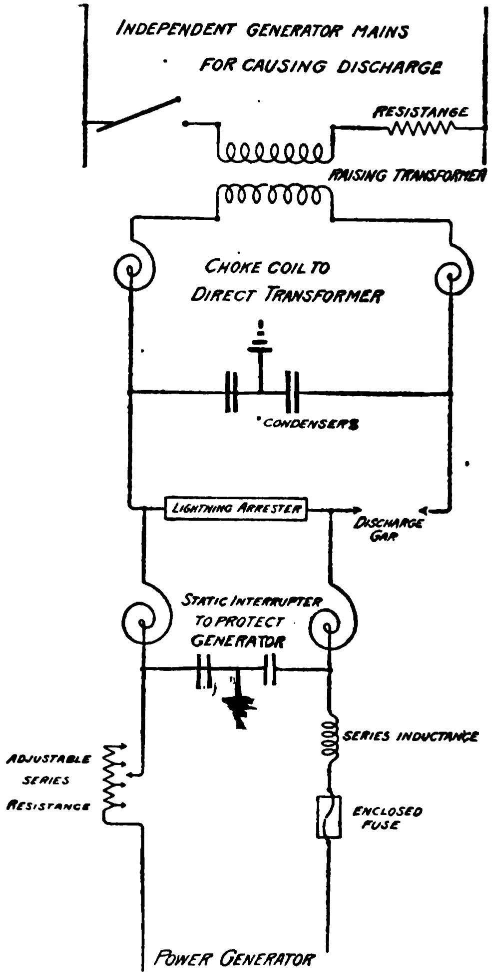

FIG. 3—Diagram of circuits for testing non-arcing power of lightning-arrester

Thus, in the case of shunted gaps the most critical point of the cycle for the discharge is different from what it is in the case of plain series gaps.

One diagram of connections for testing the non-arcing power of arresters is shown in Fig. 3. This is capable of various modifications. Reference is suggested to the various papers above referred to by Mr. Creighton and the writer. The arrangement shown by Mr. Creighton is presumably satisfactory where applicable.

Attention is again called to the fact that except where arresters have an inherent faculty of limiting the flow of current, tests to be of value must be made upon high-capacity generators and circuits; they are then very troublesome to make and involve considerable danger to the generator and other apparatus connected to the test circuit, both from the heavy short-circuits and from static strains. Line choke-coils playing practically no part in the arc-suppressing power are not involved in this test.

Disturbance of operation. When the discharge of an arrester offers a free path for the flow of generator current, the result is the lowering of the line voltage to such an extent as to cause synchronous apparatus to drop out of step, and, in view of the heavy current taken by the arrester, the opening of the circuit-breakers or the blowing of fuses. This is a most serious matter in practical operation and has caused a great many shut-downs. These shut-downs are serious, as the whole system must be started again, including the synchronizing of generators, synchronous motors, and synchronous converters. The critical conditions evidently are the generator current taken during the discharge, and the length of time before its suppression; for example, a current strength which in one alternation would be insufficient to open a circuit-breaker might, if continued for a dozen alternations, cause this result. Arresters which sufficiently limit the generator current following the discharge will cause no disturbance; and arresters suppressing the generator current within an alternation or so will undoubtedly cause no trouble, however great this current. Arresters utilizing series resistance and drawing only a few times full-load current would not be expected to open breakers or throw out synchronous converters; fuse arresters utilizing a small wire-enclosed fuse which open the circuit very quickly are probably safe, but horn arresters and their equivalent will usually disturb the system.

Tests to determine whether or not a definite arrester will in general cause this trouble are impracticable, for the different settings of breakers, the different designs and loads of synchronous apparatus, together with the different location of discharges, will render a general determination out of the question. However, it may often be concluded from general considerations that an arrester cannot even take current enough to disturb the system, or that it is sure to take current enough to cause trouble.

Under specific sets of conditions, as at some particular plant, by selecting the most sensitive condition, it may be determined by trial whether an arrester discharge is likely to cause disturbance of the operation, by repeating the test just described for determining the non-arcing power of arresters. This will, however, usually be considerable of an undertaking and not worth while.

Capacity for frequent discharges. It goes without saying that every arrester should be able to withstand as many successive discharges as it may meet in actual service. Unfortunately, this condition is exceedingly variable and impossible of general determination. High-voltage arresters will presumably discharge much less frequently than will low-voltage arresters, as in the former minor disturbances will not be able to pass to the ground. Furthermore, on alternating-current circuits at least, discharges occurring at one part of a cycle are more severe than discharges occurring at another, which tends to relieve the arrester. Under the conditions in which tests for non-arcing power are feasible, tests to determine the capacity for frequent discharges may be made. The parts particularly subject to deterioration under these conditions are series and shunt resistance, magnet-coils, and the cylinders in multigap arresters.

On low-voltage circuits, direct and alternating, where working conditions are more easily reproduced, such tests are often feasible. On high-tension alternating-current circuits, however, they are not often worth while.

Tests for determining capacity for frequent discharges should be made as already described for determining the non-arcing power of arresters. A number of discharges should be produced in succession at intervals of some seconds, the exact number of repetitions and the intervals being determined according to the circumstances of the case.

Deterioration, etc. There are a number of other characteristics of great importance in the choice of arresters which, however, cannot readily be made a subject of test. Arresters should be robust; the resistances should be of a character not to corrode or otherwise deteriorate with time; they should be as simple as possible and the parts likely to deteriorate should be replaceable.

To require a renewal by hand after a discharge, before an arrester is ready for a second discharge is a serious handicap.

Conclusion. It is evident from the analysis of the advantages, disadvantages, and limitations of the various possible tests of lightning-protective apparatus, that certain tests are of great value in connection with certain types of arresters, but not with all types, and that some of the tests are difficult and awkward to make. It would thus seem that tests should be introduced into the standardization rules cautiously and gradually.

On the other hand, there will be a great advantage in many cases in testing lightning-arrester apparatus; for example, a ready means of correctly sizing up the numerous low-voltage arresters, especially railway arresters, which appear from time to time is desirable. Furthermore, the fact that certain tests have the stamp of approval of the Institute will do much to cause designers to put their apparatus in condition to meet the tests. even if the tests be so inconvenient as rarely or never to be imposed. Again, a careful consideration of a properly chosen set of rules will help materially to give to electrical engineers who have not paid much attention to static phenomena a clear idea of the fundamental conditions to be kept in mind.

The following tests are suggested for general consideration as suitable for the approval of the Institute:

1. In all lightning-arrester design, the insulation strength should be required to stand the abrupt application of the discharge of a condenser of at least 0.01 microfarad capacity, charged to a potential three times normal arrester potential, and not less than 50,000 volts, without sparking between parts or to ground. Where it is inconvenient to get a discharge of this severity, arresters, alternating-current and direct-current, for not over 3,000 volt lines can be roughly tested with a smaller capacity or lower potential, but no tests with capacity less than 0.0025 microfarads or voltage less than 30,000 should be relied upon.

2. Breakdown voltages at normal frequency should be determined in all cases, following, where applicable, all the requirements laid down in the standardization rules for the testing of insulation strength.

On voltages of 40,000 and higher, the test should if possible be made with the arrester installed in position, and in any case with the same relation to surrounding grounded or charged objects as it is to have in final installation.

3. Where general considerations are not sufficient to determine the amount of impedance offered to a discharge, comparative tests between arresters may be made by noting the needle-gap equivalents of two or more arresters, by passing across the arresters separately or in series the discharge of a condenser of a few hundredths microfarad capacity charged to a potential not less than 50,000 volts, or less than three times the normal voltage of the arrester. This test will be of relatively little value with an arrester including series resistance of equivalent characteristic, since the test will show simply the voltage of the discharge in each case. Such comparative tests may be made with smaller capacities and lower voltages, though they will not be as trustworthy.

The impedance offered the discharge should be measured by a needle-point spark-gap in shunt to the terminals of the arrester, and set to take half the discharges. The needle-point gap should be shielded by metal, if near the main discharge-gap.

4. Where general considerations are not sufficient to determine the non-arcing power of an arrester, a test may be made by passing sparks over the arrester when connected to a source of electromotive force of sufficient power to supply, without dropping its potential, all the current which the arrester will take. In no case need a generator power, greater than the maximum to which the arrester is to be subjected, be used. In all cases the maximum series inductance to be found in service must be included in the generator circuit.

With arresters which offer no impedance to the discharge, such as the horn type, the fuse arrester, and the multigap arrester without series resistance, etc., reliable tests can be made only on the maximum generator power to which the arresters are to be exposed.

Non-arcing tests are difficult and dangerous for apparatus in all cases except where the generator current is strictly limited. The testing apparatus should be protected both from the static discharge and from the effects of the short-circuits.

5. Endurance tests may be made in the same manner as tests of non-arcing power. The discharges should be repeated at intervals of some seconds. The exact interval and continuance of test must be a matter of judgment in each individual case.

This test is especially useful and feasible in connection with low-voltage arresters, such as direct-current railway types.

6. In addition to the behavior of arresters under the above tests, other features should receive consideration; for example, the disturbance of normal operation caused by a discharge, robustness and permanency, simplicity, whether or not replacement is required after a discharge, etc.

As the only final test of a lightning arrester is actual experience extending over considerable time and repeated in many places under different conditions, no general conclusions should be drawn from short-time trials. Such a determination usually requiring years, the considerations and tests enumerated above are of great practical value in determining the relative merits of different types of apparatus.

APPENDIX I

The reasons for concluding that very high frequencies do not have to be considered in the protection of commercial lines may well be somewhat elaborated. Since the quality which renders the discharge of a static surge of a given magnitude exceptionally difficult is very great abruptness, that is, very sudden arrival of charge, we should here consider not strictly the frequency of discharges, but rather the form of the initial wave-front. Strictly speaking, the term frequency is applicable only where there is an oscillating current or potential. The term abruptness of discharge is more generally applicable. This abruptness of charging depends upon the time required for a given point to pass from normal to a given abnormal potential. This time is especially short with very high charging potential and low inductance in the charging path.

Every lightning-arrester has some capacity; so have the line wire outlets, insulator tie-wires, and every conductor or patrol conductor connected with the line. Consequently, to raise the potential at the lightning-arrester discharge-gap to a dangerous point, a certain amount of charge is required. Since this charge is transmitted to the arrester by the line wires, there will be a minimum length of wire which will be sufficient to store charge enough to cause this rise of potential. Such a value as ten feet of line wire would seem to be very conservative as the minimum limit of capacity which could store sufficient energy to produce material strain. The capacity of two transmission wires, 10 feet long, is approximately 1.5×10^{-5} microfarads. It is hard to imagine a possible case in which such a length of wire can be abruptly charged through a path having less inductance than that of 5 feet of such a transmission wire, which will be about 4×10^{-6} henrys. Consequently, since the time of the complete discharge period of a condenser through an inductance is $= 2\pi\sqrt{C L}$, in which expression capacity may be farads and inductance henrys, the frequency of discharge of this condenser through this inductance will be approximately 20,000,000, per second. This is presumably the maximum frequency which need ever be considered in a transmission line, and even this is probably too high.

The only conclusion to be drawn from the above is that in a general way we may neglect the effects of any disturbances having a higher frequency than a few million periods per second. It is of course true, however, that, since the inductance and capacity of the transmission line is distributed, the above formula cannot be applied directly thereto. The true results will not differ radically from those derived by the assumptions made. As further reducing the probability of harmful effects being produced by very high frequencies, it should be noted that every irregularity of form, every insulated tie-wire, every branch connection of any kind, or leakage into air over insulators, and any current set up in other conductors, tend, especially with very high frequency, further to break up an advancing wave and also to dissipate its energy.

A few outer turns of a transformer winding have a large enough electrostatic capacity to be of very material moment in keeping down potential rises from very high-frequency discharges; for example, consider the outside layer of a transformer coil, which may be taken as three-fourths of an inch wide. Such a transformer as would be connected to a high-tension transmission line would have perhaps a mean length of turn of six feet, giving an exposed area on the top and edges of the first layer of about 75 square inches. The mean distance of such a layer from grounded objects, or objects acting as though grounded for the necessary brief instant of time, would be not far from two inches in a high-tension transformer. The specific inductive capacity of the insulating material is at least three, giving a capacity of 2.5×10^{-5} microfarads. This is equal to about 10 or 15 feet of transmission line. This estimate is probably very much too low, since, if the frequency is high enough so that only the first layer is affected, the next layer or two will act as though grounded and will increase the capacity of the first layer ten or twenty times. In other words, as far as the protection of transformers from ground is concerned, there must be a very considerable volume of charge at high potential passed into the winding before a jump to ground will result. The immediate leads of the transformer are presumably protected by this capacity, and indeed they add some capacity of their own. On the other hand, station wiring gets no benefit therefrom, when the transformers are disconnected.

In general, then, in view of the fact that there must be in all commercial lines at or near the arrester a certain minimum capacity, which in a general way for the purpose of discussion may be assumed as at least equal to 10 or 15 feet of transmission line, no disturbances involving a materially less capacity can cause serious damage. Consequently, no higher frequencies than can occur in connection with the minimum capacity need be considered in lightning-arrester work. This frequency will probably not exceed a few million per second. The same general line of reasoning applies to low-tension line wires. With these, the values of electrostatic capacity and all leakage factors are greater than for high-tension lines.

APPENDIX II

There are certain limitations in the severity and possible forms of discharges from commercial transmission lines which are important in considering the impedance offered to discharges by various designs of arresters.

The exact maximum electrostatic capacity that can ever, in a commercial circuit, be so located as to be abruptly discharged through a lightning-arrester is very difficult to estimate accurately. The conditions of the test recommended for measuring the impedance to discharge of an arrester are very severe, more severe probably than are likely to be met with in practice, for the following reason: In the test recommended, the total charge of the condenser is passed directly against the arrester through only the impedance of a few feet of wiring. In an actual transmission plant, there can be connected so closely to the discharge path of the arrester only 100 or 200 feet of line and at most a few high-tension transformers. This capacity will be increased somewhat by tie-wires, insulator surfaces, bushings, outlets, etc. Taking these things together, however, the capacity within a few feet's discharge of the arrester will fall far short of a hundredth of a microfarad. On the other hand, there may be in the immediate neighborhood a capacity considerably larger than this amount. Such excess of capacity, however, must discharge through some tens or hundreds of feet of transmission line, which will very much reduce its severity on the arrester discharge.

Neglecting the concentrated capacity closely adjacent to the arrester, which has already been described as limited to a quantity presumably much less than a hundredth of a microfarad, the current passing from the transmission line proper may be likened to the discharge of water from a long uniform trough. If such a trough filled with water be allowed to discharge by the opening of one end, there will be a sudden rush as the water accumulated at this end passes out, but this rush will be immediately followed by a steady stream of water of practically uniform section while the trough empties itself. The rate of flow at the outlet once established on this steady basis will not change materially until after the " falling " wave which passes backward reaches the end of the trough and is reflected again toward the outlet. Similarly, with the transmission line; assuming it to be charged to a very high potential and the discharge to start at one end over an arrester, there will be an initial rush of the charge stored in the immediate neighborhood of the arrester (this would include that stored in bushings, transformers, branch wires, etc.), but when once this charge, which is limited in amount by the conditions already stated, has once passed, further charge will flow out of the line through the arrester at a more or less uniform rate which is determined by the relative inductance and capacity of the transmission line, but which thus produces no steadily increasing demand on the discharge capacity of the arrester. If, instead of the whole transmission line being charged to this high potential, the disturbance be one of high frequency, this is equivalent simply to shortening the trough of water or the transmission line and will relieve the arrester so much the more easily.

Evidently, an arrester which discharges somewhat slowly will have a harder task to perform, since the distance of the farthest charge which can discharge directly through the arrester on the initial breakdown without material opposition from line inductance will extend to a greater distance; for example, an arrester with series resistance will be more likely to receive an absolute direct discharge from as great a capacity as a hundredth of a microfarad, than will a fuse-type arrester.

Even in the severe condition in which a direct stroke of lightning reaches the transmission wire at 1000 feet from the arrester, a similar limitation exists, since all charge, above that necessary to bring the potential of the line wire to the point of breaking to earth from the line over insulators, is discharged directly to ground, and, as before, we have only the charge on the transmission wire to be discharged over the arrester. There is, however, one exception; namely, when the lightning stroke is continuous for some relatively considerable period of time, in which there will be a transfer of current over the line wire through the arrester to ground, not in the form of a wave or surge (relying on the distributed inductance capacity for its transmission), but as an ordinary current in a conductor governed by the impedance of the line. In this case, the effect of the inductance of the line and the arrester discharge path will soon disappear leaving the resistance of the line and of the arrester to withstand the voltage of the discharge. How common such a condition is at the present time is a mere matter of speculation.

Mr. R. P. Jackson, in his paper of last December on "Recent Investigation of Lightning Protective Apparatus," called attention to the fact that there is a limit to the amount of discharge current which can be obtained from the electrostatic capacity of a transmission wire at a definite voltage regardless of the length of the line.

It may be thus concluded that there is a surprisingly low limit to the severity of the discharge which an arrester can be called upon to discharge from a transmission line, and it is the opinion of the writer that the "several hundredths of a microfarad" recommended by this paper in the test for measuring the impedance offered to discharges is justifiable principally to give a margin of safety and to provide in the most practical available manner for the fact that the actual arrester will have to discharge lines charged to a considerably higher potential than that of the test, which, of course, renders the condition more severe.

The writer wishes to take this opportunity to make the plea that it would be far better in discussing lightning-arrester problems to avoid expatiating upon what we do not know and cannot know about lightning, and statements to the effect that the conditions are infinitely various and incomprehensible; and to make a serious effort to determine and explain such limitations and facts as we may know and can determine from known laws and from experience. If this be done, the subject would lose most of its mystery; operating engineers would be able coherently and intelligently to observe and judge by what they see, and the advancement of lightning-protection would be very much facilitated.

APPENDIX III

Various papers bearing upon the reaction of lightning on transmission lines, and of the various characteristics and performances of lightning-arresters for light and power circuits have appeared from time to time in the TRANSACTIONS AND PROCEEDINGS of the American Institute of Electrical Engineers. For convenience they are here enumerated.

" Lightning Arresters and the Photographic Study of Self-induction." E. G. Acheson. Vol. VI, 1889.

" Some Possible Modifications in the Methods of Protecting Buildings from Lightning." N. D. C. Hodges. Vol. VIII, 1891.

"Lightning Arresters and the Discovery of Non-arcing Metals." Alex. J. Wurts. Vol. IX, 1892.

" Discriminating Lightning Arresters and Recent Progress in Means for Protection against Lightning." Alex. J. Wurts. Vol. XI, 1894.

" Theoretical Investigation of Some Oscillations of Extremely High Potential in Alternating-High-Potential Transmissions." Chas. P. Steinmetz. Vol. XVIII, 1901.

" Static Strains in High-Tension Circuits and the Protection of Apparatus." Percy H. Thomas. Vol. XIX, 1902.

" The Function of Shunt and Series Resistance in Lightning Arresters." Percy H. Thomas. Vol. XIX, 1902.

"The Grounded Wire as a Protection against Lightning." Ralph D. Mershon. Vol. XXII, 1903.

"Safeguards and Regulations in Operation of Overhead Distributing Systems." W. C. L. Eglin. Vol. XXII, 1903.

"Protection of Cables from Arcs Due to the Failure of Adjacent Cables." W. G. Carlton. Vol. XXIII, 1904.

"The Protection of High Pressure Transmission Lines from Static Discharges." H. C. Wirt. Vol. XXIII, 1904.

"High-Power Surges in Electric Distribution Systems of Great Magnitude." Chas. P. Steinmetz. Vol. XXIV, 1905.

"An Experimental Study of the Rise of Potential in Commercial Transmission Lines Due to Static Disturbances Caused by Switching, Grounding, etc." Percy H. Thomas. Vol. XXIV, 1905.

"Some Experiences with Lightning Protective Apparatus." Julian C. Smith. Vol. XXIV, 1905.

"Notes on Lightning Arresters on Italian High-tension Transmission Lines." Philip Torchio. Vol. XXIV, 1905.

"Performance of Lightning Arresters on Transmission Lines." N. J. Neall. Vol. XXIV, 1905.

"Some Experiences with Lightning and Static Strains on a 33,000-Volt Transmission System." Farley Osgood. Vol. XXV, 1906.

"Methods of Testing Protective Apparatus." E. E. F. Creighton. Vol. XXV, 1906.

"Protective Apparatus for Lightning and Static Strains." H. C. Wirt. Vol. XXV, 1906.

"Recent Investigation of Lightning Protective Apparatus." R. P. Jackson. Vol. XXV, 1906.

"Lightning Phenomena in Electric Circuits." Chas. P. Steinmetz. Vol. XXVI, 1907.

"Protection against Lightning, and the Multigap Lightning Arrester." D. B. Rushmore and D. Dubois. Vol. XXVI, 1907.

"New Principles in the Design of Lightning Arresters." E. E. F. Creighton. Vol. XXVI, 1907.

"Notes on Hydroelectric Plant Organization and Operation." Farley Osgood. Vol. XXVI, 1907.

"Potential Stresses as Affected by Overhead Conductors." R. P. Jackson. Vol. XXVI, 1907.

CURVES OF THE NON-ARCING POWER OF MULTIGAP LIGHTNING-ARRESTERS AND THE SHUNTING POWER OF OHMIC RESISTANCE.

These curves and descriptive data are supplementary to a paper by the writer read before the annual convention of the American Institute of Electrical Engineers in June, 1902, and entitled, "The Function of Shunt and Series Resistance in Lightning Arresters." In the original paper, the principal conditions governing the non-arcing power of multigap arresters on constant potential alternating-current circuits were discussed. The results from which these conditions were determined had been plotted in the form of a series of curves which were not at that time published. These curves, which are the result of a very large number of tests at several voltages and on various circuits, are here reproduced.

These curves although not to be interpreted with minute accuracy, which would be out of the question in work of this character, are believed to be thoroughly reliable under general commercial conditions. They are, of course, not of absolutely general applicability, since, for example, practically all the tests were made with gaps at or near one-thirty-second of an inch, and would presumably not hold closely for widely different lengths of gap; also, the curve showing the shunting power of ohmic resistance is plotted on the assumption that the number of series and shunt-gaps is approximately the same. There are, however, so far as the writer is aware, no limitations such as have just been mentioned, which are not clearly stated either in connection with the curves themselves or in the original paper referred to.

It is expected that these curves will be of interest in connection with the papers, to be presented concurrently herewith, on the subject of the testing of lightning-arresters.

The general method of making these tests is fully described in the original paper, and consisted in passing static sparks repeatedly, at instants of time determined by chance, across a series of gaps which were connected to a generating system including resistance and inductance where necessary, so that a known current would flow through a known inductance upon short-circuit. The number of gaps was varied in repeated trials until it was determined how many would always suppress the arc following a static discharge, and also what was the greatest number of gaps which could be made to fail. Similarly with the shunting power of resistance. With known conditions of short-circuit current from the generator, static discharges were passed repeatedly until both the condition of failure and the condition of minimum successful operation were obtained.

The tests on 12,500- and 25,000-volt circuits were made on one or two generators of 5,000 h.p. capacity and having an exceptionally large flywheel capacity. It will be noted in the curves that free short-circuit currents were not taken from the generators. The currents actually used were, however, increased up to the point where burning of the cylinders became a limiting factor for commercial work. It is obvious from the form of the curves that larger currents flowing from the generator would greatly reduce the non-arcing power of the gaps and ultimately eliminate it.

It may be stated that a line of lightning-arresters adapted to all voltages from 2,500 to 50,000 has been designed from these curves. In some five or six years of operation, so far as the writer knows, they have never shown any failure to suppress the generator arc. In a very few instances, where by some accidental means a portion of the gaps has been cut out or a part of the resistance short-circuited, trouble has occurred, but this cannot be considered a failure of the arrester to be non-arcing.

Fig. 1 shows a number of one-thirty-second-of-an-inch gaps necessary to suppress the generator arc under the worst condition of static discharge with different initial short-circuit amperes, with different amounts of inductance in the generator circuit, and applies to circuits of 2,500 volts, 3,000 alternations. Each curve is for a definite inductance.

On 2,500-volt circuits, the non-arcing power is nearly inversely proportional to the initial current up to 500 or 600 amperes, with a low inductance.

Fig. 2 shows similar curves fo a 4,800-volt circuit, both at 3,000 and 7,200 alternations with various inductances.

On 4,800-volt circuits, the non-arcing power is still nearly inversely proportional to the initial current, especially with low values of inductance. The increase of the inductance makes an enormous decrease of non-arcing power.

Fig. 3 shows similar curves for 12,500-volt circuits, at 3,000 alternations. It should be noted in this figure that the very high values of inductance cause an enormous decrease in the arc-suppressing power of the cylinders. This shows how little can be determined as to the non-arcing power of a given arrester arrangement without a knowledge of the inductance in the circuit. It will also be noted in this figure that in general the curves bend up more sharply than before, showing that the

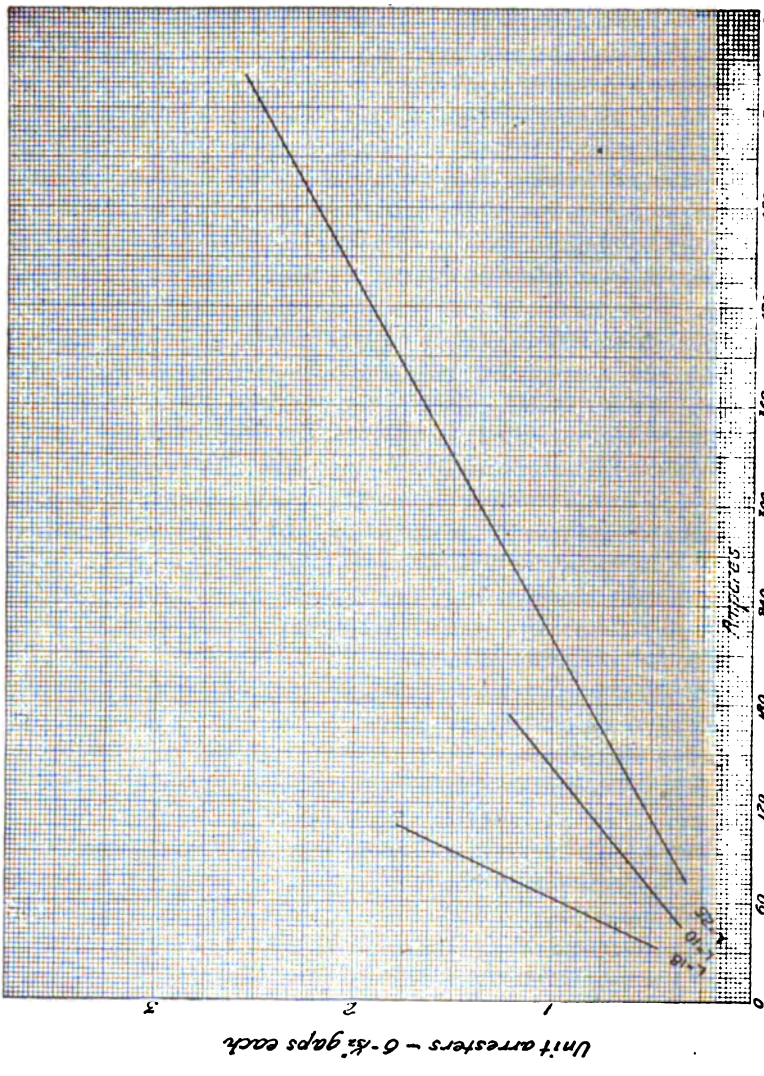

FIG. 1—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 2,500 volts, 3,000 alternations

high tension brings in a condition which is very exacting on the arc-suppressing power of the arresters.

On 12,500-volt circuits, the effect of the usual amounts of inductance found in commercial circuits becomes more important, and the non-arcing power drops and begins to decrease more rapidly than the initial current increases.

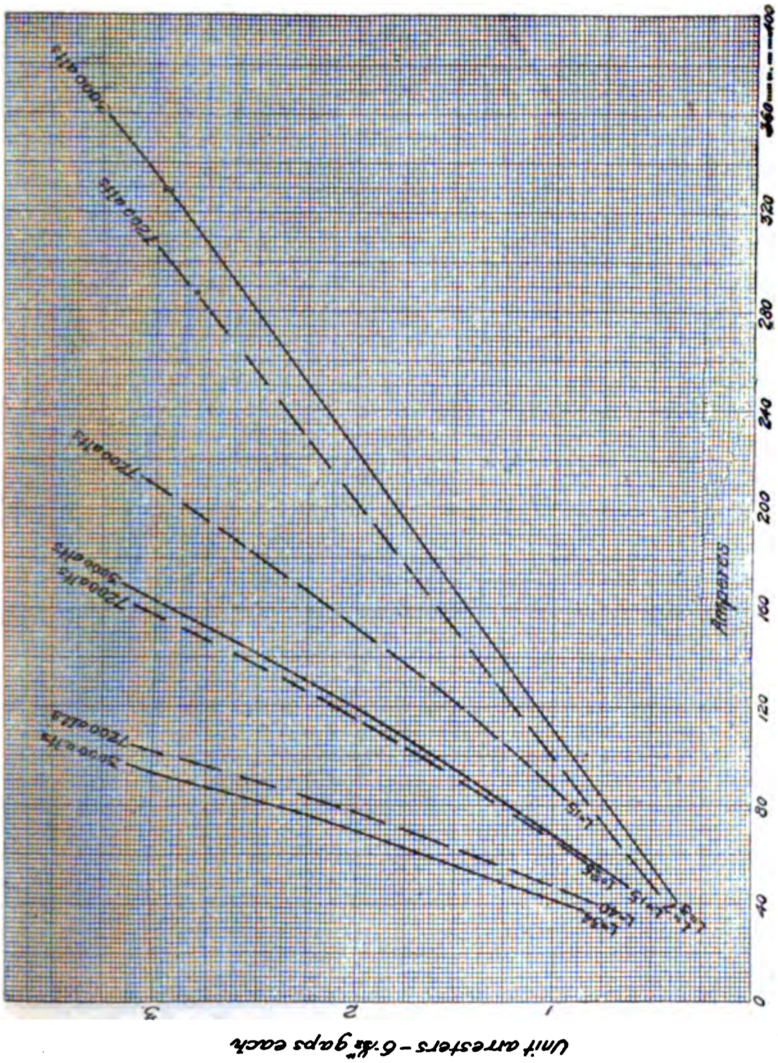

FIG. 2—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 4,800 volts, 3,000 and 7,200 alternations

Fig. 4 is similar to Fig. 3, except that the curves are for 25,000 volts and 3,000 alternations. In this figure, the tendency of the curves to bend upward is much more marked than in Fig. 3. In other words, the limitation of the initial short-circuit current is much more necessary in high-tension circuits than in low-tension circuits.

On 25,000-volt circuits the non-arcing power drops still lower on account of the predominance of the inductance of the circuit, and becomes nearly inversely proportional to the square of the initial current. The necessity of some resistance in such a circuit is very evident.

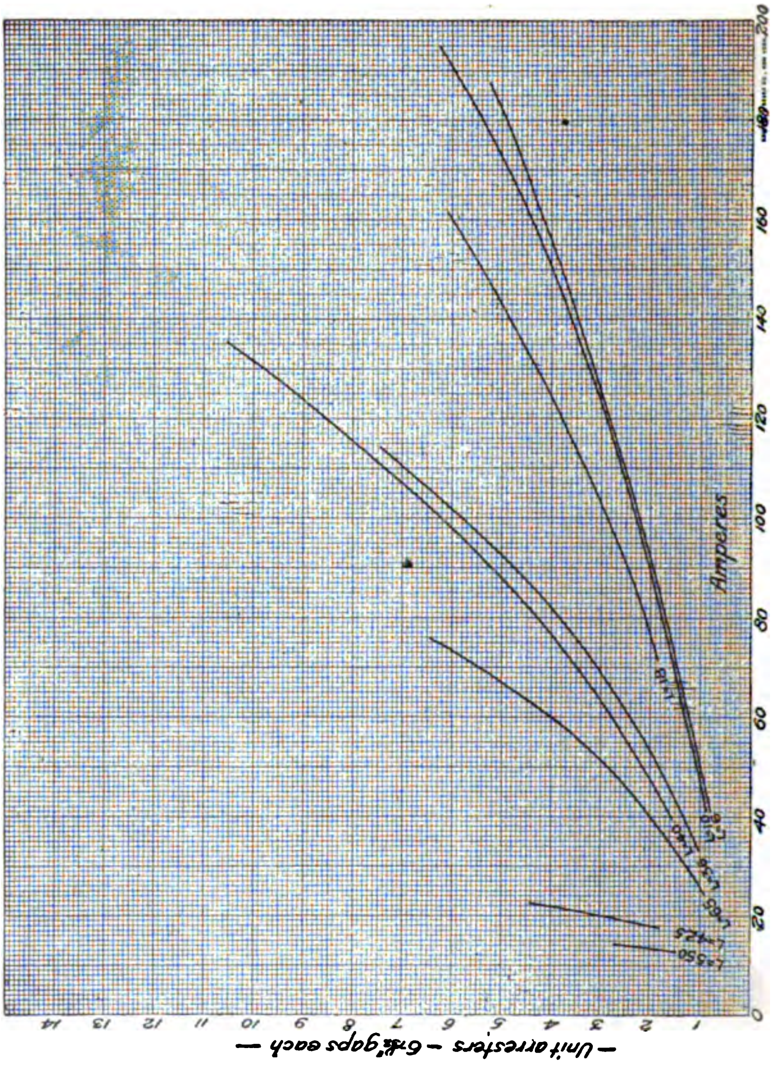

Fig. 3—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 12,500 volts, 3,000 alternations

Fig. 5 shows for different initial short-circuit currents in the series gaps of a combination of series and shunted gaps with shunt resistance, the number of ohms per shunted gap which will just cause a dropping out of the arc in the shunted gaps. It will be noted that this value varies enormously with the initial short-circuit current, and that, for currents over perhaps 200 amperes, there is little or no shunting power for any useful value

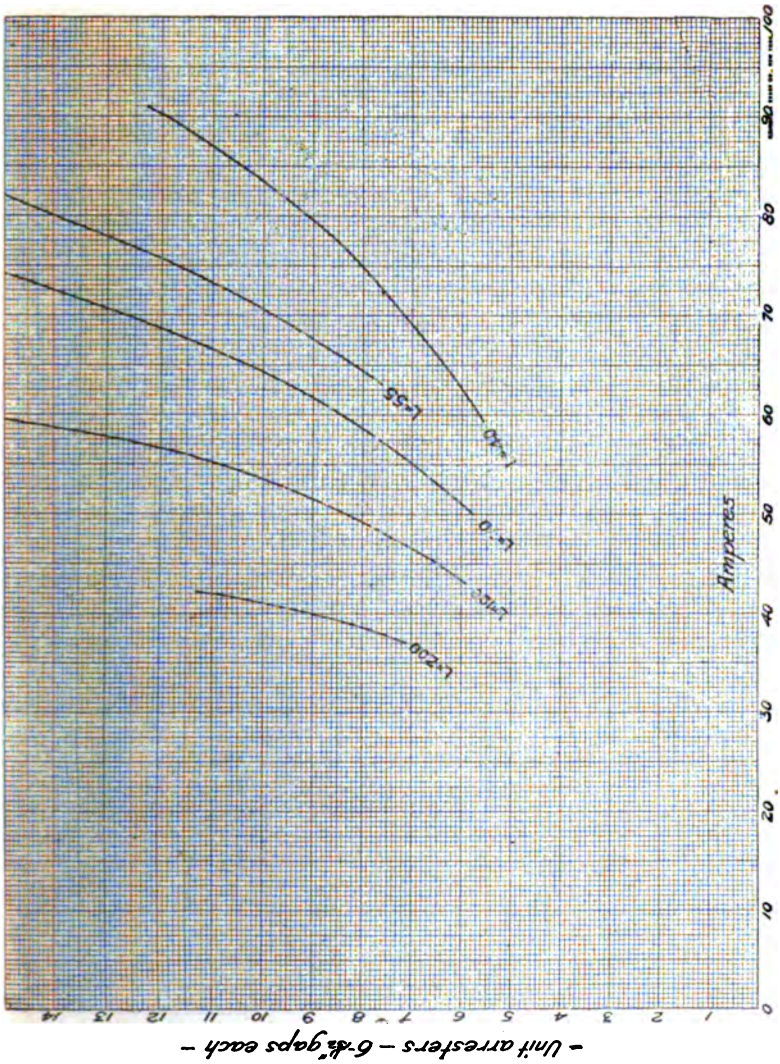

Fig. 4—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 25,000 volts, 3,000 alternations

of shunt resistance. The gaps are as before one thirty-second of an inch, between Wurts's non-arcing metal knurled cylinders. The number of shunted gaps is always equal to the number of series gaps.

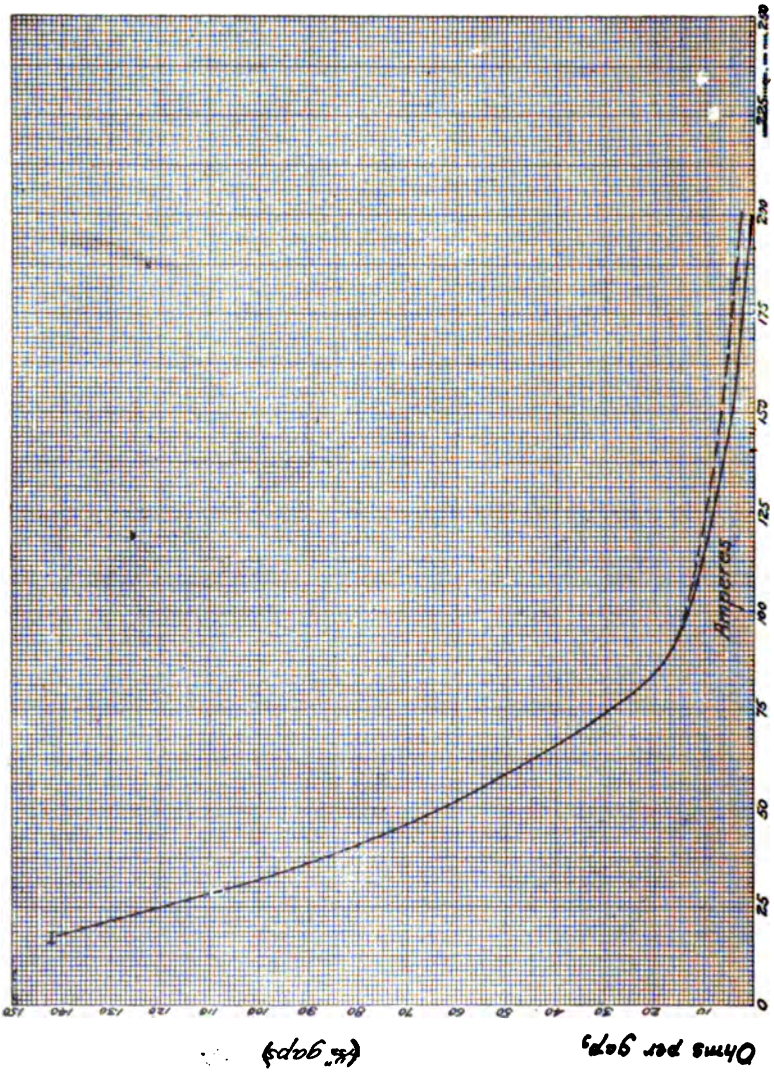

FIG. 5—Shunting power of shunt resistance. Maximum ohms per gap able to withdraw the generator arc from the shunted gaps with various initial short-circuit currents. Number of series gaps equals number of shunted gaps

For instance, with 25 amperes initial current a resistance of 120 ohms will just withdraw the current for the shunted gaps while with 175 amperes only from 2 to 5 ohms may be used, according to conditions.

The value of a given number of ohms per gap with a given short-circuit current is not entirely independent of the total voltage on the circuit of the inductance, etc., but is affected by these characteristics only to a minor degree. With high currents on low voltages, such as 2,500 volts, the shunting power is somewhat higher than with the higher voltages.

In estimates of the non-arcing power of arrester arrangements on various circuits, the initial short-circuit current is the dominating factor and the method of calculation becomes of importance. In these curves this current is calculated from the generated voltage of the supply, taking into account the total ohmic resistance in circuit, including rheostats, lines, and armature windings, the inductance of all coils introduced, the inductance of the line and of the armature, together with the estimated field reaction of the current in each case. It is assumed that the resistance of the arresters during discharge was practically zero. This method is not absolutely accurate, partly because the gaps have some resistance, partly because an accurate determination of the armature impedance and field reaction of the generator is difficult to make, and for other reasons. But this method does give values of current dependent upon the essential determining factors and is undoubtedly sufficiently accurate for all practical purposes. Of course, in using the data of the curves for other circuits, calculations should be made according to the same methods.

Reference to the writer's original paper on this subject is suggested for a description of the method of design of a non-arcing arrester for a given system from the basis of these curves.

A discussion of multiple shunt resistance will be found in papers by E. E. F. Creighton and by D. B. Rushmore and D. Dubois in Vol. XXVI of the TRANSACTIONS of the American Institute of Electrical Engineers, 1907.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

A PROPOSED LIGHTNING-ARRESTER TEST

BY N. J. NEALL

It is generally recognized that the worst disturbances to an electrical transmission system from lightning are due to the unbalancing of the circuit-elements after the passage of the initial lightning charge to ground.

In the development of lightning-arresters, provision must be made not only to discharge freely any atmospheric disturbances which take place near by, but to prevent as far as possible any short-circuit on the system which might thereby arise, should two legs of the line be simultaneously discharged. From this it follows that lightning-arresters, in the very act of relieving the line, introduce other conditions of potentially great destructiveness, such as short-circuits, sudden grounds, and oscillations.

Since it is impossible to predict where any given lightning disturbance will arise on a transmission line, the assumption is made here that this is ordinarily of no consequence, if it is not at the lightning protective apparatus. Any source of disturbance other than lightning which causes the lightning-arresters to operate may, however, properly be included here.

Fig. 1 shows the elements of the test. A spark from an induction-coil is made to pass over all the gaps of the lightning-arresters under test. This forms a bridge for either a short-circuit by line current (provided two legs of the line are simultaneously discharged) or for the passage of charging current from the stored capacity of the system, as the case may be.

The apparatus required consists of an induction-coil operated from several cells of a storage-battery by means of a mechanical vibrator. A small switch in series therewith enables the discharge to be controlled at will. A condenser is placed in series with each terminal of the induction-coil, the one being grounded and the other being led through spark-gaps to such a point of the series of the lightning-arrester gaps that the spark from the coil will divide and pass over them simultaneously in the direction of line and ground respectively.

Special gaps should be inserted in the induction-coil spark-circuit before connecting to the arrester under test to prevent a decrease in insulation strength to ground of the arrester itself.*

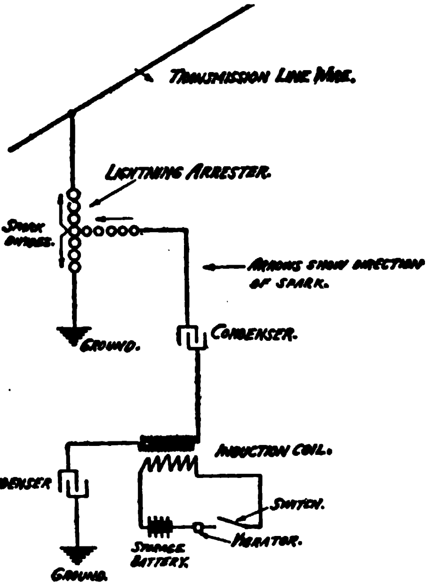

Fig. 1.
Shows Principle of Test.

Figs. 2, 3, 4 and 5 are self-explanatory.

It will be seen from the diagrams that the required insulation strength of the condensers, thus used in testing any polyphase system, is only half the nominal voltage between legs, for two condensers are always in series. Thus, for a test of a 50,000-volt line only 25,000-volt condensers are required.

With the exception of several laboratory tests, made first in

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*See Ingram, *Elec. Journal* Vol. IV, No. 4.

Minneapolis in September, 1906, on a 2300-volt circuit to prove the elements of the method, no trials have been made of this method on transmission lines. There is no apparent reason why it should not be used, save that, when the possibilities of the method are realized, most transmission operators will undoubtedly be afraid to try it lest it may demonstrate itself too successfully.

There are undoubtedly plants in this country, and perhaps abroad, whose operators would be glad to avail themselves of any

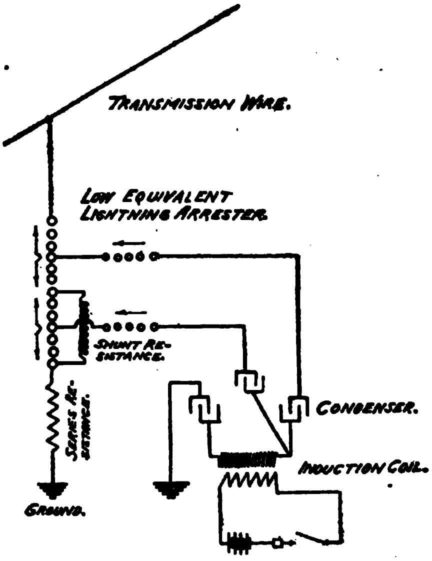

FIG. 2.

SHOWS SPECIAL APPLICATION OF PRINCIPLE TO LOW EQUIVALENT LIGHTNING ARRESTER FOR INITIAL DISCHARGE OVER ALL GAPS.

such method of generating their own "lightning"—to employ a late application of this term—and the ideas contained herein are therefore presented with the hope that they may pave the way to increased knowledge of lightning disturbances and protection against them.

The following ideas have been suggested in this connection:

1. The apparatus must be adjusted in size and connection to individual requirements.
2. The effect of a disturbance can be measured positively by

the simultaneous use of tell-tale papers at all known points where discharges take place to ground.

3. The tests may be varied to suit any requirements; namely, short-circuits, grounding, phase to phase, etc.; and may be made simultaneously at extreme points of a line with duplicate test sets, if desired.

The following characteristics have been noted, and should be allowed for:

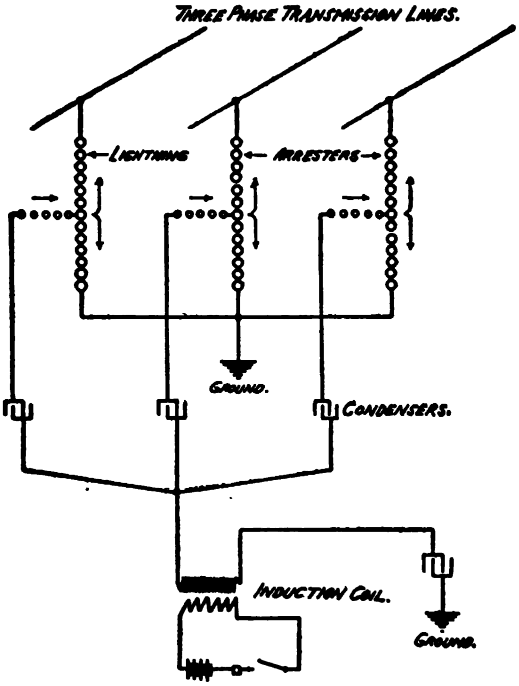

Fig. 3.

Shows Method of Connection for Testing Lightning Arrester Groups on Three Phase Systems.

1. The coil must give a fat spark of considerable length. Such a coil as is used in wireless telegraphy is well suited to this.

2. The condensers need not be of great capacity. They may be of heavy glass coated with tin-foil and immersed in oil in stone jars.

3. There is apparently a definite limit to the number of gaps over which line voltage will break simultaneously with a given

static discharge. This has been noted in several cases and is quite marked. Any increase in the number of gaps, while apparently not affecting the spark, will prevent the arc.

4. Cells of storage battery permit the set to become portable, and thus enable field tests easily to be made.

5. The apparatus may be made quite rugged. In case of high voltage, the exciting-circuit knife-switch may be opened and closed by an insulating handle to protect the operator against possible break-down of insulation between line and ground.

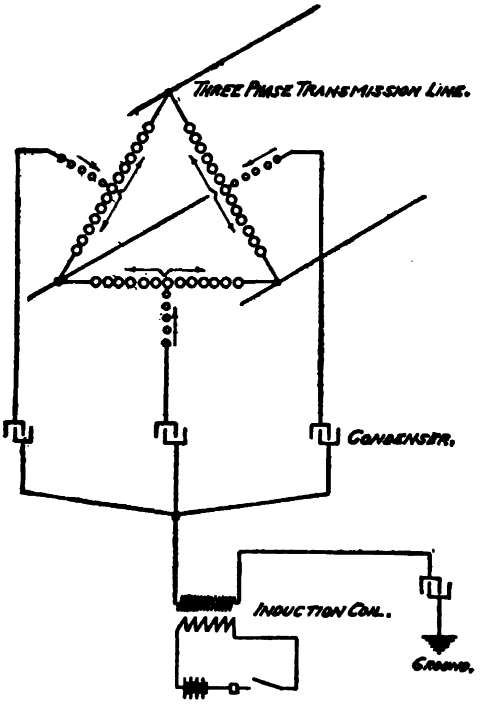

Fig. 4.
Showing a Suggested Method of Testing Phase to Phase.

6. The advantage in this method lies in its readiness for operation when required, its simplicity, and the fact that the induction-coil spark does not coat the cylinders or gaps with any metallic fumes.

7. It may be used for any lightning protective apparatus consisting of air-gaps between line and ground.

8. It is a method of as great value to the operator of the line as it is to the manufacturer of lightning-arresters, because it gives him the best possible method of determining how successful the lightning apparatus is in meeting the demands which he deliberately produces.

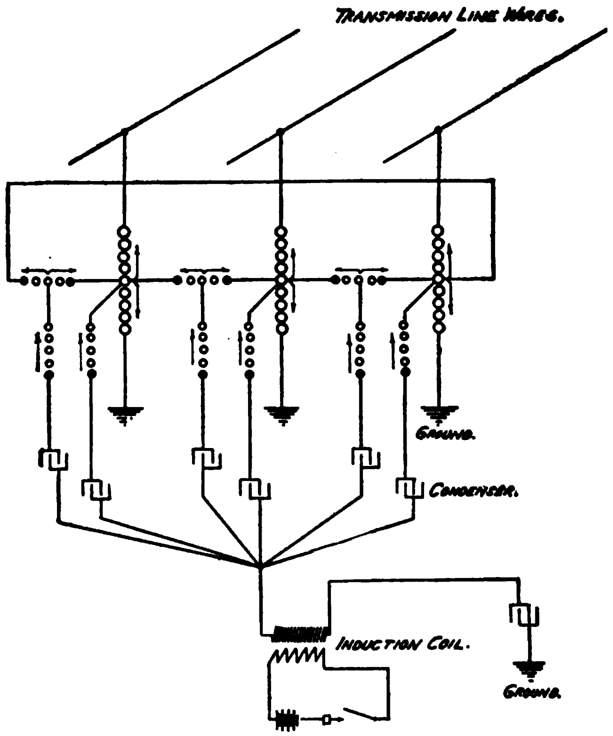

FIG. 5.

SHOWS A SUGGESTED METHOD OF TESTING THE MULTIPLEX PRINCIPLE ON A THREE PHASE SYSTEM.

9. Its intrinsic value rests on the importance of knowing as far as possible how great these disturbances may be, how efficient any given system of protective apparatus is to handle them, and of discovering to what degree any given transmission system contains in itself elements of length, arrangement, and character of apparatus tending to prolong or increase the disturbances once initiated.

DISCUSSION ON "LIGHTNING-ARRESTERS", AT NIAGARA FALLS, N. Y., JUNE 25, 1907

E. E. F. Creighton: I agree with Mr. Thomas on the main features of his paper, but disagree in regard to a few minor clauses, relating particularly to the equivalent spark gap. I wish to express my appreciation of the work he has done in the latter part of his paper in determining the number of gaps to obtain non-arcing conditions. I think that Mr. Thomas' test is more favorable to the arrester than it should be, for we can not make the test in the laboratory too severe. This statement is based on the arguments already given in my paper, on the variations in frequency that can occur on the line and the variations in potential of lightning itself. These factors can not be regulated further than slightly to diminish them by putting an overhead ground-wire above the line; therefore any arrester, no matter whether for low-potential or high potential, should be built to withstand any potential or frequency of lighting, and any duration if it is designed for continuous lightning.

Has Mr. Neall ever attempted to get a discharge from an induction coil over a large number of gaps? This discharge from the induction coil over the multigap corresponds to the half-wave test published in the March PROCEEDINGS 1906. The half-wave test on the multigap arresters shows that it gives an exceedingly high equivalent needle-gap. That has been the basis of our design for this year, for multigap arresters, to reduce this effect. This half-wave test corresponds presumably to the portion of the low-frequency surge on the line, and we have been enabled so far to spark from ground every few minutes by the induction coil. I have a great many tests of that kind, and shall be glad to publish them later. I ask Mr. Neall if he assumed a sparking over, and by what means he has been able to get over a great many gaps.

N. J. Neall: Without knowing what Mr. Thomas would set forth in his paper, I find that I could take paragraph 4 of his recommendations as a basis for the contribution to the Institute which I make this evening.

It is safe to say that the commercial testing of lightning-arresters to-day by the manufacturers is not carried much beyond 2500 volts in the factories, or above 25,000 volts in practice. The long term of years during which 25,000-volt lightning-arresters have now been in service has enabled arresters up to this voltage to become fairly satisfactory. But for voltages above this it is perfectly safe to assert that no manufacturing company to-day could make any such tests on lightning-arresters as have been stipulated by Professor Creighton and Mr. Thomas. One of the reasons for this is the large apparatus required, its costliness, and the difficulty of placing it in the factory, where it would hold up considerable work going through for customers.

It was for this reason that last year the method which I have proposed was devised in order that a collection of various well-known forms of lightning protective apparatus for station and for line service might be given a service test to determine their true merits. The principle of the test consists in passing a static discharge over the gaps of the lightning-arrester in such a way as to form a path for either a passage to ground of the stored capacity of the system or for such short-circuits as may be desired.

Those of us who are familiar with the practices of wireless telegraphy will recognize in the method a form which has been employed in that connection, but until I discussed the proposed test with Professor Reginald Fessenden in another connection, I was not aware that such was the case. I believe, however, that the application in this instance is original with me.

I would lay particular emphasis upon the opportunity which this test will now give the operator as well as the manufacturer to test out the arresters in practice, and for this reason I cannot too heartily urge the cooperation of the manufacturer and the operator to the end that more positive information be obtained as to lightning protective apparatus operation.

Chas. P Steinmetz: Professor Creighton's paper is essentially positive. He discusses all those tests which it is desirable to make on lightning protective apparatus so as to assure their satisfactory operation, their operativeness as far as our present knowledge of lightning phenomena goes Mr. Thomas' paper shows us what tests we should make, tests that are very difficult to make, and in many cases almost impossible except with special facilities.

I believe the conclusion to be drawn from these two papers is that the testing of a lightning-arrester is not the same as the testing of other electrical apparatus Other apparatus can be tested before the customer and approved, but with the lightning-arrester it is essentially a test of a type to be made on one or a few samples of the arrester, to show whether it—or rather a duplicate of it—will probably be able to cope with the lightning phenomena. After carrying out all of these tests, for instance to determine the limits of the discharge capacity, there will probably be not much left of that particular lightning-arrester. Hence the testing of the lightning-arresters is somewhat similar to that of incandescent lamps. Incandescent lamps cannot be completely tested for life without destruction, and only a certain small percentage of the product is tested, and the rest judged by the performance of the tested (and destroyed) percentage.

The first attempt to test lightning-arresters similar to standard apparatus is given in Mr. Neall's paper. Naturally, such a test is to some extent rather dangerous to the arrester as well as to the system. It is the starting of a discharge of an induction coil. If, instead of a vibrator operating the induction coil, we operate it by a Wehnelt interrupter, or substitute in its place a

Tesla transformer to set off the discharge, it gives a very good way of testing the endurance of the arrester for the recurrent surge as described by Professor Creighton. That means that in all probability in the case of all the commercial arresters at present in use it would be from a few minutes to a few seconds before they would go up in conflagration, because most arresters are built to cope with transitory surge oscillations, transient discharges, and not with recurrent surges. This method of testing by sending a single impulse through by closing the switch of the Ruhmkoff coil, and immediately opening it, will give a single discharge or a few successive discharges, but by closing the switch and keeping it closed, with the rapidly operating induction coil or Tesla transformer, it will give a recurrent surge such as is met with in practice with a spark discharge between the cable conductor and the cable armor, or with the spark discharge from an isolated transmission line to ground through a broken insulator.

Such a recurrent surge as we know now is not taken care of by most types of lightning-arrester, but requires additional protective devices, as explained by Professor Creighton. It requires an aluminum cell permanently connected from line to ground. That brings up the second point to which I desire to call your attention, and that is that all these statements of tests with different forms of lightning-arresters may possibly have to be modified slightly here and there. For instance, to test the discharge voltage, as laid out by Mr Thomas, we cannot always apply the Institute test of gradually raising the voltage until the discharge takes place, and then keep it on for a minute. In some types of arrester, as exemplified by the water jet—which we are told gives such good results abroad, especially in countries where lightning is not particularly severe—or the aluminum arrester, there is no definite discharge voltage. Their discharge voltage is the normal operating voltage, because they continuously carry a small current and in such case the test would have to be modified. I especially refer to the aluminum arrester, because in this country where lightning is rather severe I do not think that the water jet would be considered as particularly useful. In this case the test may be made by inserting in series with the lightning-arrester the short-circuited secondary of a transformer, and then suddenly opening the secondary circuit, while energizing the primary with impressed electromotive force, that is, suddenly raising the voltage on the lightning-arrester by a certain definite value, say 5%, or 10%, or 50%, and then measuring the instantaneous rush of the discharge current. The discharge current, even if the rise of voltage is moderate, say 10%, may be very large in the first moment, but rapidly dies out, the lightning-arrester adjusting itself to the higher voltage. Some other modifications of tests would also have to be made, which would be obvious to the one who studies the particular lightning-arrester. In general, the conclusion is that the testing of the lightning-arrester, to get absolute results on its probable performance in actual operation, is not so simple as testing other apparatus, generators, etc., but requires the coöperation of the customer with the manufacturer and also requires special facilities, quite elaborate facilities, really to get a complete and reasonable and effective test.

P. H. Thomas: I am surprised that none of the manufacturers of commercial lightning-arresters has made a protest against the rather uncertain and indefinite tests here proposed for Institute sanction, as I am inclined to be sceptical about the wisdom of the Institute's attempting to standardize lightning-arrester tests at the present time. The Institute should be very careful about approving methods of testing lightning-arresters that cannot be conducted by engineers of ordinary experience, methods by which such engineers would not usually be able to produce identical results. There are not more than one or two of the tests proposed that can be so conducted by the average engineer. Mr. Creighton's recommendations seem to be intended for individual research by experts and designers of lightning-arresters, rather than tests to be undertaken by commercial engineers.

I feel also doubtful about the wisdom of making any more definitions at present. It is hard to keep track of definitions made by the international societies and conventions; and if we make any more I think it will lead to complete confusion.

It is too soon to attempt to make standard rules for testing electrolytic arresters. There is a good deal of laboratory information, perhaps, and a good deal of inference as to what their characteristics will turn out to be; but, until a considerable number of engineers become pretty familiar with them, and the plants in which they are installed have seen more experience, I think we should refrain from adopting any standard tests. I do not wish to make any insinuations about the value of the electrolytic arrester, but I think we should go slow on general principles before standardizing tests.

Mr. Neall's paper shows an ingenious arrangement and one which might work conveniently in some cases, provided the induction coil will cause sparking over the gap, which I think is doubtful in most cases. As Dr. Steinmetz has pointed out, it is necessary to have a single spark at a time, not a series of sparks more extended, except in the case of an endurance test. With one or two exceptions, relative tests are the only valuable tests. It is not possible to say that the arrester has so many absolute units of protective power.

W. S. Lee: If some system could be devised for testing the lightning-arresters where installed it would be an excellent thing, and I think it should be given some consideration as it would help out the man who thinks he has an arrester but really has not. We should have some test, if possible, which could be made periodically, to find out whether the arresters on lines are good or useless. Having to contend with a great deal of trouble every year with lightning-arresters, I think the time has come when some reliable tests should be devised which could be applied to the arresters while they are in service.

N. J. Neall: In answer to Professor Creighton's question—the requisite spark strong enough for a given discharge has not been fully determined. For low-voltage preliminary experiments it was easy to obtain more spark than was actually necessary in order to have the arc take the spark as a bridge.

Another important consideration, discovered almost at the outset, is the impossibility of obtaining a spark from gaps to ground if the condenser heads are connected directly to the high-tension feeders, because the power in the high-tension system is sufficient to hold the condenser charged. It is for this reason that connection is made to the middle point of the series of gaps between the line and ground in order that the discharge may have full play in both directions.

I should like to make the following suggestions in connection with the papers by Messrs. Creighton and Thomas.

1. *Nomenclature*. The names, definitions, and recent classification of lightning-arrester characteristics while entirely proper from the standpoint of theory, strike me as being unduly elaborate and unnecessary for the purpose for which standardization rules were originated. It seems to me that nomenclature can be overdone, not to speak of misleading the general manufacturer and operator who is not necessarily a technician.

Practical lightning development and testing should be kept as simple as possible in order to free it from any mystery which can be so easily attached to this branch of the art.

2. *Apparatus*. It will be observed that the methods proposed for the development of lightning protective apparatus, even under the most favorable laboratory conditions, do not permit a thorough investigation of the devices under operation much above 5000 volts.

Practical application of lightning protective apparatus is now fairly well established up to 30,000 volts. What is needed is information as to its behavior at a higher voltage, 50,000 volts and so on, so that in selecting any standard test in its development this difference in the character of the service should be borne fully in mind.

As a matter of fact the only test of final value is a practical one. A method to this end has been described previously in the PROCEEDINGS. It consists in a careful observation by means of tell-tale papers as to the operation of all protective apparatus on a given system so that any recommendations by the Institute under the head of Standardization Rules should give some mention of this.

3. *Tests proposed*. I heartily approve of the tests proposed by Mr. Thomas as being practical. While they do not cover the case absolutely, they furnish all the information that would usually be required.

If to his proposed tests, a further one should be added to cover investigation by means of tell-tale papers over a long period, there should be sufficient data to eliminate considerable uncertainty.

4. *Needle-point spark-gap.* It seems to me that the most serious danger to the general engineering field lies in the proposed " standardization " of the needle-point spark-gap.

Those members of the Institute who have studied spark-gap performance know that it is very difficult to check the curve which has so far been accepted as standard. Now merely to extend the range of readings on this curve at higher voltages without a thorough study of the phenomena entailed strikes me not only as injudicious, but likely to destroy the prestige which should attend the publication of any data of this character.

It is not my intention to go into the characteristics of spark-gaps of various forms for voltage measurements, since this would well be the subject of a number of papers. It is of as much importance as contributions on lightning-arrester tests. I would therefore respectfully protest against the unqualified use of this form of gap, particularly for very high voltages as at present proposed; in its place I would substitute the gap made with spherical noses backed by metallic discs in order to reduce the opening for a given voltage as well as to straighten and fix the curve therefore.

Charles E. Waddell (by letter): The mountain and Piedmont districts of North Carolina are subject to severe electrical storms of frequent occurrence. On the breaking of winter in the latter part of February or the early part of March, the first destructive storms usually occur; then follows a lapse until the latter part of May or early June, at which time they are at their worst, and from which climax there is a gradual diminution in violence until, early in September, the electrical storms practically cease.

As it is the expressed purpose of the Institute to gather all information pertaining to the subject of lightning, thereby hoping to correlate sufficient data to solve the problem of protection, it is purposed in this paper to recite two instances a little out of the ordinary.

The plant that has suffered more than any other in the mountains is that of the Haywood Power Company on the Pigeon river, twelve miles from Waynesville. The equipment consists of a 400-kw. three-phase, 60-cycle, 13,000-volt hydroelectric unit. The 12-mile transmission line is composed of three No. 2 B. & S. aluminum cables, supported on Thomas 5-T insulators, and on wood poles spaced 200 feet apart. The line runs over mountain ranges and across valleys, touching altitudes of 4000 or 5000 feet.

The lightning protection originally installed was of the highest grade of one of the well-known arresters. Some little difficulty was experienced in obtaining a good " ground ", but after this was overcome the management felt perfectly safe. The opening of the following season was, however, heralded by the destruction of coil after coil in the generator, until at the time the author was called in, out of 54 coils in the armature 40 had been burned out and repaired, and the machine was then running with 13 coils out. Matters had reached a point

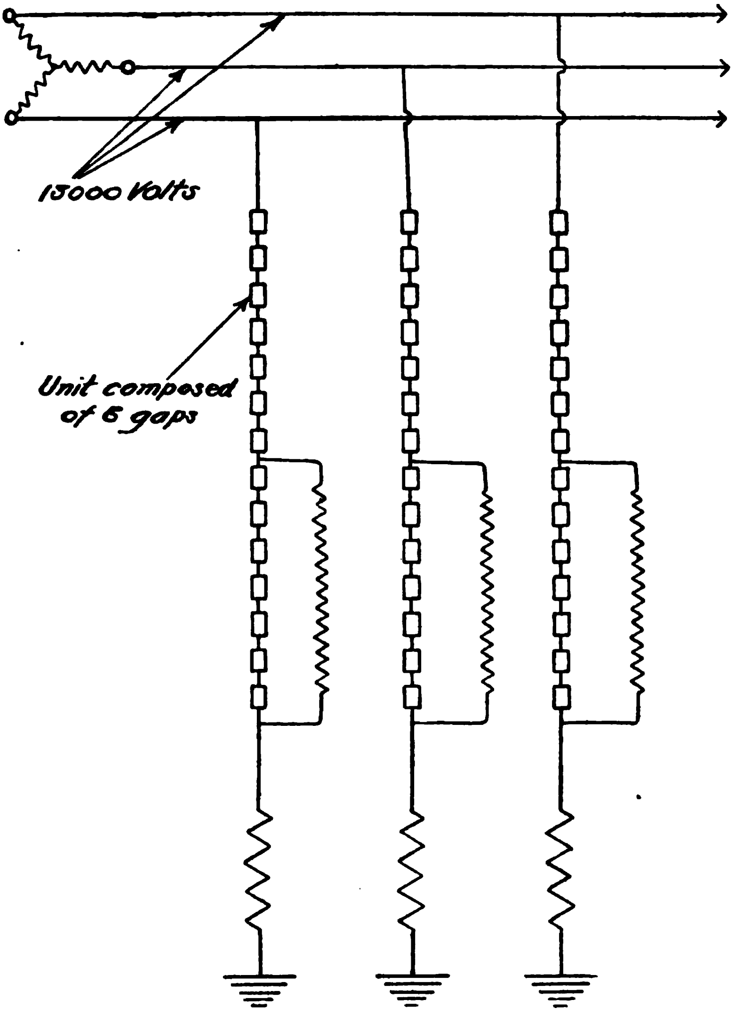

Fig. 1.

where on the slightest manifestation of an electrical disturbance the plant was shut down.

An examination revealed the singular fact that not a single coil had grounded on the frame, but had in every instance ruptured on the ends. While in the station a powerful arrester

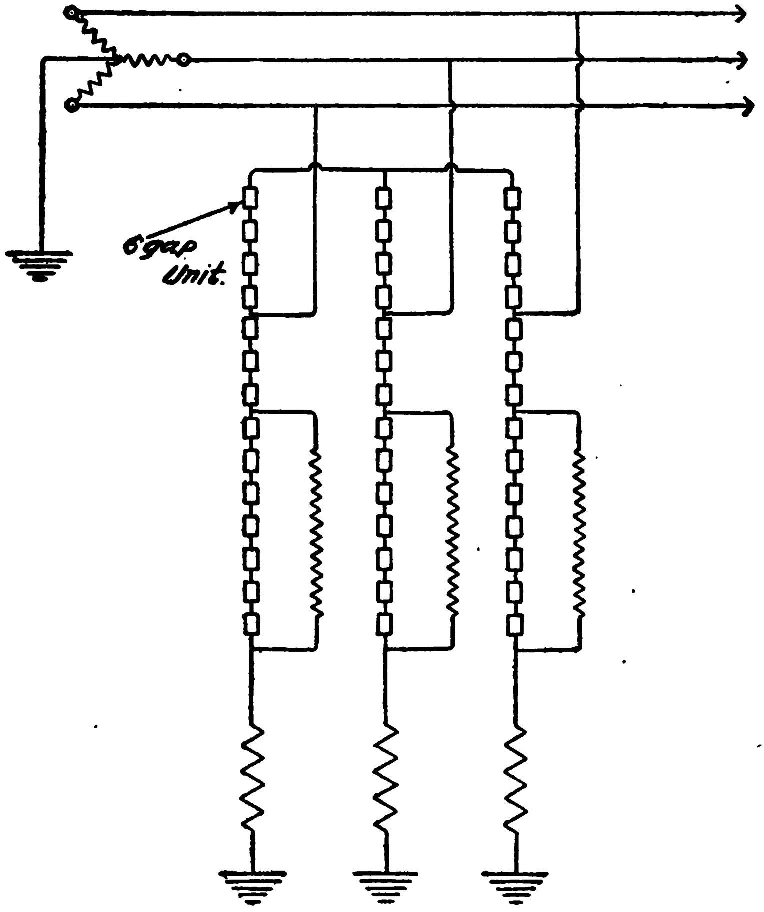

Fig 2

discharge took place, and it was observed that the polyphase electrostatic ground detector which had previously been in a quiescent state became most unstable, erratically fluctuating first one way and then the other, and this was followed in a few moments by the giving way of a coil, and the inevitable shutdown.

The writer concluded that the rupture was due to a static stress that slowly built up, and that the inductive discharge from the electrical storm merely intensified the effect; this opinion was sustained by the attendant's statement, that ruptures occurred when no storm conditions prevailed, and that the line was frequently observed to deliver a brush-discharge at the wire entrance.

Inspection of the generator disclosed the fact that the armature was Y-connected. It was decided to ground the neutral point, consequently reducing the potential between each line wire and the earth to 7500 volts.

The arresters were of a design suited to a maximum potential of 18,000 volts and were connected as shown in Fig. 1.

Experience in a number of cases leads the writer to the conviction that it is as necessary to provide a path for a free discharge between the lines themselves as it is to provide a path to the earth, it was therefore determined to modify the arrester connection, making the changes shown in Fig. 2, and the result was that immunity was obtained.

The coils breaking down on the ends between turns, apparently indicating no disposition to ground, and avoiding puncture in the slots, would seem to indicate that the concentrated magnetic field, with the presence of iron, afforded a repelling effect, driving the static charge as far away as possible.

The second case is not solely a lightning discharge but is more complicated and may in part be attributed to high-potential oscillations or waves.

Included in the Weaver Power Company's distribution system is the Elk Mountain line, a circuit that is in all less than a mile long, which supplies mills in the vicinity of the power house, and the Biltmore line, a circuit nine miles long supplying at that time the Biltmore sub-station only. Both circuits had been in service for about a year and had given no trouble, the line potential being but 6600 volts and the insulators Locke's No. 298.

The transformers at Biltmore were connected in delta with a spark-gap on one leg of the secondary winding. In making some changes at the Elk Mountain mills it was decided to connect the transformers in Y. The neutral was not grounded.

Shortly thereafter a storm occurred, and during its progress an insulator and cross-arm were destroyed on the Elk Mountain line. Nothing was thought of the incident, a defective insulator being assigned as the cause; but the second, third, and fourth repetition of the trouble led to the conclusion that the insulators were not at fault, and that a more subtle cause was responsible.

Not long after the lightning season was over, an underground cable broke down on the Biltmore distribution system, followed, as it always is, by a continuous discharge on the secondary spark-gap. While this was occurring, the main plant telephoned that an arm and insulator were burning on the Elk Mountain line. The discharge at Biltmore was then saddled with the responsibility, and it was decided to provide the neutral of the transformers at the Elk Mountain mills with a spark-gap. This done, it was observed that when one line discharged the other inevitably followed. Since that time no more insulators have given way.

In each of the foregoing instances stress was purposely laid on the type of insulator: In the case of the Haywood Power company the insulator was of a pattern that afforded very little leakage. The insulator of the Weaver Power Company affords a considerable leakage. The lines of the North Carolina Power Company parallel those of the Weaver Power Company, and are also equipped with an insulator on which the leakage is negligible.

With the exception of a few potential transformers destroyed when the plant first started, and the above trouble, the Weaver company has been practically safe from lightning troubles, while the other two concerns have experienced not a little inconvenience and loss. In view of these circumstances it would seem not an unreasonable conclusion that a slight leakage distributed over an entire distribution system affords considerable protection against static discharges, and that occasionally by the merest accident a condition of this kind is obtained.

Where violent discharges have passed over the arresters in the Weaver Power Company's station in every case that was investigated it was found that such discharges had occurred immediately before rain started to fall, and that once the insulators, arms, and poles were wet the discharges became less frequent and less severe, a fact that in the author's opinion tends to confirm the above theory.

In justice to the manufacturers of the insulators, it should be stated that the existence of leakage on the particular type is no reflection on the quality, for they are in every respect eminently satisfactory, but is due to the use of a type scarcely large enough for the service.

A paper presented at the Annual Convention Meeting of the Amercian Institute of Electrical Engineers, Niagara Falls, June 25, 1907.

INDUCTIVE DISTURBANCES IN TELEPHONE LINES.

BY LOUIS COHEN.

The inductive action of one telephone line on another, producing what is commonly known as cross-talk, presents an important problem to the telephone engineer. The induction is both electromagnetic and electrostatic. A variable current passing through any circuit is accompanied by a variable magnetic field, which will produce electric currents in neighboring circuits. In addition to this there exists also an electrostatic effect, a charge on one conductor will induce charges on all neighboring conductors, and any variation in the charge will produce an electric current. We thus have two distinct phenomena acting simultaneously, both causing trouble on telephone lines. It is to be noticed, however, that the two effects act in opposite directions. The establishment of a current in one circuit is accompanied by an induced current in any neighboring circuit in the opposite direction, while when the current in the inducing circuit is decreasing, the induced current will be in the same direction. In the case of electrostatic induction the conditions are reversed. When both forms of induction act together we obtain a resultant effect which depends on the various electrical constants of the lines and their relative importance. It would appear therefore quite evident that to obtain a knowledge of the effect due to induction, we must first be able to ascertain the relative importance of one form of induction as compared with the other, and to determine the factors which enter in fixing the magnitude of each. A thorough knowledge of these factors may be of considerable assistance in improving the conditions of telephone lines, or at least it may suggest some methods for overcoming induction effects which are a source of considerable annoyance to users of telephones.

In a paper presented before the American Institute of Electrical Engineers in 1891,* Mr. J. J. Carty discussed a series of experiments which he had conducted to determine the relative importance of the electrostatic as compared with the electromagnetic induction. His conclusions were that the electromagnetic effect is entirely negligible as compared with the electrostatic effect; in fact in his experiments he has not been able to detect any electromagnetic effect at all. In the discussion of his paper Mr. Carty made the following statement:

> "I go so far as to set forth that the effect of electromagnetic induction between parallel telephone wires may be neglected. That is, that when a man is talking on one wire and his speech is heard by induction on a parallel wire, that that speech finds its way between the two wires by virtue of electrostatic induction, and that electromagnetic induction is entirely negligible."

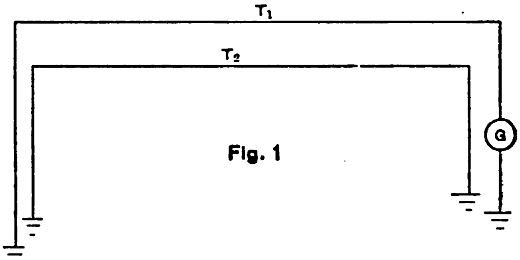

Fig. 1

This view expressed by Mr. Carty has generally been accepted by telephone engineers, and is usually given a very prominent place in all text books on telephony.

In what follows I shall discuss this question from a mathematical standpoint, and shall show that not only is the electromagnetic induction not a negligible quantity, but that in some cases the electromagnetic effect may be much larger than the electrostatic effect; and I shall further show that the results Mr. Carty obtained were correct, that under the conditions of Mr. Carty's experiments he could have obtained only an electrostatic effect. To infer, however, from his results, as Mr. Carty has done, that what is true for the case he experimented with—

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* J. J. Carty, Transactions. of the A. I. E. E. 1891. Vol. 8, page 114.

a line three hundred feet long—is equally true for a line so many miles long is, as I will show, quite erroneous.

Suppose we have two lines T_1 and T_2 running parallel to each other and both are grounded at the two ends; T_1 may be a power circuit or telephone circuit, G is a source of an alternating electromotive force, and T_2 a telephone line. We wish to consider what is the nature of the induced currents in line T_2.

Let L_1, R_1, C_1, denote the self-inductance, resistance, and capacity per unit length of line T_1, and similar letters with suffix 2 denote the same constants of line T_2; M will denote the mutual electromagnetic inductance and C_{12} the mutual electrostatic inductance. Let also x and y denote the currents, V_1 and V_2 the potentials at any point on the lines T_1 and T_2.

The algebraic sum of the forces acting at any point on the two lines will be given by the following equations:

$$L_1 \frac{d\,x}{d\,t} + R_1\,x + M\,\frac{d\,y}{d\,t} + \frac{d\,V_1}{d\,s} = 0 \qquad (1)$$

$$L_2 \frac{d\,y}{d\,t} + R\;v + M\,\frac{d\,x}{d\,t} + \frac{d\,V_2}{d\,s} = 0$$

We also have the electrostatic relation,

$$C_1\,V_1 + C_{12}\,V_2 = q_1 \qquad (2)$$

$$C_2\,V_2 + C_{12}\,V_1 = q_2$$

By the aid of the equations of contim

$$\frac{d\,q_1}{d\,t} = -\frac{d\,x}{d\,s}$$

$$\frac{d\,q_2}{d\,t} = -\frac{d\,y}{d\,s}$$

we may write equations (2) after differentiating with respect to t in the following form:

$$C_1 \frac{d\,V_1}{d\,t} + C_{12}\,\frac{d\,V_2}{d\,t} = -\frac{d\,x}{d\,s} \qquad (3)$$

$$C_2 \frac{d\,V_2}{d\,t} + C_{12}\,\frac{d\,V_1}{d\,t} = -\frac{d\,y}{d\,s}$$

Differentiating equations (1) with respect to s we get:

$$L_1 \frac{d^2 x}{d t d s} + R_1 \frac{d x}{d s} + M \frac{d^2 y}{d t d s} + \frac{d^2 V_1}{d s^2} = 0$$

$$L_2 \frac{d^2 y}{d t d s} + R_2 \frac{d y}{d s} + M \frac{d^2 x}{d t d s} + \frac{d^2 V_2}{d s^2} = 0 \tag{4}$$

If we differentiate equations (3) with respect to t, and introduce the values of $\frac{d^2 x}{d s d t}, \frac{d^2 y}{d s d t}$ thus obtained into equations (4) and also the values of $\frac{d x}{d s}$ and $\frac{d y}{d s}$ from equations (3) we shall obtain the following equations:

$$L_1 C_1 \frac{d^2 V_1}{d t^2} + L_1 C_{12} \frac{d^2 V_2}{d t^2} + R_1 C_1 \frac{d V_1}{d t} + R_1 C_{12} \frac{d V_2}{d t}$$

$$+ M C_2 \frac{d^2 V_2}{d t^2} + M C_{12} \frac{d^2 V_1}{d t^2} = \frac{d^2 V_1}{d s^2}$$

$$\tag{5}$$

$$L_2 C_2 \frac{d^2 V_2}{d t^2} + L_2 C_{12} \frac{d^2 V_1}{d t^2} + R_2 C_2 \frac{d V_2}{d t} + R_2 C_{12} \frac{d V_1}{d t}$$

$$+ M C_1 \frac{d^2 V_1}{d t} + M C_{12} \frac{d^2 V_2}{d t^2} = \frac{d^2 V_2}{d s^2}$$

Assuming that the impressed electromotive force be simple harmonic, that is the real part of $E e^{ipt}$ say, then the potentials at any point along the lines will be simple harmonic, and therefore we may put:

$$\frac{d^2 V_1}{d t^2} = - p^2 V_1, \quad \frac{d V_1}{d t} = i p V_1$$

$$\frac{d^2 V_2}{d t^2} = - p^2 V_2, \quad \frac{d V_2}{d t} = i p V_2$$

Introducing these values in equation (5) and rearranging we get:

$$\frac{d^2 V_1}{d s^2} = a_1 V_1 + b_1 V_2$$

$$\frac{d^2 V_2}{d s^2} = a_2 V_2 + b_2 V_1 \tag{6}$$

Where,

$$\begin{aligned} a_1 &= -p^2 L_1 C_1 + i p R_1 C_1 - M C_{12} p^2 \\ b_1 &= -p^2 L_1 C_{12} + i p R_1 C_{12} - M C_2 p^2 \\ a_2 &= -p^2 L_2 C_2 + i p R_2 C_2 - M C_{12} p^2 \\ b_2 &= -p^2 L_2 C_{12} + i p R_2 C_{12} - M C_1 p^2 \end{aligned} \tag{7}$$

Each of the equations (6) contains two dependent variables which make it rather difficult to solve. We can, however, transform equations (6) into equations containing only one dependent variable by the following device:*

Put

$$\begin{aligned} V_1 &= W_1 + W_2 \\ V_2 &= f_1 W_1 + f_2 W_2 \end{aligned}$$

where f_1 and f_2 are arbitrary constants.

Equations (6) will transform into the following:

$$\frac{d^2 W_1}{d s^2} + \frac{d^2 W_2}{d s^2} = (a_1 + b_1 f_1) W_1 + (a_1 + b_1 f_2) W_2$$

$$f_1 \frac{d^2 W_1}{d s^2} + f_2 \frac{d^2 W_2}{d s^2} = (a_2 f_1 + b_1) W_1 + (a_2 f_2 + b_2) W_2$$

Eliminating first W_1 and then W_2 we get the following equations:

$$(a_2 f_2 + b_2 - a_1 f_1 - b_1 f_1 f_2) \frac{d^2 W_1}{d s^2} + (a_2 f_2 + b_2 - a_1 f_2 - b_1 f_2^2) \frac{d^2 W_2}{d s^2}$$
$$= (a_1 a_2 - b_1 b_2)(f_2 - f_1) W_1 \tag{8}$$
$$(a_2 f_1 + b_2 - a_1 f_1 - {}_1b f_1^2) \frac{d^2 W_1}{d s^2} + (a_2 f_1 + b_1 - a_1 f_2 - b_1 f_1 f_2) \frac{d^2 W_2}{d s^2}$$
$$= (a_1 a_2 - b_1 b_2)(f_1 - f_2) W_2$$

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*See O. Heaviside coll. papers, vol. 1, p. 126.

now determine f_2 and f_1 from the equations

$$a_2 f_2 + b_2 - a_1 f_2 - b_1 f_2^2 = 0$$

$$a_2 f_1 + b_2 - a_1 f_1 - b_1 f_1^2 = 0$$

that is,

$$\left.\begin{aligned} f_2 &= \frac{a_2 - a_1 - \sqrt{(a_1 - a_2)^2 + 4\, b_1\, b_2}}{2\, b_1} \\ f_1 &= \frac{a_2 - a_1 - \sqrt{(a_1 - a_2)^2 + 4\, b_1\, b_2}}{2\, b_1} \end{aligned}\right\} \qquad (9)$$

Equations (8) will reduce to the following:

$$\left.\begin{aligned} \frac{d^2 W_1}{d\, s^2} &= \overline{K^2}\, W_1 \\ \frac{d^2 W_2}{d\, s^2} &= P^2\, W_2 \end{aligned}\right\} \qquad (10)$$

where,

$$\left.\begin{aligned} \overline{K^2} &= \frac{(a_1\, a_2 - b_1\, b_2)\,(f_2 - f_1)}{a_2 f_2 + b_2 - a_1 f_1 - b_1 f_1 f_2} \\ P^2 &= \frac{(a_1\, a_2 - b_1\, b_2)\,(f_1 - f_2)}{a_2 f_1 + b_2 - a_1 f_2 - b_1 f_1 f_2} \end{aligned}\right\} \qquad (11)$$

The complete solutions of (10) will be the following:

$$\left.\begin{aligned} W_1 &= A \cos \mu\, (l - s) + B \sin \mu\, (l - s) \\ W_2 &= D \cos \mu_1\, (l - s) + F \sin \mu_1\, (l - s) \end{aligned}\right\} \qquad (12)$$

The constants are to be determined from the following boundary conditions:

When

$s = 0,\quad V_1 = E\, e^{ipt} \quad V_2 = 0$

$s = l,\quad V_1 = 0, \quad V_2 = 0$

Now,

$$W_1 = \frac{f_1 V_1 - V_2}{f_1 - f_2}, \qquad W_2 = \frac{f_2 V_1 - V_2}{f_2 - f_1}$$

Hence, when $s = 0$

$$W_1 = A \cos \mu l + B \sin \mu l = \frac{f_1 E e^{ipt}}{f_1 - f_2}$$

$$W_2 = D \cos \mu_1 l + F \sin \mu_1 l = \frac{f_2 E e^{ipt}}{f_2 - f_1}$$

When $s = l$,

$$W_1 = A = 0$$
$$W_2 = D = 0$$

and therefore,

$$B = \frac{f_1 E e^{ipt}}{(f_1 - f_2) \sin \mu l}$$

$$F = \frac{f_2 E e^{ipt}}{(f_2 - f_1) \sin \mu_1 l}$$

Introducing the values of the constants thus obtained into equation (12) we shall obtain the following values for V_1 and V_2:

$$V_1 = W_1 + W_2 = \left(\frac{f_1 \sin \mu (l - s)}{\sin \mu l} - f_2 \frac{\sin \mu_1 (l - s)}{\sin \mu_1 l} \right) \frac{E e^{ipt}}{f_1 - f_2}$$

(13)

$$V_2 = f_1 W_1 + f_2 W_2 = \left(\frac{f_1^2 \sin \mu (l - s)}{\sin \mu l} - f_2^2 \frac{\sin \mu_1 (l - s)}{\sin \mu_1 l} \right) \frac{E e^{ipt}}{f_1 - f_2}$$

The values of μ and μ_1 may be obtained by inspection of equation (10) which gives

$$- \mu^2 = \overline{K^2} = \frac{(a_1 a_2 - b_1 b_2)(f_2 - f_1)}{a_2 f_2 + b_2 - a_1 f_1 - b_1 f_1 f_2}$$

(14)

$$- \mu_1^2 = P^2 = \frac{(a_1 a_2 - b_1 b_2)(f_1 - f_2)}{a_2 f_1 + b_1 - a_1 f_2 - b_1 f_1 f_2}$$

The value of the currents in the two lines can be easily obtained from equation (13) by the aid of equation (3). Thus:

$$\begin{aligned} -x = \Bigg[C_1\, i\, p \left(\frac{f_1 \cos \mu\,(l-s)}{\mu \sin \mu\, l} - f_2\, \frac{f_2 \cos \mu_1\,(l-s)}{\mu_1 \sin \mu_1\, l} \right) \\ + i\, C_{12}\, p \left(\frac{f_1^2 \cos \mu\,(l-s)}{\mu \sin \mu\, l} - \frac{f^2_2 \cos \mu_1\,(l-s)}{\mu_1 \sin \mu_1\, l} \right) \Bigg] \frac{E\, e^{ipt}}{f_1 - f_2} \\ -y = \Bigg[C_2\, i\, p \left(\frac{f_1^2 \cos \mu\,(l-s)}{\mu \sin \mu\, l} - \frac{f_2^2 \cos \mu_1\,(l-s)}{\mu_1 \sin \mu_1\, l} \right) \\ + i\, C_{12}\, p \left(\frac{f_1 \cos \mu\,(l-s)}{\mu \sin \mu\, l} - \frac{f_2 \cos \mu_1\,(l-s)}{\mu_1 \sin \mu_1\, l} \right) \Bigg] \frac{E\, e^{ipt}}{f_1 - f_2} \end{aligned} \qquad (15)$$

Rearranging we obtain:

$$\begin{aligned} -x = \Bigg((C_1 f_1 + C_{12} f_1^2) \frac{\cos \mu\,(l-s)}{\mu \sin \mu\, l} \\ - (C_1 f_2 + C_{12} f_2^2) \frac{\cos \mu_1\,(l-s)}{\mu_1 \sin \mu_1\, l} \Bigg) \frac{i\, p\, E\, e^{ipt}}{f_1 - f_2} \\ -y = \Bigg((C_2 f_1^2 + C_{12} f_1) \frac{\cos \mu\,(l-s)}{\mu \sin \mu\, l} \\ - (C_2 f_2^2 + C_{12} f_2) \frac{\cos \mu_1\,(l-s)}{\mu_1 \sin \mu_1\, l} \Bigg) \frac{i\, p\, E\, e^{ipt}}{f_1 - f_2} \end{aligned} \qquad (16)$$

The second equation of (16) gives us the final expression for the currents in any wire due to electromagnetic and electrostatic induction of a parallel wire. The inducing line may be part of a power circuit, lighting circuit, or a similar telephone line. In deducing equations (16) we have taken account of the difference in dimensions, or electrical constants, of the two lines which react upon each other, which will of course be the case if we wish to calculate the currents induced in a telephone line by a power circuit running parallel to it.

According to some recent reports, the introduction of the single-phase electric railway plays havoc with service on telephone and telegraph lines which parallel the railways. This will in all probability be a very serious problem, and a careful consideration of equation (16) will give us a better insight into the nature of the problem and the magnitude of the disturbance. It may also possibly suggest some means for eliminating these disturbances or at least reducing them to a minimum. I hope to consider this phase of the problem in another paper, but for the present I shall limit my discussion to the case of two parallel telephone lines.

If it is the influence of two telephone lines on each other that we wish to investigate, then equations (16) will be somewhat simplified; for in that case we find by examining equations (6) that

$$a_1 = a_2 \qquad\qquad b_1 = b_2$$

equations (9) will therefore reduce to

$$f_1 = -f_2 = 1$$

Hence equations (16) will become,

$$x = \tfrac{1}{2}\left((C+C_{12})\frac{\cos\mu\,(l-s)}{\mu\sin\mu\,l} + (C-C_{12})\frac{\cos\mu_1\,(l-s)}{\mu_1\sin\mu_1\,l}\right) i\,p\,E\,e^{ipt}$$

$$-y = \tfrac{1}{2}\left((C+C_{12})\frac{\cos\mu\,(l-s)}{\mu\sin\mu\,l} - (C-C_{12})\frac{\cos\mu_1\,(l-s)}{\mu_1\sin\mu_1\,l}\right) i\,p\,E\,e^{ipt} \tag{17}$$

The values of μ and μ_1 are given by equations (14) which in the case of two parallel wires reduce to the following:

$$\begin{aligned} -\mu^2 &= a+b = -p^2(L+M)(C+C_{12})+i\,p\,R\,(C+C_{12}) \\ -\mu_1^2 &= a-b = -p^2(L-M)(C-C_{12})+i\,p\,R\,(C-C_{12}) \end{aligned} \tag{17}$$

μ and μ_1 are of course complex quantities, putting

$$\mu = \alpha + i\,\beta \qquad \mu_1 = \alpha_1 + i\,\beta_1$$

and solving for α, β, α_1 and β_1 we get

$$\begin{aligned} \alpha &= \sqrt{\tfrac{1}{2}\,p\,(C+C_{12})\,\left[\sqrt{p^2(L+M)^2+R^2}+p\,(L+M)\right]} \\ \beta &= \sqrt{\tfrac{1}{2}\,p\,(C+C_{12})\,\left[\sqrt{p^2(L+M)^2+R^2}-p\,(L+M)\right]} \\ \alpha_1 &= \sqrt{\tfrac{1}{2}\,p\,(C-C_{12})\,\left[\sqrt{p^2(L-M)^2+R^2}+p\,(L-M)\right]} \\ \beta &= \sqrt{\tfrac{1}{2}\,p\,(C-C_{12})\,\left[\sqrt{p^2(L-M)^2+R^2}-p\,(L-M)\right]} \end{aligned} \tag{18}$$

It remains now to separate the values of x and y into the real and imaginary parts, for the actual currents in the lines will be the real parts of the values of x and y as given by equation (17). Now

$$\frac{i\,p\,E\,e^{ipt}}{\mu\sin\mu\,l}=\frac{i\,p\,E\,(\cos p\,t+i\sin p\,t)}{(\alpha+i\,\beta)\sin(\alpha+i\,\beta)\,l}=$$

$$\frac{2\,(\alpha-i\,\beta)\,(\sin\alpha\,l\,(e^{\beta l}+e^{-\beta l})-i\cos\alpha\,l\,(e^{\beta l}-e^{-\beta l}))\,E\,i\,p\,(\cos p\,t+i\sin p\,t)}{(\alpha^2+\beta^2)\,[\sin^2\alpha\,l\,(e^{2\beta l}+2+e^{-2\beta l})+\cos^2\alpha\,l\,(e^{2\beta l}-2+e^{-2\beta l}]}$$

the real part of which is

$$\frac{2\,E\,p\Big[\Big\{\beta\cos\alpha\,l\,(e^{\beta 1}-e^{-\beta l})-\alpha\sin\alpha\,l\,(e^{\beta l}+e^{-\beta l})\Big\}\sin p\,t+\Big\{\beta\sin\alpha\,l\,(e^{\beta l}+e^{-\beta l})+\alpha\cos\alpha\,l\,(e^{\beta l}-e^{-\beta l})\Big\}\cos p\,t\Big]}{(\alpha^2+\beta^2)\,(e^{2\beta l}+e^{-2\beta l}-2\cos 2\,\alpha\,l)}$$

$$=\frac{2\,E\,p\sin(p^{t}\,\phi)}{\sqrt{(\alpha^2+\beta^2)\,(2\cosh 2\,\beta\,l-2\cos 2\,\alpha\,l)}}\tag{19}$$

Where $\tan\phi=$

$$\frac{\beta\sin\alpha\,l\,(e^{\beta l}+e^{-\beta l})+\alpha\cos\alpha\,l\,(e^{\beta l}-e^{-\beta l})}{\beta\cos\alpha\,l\,(e^{\beta l}-e^{-\beta l})-\alpha\sin\alpha\,l\,(e^{\beta l}+e^{-\beta l})}\tag{20}$$

When $\beta\,l$ is a very small quantity, then approximately

$$\tan\phi=-\frac{\beta}{\alpha}\tag{21}$$

When $\beta\,l$ is very large, then the above equation will be approximately

$$\tan\phi=\frac{\beta\sin\alpha\,l+\alpha\cos\alpha\,l}{\beta\cos\alpha\,l-\alpha\sin\alpha\,l}\tag{22}$$

At the end of the line, say when $s=l$, the values of the currents will therefore be given by the following equations:

$$\begin{aligned}-x_l&=E\,p\left\{\frac{(C_1+C_{12})\sin(p\,t+\phi)}{\sqrt{(\alpha^2+\beta^2)\,(2\cosh 2\,\beta\,l-2\cos 2\,\alpha\,l)}}+\frac{(C_1-C_{12})\sin(p\,t+\phi_1)}{\sqrt{(\alpha_1^2+\beta_1^2)\,(2\cosh 2\,\beta_1\,l-2\cos 2\,\alpha_1\,l)}}\right\}\\-y_l&=E\,p\left\{\frac{(C_1+C_{12})\sin(p\,t+\phi)}{\sqrt{(\alpha^2+\beta^2)\,(2\cosh 2\,\beta\,l-2\cos 2\,\alpha\,l)}}-\frac{(C_1-C_{12})\sin(p\,t+\phi_1)}{\sqrt{(\alpha_1^2+\beta_1^2)\,(2\cosh 2\,\beta_1\,l-2\cos 2\,\alpha_1\,l)}}\right\}\end{aligned}\tag{23}$$

The second equation of (23) represents the current at one end of the line T_2 due to the electromagnetic and electrostatic induction. We may put equation (23) in a more convenient form, thus:

$$y_l = E\,p\sqrt{A^2+B^2-2AB\cos(\phi-{}_1\phi)}\,\sin(p\,t+\phi) \tag{24}$$

Where

$$\left.\begin{aligned} A &= \frac{C-C_{12}}{\sqrt{(\alpha_1^2+\beta_1^2)\,(2\cos h\,2\,\beta_1\,l-2\cos 2\,\alpha_1\,l)}} \\ B &= \frac{C+C_{12}}{\sqrt{(\alpha^2+\beta^2)\,(2\cos h\,2\,\beta\,l-2\cos 2\,\alpha\,l)}} \\ \tan\phi &= \frac{A\cos\phi_1-B\cos\phi}{A\sin\phi_1-B\sin\phi} \end{aligned}\right\} \tag{25}$$

The maximum value of the current will evidently be,

$$E\,p\sqrt{A^2+B^2-2AB\cos(\phi-\phi_1)}.$$

Now to find the ratio of the electrostatic to the electromagnetic induction, we calculate the value of y_l as given by equation (24) first on the supposition that $M=0$; that is, that the whole effect is purely electrostatic, and then calculate the value of y_l on putting $C_{12}=0$; that is, assuming that the effect is purely electromagnetic. We can thus obtain an estimate of the relative importance of the two forms of induction in causing disturbances in parallel lines. The values of the various electrical coefficients which enter into the calculations were determined from formulas given by Mr. Heaviside[*] in his collected papers, which are as follows:

$$L = \tfrac{1}{2}+2\log\frac{2\,h}{r}$$

$$M = \log\frac{d^2+(h_1+h_2)^2}{d^2+(h_1-h_2)^2}$$

$$\left.\begin{aligned} C_1 &= \frac{2\log\dfrac{2\,h}{r}}{\left(2\log\dfrac{2\,h}{r}\right)^2-\left(\log\dfrac{d^2+4\,h^2}{d^2}\right)^2} \\ -\,C_{12} &= \frac{\log\dfrac{d^2+4\,h^2}{d^2}}{\left(2\log\dfrac{2\,h}{r}\right)^2-\left(\log\dfrac{d^2+4\,h^2}{d^2}\right)^2} \end{aligned}\right\} \tag{26}$$

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[*] O. Heaviside collected papers, Vol. 1, pp. 44 and 101.

These formulas apply to the case of parallel suspended wires where h is the height above the ground, d is the distance between the wires, and r is the radius of the wire.

Let us now consider an example; suppose the two wires are 1.25 cm. apart, and at about 1000 cm. above the ground let the radius of each wire be 0.1 cm., then we find

L = 0.00203 henry per kilometre.
M = 0.00147 " " "
C = 0.0118 mf. " "
$-C_{12}$ = 0.0088 mf. " "
R = 3 ohms per kilometre approximately.

Using these values for the constants of the lines, I have calculated the maximum of the current y_l, as given by equation(24),

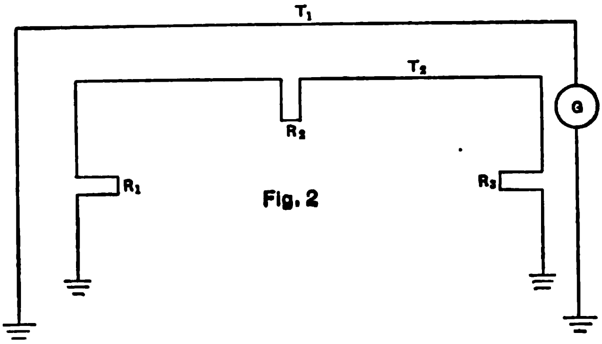

Fig. 2

first assuming that we have only electrostatic induction; that is, $M = 0$, and second assuming that we have only electromagnetic induction; that is, $C_{12} = 0$. The ratios of the two forms of induction for various lengths of lines given below:

	$\frac{e.\ s.}{e.\ m.}$
0.1 km.	0.02
100 km.	0.44
1000 km.	1.6

From this short table it will be seen that for the particular case under consideration, the electromagnetic induction is far larger than the electrostatic; but as the length increases the electrostatic is gaining more rapidly than the electromagnetic, and thus at 1000 km., the electrostatic has overpowered the electromagnetic. In obtaining the above results we have assumed that our line does not have any telephone receiver in it, which is of course not the important case. In the case of a long line, however, say 100 km. or more, where the inductance of the line is large, compared with the inductance of the receiver, the introduction of a receiver will not modify the result to any great extent, but in the case of a short line, the introduction of one or more receivers may affect the results to a very great extent. Let us consider for example one of Mr. Carty's experiments.

There are two lines of about 0.1 km. long stretched side by side at a distance of about 1 cm. and there are three telephone receivers in the second line, the complete solution of this problem is not of course so simple, yet as an approximation we may consider the introduction of the telephone receivers in such a short line as a distributed inductance and resistance. If the inductance of each receiver is 0.05 henry and its resistance is 50 ohms, then for such a short line, the inductance per unit length will be $L = 1.5$ henry and $R = 1500$ ohms. Assuming these to be the constants of our line we find, on calculating as in the previous cases, that the current due to electromagnetic induction is practically zero, and it is only the current due to electrostatic induction that has any appreciable value, and this is what Mr. Carty obtained experimentally. To infer from this that electromagnetic induction is negligible in all cases is however, certainly incorrect. In the case of a long line, say 500 km., the induction and resistance of the telephone receivers will not modify to any great extent the constants of the line, and in that case the electromagnetic induction is just as important as the electrostatic induction. Which is the more important depends a great deal on the length of the lines, their height above the ground, and their distance apart. By varying any one of the above factors we shall vary the ratio of the electromagnetic to the electrostatic induction.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N.Y., June 26, 1907.

CHOKE-COILS VERSUS EXTRA INSULATION ON THE END-WINDINGS OF TRANSFORMERS

BY S. M. KINTNER

Surges along a transmission line are stopped and thrown back by choke-coils in a manner analogous to the reflection of water waves by a breakwater at the entrance to a harbor. The quiet of a harbor is obtained by setting up a strong wall capable of withstanding the shock of the waves that strike against it; so is the analogous quiet of a transformer obtained by placing a choke-coil in the path of a disturbance.

A choke-coil will be effective in reflecting and shielding all back of it according to its strength. The strength of a choke-coil is measured by its inductance and its insulation. If the former is small, but little reflection will take place, the surge passing through the coil and continuing beyond it. If the insulation of the coil is weak and the inductance is of sufficient value to retard the on-coming wave and throw it back on to the line, the rise of voltage will cause a discharge over the coil-face and the wave will continue past the coil. These two conditions can be likened to a breakwater consisting of piling spaced so as to have little effect in retarding an incoming wave in the first instance; and in the second instance to a breakwater of insufficient height, so that the waves pass over it.

With a given choke-coil on a given line, a certain fixed amount of protection will be afforded any apparatus placed back of the coil. There is no relation between the coil and the apparatus being protected that will make the coil more or less effective in its operation of throwing back surges that come in from the line. The choke-coil will produce the same percentage of reflection regardless of what it is protecting, and consequently can be said to be affording the same protection.

Tests indicate that the same percentage of protection will be afforded by the same coil for all parts of the same transformer; that is, measurements made over 200 turns of the winding of a transformer which was being subjected to static surges from a discharging condenser: first, when the transformer was unprotected; secondly, when it was protected by a choke-coil. showed practically the same percentage of protection afforded by the choke-coil when the measurements were repeated over only 20 turns of the transformer. A long series of tests, the results of a part of which have been recently made known to the Institute by Mr. R. P. Jackson,* have convinced the writer of the truth of the above statements.

In choosing a choke-coil for a particular installation, the matter resolves itself into a consideration of: 1, the possible surge the apparatus can withstand safely; 2, the probable surge that can be transmitted over the proposed line, the line insulation indicating the maximum voltage that the surge can have during transmission; 3, the maximum allowable inductance that will not seriously affect the line regulation if an external choke-coil is used; 4, a consideration of the amount of money to be expended for choke-coils as insurance against interruption; 5, the selection of a choke-coil which will most nearly meet the above conditions, the selection being guided by the above, combined with the results of tests and curves similar to those shown in Mr. Jackson's paper.

The question of whether part of the transformer winding should be made strong enough to withstand the surges—and thus have within its own windings a choke-coil that protects the rest of the apparatus—or whether an extra coil should be used, will be discussed below.

The following is a list of the advantages and disadvantages of separate choke-coils.

Advantages:

1. On a choke-coil there is normally no voltage between turns, and consequently no tendency to hold a short-circuit in the event of a momentary surface-discharge.

2. The choke-coil permits the construction of a transformer with uniform insulation throughout. This permits the safe

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* PROCEEDINGS A. I. E. E. December, 1906, p. 843.

working of such a transformer with several methods of connection to the line.

3. The choke-coil allows the safe use of a cheaper transformer.

4. The choke-coil can be insulated much more strongly than a transformer.

Disadvantages:

5. Increase in the number of pieces of apparatus.

6. Increase in complication of station wiring when external choke-coils are used.

1. One of the greatest advantages of choke-coils over extra insulation on the transformer windings lies in the fact that the choke-coil does not normally have a voltage between turns. In the event of a choke-coil insulation failing between turns, nothing in the nature of a short-circuit results, as there is no voltage-difference to maintain an arc. On the other hand, a failure between turns in the insulation of a transformer is vital, and it is almost certain to result in a transformer burn-out. A part of the choke-coil will be cut out and will be inoperative, and consequently the coil less effective as a whole is the worst that can result from such a failure in the coil insulation.

2. The second point of superiority of the choke-coil—allowing the use of a transformer which is uniformly insulated—is of great advantage to the builder, as well as to the operator.

In the majority of specifications for power transmission transformers, it is required that the transformer be capable of operating at one-half voltage at full rated capacity. In general, it is expected also that occasion may arise when the transformer may be operated either in star or delta connection.

It is evident that to meet all the above conditions with certain parts of the transformer specially insulated, involves some very complicated insulation arrangements, and requires extra insulation on a large part of the whole transformer.

3. In consideration of the third point, that of cost of transformer, it should be remembered that the better grade of power transmission transformers of 1000 kw. and upward are wound with copper ribbon, one turn per layer. These coils are insulated uniformly throughout, so as to stand momentary voltages of from 5000 to 9000, between turns. In order to get this result, only about 8 to 10% of the available winding space can be used for copper, the rest being given up to solid insulation and oil-ventilating ducts. An increase in insulation over the above is not desirable with the insulating materials in use at this time;

for two reasons: first, the coils cannot be made strong enough mechanically to stay in place under the shocks to which they are subjected; secondly, the extra insulation retains the heat from the copper, and thus either burns out or necessitates a much lower rating of the transformer.

It is very difficult for workmen to handle large coils with extra heavy insulation without injury to the insulation.

It is therefore evident that a cheaper transformer can be employed when a protecting choke-coil is used.

4. The fourth advantage of the choke-coil is that much better insulation can be obtained in it than in a transformer. This is due to the fact that more material can be used between turns, and it can be disposed to better advantage by allowing more extension beyond the copper than can be employed economically in a transformer coil; also, the shape of the coil is much simpler than that of the average transformer coil and thus more readily lends itself to better insulation.

5-6. The disadvantages of the choke-coil over the extra insulation are two in number; first, an increase in the number of pieces of apparatus; secondly, an increased complication in the station wiring when an external choke-coil is used. Both of these disadvantages are very materially reduced when it is permissible to mount the choke-coils inside of the transformer tank. It is thus possible to make the choke-coil a part of the transformer terminal, the coil being connected on the inner end of the terminal.

For some installations it is possible to use choke-coils mounted out in the air and thus made a part of the station wiring, but in general the oil-insulated coil is to be preferred. Past practice has been to have each oil-insulated choke-coil mounted in its own tank, but there seems to be no good reason why they cannot be placed inside the transformer tank and thus save considerable floor space as well as outside wiring.

After a thorough consideration of what is involved in the above points, it is the writer's opinion that, for a given expenditure to provide protection against surges, more can be obtained by the use of choke-coils than by extra insulation on the transformer.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, June 26, 1907.

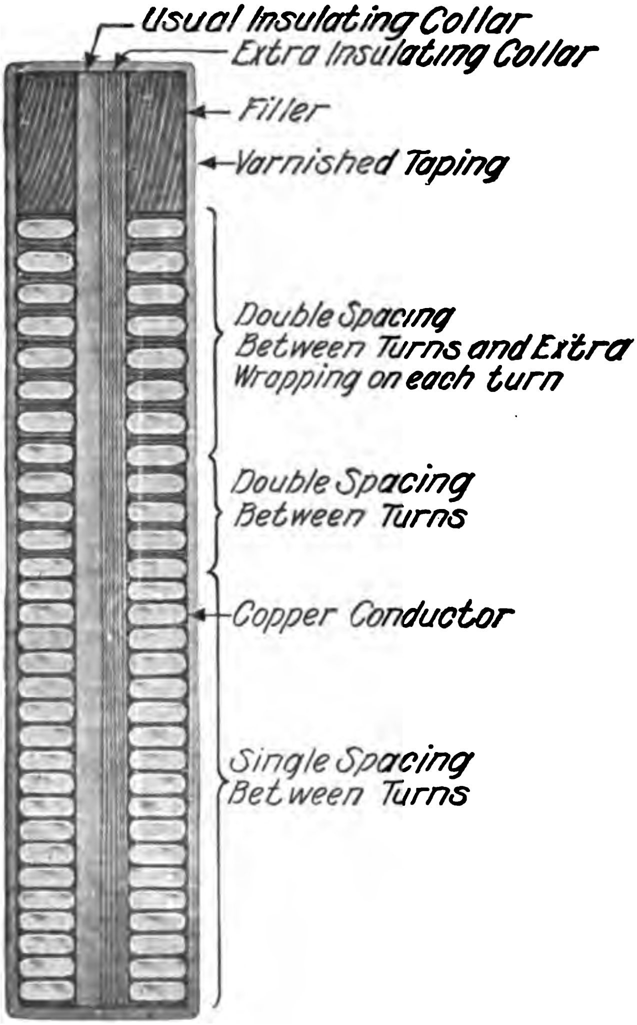
PROTECTION OF THE INTERNAL INSULATION OF A STATIC TRANSFORMER AGAINST HIGH-FREQUENCY STRAINS

BY WALTER S. MOODY

Most forms of lightning-arresters, especially those of the multi-gap type, protect transformers against high-frequency even better than against low-frequency strains so far as these strains exist between either the high- and the low-potential windings, or between either of these windings and any other part of the transformer; because the high frequency causes a greater condenser charging current to flow across the gaps at the line end of the arresters, thereby reducing the resistance of these gaps. They do not, however, always prevent strains far in excess of normal being thrown upon the adjacent turns and layers of the windings; because, although the high frequency strain may be less than the working voltage, the frequency, and consequently the wave-length may be, and generally is, such as to concentrate this strain on a relatively small portion of the turns at the end of the windings connected to the line.

There is a wide range in the frequency of the oscillations that may be set up in a given circuit under varying conditions due to atmospheric disturbances, partial grounds, switching, etc., this range easily extending from normal to several hundred thousand cycles. In the effort to impede all or a greater part of the high-frequency disturbances that try to penetrate the transformer windings, it has been quite common practice to place reactance-coils between the lightning-arresters and the transformers. While such coils are undoubtedly advisable and are quite effective, their use is attended with some objections.

A wide range is found in the size of such coils employed by different authorities, varying from, say, 10 ft. of conductor wound in a small diameter open spiral to several hundred feet wound in forms more difficult to insulate. Evidence of more or less effectiveness of any of the different forms is usually forth-



Cross Section of Transformer Coil Showing Reinforced Insulation

FIG. 1

coming, inasmuch as sooner or later there are sure to be conditions that will generate very high voltages and frequencies.

If, however, the reactance is such as to be effective against moderately high-frequency oscillations, it must, since it is connected between lightning-arrester and transformer, offer a very high impedance to the high frequency of the oscillatory currents which will usually be set up within the transformer itself when a bound charge within it is released by a stroke of lightning relieving some overhanging cloud. Under such conditions, it is almost as bad to hold back the charge in the transformer as to keep a wave from entering under other conditions.

FIG. 2.

It is not my intention to add anything to what has been so ably said by Mr. Percy Thomas, Dr. Steinmetz, and others regarding the theoretical considerations involved in this problem. I simply wish to explain how a theory, that very little preventive reactance is necessary to protect the winding of a transformer whose outer turns are heavily insulated, has been carried out and tested on a large scale during the last four years.

The idea was naturally first put into practice in connection with large high-voltage transformers, but it has been gradually extended, although not so thoroughly, to smaller units operating on pressures as low as 10,000 volts. Thin coils, wound with one turn per layer of flat conductor, such as are commonly used in all the better sort of large transformers, are best adapted to such reenforcement of the insulation between turns.

It is practicable to reenforce a considerable portion of the turns of a large transformer coil so that it will withstand from 2,000 to 20,000 volts per turn without greatly decreasing the space-factor of the winding or causing any considerable increase in cost. It is not practical to use as heavy insulation as this in small units, but, as the size decreases, the length of a turn also decreases, so that the difference of potential between two turns due to a given high-frequency wave is correspondingly less. One should aim, therefore, to have, not a given insulation strength per turn in this reenforced portion of a winding, but a given strength per foot. In like manner it is desirable to reenforce, not the same percentage of the total length of conductor in all cases, but more nearly the same total length, since a given wave will penetrate about the same linear distance into a transformer winding whatever the total length of conductor may be.

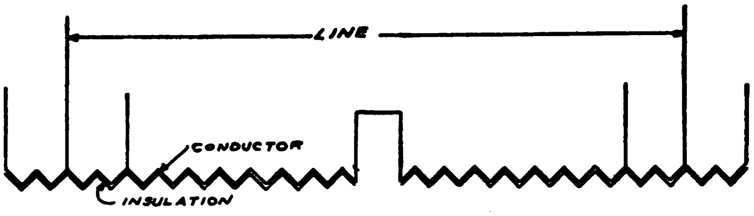


DIAGRAM OF TRANSFORMER WINDING SHOWING TAPS FOR DIFFERENT VOLTAGES BROUGHT OUT NEAR THE ENDS OF THE WINDING

FIG. 3

In large transformers wound for 75,000 volts or less, it is practicable to resist a high-frequency wave whose magnitude is equal to the working voltage in some hundred feet or less of conductor. This means that a wave-length of 200 ft. or more, corresponding to a frequency of, say, 5,000,000 cycles, could be taken care of by such a transformer. If, in addition to this reenforcement, the transformer has an external reactance of some 50 ft. in length, a very considerable reduction of potential between the first few turns will result.

Figs. 1 and 2 show a coil of a 2000-kw. 60 000-volt transformer in cross-sectional and side view respectively, which has such tapered reenforcements of the insulation between the outer turns. The cross-section clearly shows the three different thicknesses of spacing insulation between turns, and the side view of the coil on the form on which it was wound shows the extra insulating on the very first turns where the voltage is likely to be more than could be economically insulated against by spacing insulation only.

The evident desirability of limiting the reenforced insulation to as short a length of the end portions of the winding as will accomplish the desired results indicates the need of a different location of tap connection than usual. Few transformers for transmission work are made without taps to admit of operation with different ratios of transformation. Frequently, such taps cover a range anywhere from 10 to 30% of the winding, and, if they are located so as to cut out the end portion of the turns, the insulation must be reenforced well within the inside tap or perhaps some 40% of the total winding.

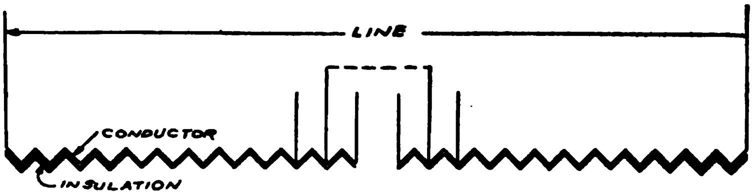


DIAGRAM OF TRANSFORMER WINDING SHOWING TAPS FOR DIFFERENT VOLTAGES BROUGHT OUT NEAR THE CENTRE OF WINDING AND REINFORCED INSULATION AT ENDS

FIG. 4

It has been our practice for some years, therefore, so to locate tap connections that they will cut out centrally located turns instead of end-turns, thereby not only placing them in an essentially safer position, but also avoiding the necessity of any more reenforcement than is required when all the winding is in service.

Some 750,000-kw. capacity of transformers embodying these ideas, ranging in size from 300 to 7500 kw., and wound for 5000 to 80,000 volts have been built in both air-blast and oil-immersed types. Most of these have been installed with a small protective reactance, but many without such protection; and not one of these transformers has yet failed from any weakness of the internal insulation, although a considerable proportion of the transformers has been installed for three years.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

NOTES ON TRANSFORMER TESTING

BY H. W. TOBEY

Transformer testing has already received a great deal of attention, and, considering the number and variety of articles upon the subject which have appeared, the ground would seem to be quite thoroughly covered, so thoroughly in fact that there would at first sight appear little more to add. But in view of the changes which have been constantly taking place and the rapid advance in transformer design, a general discussion of the subject at this time may be of value. Experience also has led to the adoption of certain methods in commercial transformer testing which for various reasons have proved satisfactory, so that a description of these with their advantages and shortcomings will perhaps prove of some interest.

Present methods of testing, like many other methods, are the result of gradual but constant development, in which the good has been as far as possible retained and the poor eliminated and replaced with something better. What was suitable for small transformers, for example, was found to be entirely unsuitable for large sizes, and methods which applied very well to transformers of low voltage had to be modified or entirely abandoned for high-voltage apparatus.

Generally speaking, it may be said that tests are required for the purpose of determining the chief characteristics of the finished apparatus, thus enabling it to be compared with the original calculations and designs, and with the guarantee. They may be classified as follows:

Conversion.
Polarity.

Resistance.
Copper loss.
Core-loss and exciting current.
Regulation.
High potential.*
High voltage.*
Temperature rise.

Conversion. This test, while a comparatively simple one to make, is nevertheless extremely important, particularly where the transformers under consideration are intended for parallel operation or for delta connection to three-phase lines.

The most satisfactory method is without doubt one employing a standard multi-ratio transformer and a single voltmeter, provided the potential of the source of current supply does not fluctuate. Then, by applying a suitable common voltage to the high-tension side of the transformer under test and the standard, the two low-tension voltages may readily be compared and the true ratio obtained.

Where the supply is at all unsteady or where the ratio of the standard varies considerably from that of the transformer under test, the two-voltmeter method is preferable. Accurate results may then be obtained by taking two sets of simultaneous readings, between which the instruments are interchanged to eliminate any dissimilarity between them.

The opposition method is also sometimes used to good advantage. With this, however, care should be used to see that the low-tension voltage of the standard and of the transformer under test are exactly in phase.

As an additional precaution, single-phase transformers which are required to operate in parallel on single-phase circuits, or delta on three-phase circuits, also delta-connected phases in three-phase transformers, should be connected as they are eventually intended to operate, and a test made for circulating current. This serves as a check on conversion measurements and is important from the fact that a slight difference in voltage between windings is apt to lead to serious results.

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*Both of these are essentially insulation tests. The terms "high potential" and "high voltage" are used arbitrarily to distinguish between a test applied between primary and secondary windings and iron, and one applied across terminals of the same winding. The first tests the strength of the insulating barriers and casing, while the second tests the insulation between turns and between layers.

Polarity. The relative positions of primary and secondary leads is ordinarily determined either by direct comparison with a standard transformer; or by applying direct current to the high-tension winding, noting the position of positive and negative connections by means of a direct-current voltmeter, then shifting the voltmeter leads to the low-tension winding and noting the voltmeter deflection upon breaking the direct-current circuit. When testing large numbers of small transformers having approximately the same voltage and ratio, the first method is quicker and more satisfactory. For power transformers having as a rule widely differing voltages, the second method is usually preferable.

Resistance and Copper Loss. In the measurement of resistance for the determination of copper loss and total resistance drop, the fall of potential method gives in general the most satisfactory results of any of the standard methods. The instruments required are less delicate than the galvanometer used in bridge measurements, may be readily calibrated, and give accurate results over a wide range.

When measuring resistances of small transformer windings, the instruments come to rest very quickly and little time is required for taking the readings. With large transformers, however, unless special precautions are taken, this is seldom true; for even with the terminals of the opposite winding short-circuited on themselves, some seconds, or even several minutes, often elapse before the instruments settle, so to speak, to a final value, and, until this settling has stopped, readings do not indicate the true resistance.

Fortunately, this condition of affairs may be overcome by forcing through the winding under test a direct current of ten or twelve times that finally required for the measurement, and after a moment or two dropping it to normal before taking the reading. (Of course during the passage of this increased current the voltmeter should be disconnected and the ammeter short-circuiting switch closed.)

While a delay of a few seconds or several minutes may do no particular harm at the time when cold-resistance measurements are made, it is extremely annoying during heat runs where measurements are taken at frequent intervals. Long interruptions of the load under these conditions are apt seriously to affect the final temperature.

Core-Loss and Exciting Current. The influence of wave-form upon core-loss and exciting current has already been carefully investigated, and the importance of using a sine-wave source of current supply is well known. It is doubtful, though, if all fully realize how far from a sine wave the electromotive force of some generators really is under actual conditions of test; that is, when supplying core loss to transformers. This may occur, even though the wave-form of the generator is entirely satisfactory under normal conditions, from the fact that the wave becomes badly distorted at low power-factors which occur when transformers, particularly those designed for low frequencies, are operated on open circuit. The extent to which this distortion may reach, and its effect on core-loss and exciting current are clearly indicated in the accompanying curves and data which follow.

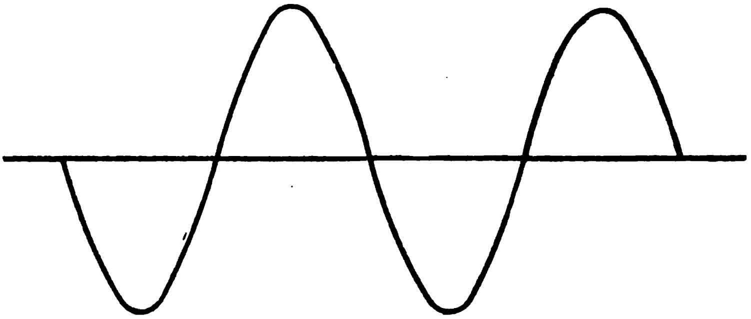

Fig. 1

The curve, Fig. 1, was taken on one of the generators in question while on open circuit. The curve, Fig. 2, was taken on the same machine while furnishing core-loss and exciting current to a transformer. It will be noted that both approximate very closely a sine wave. The oscillograph curve shown in Fig. 3 was taken while a generator, having a very peaked wave, was exciting the same transformer at the same voltage. The resulting core-loss and exciting-current measurements are given as follows:

First case; sine wave, core-loss 1177 watts, current 33.5 amperes.

Second case; peaked wave, core loss 924 watts, current 15.4 amperes.

By comparing these sets of readings it will be seen that in changing the source of supply from one, giving very nearly a sine electromotive-force wave, to one giving a peaked wave, the core-loss decreased to 79% and the exciting current to 44% of the original values.

Another transformer, measured under conditions shown in Fig. 3, and again under conditions indicated by Fig. 4, required respectively 5500 and 7325 watts core-loss and 25.3 and 47 amperes exciting current, an increase of 33% and 87% respectively. These readings show the variations which may occur with peaked waves of the same general character.

These figures clearly indicate the importance of referring all measurements to a standard form of wave. At first sight the peaked wave would seem to have some advantages over the sine wave, owing to the lower core-loss and exciting current values which result. After all sides of the question are considered, however, including among other things the effect of wave-shape on insulation strains, etc., a sine-wave electromotive force is undoubtedly the best. And what is equally important, the generator from which the supply is obtained should not only maintain the standard wave-form on open circuit and on non-inductive loads, but also on low power-factor inductive loads; *i.e., under the conditions of test.*

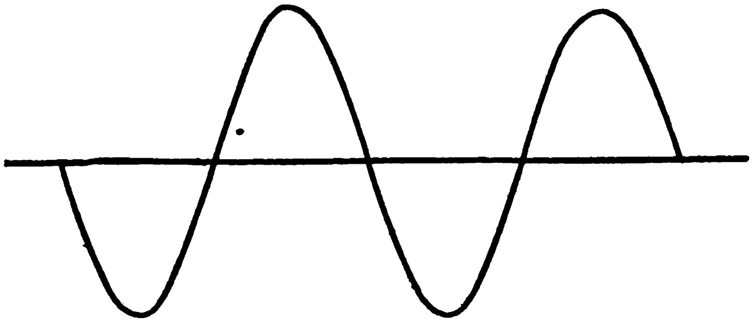

FIG. 2

In the measurement of core-loss on three-phase transformers, the windings across which the readings are taken should be Y connected and the opposite windings left open in case they are intended for delta connection. Otherwise, the circulating current due to unequal distribution of flux in the core and to the short-circuiting of the odd harmonics would show up as an increase in core-loss, thus giving incorrect results. In case the transformer windings on one side are delta connected, and for any reason cannot be changed, it is preferable to connect both sides in delta before taking the core-loss measurement. The resulting circulating current will then occur in two windings instead of one, and, being proportionally less, will produce smaller disturbing losses in the copper than if but one winding alone is delta connected.

Regulation. In general, it is now customary to determine the regulation of a transformer by one of the several methods which require impedance measurements with one of the windings short-circuited on itself, this having entirely superseded the old way of measuring the voltage with transformer free and loaded.

Here, too, it is important to employ a generator which will give a sine wave at low power-factor loads, for while it is true that the wave-shape does not affect the measurements so seriously as those mentioned under the preceding heading, nevertheless the variation is fairly well marked.

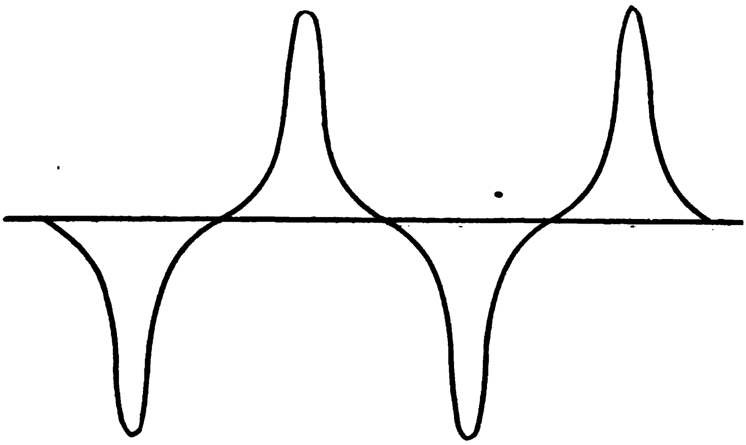

FIG 3

High-Potential Test. On low-voltage transformers this test is not a difficult one to apply correctly, but where the voltage is high the question is entirely different, and the chance for error is large. This is chiefly because of the absence of a suitable means of measuring high potential. To be sure, either the conversion method or the spark-gap method may be used, though both are open to criticism. Individual conditions alone can determine which is most suitable.

If the testing transformer has extremely close inherent regulation, and the charging current under conditions of test is but a small proportion of its normal current capacity, it is reasonably safe to rely upon the low-tension voltmeter reading, and to consider that this times the ratio of conversion is an approximate indication of the high-tension voltage. If these conditions do not exist, the spark-gap method must be relied upon. It should be used, however, with great care.

As the conditions under which the testing outfit operate are changed entirely by the introduction of the transformer under test, it is obviously not right to measure the high-tension voltage by spark-gap before this transformer is connected. On the other hand, if the transformer is connected in, together with the properly adjusted spark-gap, and the voltage is raised until the latter arcs over, high-frequency oscillations almost invariably occur and result in a rise in voltage. The final value of this voltage may be considerably higher than that required, resulting possibly in an uncalled-for break-down of insulation.

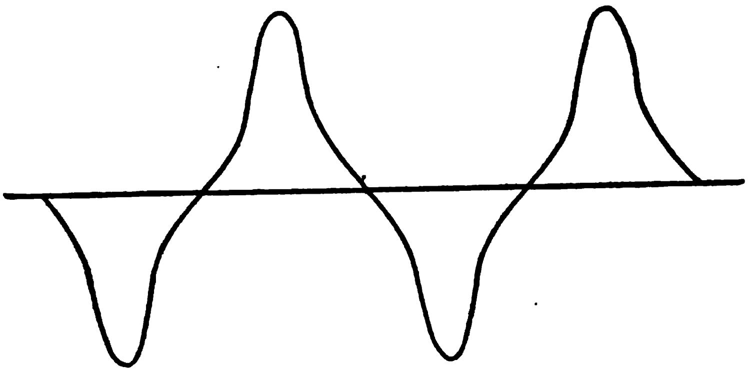

FIG. 4

Such a disturbance may be overcome in one of two ways, both of which have been tried with satisfactory results. The first consists of inserting in series with the gap a high resistance,* the presence of which prevents the occurrence of a high-frequency disturbance when the spark-gap breaks down. The only precaution necessary in the use of this auxiliary resistance

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*For potentials ranging from 100,000 to 200,000 volts, a resistor consisting of a dozen U-shaped glass tubes one-half inch inside diameter and two feet in length will be found satisfactory. These should be mounted in a suitable rack, filled with water and connected in series.

is the calibration of the spark-gap with the resistance in series, as its presence will in general increase the effective value of the gap. In other words, the distance between needle-points, as given in the Standardization Rules, may need to be decreased by from 5% to 10% to obtain correct results.

The other method, referred to above, consists in making all connections for the high-potential test and placing the spark-gap across the circuit, the gap previously having been set, however, for a somewhat lower voltage than that required, two-thirds for example. The voltage is then increased, and the low-tension voltmeter reading is noted at the moment the spark-gap breaks. The gap is now disconnected and the electromotive force again raised until the voltmeter reading, in the case cited, is 50% greater than before. The desired potential is thus obtained with fair accuracy without any disturbance in the circuit.

The importance of using a sine-wave generator for supplying current to the testing transformer is hardly to be questioned. Otherwise, it will be extremely difficult to obtain the desired testing strain.

As to varying the voltage of the high-potential transformer, several methods are possible, including the use of a variable resistance, a variable reactance, or changing the excitation of the generator field. The first, except perhaps in the case of low-voltage tests on small apparatus, should not be resorted to, as it has a very disturbing effect on the wave-form. The second gives more satisfactory results in this respect, and serves very well when the required range is not too great. In general, the last method, which is that of varying the generator-field excitation, is perhaps most often used, chiefly because it enables the voltage to be varied gradually over a wide range. Low field-densities, however, are apt to lead to armature reaction if the machine is furnishing anything like full-load current, so that even with this method some distortion of wave-form may result.

A discussion of this branch of the subject would hardly be complete without some reference to the effect which the time of application of the high potential has on the resisting strength of insulation. In other words, if an insulating material will safely withstand 50,000 volts for one minute, what potential will it withstand if the test is continued for five minutes and what will it resist indefinitely?

This relation between time and voltage is fairly well represented by the curve shown in Fig. 5. This was obtained from a series of tests on sheet insulation, potential from a 60-cycle sine-wave generator being applied to two brass discs arranged on opposite sides of the test piece.

It will be noted that for periods of one minute the sample safely withstood a pressure of 65,000 volts. For five-minute tests it was necessary to lower the pressure to about 70% of this value, or 46,000 volts; while, in order to resist the test indefinitely, the applied voltage had again to be lowered to 27,500 or about 40% of its original value.

These figures can hardly be taken as general, for they change considerably with different kinds of insulation and the resulting curves assume widely varying forms. In most cases the reduction in strength as the length of the test increases, is much less than indicated above, so that in comparing the instantaneous test and continuous test, for example, the reduction is nearer 50% or 60% instead of 70% as in the sample noted. These figures serve to emphasize, nevertheless, the undesirability of long-continued strains, and tend to confirm the advisability of retaining the present one-minute standard.

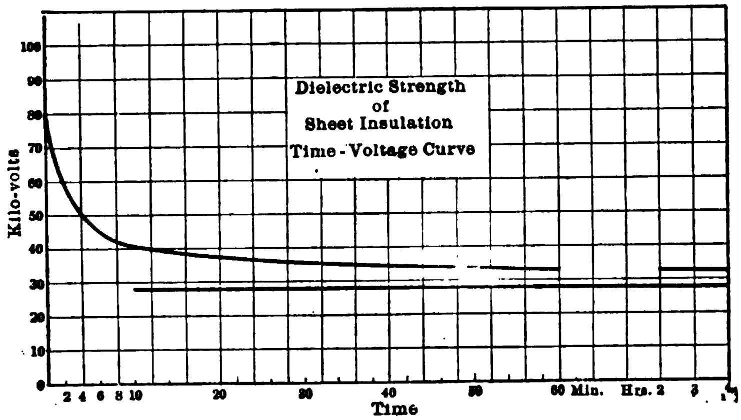


FIG. 5

High-Voltage Tests. The test which determines the strength of insulation between turns, between layers, and between leads, is equally as important as the "high-potential" test just referred to. If the transformer windings withstand double voltage, or, in the case of lighting transformers, triple voltage, their internal condition is reasonably well assured.

In applying this test, it is usually advisable, and in most cases necessary, to use a frequency considerably higher than that for which the transformer was designed; otherwise, the exciting current becomes so excessive as to make it difficult or even impossible to obtain the desired increase in voltage.

In general, satisfactory results are obtained by employing a frequency as much above that for which the apparatus is designed as the test voltage is above normal terminal voltage. With a 60-cycle transformer under consideration, for example, 120-cycle current gives good results for double voltage tests, while 180 cycles is usually satisfactory for triple voltage. A 180- to 200-cycle generator answers very well therefore in the majority of instances.

Temperature Tests. Except perhaps in the case of special tests on small transformers, or where a single transformer is to be tested, the differential method of applying load for the temperature test or heat run is the most satisfactory and probably the one most universally used. This ensures very nearly the conditions of actual operation, enables the work to be carried on with a minimum waste of power, and requires a comparatively small amount of auxiliary apparatus. The total losses occurring are in general somewhat in excess of those which would take place if the transformer were normally excited and loaded on a dead resistance, or if it were operating under actual conditions of service, therefore the results are always on the safe side.

While it is perhaps preferable to make this run at normal frequency, both on the exciting and loading side, still this is not absolutely essential to satisfactory results. In fact, two entirely different frequencies may be employed if desired, it merely being necessary to adjust the exciting voltage so as to obtain what has already been found to be the true core-loss at normal frequency and then to feed the required current into the other side. (By normal frequency is meant the frequency at which the apparatus is intended to operate).

The resistance readings, taken at intervals during the run for the purpose of temperature determinations, should obviously be made with the shortest possible delay in view of the necessary removal of load at such times. It is here, therefore, that the precaution mentioned under the subject of " Resistance and Copper Loss " is most useful. By observing this, and by employing a suitable arrangement of double-throw switches to which the measuring instruments and source of direct-current supply may be permanently connected, the time required to take a resistance reading is reduced to a minimum.

General. The order in which tests should be made depends more or less upon local conditions, so that no fixed rule can be given, nor, in fact, is one necessary. The general order in which the tests have here been described is perhaps as good as any. It has the advantage of placing the heat run at the end, so that, in case any part of the insulation has been injured by previous tests, the fault becomes evident while the transformer is under load and operating under service conditions. It is sometimes considered advisable, however, after the heat run has been finished, to repeat the measurements of core-loss and exciting current. Any defect in the winding then becomes apparent at once.

The question of instruments with which to carry on the various tests has not been touched upon, for this forms a complete subject in itself. It is needless to say that the selection of instruments should be made with the utmost care, as on their construction and accuracy depends the value of the tests.

Not only should they be selected carefully, but the same care should be exercised in their handling and use, and frequent calibrations, at least as often as once a week, should be the rule.

Testing as a whole requires painstaking and constant study, and changing conditions of design and construction must be carefully followed if it is to fulfil its purpose.

DISCUSSION ON "CHOKE-COILS VERSUS EXTRA INSULATION ON THE END-WINDINGS OF TRANSFORMERS," "PROTECTION OF THE INTERNAL INSULATION OF A STATIC TRANSFORMER AGAINST HIGH-FREQUENCY STRAINS", AND "NOTES ON TRANSFORMER TESTING", AT NIAGARA FALLS, N. Y., JUNE 26, 1907

S. M. Kintner: I have tried to make clear in this paper that, for a given expenditure to safeguard against transformer interruptions caused by line surges, more can be accomplished by the use of choke-coils and transformers with reasonable insulation than by adding extra insulation on the end-turns of the same transformer and omitting the choke-coil. It is not my contention that an inferior insulation can be used when choke-coils are employed and satisfactory service got with such an arrangement. Reasonable insulation on transformers of 1000 kw. and upward should be able to withstand from 5000 to 8000 volts between turns.

A. H. Pikler: At the meeting on December 28, 1906, while discussing the paper of R. P. Jackson on lightning protection, the chairman of the transmission committee said:

> If we must have choke coils, let us put them in the same case as the transformers, and so save the complication in station wiring Better still, let us do away with them altogether, and put such amount of insulation as may be recessary on the end-turns of the transformers; such amount of insulation as will take care of considerable strain between the end-turns Then if we use a low-resistance arrester or its equivalent, we shall, I think, have ample protection.

This was the first time I had heard advocated such principles. They must have been considered of particular importance and interest because this very subject is treated in two papers of the present convention. Mr. Kintner recommends the use of a choke-coil within the transformer tank, with no extra insulation on the transformer winding; Mr. Moody recommends the extra heavy insulation of the end-turns, and considers the choke-coil superfluous.

From the points of view of both the designer and the operator or station man, I consider the application of either scheme a retrograde step. In designing we should strive for simplicity in construction. The transformer is a simple and classical piece of standard electromechanical apparatus; to use part of the transformer to perform a duty entirely different from that of transforming and transmitting of electrical energy, viz., the duty of the protective apparaus, endangers the simplicity of transformer construction, and both the transformer and the choke-coil would eventually suffer. This is true whether the choke-coil be within the transformer tank and no extra insulation is used on the transformer coil, or the choke-coil be made an integral part of the transformer by putting extra heavy insulation on its end-turns. From the point of view of the station man, I should expect the protective apparatus to protect the main equipment even at the cost of destruction of the protective apparatus itself.

Therefore I recommend the use of the choke-coil outside of the transformer tank, and also extra insulation on the end-turns of the transformer; but the extra insulated end-turns not at all intended to take the entire duty of the choke-coil. Then if something must break down, it will be the choke-coil outside of the transformer tank. Its cost is only a few per cent. of the cost of the transformer, and the interruption of operation of the power plant will last not more than a few minutes, whereas if the choke-coil is inside the tank, either as a separate piece of apparatus or as an integral part of the transformer, this interruption may last for hours or even days.

We all know that in the case of resonance; that is, when the periodicity of the disturbance, the induction, and capacity coefficient have the following relation:

$$2\pi \sim = \frac{1}{LC}$$

then the phase displacement will have the value

$$\phi = 0$$

and the rush of current will be impeded only by the ohmic resistance

$$I_{max} = \frac{E}{R}$$

and a breakdown follows.

This is what Dr. Steinmetz had in mind when he perpetrated the conundrum: "When is a choke-coil not a choke-coil?"

P. M. Lincoln: I am of the opinion that the choke-coil in connection with high-voltage transmission and high-voltage transformers is a perfectly logical piece of apparatus to use, and the reasons for its use, I believe, are completely, although briefly, set forth in Mr. Kintner's paper and the other papers which deal with the subject. I do not believe we can emphasize too much the value of the choke-coil, owing to the fact of the adjacent turns of the choke-coil having no voltage continually applied between them, as is the case in the transformer. When we come to analyze the matter of putting extra insulation on end-turns of the transformer, we find that it means usually considerably more than is indicated by the paper which was presented by Mr. Moody. Transformers are specified often not only to run upon full voltage, but also to run upon half voltage; also they are frequently specified to be able to run with a delta connection for one high-tension voltage, and a star connection for another; and further, they are often specified to have a range in ratio of 10 or 20 per cent. Therefore, virtually all the taps have to be end taps, with the result that we have to extend that heavy insulation practically from one end to the other. If, therefore, we can take a separate piece of apparatus, such as a choke-coil, and design and install that so that all of these heavy surges which come in can be developed across the turns of the choke-coil, we can thereby save considerable in the transformer and also protect the apparatus to a greater extent.

J. W. Fraser: Looking at this subject from a commercial point of view, I believe that the size of transformers should have something to do with this question. We have on our system, for instance, forty small sub-stations, varying in capacity from 600 kw. to 3000 kw., and will ultimately have a great many more. We practically install four sizes of transformers: 200 kw., 300 kw., 500 kw. and 1000 kw. If we should design each sub-station for large oil-insulated choke-coils, the building would cost considerably more, and the coils would cost nearly as much as a spare transformer. So we have decided to use the coil with large impedance in generating stations where the cost of the transformer warrants it, and comparatively small air-insulated choke-coils, say 20 or 30 turns, in our sub-stations. We make the small choke-coils ourselves at a very small cost. By keeping one or two spare sub-station transformers of each size in stock at some central point of our system we eliminate any chance of a long shutdown.

W. N. Smith: I am disposed to agree with Mr. Kintner in the matter of having separate choke-coils outside the transformer. The tendency toward standardization would naturally incline us toward simplified transformer construction. I look forward to the time when companies operating large transformers will treat them as they do generators, and make their own repairs when they burn out. It frequently happens that when a large transformer burns out, it has either to be sent back to the factory, or an expensive corps of winders has to be sent to the point where it happens to be located. The simpler the transformer coils can be made, the less will be the necessity for such an expensive repair operation. When it is possible for a large power or lighting company with several sizes of transformers to carry in stock a minimum number of standard transformer coils for repairs, economy will result. Viewed from this standpoint, the employment of separate choke-coils will tend toward the standardization of transformers. I also believe it is desirable to have the extra protection of choke-coils for other things than the transformer itself, particularly in a sub-station. Lead-covered cables are extremely sensitive, and as liable to break down as the winding of a transformer, and I believe that the choke-coil is of considerable use as a general protective device in preventing destruction of cables where used in the outside portions of the transmission line, as well as in power houses and sub-stations.

It may be impossible to devise standard choke-coils applicable to all conditions; but as another speaker has said, the power companies are perfectly able to devise them to suit particular conditions.

Another point to consider is the location of the choke-coil in the circuit. That depends to some extent upon the construction of the choke-coil whether it is mounted on a wooden support or porcelain insulators or immersed in oil in an iron case. As surges frequently jump across from a transformer or choke-coil to the iron of the containing case, and can thus make destructive short-circuits, the position of the choke-coil in the circuit should be such that there is some protection outside of it in the shape of fuses or circuit-breakers, particularly if it is to be confined in an iron case. While a believer in the choke-coil, I desire to call attention to this problem of so placing it that a possible short-circuit from some part of it will not cause more damage than it is intended to prevent.

Charles W. Stone: One thing not yet considered is that in one instance a long overhead line was carried into a distributing station, and from this station underground for a considerable distance. In this distributing station lightning-arresters with multiplex connections and choke-coils were installed; the idea being to keep any disturbances which took place on the overhead line away from the cable system. It was found that disturbances occurred in the cable system, and on account of the installation of choke-coils were prevented from discharging across the multiplex connections of the lightning-arresters. Therefore in this case it would be better to have eliminated the choke-coils. The other alternative would have been to put in two sets of static dischargers; one on the overhead line, and one on the cable system, which would have added considerably to the expense and complication. Of course if a choke-coil is placed in circuit and is air-insulated and has a comparatively few number of turns, it might be possible that high-voltage disturbances on the cable system would jump across the turns of the choke-coil, and discharge themselves across the multiplex connections of the lightning-arresters, as just explained by Mr. Berg.

E. E. F. Creighton: I have attempted to make laboratory measurements on choke-coils to determine some method by which we could choose their dimensions, and I think we shall have to go back to the fundamentals to find out just what the choke-coil is for. With Mr. Berg and Mr. Stone, I think that the choke-coil is sometimes disadvantageous. The function of the choke-coil is to prevent or to hold back high-pressure high-frequency surges long enough to permit the lightning-arrester to get into operation. Every lightning-arrester in operation to-day has a certain dielectric spark lag; that is to say, after the potential is applied to the lightning-arrester there is a brief interval, a few millionths of a second, before the lightning-arrester begins to discharge and lower the voltage on the system. If there is no choke-coil between the lightning-arrester and the transformer, the end-turns of the transformer receive this high potential strain during the interval that the lightning-arrester is getting into operation. These high-frequency disturbances nearly always come from an external source; consequently the practice has been to place the lightning-arrester on the outside of the choke-coil. If the lightning is internal, the choke-coil is then more or less disadvantageous according to its value in inductance. One solution of that problem is to use a large inductance in a choke-coil and to place lightning-arresters both inside and outside the choke-coil. A laboratory experiment demonstrates these statements.

The disrupted discharge method is used with the following apparatus: two choke-coils representing the two choke-coils in the line, a spark-gap on the outside of the choke-coils, on the side the disturbance is coming from, and another spark-gap on the inside of the choke-coils.

The circuit can be better illustrated by Fig. 1. The outside gap is in the location of the lightning-arrester. Now produce a discharge on the outside; set the outside gap so that it will spark, and the spark at the inside gap is comparatively small and weak. On the other hand, open the outside gap until the potential can no longer bridge the gap, and the potential on the inside gap will rise to such a value as to give a spark more than twice as long as the outside gap. On one test, the outside gap was not sparking with a setting of one inch, and the inside one was sparking with a setting of two and one-half inches.

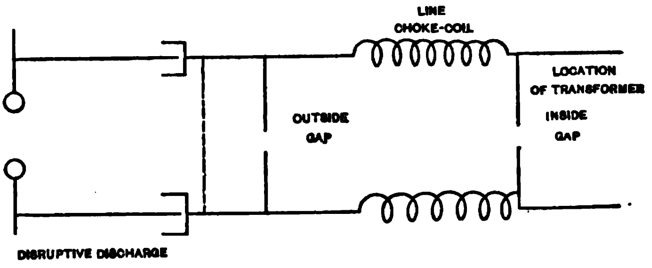


Fig. 1

It seems to me that is sufficient proof, either that this choke-coil should be protected on the inside, or the choke-coil made small enough so as not to magnify the potential on the inside. It is usually a difficult matter to explain just why higher potentials occur on the inside. In this case, of course, the potential came from the outside.

An experience I had last Friday would perhaps be of interest, showing that even with very high values of inductance the transformer cannot be protected from the high potentials. In making some tests on insulators to determine the gap necessary to place on horns in parallel with the insulator to protect it, a condenser was placed across the transformer operating at about

75,000 volts. After three or four strokes, the transformer insulation broke down inside, and on making an examination of it we found it was not the end-turns which were affected, but the third coil down from the end. This transformer is designed to operate at 100,000 volts, and has been used for hundreds of thousands of discharges. We have, however, always used a protective device in connection with it. In the test I refer to it was used without protecting device. In that case you can see there must have been some combination of inductance and capacity giving a resonant condition, which produced high potential very far internally in the transfoimer. The subject is not simple.

William McClellan: I have advocated external choke-coils and shall continue to do so until there is produced a good low-resistance lightning-arrester with the attributes of an ordinary safety valve; in other words, until the potential at the transformer terminals can be kept practically constant. Extremely low-resistance fuse-arresters work quite well, but they are not self-renewing. Certain types of the horn arrester have given some satisfaction, but they are uncertain. The real question is not so much shall an external choke-coil be used, but shall it be a simple air-insulated coil of a few turns, or an elaborate oil-insulated coil in separate case.

W. S. Lee: As an operating man I am in favor of both choke-coils and extra insulated end-turns. I am continually trying to improve the lightning protective apparatus by putting on first one kind of choke-coil, and then another. Our company is in favor of heavy insulated end-turns and want them on all transformers, for in practical operation, when lightning from the line strikes into the end-turns, we usually find that it goes to the case at entrance to transformer, or burns the terminals off. As Mr. Fraser has told you, we have in the neighborhood of forty stations on our line, grouped about at different places. Some of these stations operate a group of cotton mills that owns the station. We have attempted to put protective apparatus at all of these places but it is not easy to get the mill owners to invest in expensive choke coils. However, in our large plants we are installing the choke-coil and getting satisfactory results.

R. P. Jackson: Mr. Moody's statement, that the disturbance is likely to proceed into the tansformer some distance in feet, is, in a way, aproximately true. I think, however, that a better way of measuring the penetration disturbance would be in henrys. Tests I have made indicate that disturbances of the commoner kind will penetrate into the transformer windings, roughly, about 0.04 to 0.06 henrys. A choke-coil of that value put outside the transformer will cause the disturbance to be absorbed or reflected, and very little will go through into the transformer. That value for a choke-coil, 0.04 henrys, is pretty high for a small transformer of low voltage, but insignificant for a high-voltage transformer.

In a paper read by me before the Institute last December, a curve was given indicating that a zero choke-coil would reflect a zero surge, and that the larger the choke-coil the more surge was reflected, with a descending curve something like a logarithmic curve. About 30 per cent. of the disturbance would penetrate through a coil of 0.04 to 0.06 henrys, while very little additional gain was to be obtained by increasing the size of choke-coil. At that point, about 70 per cent. of the surge was reflected, or failed to appear any farther in the windings, so it would seem that if extra insulation were to be put on the proper number of end turns to get safety, we should cover approximately the number of henrys previously given; or 0.04, not considering the iron, which would be a reasonable amount for this extra insulation to be placed upon.

I doubt if any harmful effect from choke-coils occurs very often. The damage to a transformer as the result of switching is usually the result of a sudden change of potential at the terminal of the transformer. Mr. Tobey's paper indicates that the breakdown of the spark-gap at the terminal of the transformer causing a breakdown of the insulation between the turns, is simply a case where the terminal suddenly dropped in potential while the rest of the transformer winding had a comparatively high potential; the result was that the charge on the interior windings attempted to get out at the point of low or zero potential, resulting in a breakdown between turns. A choke-coil at the terminal of a transformer will simply make this change of potential at the terminal more slow in occurring; that is to say, this sudden change occurs at the terminal of the choke-coil instead of at the terminal of the transformer, so that unless the cases are very special—something I have not encountered—the disturbances, whether from the inside or the outside, will be dampened out; their effect on the transformer will be much less if there is a choke-coil of some appreciable inductance than if there be no choke-coils. In other words, the disturbance reaches some distance into the windings from the end or terminal, whether this be the terminal of the transformer, or of the choke-coil.

If the electrolytic lightning-arrester makes good its promise, I think there will be a fair chance of either omitting the choke-coil entirely or making it much lighter, because the electrolytic arrester will be able to keep the potential to a fixed point at the terminals of the transformer.

"When is a choke-coil not a choke-coil?" was, I believe, propounded by Dr. Steinmetz sometime ago. This conundrum has very little bearing on practical matters. If the frequency is so high that, due to condenser effect, it will go through a choke-coil, it will also go on through the transformer for the same reason, and do no damage in either case, so that then one can truthfully say that when a choke-coil is not a choke-coil, there is no need of a choke-coil.

C. P. Steinmetz: The purpose of the choke-coil is to protect the station apparatus against the entrance of high voltage. Therefore, the choke-coil must be between the apparatus to be protected and the source of high voltage, that is, the transmission line as the main source. The choke-coil must therefore be immediately at the transmission line, next to the lightning-arrester. As a good and convenient location for the choke-coil, I recommend the transformer tank. That means, however, that the transformer must be the first piece of apparatus on the transmission line. This is seldom the case. Frequently a number of transformers feed together into high-potential bus-bars and a number of transmission lines are operated from the same bus-bars. In that case, then, we have the transformer switches between the transformer and the high-potential bus-bar, and the feeder switches between the bus-bar and the transmission line. Now, these high-potential bus-bars, the transformer switches, the feeder switches, the current transformers, the connection of the potential transformer —all must connect in between the choke-coil and the transformer; otherwise these different pieces of apparatus are not protected by the choke-coil. This appears to me rather to make the arrangement complicated and impracticable where the choke-coil is desired in the same case with the transformer. Furthermore, we must consider that the choke-coil receives lightning potential; that is, it requires a much more careful installation than the transformer, and the liability to puncture by discharges jumping across surfaces, etc. at the entrance to the choke-coil is much greater than that with any other apparatus and it appears to me the immediate neighborhood of the choke-coil to other apparatus is just as undesirable as that of the lightning-arrester. To avoid this difficulty one very simple way is to have no insulation but air, and it may then be feasible to put a choke-coil out-doors, up on the poles between the transformer station and the lightning-arrester house, where such exists. In those cases where there is other apparatus between the transformer and line, then in addition to the choke-coil which is on the line we require either a second choke-coil at the transformer, or special protection of the transformer, because the transformer also is a source of high potential, as Mr. Thomas showed us some years ago, and we have to guard against that also. The simplest way is the extra insulation on the transformer, which in this instance appears not as alternative to the choke-coil on the line, but as a protection against self-destruction of the transformer, in addition to the protection afforded by the choke-coils against the entrance of high potential from the outside.

The second point I desire to draw attention to is the curious experiment of Professor Creighton, where at the point beyond the choke-coil the voltage of the disturbance was greatly increased. Let us, for instance, consider the transmission of 10,000 kw., at 33,000 volts, 60 cycles, three-phase 33,000; volts between lines means 19,100 volts from line to ground, and 175 amperes per line. Assuming the choke-coil to consume one per cent. of the voltage, that is, a very large choke-coil, as proposed, this gives a reactance:

$$x = \frac{191}{175} = 1.09 \text{ ohms},$$

hence an inductance:

$$L = \frac{x}{2 \pi N} = 2.88 \text{ mh.}$$

This choke-coil is interposed between the line and the station wiring, which station wiring also has a certain electrostatic capacity, though small it may be. That means you have an inductance in series to a capacity.

Estimating the capacity of the station wiring, that means of the connection from the choke-coil to the transformers over the different switches, circuit-breakers, bus-bars, etc., as equivalent perhaps or of a magnitude of something like 50 feet of wire, that would give you a capacity of about

$$C = 0.0002 \text{ mf.}$$

The frequency or resonance of this combination of capacity and inductance in series would then be:

$$N = \frac{1}{2 \pi \sqrt{LC}} = 200{,}000 \text{ cycles},$$

approximately. Any disturbance, wave, impulse or oscillation, coming from the transmission line and approaching this combination of choke-coil and station wiring, if of this frequency, or containing a component of this frequency, meets resonance, and the choke-coil generates voltage, raising the voltage in the station to—theoretically—infinity. Well within the range of lightning frequencies is 200,000 cycles; that is, impulses of static induction from the clouds, etc. A large choke-coil even with moderate voltage may build up, due to the inductance of the choke-coil in series to the station capacity, and produce a high voltage, and instead of protecting, the choke-coil so may produce destructive voltages, by resonance with the capacity of the station wiring. That is, a large choke-coil may be a source of danger, and this danger must be kept in view. At much higher frequency, and lower capacity and inductance, this phenomenon was shown experimentally by Professor Creighton: the inductance of the choke-coil in series with the capacity of the connection back of it, raising the voltage of the leyden jar discharge to the much higher value observed beyond the inductance.

The conclusions to be drawn therefrom are that the length of wiring between the choke-coil and the transformer should be as short as possible, and that the choke-coil should be of as low inductance as possible; that is, as low an inductance as will still give a sufficient decrease of the steepness of the wave-front to allow the lightning-arrester to take up the discharge; but not more than that, because any increase beyond that inductance lowers the frequency of resonance and therefore increases the liability of picking up destructive voltages from line impulses. These two conditions should be very carefully adhered to: the lowest possible static capacity of the circuit between the choke-coils and transformer end of the line, and the lowest possible inductance of the choke-coil which still gives sufficient protection, and with these two limitations I also believe in the desirability of the choke-coil between the overhead line and the station, because it decreases the steepness of the wave-front of the incoming wave, and so acts beneficially.

Ralph D. Mershon: I do not care much for choke-coils, unless they are small enough to be put out of doors. In my opinion, choke-coils inside the station make the station wiring very difficult. If indoor choke-coils are used, they should be inside the transformer case; otherwise, I would rather have the end-turns of the transformers insulated to act as choke-coils. It seems to me there is a good deal of needless objection made to insulation of the end-turns in cases where different voltages must be obtained. Mr. Moody shows how voltage taps can be got without interfering with the end-turns, by varying the number of turns at the middle of the winding, instead of at the ends of the winding. It seems to me that in the case of multiple and series connection, to obtain full or half voltage, a somewhat similar course could be followed, and the same end-turns used for the multiple or series connection. Of course, in such cases, the end-turns will have to be made with a carrying capacity sufficient for the multiple connection. In most cases, I do not think this would be a serious matter.

The depth to which the disturbance penetrates a transformer is a matter of frequency. Until we get further data as to the frequencies which actually occur in practice, it seems to me that we cannot make much headway in determining how far the disturbance penetrates.

In regard to Mr. Tobey's paper, in most cases I have found it very difficult to measure the resistance of large transformers by the fall-of-potential method, because of the difficulty of keeping the direct current perfectly steady. It is not always possible to have a storage-battery for such measurements, and the voltage of a generator driven from commercial circuits generally varies enough to introduce serious errors into the measurement. I would like to know what source of current Mr. Tobey uses in this method of measuring the resistance of transformers in the field.

I judge from Mr. Tobey's paper that he contemplates making the resistance test before the temperature test. It seems to me the resistance test should be made after the temperature test and with the transformer at normal temperature. I gather, also, that he has in mind making the final insulation test before the transformer goes out of the factory. Such practice I do not consider as either proper or safe. A transformer might stand 500,000 volts in the factory; but by the time it has been shipped and installed, it might not be able to stand 5,000. What the customer wants to know is what the transformer will stand after it has been installed and under operating conditions, as regards temperature, etc.

I am rather surprised at the dielectric time-voltage curve given in Mr. Tobey's paper. I had no idea that the dielectric strength of insulation in ordinary use diminished so rapidly or diminished to such an extent as he shows. It would be interesting to know the nature of the insulation on which the curves are made. If the curves are correct, it seems to me that we should have more than a double-potential test of transformers.

If the end-turns of transformers are to be more heavily insulated than the rest of the winding, what is the most satisfactory and intelligent way of specifying such insulation? And what sort of a test can be given the transformer to find out that the end-turns have been insulated in accordance with the specifications?

D. B. Rushmore: In any commercial installation, I think there is no question but that some kind of choke-coil should be installed, and, as a matter of fact, always is installed. The problem is, what kind of choke-coil should be used and what amount of reactance should it have.

The choke-coil is of use in preventing the entrance into the station of current from a lightning disturbance on the line. A lightning disturbance usually takes place during a rain storm when the insulators are wet and break down at the lowest point. The transformers are usually insulated to withstand twice the operating voltage. They will withstand that, and as a matter of fact a great many high-potential transformers will withstand three and a half times normal operating voltage before rupture takes place. If any disturbance occurs on a transmission line, it need only be reduced very slightly in order to protect the transformer, if it has not gone over the insulators.

Lightning disturbances are of a very high frequency, as shown by the short distance which they travel before they break over insulators when the voltage is sufficiently high. The suggestion has been made to protect a station by using fine wires leading into the station, wires of such diameter that an increase of voltage of 75 to 100% above the normal operating value will be above the corona effect on the wires, and thus the automatic disturbance will be largely dissipated outside the power station.

W. LeRoy Emmet: In these high potential disturbances operating through inductive circuits, the danger lies in a condition of elasticity. All of these highly insulated circuits are electrically in a perfectly elastic condition. There is no energy dissipation, and consequently, inductance combining with capacity produces a condition equivalent to that of an efficient spring. If these circuits could be made inelastic, they would absorb such vibrations as Mr. Steinmetz describes. With very high frequencies, small capacities, small inductance may create very high local voltages. It occurs to me that in Mr. Moody's arrangement of insulated turns on the transformer, the practical efficacy may lie somewhat in the fact that the insulation has some power of absorbing energy, and so forms a sort of gradient of potential that penetrates the transformer; whereas with a device like a separate choke-coil, incapable of absorbing any energy itself, that gradient does not exist, and a point of high potential may occur beyond the choke-coil. I had one experience which was perfectly definite, where a choke-coil inserted between a line and apparatus, caused repeatedly the puncture of the apparatus and the failure of the lightning-arrester. It was in a certain case where lightning always came the same way and acted the same way on the circuit. When that choke-coil was put in, the lightning made trouble, and when the choke-coil was out, the lightning made no trouble. In such a case we have a vibrating system with conditions very difficult to predict. If we could have inside the choke-coil or somewhere near the terminal of the transformer some means of dissipating energy, something that would absorb the impulses of high period and voltage, it would kill the resonance, and it seems possible that the leakage and dielectric hysteresis in the insulation may do this; local absorption of energy in the iron may also effect the condition. The electrolytic lightning-arrester should be applicable. It seems to me that some effort in these directions might be expected to give good results.

O. S. Lyford, Jr.: There is one important feature of the choke-coil proposition which I have not heard discussed since I came into the meeting. In his list of objections to choke-coils as now used, Mr. Kintner omitted an important objection to a coil of high reactance immersed in oil; namely, the use of additional high-tension terminals carried out through a grounded case. In a high-voltage transformer station equipped with oil circuit-breakers and choke-coils we now have seven or eight such high-tension terminals per phase; two, or possibly three, for the main transformer, one for the series transformer, two for the choke-coil, and two for the circuit-breaker. Insulation failures occur most frequently in the bushings around such terminals, and it is therefore very desirable to minimize the number of such terminals. Putting the choke-coil inside the transformer case, as proposed by Mr. Kintner, is a step in this direction and also takes care of the point which Dr. Steinmetz raised, that the choke-coil should be as near the transformer winding as possible, but it leaves us still in a dilemma, as we have not afforded to the circuit-breaker and series transformer such protection as the choke-coil gives to these devices. Mr. Kintner claims that a choke-coil affords a fixed amount of protection to any apparatus placed back of it and to obtain this protection we desire to place the choke-coil between the line and all other apparatus.

One logical way to take advantage of Mr. Kintner's suggestion and at the same time minimize the number of high-tension terminals and put the maximum amount of equipment back of the choke-coil, is to put the whole outfit, choke-coil, circuit-breaker, series transformer, and main transformer, all in one tank. There would then be only two, or possibly three, high-tension terminals per phase, and all the apparatus except these terminals would be protected by the choke-coil. I believe this is a practicable arrangement and I recommend it for your consideration.

H. W. Buck: This discussion for and against choke-coils sounds a good deal like a conference on the subject of church unity. Every man is setting forth certain dogmatic beliefs which he has for or against choke-coils. One man may have had a certain experience under a certain combination of circumstances with a choke-coil, which has led to the destruction of his apparatus, and for all time thereafter he condemns choke-coils. The next man has had very good success during certain seasons with similar appliances, while he had choke-coils on his system, and for that reason he is equally certain that the smooth operation of the system has been because of the choke-coils. Both conclusions are probably without any ground whatever. The circumstances which lead to surges of potential which bring destructive results to electrical apparatus have an infinite number of combinations: they depend upon the length of the circuit, the number of sub-stations, the size of the transformers, the transmission frequency, the particular character of the country where the lightning stroke took place, the voltage of the line, the conditions of operation at the moment, the load on the line, the question whether any circuit-breakers went out at the moment or not, etc. Under these conditions, in my opinion, it is absolutely impossible to calculate the problem beforehand mathematically, and equally impossible to demonstrate it experimentally. General conclusions can be figured under a given set of circumstances mathematically; or the transmission system can be set for a certain set of conditions, experiments made, and conclusions reached, but as to whether a choke-coil can be condemned as a universally useless piece of apparatus or praised as an apparatus which cures all lightning or surge troubles cannot be decided at the present moment, and in my opinion can never be conclusively decided.

S. M. Kintner: Mr. Pikler apparently misunderstood me when he took the stand that I recommended the use of choke-coils inside the transformer case. I did not offer that as a recommendation, but merely as a suggestion of a means by which some objections made to the use of choke-coils might be overcome.

Professor Creighton has shown the results of an experiment in a diagram upon the board, and quite general conclusions have been drawn from it. I would like to show by a sketch an experiment I made, and state the results obtained. The experiment was quite simple. This was also a laboratory experiment. I arranged the apparatus as shown in the following sketch, Fig. 2.

In this diagram it will be seen that a static machine (Holtz or one of that type) supplies a charge to an insulated sheet of tin which represents a cloud. Directly below this sheet is another, also insulated from earth, which represents the capacity of a transmission line both to earth and to the cloud. The imitation transmission line leads into a metal box which can be considered as representing the power-house building, or even the transformer-case which is always of metal and grounded. Gap A represents the lightning-arresters, while inductance coil *L*, condenser *C*, are representative of the transformer. Spark-gap *B* is a measuring gap and is used in determining the momentary voltage maximums to which the transformer windings may be subjected in strains to ground when charged clouds in the vicinity of the power-house were discharging.

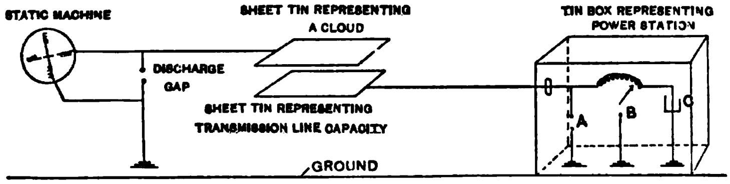


FIG. 2

In brief, the results of the tests showed that gap *B* never discharged when it was larger than gap *A*, and the general conclusion drawn was that a transformer protected by a lightning-arrester would not be subjected to shocks, due to bound charges inside the transformer when they were released by a cloud discharge in the immediate neighborhood, that were in excess of the voltage setting of the lightning-arrester.

W. S. Moody: Of course the purchaser can specify the amount of insulation, or the test that it should be capable of withstanding, but it is hardly practicable to make tests to check this in the finished apparatus. I think the best that can be done in the way of testing is to make up a sample coil with insulation identical to that which will be used in the transformer, and then test the sample. I believe that if we use insulation between layers which will withstand something like 25 per cent. of the line voltage for the outer portion of the winding, we will have a very safe design. Theoretically, a uniformly tapered insulation should be used, but practically, it is out of the question to make more than two or three steps in the amount used. We start with an insulation between adjacent turns or layers that will stand 25 per cent. of the line voltage, and taper this in two or three steps to the normal insulation at a point, say 200 feet, within the winding.

Ralph D. Mershon: To what percentage of the total winding would you give the heavier insulation?

W. S. Moody: I do not think that we can attempt to determine this with any great accuracy. In most transformers 200 ft. should give a length which would absorb any voltage which a good lightning-arrester will not discharge if the voltage is really what is commonly known as high frequency.

H. W. Tobey (remarks made before reading the paper): In the preparation of this paper, the idea was to describe in general some of the more important features of up-to-date transformer testing and also to outline a few of the methods which have been proposed and for one reason or another have been discarded. (Mr. Tobey read the paper, and then replied as follows to various questions):

We find we have usually obtained better results by using a storage-battery for the source of direct-current supply than by using an exciter. If an exciter is used, it is usually found desirable to place in series with it and the resistance to be measured, an auxiliary resistance of such value that the exciter may be operated at approximately normal voltage. Under these conditions, there is ordinarily but trouble due to unsteady voltage. We have felt, as I said in the paper, that it was rather better to make the high-potential test before the heat run, so that in case the insulation was injured by the latter test, the fact would become known during the heat run. There is no other reason, however, why the order of the tests could not be changed if thought desirable.

As to the curve referred to in the latter part of the paper, I may say that it was based on tests made on paper insulation and was purposely selected because it showed a marked difference in dielectric strength between the short time test and the long continued test. The difference is more marked in this curve than we find in ordinary insulation. Usually the change is perhaps 30 per cent.; that is, the dielectric strength would be 30 per cent. less in continued operation than when subjected to an instantaneous test. Attention should also be called to the fact that the sample in question consisted of one thickness only, whereas ordinarily in transformer construction the insulation is made up from a number of laminations so that the factor of safety is well on the safe side.

E. J. Berg (by letter): To me it would seem that relatively small reactive coils and reinforced insulation of the end-turns afford the best protection.

The breakwater analogy used in Mr. Kintner's paper is perhaps as close as any mechanical comparison could be, but it must be remembered that waves are set up on each side of the breakwater and that the apparatus to be protected is located on one side thereof. Consequently, whereas the breakwater affords a good protection for a wave coming from the outside it is objectionable for waves coming from the inside.

Briefly, since not only the line, but electrical apparatus connected to the line under certain conditions that are brought to a very high potential above ground and are suddenly discharged through the lightning-arresters, it is obvious that whereas the reactive coil between the apparatus and the lightning-arrester will afford a protection from the surge which comes from the line, it would be detrimental for the surge which comes from the apparatus itself.

Unfortunately, the inductance and capacity of the electrical apparatus is very small compared with that of the line, or a reasonable section thereof, therefore the frequency of discharge of the apparatus is much greater than the frequency of the discharge of the line. A reactive-coil which has a considerable reactance for the line frequency has an enormous reactance for the surge from the apparatus and therefore may prevent its reaching the lightning-arrester, and may even intensify the voltage.

A practical demonstration of this action of reactive-coils was found some years ago in a commercial installation where reactive-coils of rather high inductance were installed between the lightning-arresters and the apparatus. Upon inspecting these coils after some lightning storms, it was found that discharges had taken place between the inside lead of the coil and ground, discharges representing very considerable voltages. In view of this and the reasons given above, it has seemed best to the writer to use air-insulated coils, which, to be sure, have relatively small reactance, but which are self healing, for excessive voltages they act as an additional number of gaps. The discharge from the transformer being able to reach the lightning-arrester over the turns instead of through them, obviously, insulated reactive coil would not answer in this case.

B. C. Shipman (by letter): The reasons for using a separate choke-coil, as given by the author, far exceed the reasons against it, both in number and force, I think the matter is generally so regarded. To depend on the insulation of the end-turns only, for protection, is hazardous. Even if trouble is escaped in nine cases, the tenth may cause very disastrous results, far outweighing any disadvantages of an additional piece of apparatus, or complexity in wiring. If it be granted that the choke-coil performs the service expected of it, it seems to me to be better engineering to hold up excessive surges and potential strains outside of a transformer, rather than to admit them and then attempt to withstand them by extra insulation. Injury to a choke-coil is comparatively unimportant; to the transformer it is serious.

The reactance of the turns of the transformer-coils themselves will vary according as the transformer is open-circuited on the secondary or not; if not open-circuited, with the load connected. In the latter case, the reactive effect of the primary being less, the extra insulation would have to extend farther into the coil than if the secondary were open-circuited. I recall one instance where three 2000-kw. transformers were connected to the transmission line, but only two were supplying current from the secondaries, the third being open-circuited. A lightning disturbance entered the station, and, passing the protective devices, broke down the insulation between turns of the idle transformer, while it left the working transformers uninjured. This I attributed to the greater choking effect of the idle transformer, causing a steeper gradient of voltage in its coils.

Regarding the advisability of putting the choke-coils in the same case with the transformer, it might be desirable in certain instances for special reasons, but in general I think it would be bad practice. There are enough complications now in a high-tension, multi-tapped, water-cooled transformer, and the interior is hard enough to get at without making it more so.

I agree with Mr. Moody on the desirability of reinforcing the end-turns of transformers, not, however, to take the full force of the extra strains, but to be able to withstand whatever portion of such strains that passes the choke-coils.

Frank G. Baum (by letter): It has been my experience that trouble due to lightning rapidly disappears as the insulation of line and apparatus improves, and when the insulation becomes what it seems it should be, the lightning trouble practically disappears. That lightning trouble is largely a matter of insulation is proved by the fact that, where 15,000-,25,000-, and 60,000-volt lines all pass through the same country, the trouble generally appears on the lower voltage lines. I doubt very much if a first-class insulator will be punctured even by a lightning bolt striking the tower, because it would seem to be very much easier for the lightning to go to the structure direct.

In the protection of a line against lightning in the section of the country where very severe lightning is prevalent, it is not a question of one method versus another, but all the precaution that can be taken at reasonable expense. In some sections extra insulation could be used, on the transformers, choke-coils externally, lightning-rods or ground-wires on certain sections of the line, also horn gaps at certain places to protect against high surges, these horn gaps probably having some resistance connected to ground. It is quite certain, however, that on a high-voltage, high-power transmission system the ordinary spark-gap arresters are useless.

A. C. Pratt (by letter): I believe thoroughly in the desirability of providing extra insulation on the outer turns of a static transformer and placing the taps for voltage adjustment near the middle of the windings. I advocated this method in 1904 in discussion of a paper by Mr. Moody and brought out the further advantage that in case the transformer is operated with less than the total high-tension winding in service, the maximum pressure to ground from the outer turns of the winding is normally never more than that from line wire to ground, which is not the case if the taps are next the outer terminals of the winding.

After eight years' experience and observation on lines operating at from 10,000 volts to 60,000 volts, I am in favor of separate choke-coils in all ordinary cases, and for substantially the same reasons as set forth by Mr. Kintner; I would however favor somewhat heavier insulation between the outer turns of the transformer than between the inner turns, as the outer turns are doubtless often subjected to quite severe strains due to switching and to the inability of the choke-coil to afford complete protection under all conditions. There seems to be no doubt as to the ability of the choke-coil to afford a very large degree of protection.

James Lyman (by letter): The resistance offered to a line disturbance depends directly upon frequency. The frequency of a surge, whether from a short-circuit, ground, or lightning discharge, may be anything from the normal frequency of the line current to a million cycles per second. If the frequency is low, as is the case with many induced lightning charges, the choke-coil offers practically no resistance. Therefore, the transformer windings should be insulated to stand such strains as will not readily be discharged over the lightning and static arrester. A form of choke-coil consisting of 20 to 50 feet of solid copper conductor wound on mandrels 5 or 6 in. in diameter with 0.25 in. air clearance between turns, takes practically no extra room and offers considerable resistance to high-frequency discharges. Extra insulation to the outside turns in high-tension transformer-coils is also recommended as an additional protection against abnormal voltage caused by high-frequency disturbances. The added insulation does not materially increase the size of the transformer, but taken together with the small choke-coils and lightning and static arresters of a reliable design give the most satisfactory results. Where choke-coils of 400 ft. of conductor have been installed between the lightning-arrester and transformers, instances of discharge across the transformer-coils have occurred, indicating a rise in voltage due to the reactance of the choke-coil in preventing the discharge of the transformer. It is my opinion, therefore, that large choke-coils are not always a protection, and, considering other objections to them, they should not be used.

Farley Osgood (by letter): I think it is better to keep the insulation of the transformer as nearly the same throughout as possible, as it saves expense and saves space in the transformer case. I can see no reason for insulating the choke-coil unless it is to be placed in a position where there is insufficient room to carry bare copper, and, generally speaking, the position would not be a good one for any high-tension equipment. If the choke-coil is made without insulation, its perfect condition or damaged state can be quickly and clearly seen, which might not be the case with an insulated coil.

The proper position for choke-coils is in the high-tension chamber, where there should be sufficient room as to make the. matter of this slight additional equipment, which virtually requires no attention, of very little consequence from a complication standpoint.

My experience has been that choke-coils are a real benefit on voltages of 33,000 or greater, and, therefore, the use of the coil is recommended in all cases.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

NOTES ON RESISTANCE OF GAS-PIPE GROUNDS

BY J. L. R. HAYDEN

Earth connections in electric circuits are frequently made by driving a gas pipe into the ground. Such grounds are of fairly high resistance, and therefore not permissible where a low resistance ground is required. Their great simplicity and cheapness makes them desirable, where very low ground resistance is not necessary, as for discharging static charges, earthing overhead ground-wires, etc. To get data on the resistance offered by such gas pipe grounds, their permanence, and the variation of the resistance with the seasons, an investigation was started two years ago.

Three gas pipes of 2.5 in. diameter were driven into the ground at distances of 15.75 ft. between I and II, and 7.4 ft. between II and III, in the lawn adjacent to Dr. Steinmetz's laboratory. The soil is a clay loam, overlaying shale rock a few feet below the surface. The pipes are driven into the following depth:

I. 3.75 ft.
II. 2.75 "
III. 3.10 "

The resistance of the three grounds was measured with an alternating 60-cycle current of 120 volts, and as return ground was used the system of the city water pipes. This return ground showed to be less than 0.01 ohms. It was therefore neglected.

Readings were taken at irregular intervals from August 1905 to August 1906, and daily from September 1, 1906 to date: during fall and spring, morning and evening readings were taken to see whether the daily temperature variation had any effects. These however, were found so small that in the attached curves the daily average has been used.

Fig. 1 shows the variation of the three ground resistances during the whole period, and Figs. 2 and 3 the variation from September 1906 to date, in larger scale, so as to show the daily values. The values are given in amperes at 120 volts 60 cycles, and so are proportional to the conductivity.

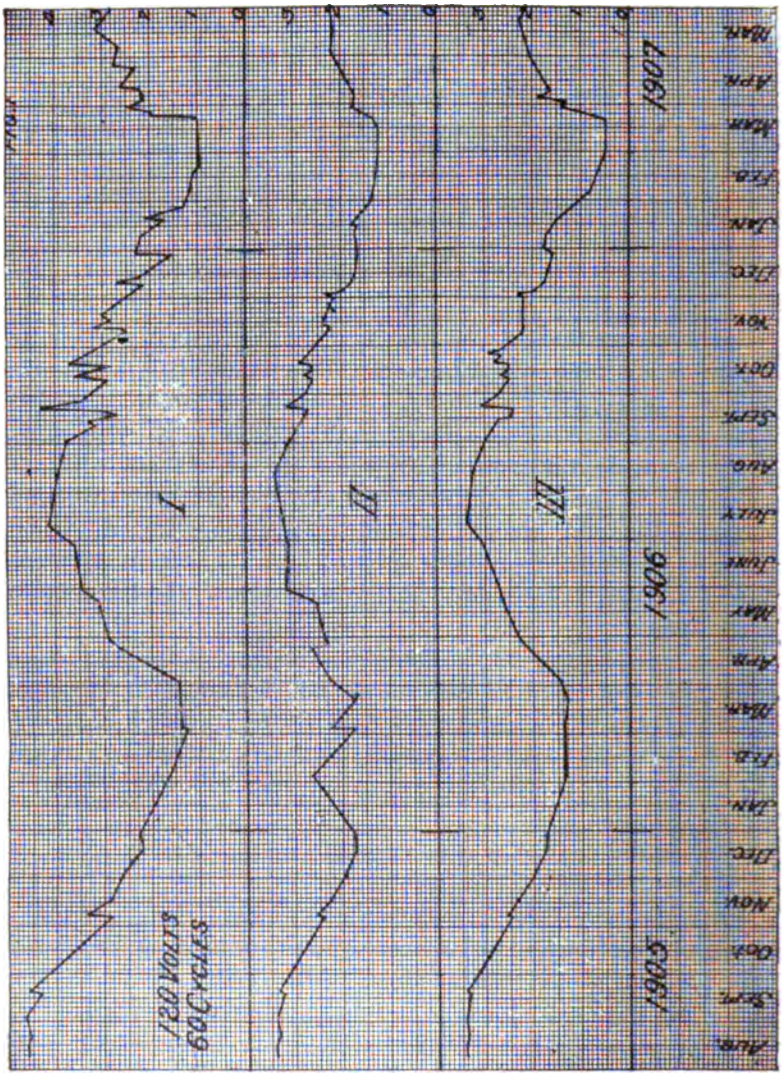


Fig. 1

The lower curve gives the daily average of **temperature**, **and** the rain fall, the height of the black line giving approximately the intensity of the rain fall.

The curves show very plainly the sudden rise of conductivity

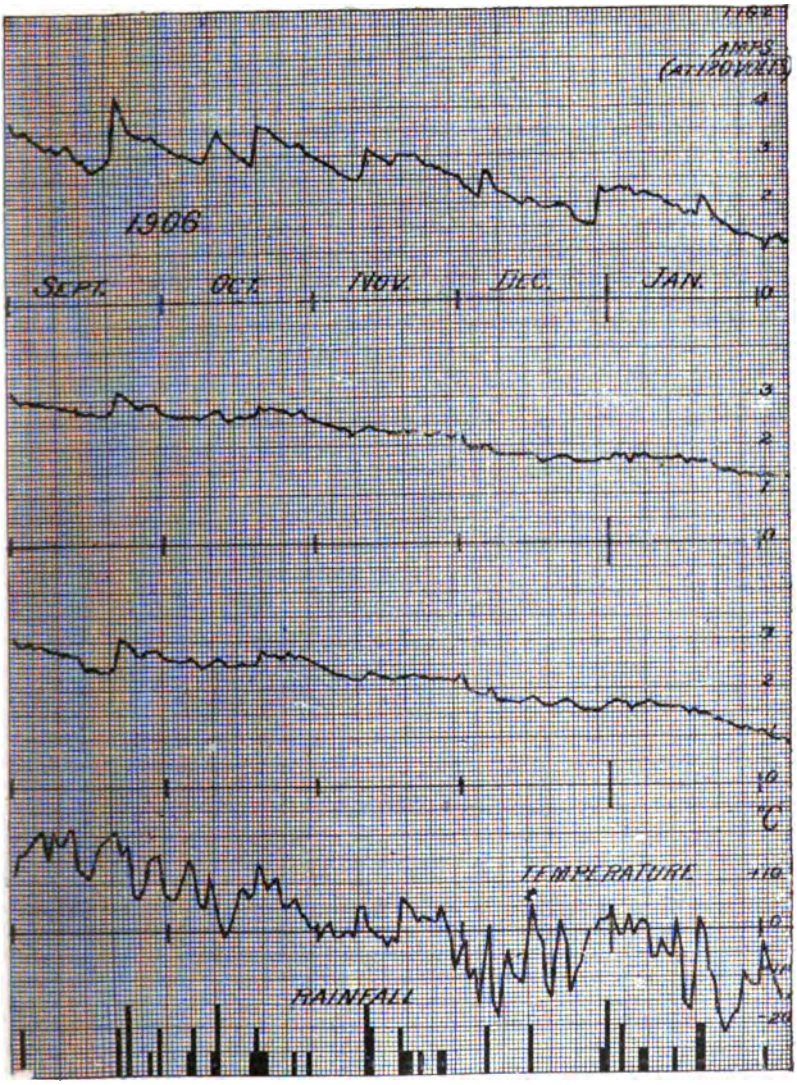


Fig. 2

at rain fall, and the gradual decrease during the following dry period. The maximum of conductivity occurs in July and August. This was rather unexpected, since the wet season is in spring. It seems that the increase of conductivity of the moisture at high summer temperature amounts to more than the increase of moisture during the wet but cooler spring season.

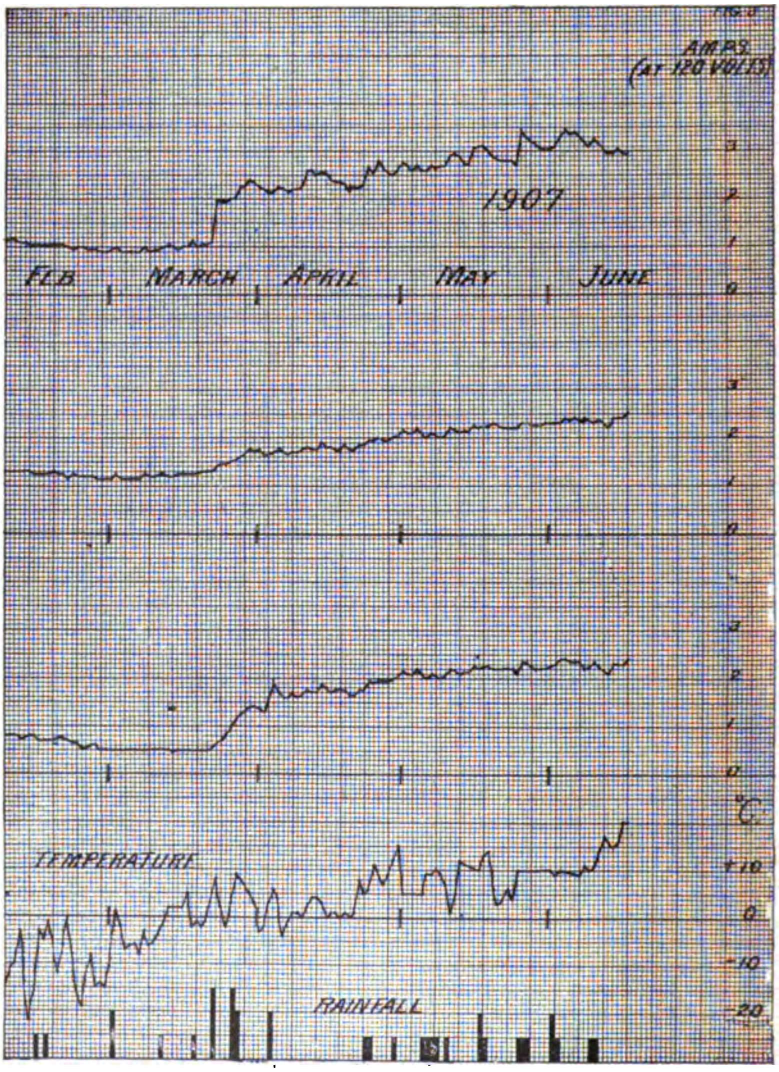


FIG. 3

The minimum of conductivity is towards the end of March. Since thunder storms occasionally occur before this period, this feature requires serious consideration. So far the values of the present year approximately repeat last year's record, except in winter: during the last winter the conductivity decreased to very much lower values than in the previous winter. Whether this was due to the greater severity of the last winter, must remain for further investigation.

Interesting is the great difference between the three grounds although closely adjacent to another. Ground I shows the effect of rain fall and dry periods very much more than II and III. II and III during summer are very closely the same, while I has a considerably higher conductivity, about 30%. From October onward the conductivity goes down, and towards the end of December, II and III, which until then were very closely alike, begin to differ; III decreasing much more rapidly, to a minimum in March, of less than 0.5 amperes or less than one-sixth of the summer value, while II reaches a minimum of 1.15 amperes or about one-third of the summer value, and I, which has been of higher conductivity during summer, falls below II towards the end of January, reaching a minimum of 0.9 amperes. Towards the end of March all three grounds rapidly rise in conductivity, with the spring thaw, in the beginning of April. II and III are again alike, and I of higher conductivity than the other two.

It seems herefrom that such gas-pipe grounds are permanent at least for some years, but show a marked annual variation, the conductivity greatly decreasing during winter. But, against expectations, even at the winter minimum, a very appreciable conductivity is left. The most important conclusion is, however, that such grounds show very great individual difference in their annual variation, even when closely adjacent to each other. This matter requires a further and more extended investigation, which has been started and will be reported upon at a future time.

An interesting and useful feature observed was that by the passage of an alternating current through the pipe into the ground, the conductivity gradually increased, for instance:

Circuit closed at noon:

0	hours after:	3.40	amperes at 120 volts
7	" "	3.90	"
9	" "	4.33	"
22	" "	4.42	"
43	" "	4.50	"
52	" "	4.69	"
75	" "	4.78	"
103	" "	4.74	"
120	" "	4.73	"

Circuit opened at noon:

0	hours after:	4.73 amperes	at 120 volts.
7	" "	4.02	"
23	" "	3.62	"

Appendix

As the daily measurements of the gas-pipe grounds have been continued during the time which has elapsed since the reading of the above paper, in Fig. 4, the record of Fig. 1 is continued to the middle of February 1908. As seen, the curves in Fig. 4 show the same characteristics and the same values as in Fig. 1:

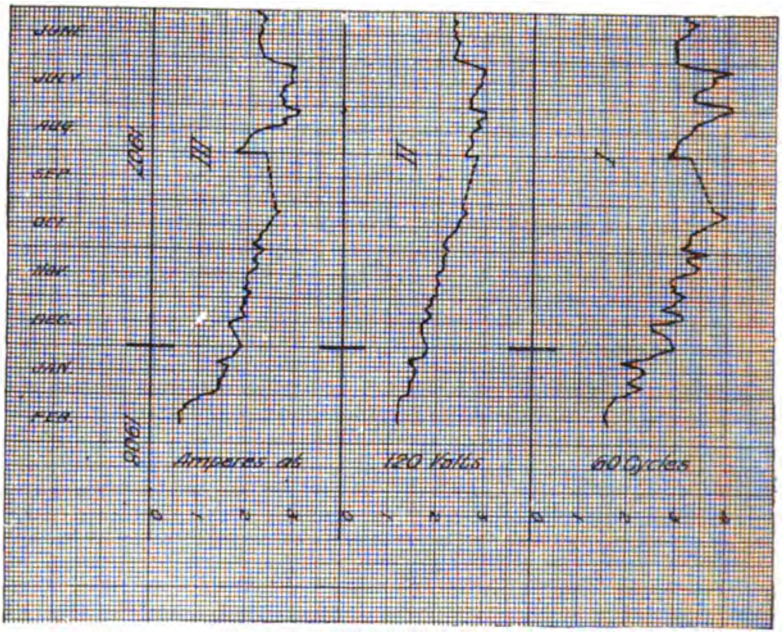


Fig. 4

I gives a higher summer maximum, and a far greater variation of the conductance with the rainfall; II and III are practically alike until the arrival of very cold weather, which this year occurred at the end of January, when III went far down below II in conductance, just as it did in former years.

It seems, herefrom, that at least during the period of observation, of nearly three years, the gas-pipe grounds showed no permanent change, but merely periodic variations with the seasons of the year.

DISCUSSION ON "NOTES ON RESISTANCE OF GAS-PIPE GROUNDS" AT NIAGARA FALLS, N. Y., JUNE 26, 1907

Chas. P. Steinmetz: It seems that the continuous passage of an alternating current through such a gas pipe to the ground increases the conductivity. This test of increase of conductivity was made in the summer time. It stands to reason that during winter the increase will be very much more because of the melting ice. The curves given in the paper show interestingly how towards the winter the conductivity gradually falls and reaches the minimum towards the end of March and then very suddenly jumps up. It also shows many times after a rainfall a sudden rise of current which gradually fades out, and how all three grounds go together until the end of the year and then the one current becomes very small, while the other is still high, and the low resistance ground has reached a higher resistance than one of the high resistance grounds.

This is only a preliminary report, but it is interesting to know that such a gas-pipe ground, which has been called bad names for a long time, seems to remain a ground even in winter when everything is frozen, even if it does not come below the frost line. It is naturally not good enough to discharge a large current, but is good enough to dissipate all electrostatic discharges which may accumulate in the line. It remains to be investigated whether grounds in different places, different soils, etc. may not give still greater values and show different results.

Ralph D. Mershon: Why not extend these investigations to other forms of ground? Why not compare pipes with some of the other forms of ground?

Chas. P. Steinmetz: That is what Mr. Hayden is arranging to do, to start an investigation on a larger scale. There have been a number of suggestions already made, in connection with gas-pipe grounds, of filling the hole up with coke and salt and other materials. It remains to be investigated, whether there is any benefit in digging a hole and filling it with coke, or whether driving a pipe into the ground is not nearly as good. Another question is as to how the character of the surroundings affect the ground, whether to drive the ground pipe in the middle of a road, or to drive it under trees. We are putting down a large number of these gas pipes scattered over the college grounds at Schenectady, and expect to get further results from these tests.

F. B. H. Paine: Do I understand that the gas pipe introduced farthest into the earth has the least resistance?

Chas. P. Steinmetz: The least resistance, or highest conductivity in summer, but in winter it falls in conductivity below the one which was less deep. The shallowest one showed the best conductivity in winter, more than twice the conductivity of the other one, which was a little deeper, and nearly twice the conductivity of the one which was deepest. We measured at lower voltages by putting high resistance in series; instead of 120 volts, 40 or 50 volts gave the same resistance.

P. H. Thomas: If you had 100 amperes it might be different?

Chas. P. Steinmetz: The resistance would probably go down, due to the heating, and so it would show the time effect. Perhaps with high voltages and extremely large currents, but with a range of 120 volts or less the resistance would be constant.

Ralph D. Mershon: We made a somewhat similar investigation. The railway companies were very particular about having our structures grounded near the tracks, and they designed some elaborate grounds, groups of steel rails surrounded with coke. Mr. Nicholson made some measurements on the concrete tower foundations and also the resistance of some of these grounds. First he tried to use a Wheatstone bridge, but the stray currents from different places in the country bothered him. Then he used a modified Wheatstone arrangement in which you make use of the stray current to measure the resistance. He got results which were concordant, but he found that with a voltmeter he could always get a voltage sometimes in one direction and sometimes in the other, between the tower and a pipe driven in the ground. Then he drove two exactly similar pipes in the ground to the same depth, and got a voltage between them. Then he put two pipes in a barrel of water and got a voltage between, and he found he could reverse the voltage by the amount of immersion of the pipe.

F. B. H. Paine: It is my recollection that the same foundation resistances were measured at different times in the year, but certainly during the summer and fall, but I think later on in the winter the variation in resistance was so slight as to be comparatively negligible: it varied between 7 and 10, and 7 and 12 ohms, at different times of the year, the same foundation, not more than that.

N. J. Neall: What is the ohmic resistance of the concrete foundations under the tower?

Ralph D. Mershon: The highest is 20 ohms, and the lowest is 3 ohms from the tower to the ground. These values were got by measuring the resistance between the two adjacent towers and assuming that half the resistance was in each one. I think there is room for further investigation in regard to these grounds, not only as to the ohmic resistance, but as to the part they play in case of surges.

Chas. P. Steinmetz: We are going to try to measure not only with 60-cycle current, but also with the high frequency current, 100 000 cycles.

Ralph D. Mershon: I got one railway company to allow me to dig a trench and put in a strip of copper—they finally agreed to let me put in galvanized iron—with some coke around it to make a good contact with the ground.

Chas. P. Steinmetz: Mr. E. J. Berg some years ago proposed to run a shallow ditch along the line and run an underground wire in the ditch and connect that up with the overhead ground wire and use it as an energy dissipating wire, instead of the ground.

Discussion

F. J. Hoxie (by letter): In 1906 and 1907, I made a series of measurements to determine the amount of protection that could be expected from pipe and plate grounds on lighting systems. The paper by Mr. Hayden shows considerably less resistance for the same area of earth contact than is indicated by my measurements. This is probably due to a finer soil and a greater amount of salts dissolved in the ground water, for plates only a few feet apart in different kinds of dirt and in the water of the same pond show large differences in resistance. References to the resistance of ground plates in electrical literature are generally indefinite, but they give the impression that a copper plate of moderate dimensions buried in permanently moist earth will have a resistance of about ten or fifteen ohms. As this is greatly at variance with the facts, in some parts of Rhode Island at least, the following measurements may be of interest.

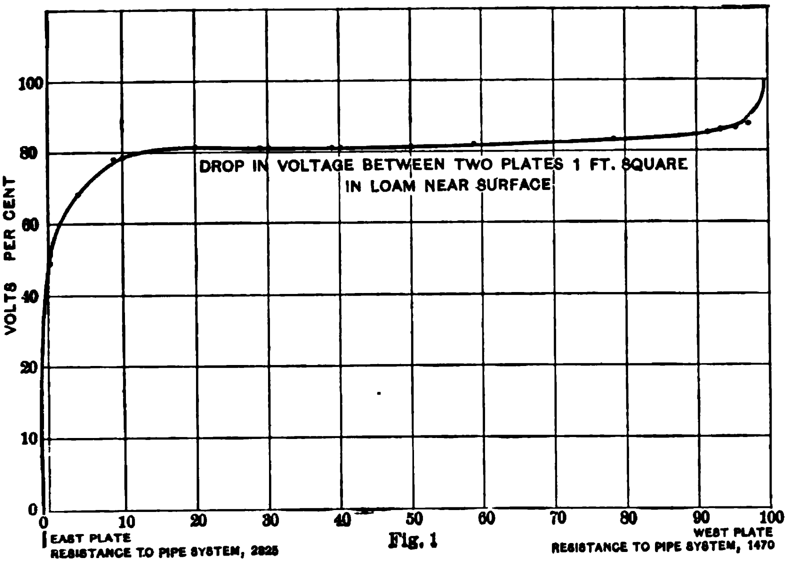


Fig. 1

These measurements were all made in Rhode Island, in a soil very free from soluble minerals. Most of them were made where there is an underlying ledge of granite about 60 ft. below the surface and the ground water level is just above this ledge. Between the ledge and the surface loam the soil is mostly silica, sand, and small stones of varying sizes, unevenly mixed and apparently the result of a violent movement of water in past ages. The well-water contains about 100 parts of mineral matter and the river-water about 30 parts in 1,000,000. The surface loam is of a reddish color, somewhat sandy, and from one to three feet thick.

The resistance of plates or pipes buried in this soil varies so greatly from the figures mentioned above that it is evident that a copper plate of any reasonable size is not a safe ground for a lighting system carrying large currents at moderate potential. By referring to the table of measurements, it will be seen that the resistance of a metal plate one-foot square in the surface loam is about 2000 ohms, in the underlying sand about 11,000 ohms, and in the ground water at the bottom of a well about 300 ohms. Rainy or dry weather makes comparatively little difference to the resistance, except in case of the sand.

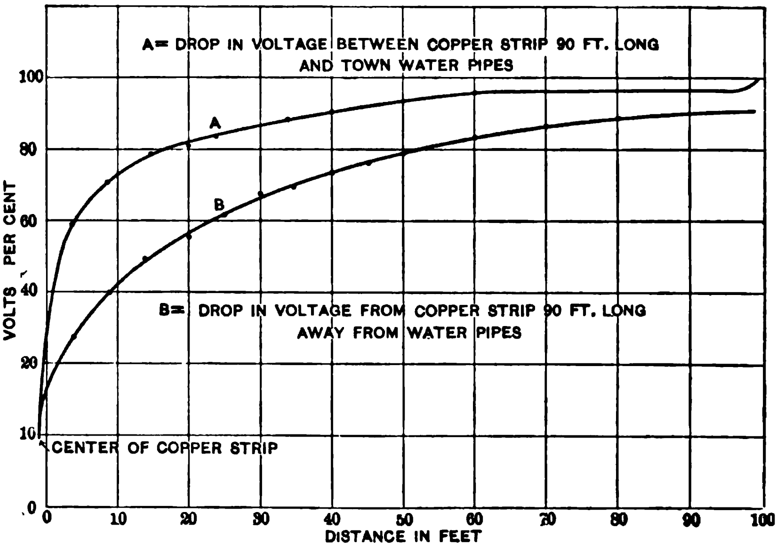


Fig. 2

As the area of a plate is increased, the resistance is not proportionately diminished, but in about the ratio of the square root of the areas; but when a number of small plates widely separated are connected to form a single ground-connection, their separate conductivities are added, as shown by the resistance of 13 ohms of the thirty 1.25-in. pipes driven into the ground five feet at intervals of 300 ft.

The curve in Fig. 1 shows the drop in potential between two plates one-foot square buried near the surface of the ground 100 ft. apart. Fig. 2 is a similar curve of the drop in potential, between a copper ribbon, buried in a straight line 90 ft. long and one foot under the surface of the ground, and a town water-pipe system.

Greater depth does not necessarily decrease the resistance of a ground plate. In this location the reverse is true until the ground water is reached, as is shown by the resistances of plates in the surface loam and in the sand where the loam has been removed. The conductivitiy of ground plates or pipes is apparently governed by the laws of solutions of electrolytes as to variation with temperature and concentration. The coarseness of the soil in contact with the plate also affects the conductivity, as the area of contact is greater with a fine than with a coarse soil, unless the plate is below the ground water level.

The method of measurement used was as follows: the 60-cycle. 104-volt, public service current was grounded on one side to the public water-pipe system, the other side of the circuit was connected to the ground to be measured through a one-ampere portable ammeter. In some of the high-resistance measurements a 10-to-1 transformer was used. The voltage was measured with a portable voltmeter. The curves were made by connecting the two ends of a german-silver wire 100 ft. long with the two sides of the circuit. The ground plates to be measured were connected as near as possible to the ends of the wire. A telephone receiver was used as an indicator, this being attached on one side to the resistance wire by a movable contact, and on the other side to a rod which was put in the earth at regular intervals between the two plates, the point of equal voltage being found on the wire and the readings plotted as per cent. of the impressed voltage.

Resistances between the town pipe system and the following:

Plate 6 ft. 2 in. by 3 ft. in still water bottom of the Pawtuxet river	32	ohms
Plate 1 ft. square in still water bottom of the Pawtuxet river	132	"
Plate 1 ft. square in current in bottom of the Pawtuxet river	232	"
One cu. ft. Pawtuxet river water between two opposite faces	2800	"
Plate 1 ft. square in rain water cistern	197	"
Plate 1 ft. square in stoned well 45 ft. deep	280	"
Plate 1 ft. square in cement cylinder well 50 ft. deep	406	"
One cu. ft. well water between opposite faces	437	"
Plate 1 ft. by 2 ft. on ledge in bottom of Pawtuxet river, rapid current	324	"
Plate 1 ft. square in stoned well 40 ft. deep	310	"
Plate 6 ft. by 2 ft. 3 in. in three bushels coke 6 ft. deep in moist black loam	113	"
1.25 in. gas pipe driven into gravelly ground about five feet	630	"
Nail driven into apple tree about 6 ft. above the ground	3855	"
Wire around and forced into bark of apple tree limb 7 in. in diameter	3030	"
Seven 1.25 in. pipes 5 ft. long and 300 ft. apart in swampy ground	15	"
Ten 1.25 in. pipes 5 ft. long and 300 ft. apart, gravelly ground	53	"
Two 1.25 in. pipes 5 ft. long and 300 ft. apart, gravelly ground	272	"
Thirty 1.25 inch pipes 5 ft. long and 300 ft. apart all kinds of ground	13	"
Plate 1 ft. square in contact with mud on top of frozen ground	3600	"
Plate 1 ft. square in sand, surface soil removed weather dry	11000	"

Plate 1 ft. square in sand, surface soil removed after hard rain	2947	ohms
Average of eight plates 1 ft. square in surface loam.	1940	"
Plate 1 ft. square under shed, ground saturated with brine, soil as above	175	"
Copper ribbon 0.5 in. wide and 90 ft. long buried in surface loam 1 ft. deep and in a straight line.		
June 10, after a heavy rain	107	"
June 23	110	"
October 6	121	"
October 7, after heavy rain	118	"
November 12, morning after heavy rain clearing up	107	"
November 12, noon clear	117	"
November 13, ground slightly frozen on top	122	"
December 2, ground frozen	142	"
March 17, 1907, ground frozen deeply and covered with snow.	155	"
Plate 1 ft. sq. in medium coarse sand bottom of warm cellar.	9600	"
Plate 1 ft. sq. in fine clay-like sand bottom of warm cellar	2160	"
Plate 1 ft. sq. in red sandy loam in bottom of warm cellar	716	"
Plate 1 ft. sq. in sifted red sandy loam under building not heated	1550	"
Plate 1 ft. sq. in highly fertilized garden loam	860	"
Plate 1 ft. sq. in very fine sand in garden under surface loam.	1000	"
Plate 1 ft. sq. in red loam just under the grass roots of orchard	2300	"
120 ft. No. 12 copper wire in straight line about 3 in. under the sod	220	"

Except the river and pipe grounds, the above measurements were all made within a few hundred feet of one another, with the geological conditions practically the same, and are mostly averages of readings made between February 1 and June 1, 1906.

J. L. R. Hayden (by letter): Mr. F. J. Hoxie's tests are very interesting and show what high resistances ordinary copper plate grounds may occasionally give. They hardly represent average conditions, but show rather an abnormally low conductivity of the soil in which they were placed.

Since presenting my paper, a large number of gas pipes, treated in different manners, have been located in different places and are being regularly tested; these show about the same magnitude of resistance, some even a much lower resistance than the grounds recorded in my paper.

It undoubtedly is necessary, when using a gas pipe or copper plate as ground, to test it first, before relying on it, and a very convenient way is to put down two pipes at some distance from each other and test them against each other. Connected in multiple for use, the resultant resistance is one-quarter or less of the sum of their resistances, as given by the test.

A good location for grounding pipes is on a lawn, and it may even be advisable to plant a lawn around the pipes, since the keeping of the grass green by watering insures moisture to maintain the conductivity of the ground, and so gives an indication of their operativeness.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

TRANSMISSION LINE TOWERS AND ECONOMICAL SPANS

BY D. R. SCHOLES

For any given transmission line there is a certain length of span which is most economical. A determination of what the economical span is, in any case, can only be made by obtaining data showing the variation of each item of cost which changes with the length of span. In a steel-tower line the cost of the tower is probably the most important among those items which vary with the length of span. As the span is made longer, the towers must be made higher and stronger. The purpose of this paper is to describe a method by which the relation between the height, strength, and cost of a tower of given form may be expressed. The application of this method to the problem of fixing the economical span will also be shown.

A transmission tower has, in general, three duties to perform:

1. It must have strength to resist wind pressure on its various members.

2. It must have strength to withstand certain external loads due to cables, guys, etc.

3. It must have strength to sustain its own weight.

The weight of a given transmission tower may therefore be considered to be made up of three components, each component corresponding to one of these sources of stress. The following equation may then be written for the weight of the structure shown in diagram in Fig. 1,

$$W = W_w + W_L + W_s \qquad (1)$$

in which W = total weight.

W_W = weight necessary to provide strength against wind pressure.

W_L = weight necessary to provide strength against external loads.

W_S = weight necessary to enable the structure to sustain its own weight.

Assume that the structure shown in Fig. 1 has been designed for a certain wind pressure, and for certain external loads of given amount and manner of application. Each member in the structure may be considered to involve three components of thickness, each component corresponding to one of the three general sources of stress. In determining the value of W_W, the stress in each member resulting from wind pressure alone would first be computed: with this as a basis, the component of thickness of each member necessary to sustain the stress due to wind pressure alone would then be calculated. Having determined the component of thickness of each member corresponding to the stated wind pressure, the value of W_W would follow directly. A similar method would be used in finding W_{SL} and W_S.

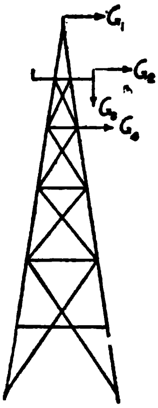


FIG I

This method will, perhaps, be made more clear by referring to Fig. II, which shows in cross-section one of the members of the tower of Fig. I.

In the figure,

t = total thickness.

t_W = thickness corresponding to wind pressure.

t_L = thickness corresponding to external loads.

t_S = thickness corresponding to weight of structure.

t_{SW} = thickness corresponding to component W_W of the weight of the structure.

t_{SL} = thickness corresponding to component W_L of weight of structure.

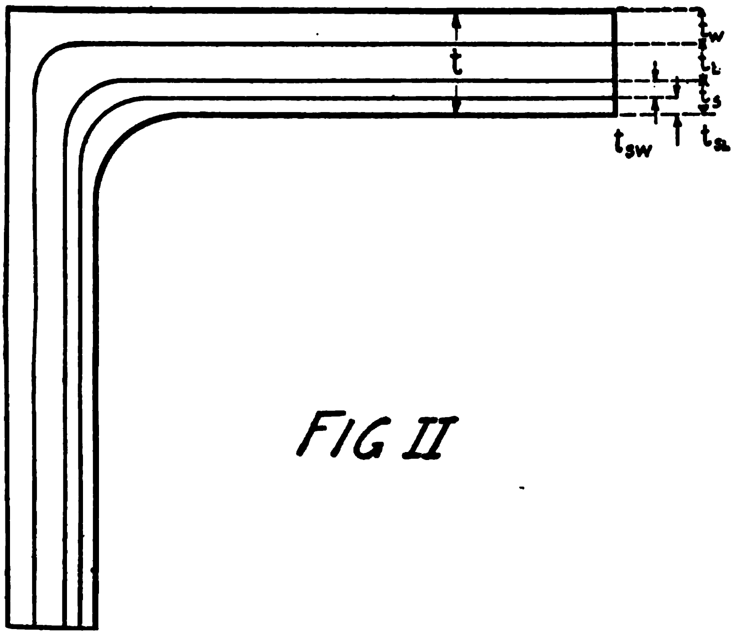


FIG II

It is seen that $t = t_W + t_L + t_s$ (2)

and, $t = t_W + t_L + t_{SW} + t_{SL}$ (3)

since $t_S = t_{SW} + t_{SL}$.

The thickness of any other member of the tower may be considered to be divided up into parts in the same manner. Since t_s is divided into the parts t_{SW} and t_{SL}, a corresponding division may be made in the term W_s of equation (1) which gives

$$W = W_W + W_L + W_{SW} + W_{SL} \tag{4}$$

where W_{SW} = weight necessary to provide strength to sustain

W_W and W_{sW}, and W_{sL} = weight necessary to provide strength to sustain W_L and W_{sL}.

The structure shown in diagram in Fig. I involves members of three general kinds; namely, beams, struts, and tension-members.

The bending moment produced in a given beam by a given load W may be expressed by the equation,

$M = CWl$ where (5)
M = maximum bending moment
l = distance between supports
C = constant, dependent on the manner in which the load is distributed.

The relation between the bending moment and the stress in the most remote fiber of the beam is given by the equation,

$$M = \frac{PFk^2}{e} \text{ where} \tag{6}$$

M = bending moment
P = stress per unit area in most remote fiber of beam
F = cross-sectional area of beam
k = radius of gyration of beam section
e = distance of most remote fiber from neutral axis.

Combining these two expressions, the equation

$$W = \frac{P'Fk^2}{Cle} \tag{7}$$

is obtained, which gives the load which the beam will carry, P' being the ultimate strength of the material in the beam.

Now if k is the radius of gyration of a given figure, the radius of gyration of a second figure similar to the first but of different size is equal to nk, n being the ratio between corresponding linear dimensions of the two figures.

If, therefore, a second beam be considered, exactly similar to the first but of different size and length, n being the ratio between corresponding linear dimensions of the two beams, the load which this second beam will carry is

$$W_2 = \frac{Pn^2Fn^2k^2}{Cnlne} = n^2\frac{PFk}{Cle}, \text{ and } \frac{W_2}{W} = n^2 \tag{8}$$

Expressed in words, this relation may be stated as follows: The load which a beam of given form will carry varies as the square of its linear dimensions.

The strength of a strut against compressive stress is given by Rankine's formula:

$$W = \frac{P' F}{1 + C \frac{l^2}{k^2}}, \text{ where} \tag{9}$$

W = ultimate strength of strut
P' = ultimate compressive strength of material
F = cross-sectional area
l = length
k = radius of gyration
C = constant, depending on kind of material.

And the strength of another strut, exactly similar to the first but of different size and length, n being the ratio between corresponding linear dimensions of the two struts, is

$$W_2 = \frac{P' n^2 F}{1 + C \frac{n^2 l^2}{n^2 k^2}} = n^2 \frac{P' F}{1 + C \frac{l^2}{k^2}}, \text{ also } \frac{W_2}{W} = n^2 \tag{10}$$

Expressed in words, this relation may be stated as follows: The load which a strut of given form will carry, varies as the square of its linear dimensions.

The strength of a tension member is directly proportional to its cross-sectional area; that is, it varies as the square of its linear dimensions.

An investigation of the action of a member subjected to torsional loads, similar to those just made for beams, struts, and tension-members, would show a like relation; that is, the load which a member of given form subjected to torsion will carry varies as the square of its linear dimensions. This investigation is not undertaken here, however, because members of this character are little used in transmission towers.

Returning to the structure shown roughly by Fig. I. It is usually assumed that the actual pressure on any part of such a structure, produced by a wind of given velocity, is directly proportional to the exposed area of that part. Now the exposed area of any part is, in general, dependent on its length and breadth, but not upon its thickness. It therefore follows that if the structure shown in Fig. III is geometrically similar to that of Fig. I, in every respect except the thickness of its parts, and is of different size, the ratio between corresponding linear dimensions being n, the load produced on any part of the second structure by a wind of given velocity is equal to n^2 times the load produced on the corresponding part of the first structure by the same wind. It also follows that the stress in any member of the second structure under these conditions, due to wind pressure, is equal to n^2 times that in the corresponding member of the first structure.

For the structure of Fig. III,

$$W' = W'_{W} + W'_{L} + W'_{SW} + W'_{SL} \tag{11}$$

and

$$t' = t'_{W} + t'_{L} + t'_{SW} + t'_{SL} \tag{12}$$

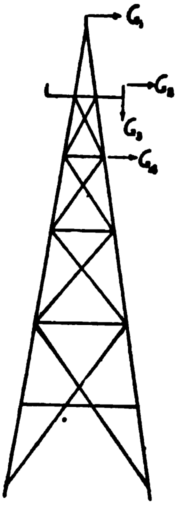


FIG III

From the foregoing discussion of the relation between the size and strength of beams, struts, etc., of given form, it is evident that

$$t'_{W} = n\, t_{W} \tag{13}$$

and

$$W'_{W} = n^3 W_{W} \tag{14}$$

both structures being calculated for the same wind pressure.

Again referring to the equation for beams,

$$W = \frac{P'Fk^2}{Cle}, \text{ or } F = \frac{WCle}{P'k^2} \tag{15}$$

It is evident that, if k and e can be kept constant, the sectional area which a given beam must have to sustain a load distributed in a given manner varies directly as the load and directly as the length of the beam. The sections commonly employed as beams are angles, channels, and I-sections. By reference to any handbook of such sections, it will be seen that for any of these sections of a given nominal size the area of the beam may vary considerably without producing more than a negligible change in the value of k or e.

Hence, if after the nominal size of a beam has been determined, it is desired to vary either the load or the length of the beam, the sectional area should be made to vary directly as the load and directly as the length of the beam.

From the formula for columns,

$$W = \frac{P'F}{1 + C\frac{l^2}{k^2}}, \text{ or } F = \frac{W\left(1+C\frac{l^2}{k^2}\right)}{P'} \qquad (16)$$

it is seen that, if the ratio l/k is kept constant, the strength of the column is directly proportional to its cross-sectional area.

From the nature of a tension-member, its strength is proportional to its sectional area.

Again refer to Fig. I. It is assumed that this structure is subjected to the loads G_1, G_2, G_3, etc., these loads being placed upon it through cables, guys, or the like. The application of each of these loads will, in general, produce certain stresses in each of the members of the structure. The stress in a given member produced by a given load will be directly proportional to the load, and the magnitude of the stress will depend on the particular position which the member occupies. If a certain system of loads, as G_1, G_2, G_3, and G_4, is applied to the structure, the resultant stress in any given part may be considered to be made up of the components $A\,G_1$, $B\,G_2$, $C\,G_3$, and $D\,G_4$; A, B, C, and D being constants. Also, if each of the loads is multiplied by a factor r, the resultant stress in any member will also be multiplied by that factor.

Moreover, if a system of loads, as G_1, G_2, G_3, etc., be similarly applied to another structure geometrically similar to that of Fig. I, but of different size, the stress produced in a given member of the second structure by these loads will be equal to that produced by them in the corresponding member of the first structure. In other words, the stress in any member is dependent only upon the geometrical form of the structure and the amount and manner of application of the loads producing it, and is not affected by the actual size of the structure.

Let the structure indicated in Fig. IV be geometrically similar to that of Fig. I in all respects except the thickness of its members. Let the system of loads, $r\,G_1$, $r\,G_2$, $r\,G_3$, and $r\,G_4$, applied to this structure be similar to that applied to the structure of Fig. I, but of different magnitude, the ratio between corresponding loads being r. Also let the structure of Fig. IV. be designed for a different wind pressure from that of Fig. I. the ratio between the wind pressures per unit area in the two cases being p.

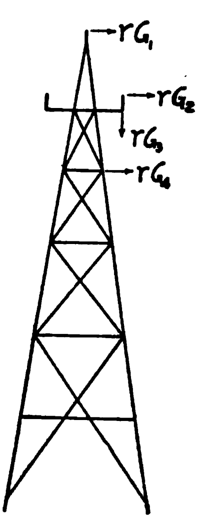


FIG IV

For the structure of Fig. IV,

$$W'' = W''_W + W''_L + W''_{SW} + W''_{SL} \qquad (17)$$

$$t'' = t''_W + t''_L + t''_{SW} + t''_{SL} \qquad (18)$$

In view of the relations pointed out between the length, sectional area, and strength of the various kinds of members involved in the structures, it follows that

$$W''_W = n^3\,p\,W_W \qquad (19)$$

$$W''_L = n\,r\,W_L \qquad (20)$$

$$W''_{SW} = n^4 p W_{SW} + \dots \qquad (21)$$

$$W''_{SL} = n^2 r W_{SL} + \dots \qquad (22)$$

To make equations (21) and (22) strictly accurate, terms must be added to represent the weight added to provide for the strength necessary to take care of each individual increment of weight. This will involve a convergent infinite series in each case. All terms of these series, except the first, are, however, relatively unimportant and will therefore be neglected.

Substituting in equation (17),

$$W'' = n^3 p W_W + n r W_L + n^4 p W_{SW} + n^2 r W_{SL} \qquad (23)$$

This is a general equation, and, given the values of W_W, W_L W_{SW}, and W_{SL} for the structure of Fig. I, it makes it possible to calculate the weight of the structure of Fig. IV. without going through the routine of calculating the stresses in each member and the sizes and weights of the parts necessary to carry these stresses.

The application of this formula to the problem of fixing the economical span for a given transmission line is obvious. A tower for a given length of span would be designed to furnish the strengths necessary for that span. The design would be made in accordance with the manufacturing facilities available for producing the structures. The stresses in each member would be carefully calculated and the values of W_W, W_L, W_{SW}, and W_{SL} found for the structure. Having found these values, the weight of any similar structure for any length of span could be determined by substitution in equation (23).

It is to be observed that this method of treating the case assumes that both wind loads and external loads are to be applied to the structure simultaneously. This is usually the case. In other cases, however, the method to be pursued would be similar, but modified to suit the peculiarities of the case.

It is also to be borne in mind that formula (23) contemplates that variations in the cross-section of any member will be made in such manner that the radius of gyration of the section will be kept proportional to n in every case, and also that no appreciable variation from geometric similarity will occur. These assumptions do not involve any appreciable inaccuracy within the range of ordinary practice.

Before the problem of providing steel towers for supporting the cables of a given transmission line can be considered, the general features of the line, its voltage, size of conductor, etc., must be fixed. To show the application of the formula just developed, the following set of general assumptions has been selected as a working basis, and it is believed that they are in accord with average high-grade practice.

GENERAL ASSUMPTIONS

System: three-phase alternating current.

Conductor: 400,000 cir. mils stranded copper. Cross-sectional area 0.3145 sq. in. Outside diameter 0.73 in. Weight per foot 1.22 lb.

Spacing: 7 ft. delta, for 500-ft. span.

Minimum clearance: 30 ft. between ground and lowest conductor at center of span.

Temperature range: 40° fahr. to 110° fahr.

Sleet: 0.5 in. all around cables. Diameter of conductor with sleet 1.73 in. Weight per foot with sleet 1.98 lb.

Wind pressure: 30 lb. per square foot normal to plane surfaces.

Test factor of safety: 2.

It is further assumed that, at occasional intervals along the line, the structures will be stayed by guy-cables in the direction of the line, and that the cost of such staying will not vary with the length of span. To provide in all structures a certain amount of strength against loads on the insulators in the direction of the line, it is assumed that in the tower for the 500-ft. span an unbalanced test load of 2000 lb. will be applied to the top of each insulator pin in a horizontal direction parallel to the line.

In explanation of the term " test factor of safety," it may be said that it has become usual for purchasers, in issuing specifications for towers, to require that the structures must show, under actual test, their ability to withstand the loads due to the assumed wind pressures, weights, etc., with a certain factor of safety. In calculating the load to be applied to the top of an insulator pin, for instance, to test it for strength against wind pressure on cables, the effective area of the cable with sleet would be multiplied by the stated wind pressure and by the factor 2. The load thus obtained would then be actually applied to the structure, and its acceptance would depend upon its ability to withstand such tests. In order that the structure may have a certain margin of strength over and above that actually required to withstand tests based on a test factor of safety of 2, the sizes of the members will be calculated with reference to a factor of safety of 2.5 based on ultimate strength.

In determining the sag corresponding to each length of span, reference has been had to the curves given in Fig. 9, calculated by Mr. Ralph D. Mershon, and here reproduced through his courtesy. These curves indicate in each case the sag for maximum temperature, this sag being so determined that, when under minimum temperature and maximum wind and sleet loads, the conductor will not be stressed beyond its elastic limit.

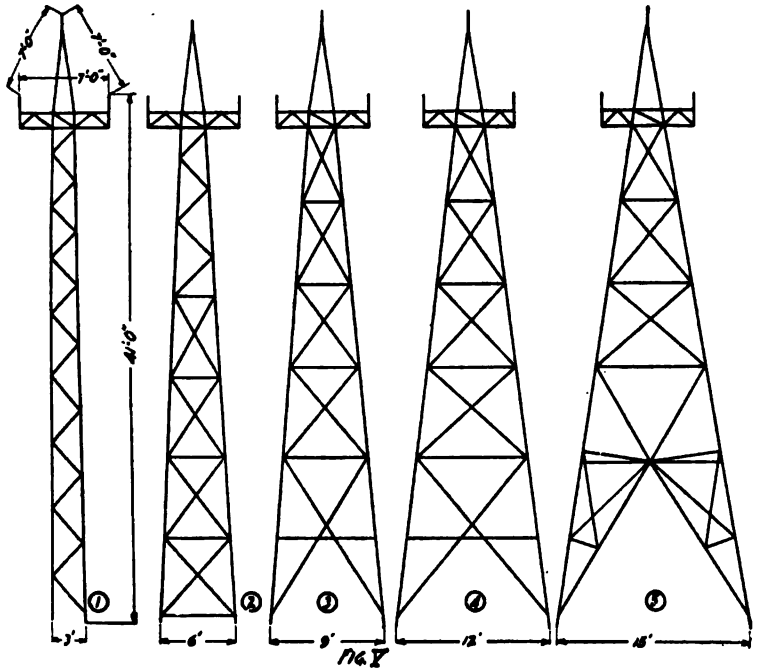


FIG. V

With the foregoing set of conditions at hand, computations have been made of the cost of each of a series of structures for a 500-ft. span these structures being of varying width of base but uniform in height. The purpose of these computations is to show the relation between the width of base and cost for such structures, and to obtain an indication as to what ratio between height and width of base is most economical. This series of structures is shown in diagram in Fig. V. A curve is given in Fig. VI showing the relation between the width of base and the cost per structure. The cost of each structure has been figured on a basis of $4.50 per 100 lb. delivered in the field. The construction involves standard angle and flat steel sections, standard butt-weld pipe, and some simple forgings. It has been assumed that all parts would be properly galvanized, so no limitation has been made as to the minimum thickness of material, it being simply required that the members be of sufficient strength to meet the conditions laid down. The construction admits of shipment knocked down and bundled, and it is believed that the figure $4.50 per 100 lb. for structures of this class delivered in the field, is quite safe.

It will be seen, by reference to the curve in Fig. VI, that the cost of the structure alone is least when the ratio of width of base to height is about 1 to 4. This conclusion has reference, of course, only to the span of 500 ft. and to the conditions and type of construction adopted.

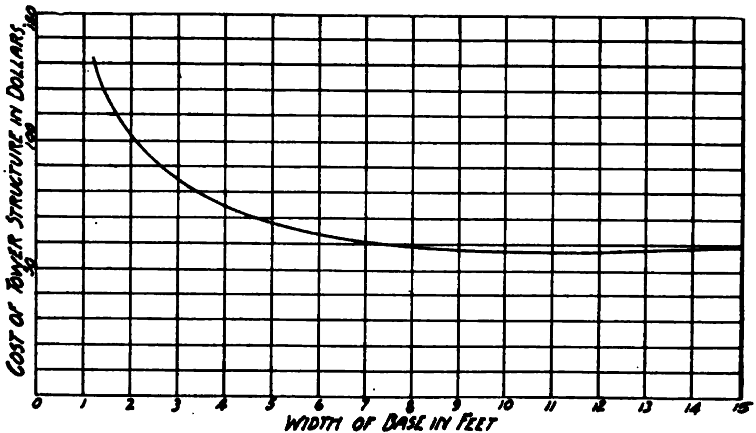


FIG VI

The width of base of the structure has an important bearing on the cost of the line, aside from its effect on the cost of the tower structure itself, since it affects the cost of foundations, the cost of right of way, and the cost of assembling and raising the structure in the field. Now it is a difficult and uncertain matter to estimate the variation of cost of these items for a general case. Hence a determination of the economical width of base for certain assumed conditions would be of but little interest in the present connection.

Application of the Formula

The structure having a width of base equal to one-fourth its height has been selected as a basis for calculations of the weights of towers for longer spans. An investigation of this structure has been made to determine the values of W_W, W_L, W_{SW}, and W_{SL}, and the following values arrived at:

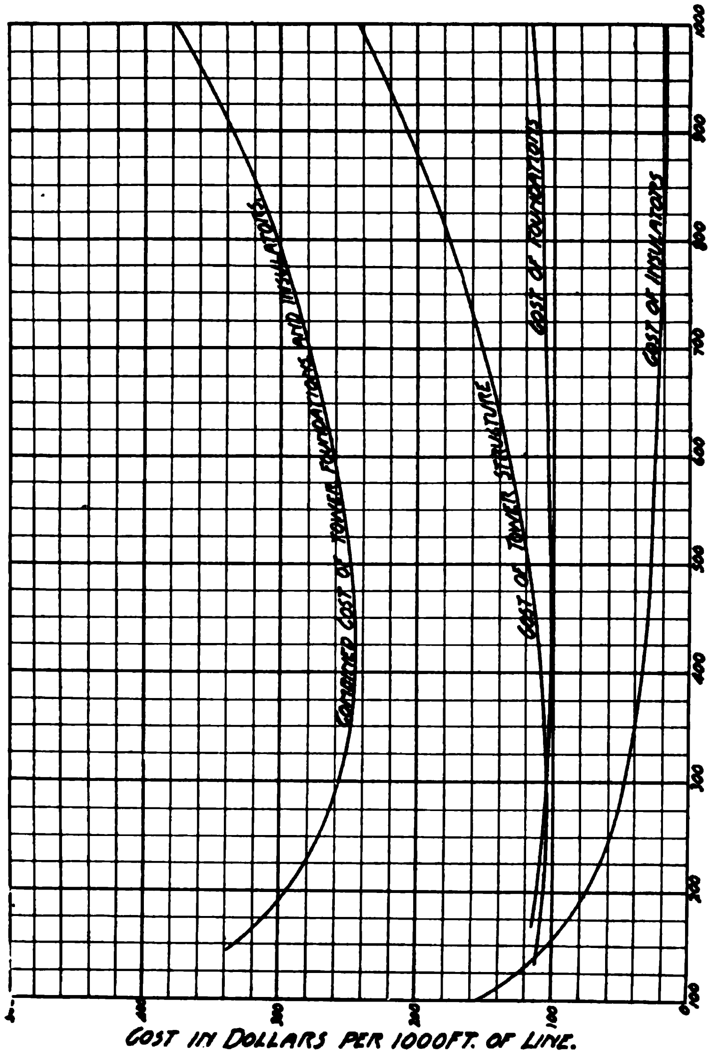


Fig. VII.

$$W_W = 383 \qquad W_{SW} = 34$$
$$W_L = 813 \qquad W_{SL} = 60$$

The table given later shows the results obtained by means of the formula for a series of towers similar to No. 4 in Fig. 5, but for spans up to 1000 ft. Since all towers in the series are to be for the same wind pressure, p is equal to unity in each case. Also, r is proportional to the length of span, since the external loads are due to wind pressure on the cables and the weight of the cables.

These results are shown graphically in Fig. VII by the curve which gives the relation between the length of span and the cost of towers per thousand feet of line. By properly representing to this same scale the cost of insulators, foundations, right of way, etc., per thousand feet of line corresponding to the various lengths of span, and adding the corresponding ordinates of all these curves, a resultant curve will be obtained. This resultant curve will show the relation between the length of span and cost of those items which vary with the length of span, and it will therefore indicate the economical span for the assumed conditions.

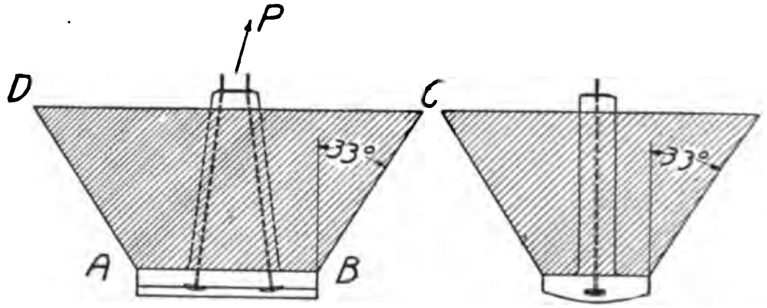


FIG VIII

A curve showing the cost of insulators per 1000 ft. of line is given in Fig. VII, the insulators having been figured at $5.00 each, erected in the tower and with the conductor secured to them.

The curve in Fig. VII showing the cost of foundations per 1000 ft. of line has reference to the type of foundation shown in Fig. VIII, and to the following method of calculation.

It is a usual assumption that the strength of a foundation against a force tending to pull it out of the ground is directly proportional to the weight of the foundation plus the weight of earth contained in the figure $A\ B\ C\ D$.

If the foundation in Fig. VIII has strength to resist a resultant force P, a second foundation, exactly similar to it but of

TABLE 1.

Span	Sag	Height	n	n^2	n^3	n^4	p	r	$n^3 p w_W$	$n r w_L$	$n^4 p w_{SW}$	$n^2 r w_{SL}$	w''
200	2.0	32.0	0.780	0.608	0.475	0.370	1	0.4	182	254	13	15	464
300	4.5	34.5	0.832	0.692	0.576	0.479	1	0.6	221	406	16	25	668
400	7.5	37.5	0.915	0.837	0.766	0.701	1	0.8	294	596	24	40	954
500	11.0	41.0	1.00	1.00	1.00	1.00	1	1.0	383	813	34	60	1290
600	15.5	45.5	1.11	1.23	1.37	1.51	1	1.2	523	1082	52	89	1746
700	20.5	50.5	1.23	1.51	1.86	2.28	1	1.4	703	1405	78	128	2314
800	26.0	56.0	1.366	1.86	2.55	3.46	1	1.6	978	1778	118	179	3053
900	33.0	63.0	1.537	2.36	3.62	5.57	1	1.8	1386	2250	190	255	4081
1000	40.5	70.5	1.72	2.96	5.09	8.76	1	2.0	1950	2800	298	356	5404

different size, would have strength to resist the force $n^3 p$, n being the ratio between corresponding linear dimensions of the two foundations. Now it seems fair to assume that the cost of such a foundation would vary directly as its volume. The cost of the foundation would therefore vary directly as the resultant force which it is capable of resisting.

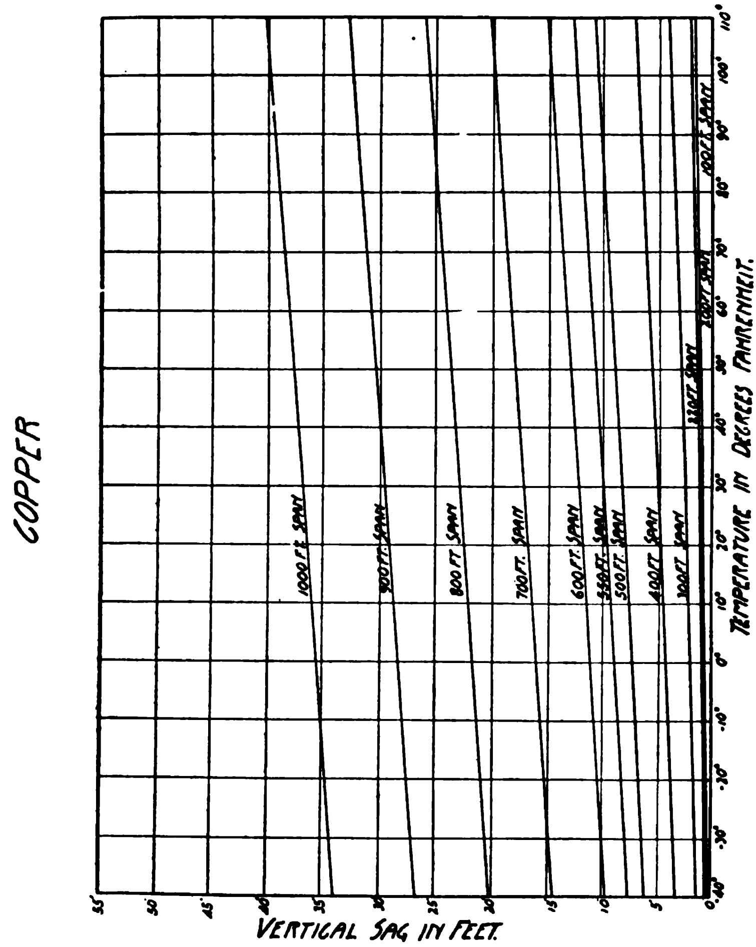


Fig. 9.

Referring to some experiments made at Chicago on a foundation similar to that of Fig. VIII, and to the records showing the actual cost of the foundation in the field ready to receive the structure, the following basis for calculation was obtained:

Resultant force sustained by foundation	24,000 lb.
Cost of foundation	$15.25

By calculating the resultant force which would come upon the foundation from each of the structures given in Table I, and making the cost of foundation for each structure proportional to that force, on the basis of the data above given, the curve showing the foundation cost per 1000 ft. of line given in Fig. VII was obtained. It is to be observed that this curve is quite flat, indicating that the foundation cost does not vary to any great extent as the length of the span is varied.

The curve of combined cost of towers, foundations, and insulators was obtained by adding the respective ordinates of the curves giving the separate costs of these items. This curve indicates that, for the assumed conditions, a span of about 425 ft. would be most economical.

It is to be observed that in the foregoing solution the determining factors are the tower cost and the insulator cost. If the price per insulator is increased, the economical length of span would be increased, and vice versa, in other words, the higher the voltage the longer the span should be.

For a low-voltage line the economical span would be somewhere between 300 and 400 ft., as far as the methods of calculation here employed can determine. Each structure in this case would, however, be a very light affair. It is probable, that, in the average case, a somewhat longer span would be decided upon in order to give each structure greater individual strength and thus make it safer against damage due to external causes.

In case it is desirable to impose limitations of this sort, the formula must be modified accordingly, by subdividing the component of weight into parts: as, for instance, by letting

$$W_L = W_{G1} + W_{G2} + W_{G3} + W_{G4}$$

where W_{G1}, W_{G2}, W_{G3} and W_{G4} are components of weight corresponding to the loads G_1, G_2, G_3 and G_4 respectively.

These loads may then be made to vary at different rates, or some may be kept constant and the others varied in such manner as may be desired. Suppose, for example, it is assumed that each structure should have strength to resist the loads due to the breakage of any two conductors. These loads would be the same regardless of the length of span, whereas the loads due to wind pressure on the cables would vary according to the length of span.

These assumptions will, in general, tend to make the economical span longer.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

LIGHTNING-RODS AND GROUNDED CABLES AS A MEANS OF PROTECTING TRANSMISSION LINES AGAINST LIGHTNING

BY NORMAN ROWE

The following is practically a summary of lightning trouble during the years 1904, 1905, and 1906, on a steel-tower long-span transmission line in the states of Michoacán and Guanajuato, Mexico.

The main transmission line, built in 1903, was the first one constructed on steel towers. These towers were of standard type, the height being 40 ft. from the top of the cross-arm to the ground. Three wires were placed upon the towers in the form of an equilateral triangle, the upper wire being supported upon a 3-in. extra heavy pipe, which formed the continuation of the tower, the other two being placed at the ends of a double channel-iron cross-arm, approximately 7 ft. in length, the sides of the triangle being 6 ft. The insulators used were 12 in. high and 14 in. in diameter. These insulators were cemented directly on cast-iron pins. The pins for the top insulators were made to screw on the 3-in. pipe; those for the side insulators had a square shank and were secured to the cross-arm by two ¾-in. bolts. The conductors were 19-strand, hard-drawn copper cable, equivalent to No. 1 B. &. S. solid copper wire. There were no wooden pins or cross-arms used on the towers. For protection against the line voltage as well as any high voltages due to lightning discharges, dependence was placed entirely on the insulators.

The ordinary length of span was 440 ft., but there were several spans of 1200 ft. and one of approximately 1600 ft. The line was designed for 60,000 volts at the generating end and

51,000 at the receiving end. The length of the line was approximately 101 miles.

The line is tapped at Irapuato, approximately 75 miles from the generating station and 26 miles from Guanajuato. At this point there is a sub-station where lightning-arresters of the usual station type are installed to protect the step-down transformers. From this it will be seen that there is a chance for the line to discharge at this point as well as over the arresters at either end of the transmission line.

FIG. 1—Showing line as originally constructed

Thus far there have been three rainy seasons, which, in the part of Mexico where the line is situated, generally last from

June until October. Heavy thunder storms come up nearly every day during July and August, and there is a storm on an average of every two days through a period of four months. During the rainy season of 1904, there was considerable trouble with lightning; the next season there was less, and during the rainy season of 1906 comparatively little trouble was experienced. The nature of the troubles, the expedients tried to overcome them, and the provisions for overcoming future lightning troubles will now be considered.

The rainy season of 1904 came on with great severity in April, two months earlier than usual, and lasted until October. The injury to the transmission line from lightning was mostly confined to the puncturing of the top insulators by direct bolts of lightning, and in most cases a hole was bored through the top insulator nearly in a vertical line to the pin. These holes were approximately one inch in diameter and the sides were glazed. Usually, the insulators were badly shattered, but on putting the parts together one could generally find the glazed hole above referred to. Some side insulators were lost, but they were almost invariably injured at the time when the top insulators on the same or adjacent towers were injured. The side insulators were never punctured from the top in a vertical direction, but in some cases they showed a small puncture in a horizontal direction from the tie-wire to the pin. In nine cases out of ten, however, they were not punctured at all, but half of the top and portions of one or both petticoats on the same side were broken, presumably by the power current following lightning discharges over their surfaces.

As the principal trouble apparently came from direct bolts of lightning striking the top insulators, it was thought advisable to erect lightning-rods on the towers on the section of the line where most trouble had occurred. At that time the placing of a grounded cable over the transmission wires was discussed, but as this could not be done before the end of the rainy season, for suitable material could not be obtained in Mexico, it was decided to put up lightning-rods and get the benefit of experience with them during the rainy season then in progress.

Lightning-rods were erected in pairs, starting from the 3-in. pipe at the point where the cross-arm in pairs was attached, and projecting up on either side of this pipe to a distance of 6 ft. above the top insulator at an angle of about 30 degrees from the vertical.

By the middle of August one-half of the line giving the most trouble was equipped with lightning-rods, and there had been erected quite a few rods on towers that were considered as being particularly exposed to danger from lightning. After the erection of these rods the difficulties were very much less, although there was still some trouble on the section of the line where they were in place. In no case were top insulators punctured through from the top as on the towers where rods

FIG. 2—Showing first change. Top insulator lowered, grounded cable in place, and lightning-rods left in position

were not in place, but when insulators were injured they usually had a part of the top and a petticoat broken on the same side. There were also a few cases where insulators were punctured in a horizontal direction from the tie-wire to the pin. During one very severe storm, eight insulators were broken on seven towers spread out over a distance of 14 towers. As the towers were spaced 12 to the mile it is improbable that the same discharge of lightning could have caused all of this trouble, unless it was transmitted over the power lines. Of the eight insulators injured none was punctured; they were apparently damaged by the current going over their side. Although these insulators were badly injured, the service on them was continued, but at a slightly reduced voltage.

One quite remarkable case happened in the Guanajuato substation, due, perhaps, to a bolt of lightning striking the line about a mile away. One of the men was standing in a balcony in Guanajuato watching the lightning display, when apparently a very heavy discharge struck the tower line, located over a hill just out of sight. At the same moment the lights in the room went out, showing that the service had been interrupted. The lightning which caused this interruption of service came into the sub-station over the top wire and jumped 4.5 ft. through air to ground, at the same time going to ground over the lightning-arresters. An insulator over which the arc formed in the sub-station had half of the top cracked off, but no injury was done to the transformers or other equipment. The towers were carefully examined near where the lightning was seen to fall, but there were no broken insulators or other evidence to show that the bolt had struck the line. However, as lightning had been previously seen to strike the towers without causing trouble, it was thought that a bolt of lightning had struck the tower line, a portion of this discharge coming over the wires into the sub-station. At the place where the bolt was supposed to have struck, the towers, on exposed places, were equipped with lightning-rods.

These cases are cited to show that insulators at a distance from heavy discharges of lightning may be subjected to very severe voltages, and, from all the data at hand, it is believed that the lightning-rods were efficient in protecting the insulators from direct bolts of lightning, and that the trouble that was still present on the section of the line equipped with lightning-rods was due to discharges traveling along the transmission wires.

During the season of 1904, the line troubles were quite evenly distributed over the first 50 miles of line out of the generating station. There were only two cases of trouble outside of this section that caused injury to the line insulators. Equipping this section with lightning-rods was begun in June and finished in August. This section of the line, except for a stretch of 15 miles, was left as equipped in August, 1904, until October, 1906, or through more than two lightning seasons. As there was less trouble on this section of the line during these two seasons than during a portion of the lightning season of 1904, it is evident that the lightning-rods were at least partly effective.

FIG. 3—Showing present appearance of line. Lightning-rods removed.

After finding that lightning-rods were not a complete protection, it was decided to make the experiment of lowering the top wire and putting up a grounded cable in its place. However, on account of delay in receiving material, very little was accomplished in time for the rainy season of 1905 and the experience with lightning during that season was the same as that obtained during the rainy season of the previous year, except that there was much less trouble.

In the winter of 1905-1906, it was decided to install larger insulators on the tower line and at the same time to lower all of the top cable to a position below one of the original side insulators. On the highest point of the tower, in place of the top transmission cable, it was decided to string over the entire line a ¼-in. 7-strand steel cable, grounded at each tower. Insulators 17½ in. in diameter, 20 in. high, were adopted for the first 60 miles of line out of the generating station, and the same insulator with a 14-in. top for the other 40 miles of line. It was unfortunate that the insulators with the 17½-in. top were not ready so as to complete the line changes in time for the rains, but half of the line out of the Guanajuato sub-station was finished before the time for severe lightning storms had arrived. The other half of the line had been equipped the first year with lightning-rods, which were still in place, the top cable being in its original position on this section, except for a distance of 15 miles.

During the rainy season of 1906, the transformers were connected in star on the high-tension side, the center of the star being grounded, and in order to detect instantly when there was a ground on the line, a series transformer was put into this grounded line and the secondary leads carried to the switchboard, where an ammeter was connected to them. With this arrangement, when an insulator broke down, or the power current followed the lightning over the insulator, the station operator could tell when there was a ground on the line, and, by shutting down at once, he was able to prevent the burning off of the transmission wire. Usually, when a ground appeared and the power was cut off, the line was found in good condition on again starting up.

There was no apparent trouble from lightning during the rainy season of 1906 on the section where the grounded cable was in place. On several occasions grounds came on the lines during lightning storms, and the power was immediately cut off in order to clear them. In general, these grounds could not be located, so it cannot be said that lightning did not go over the surface of the insulators on the section where the grounded cable was in place. The section where there was no grounded cable in place, but where the lightning-rods were erected, still gave some trouble, but the total amount was much less than in any preceding year.

The part of the line found to be the hardest to protect during all three rainy seasons was the middle of the 75-mile section from the generating station to Irapuato; in other words, the part of the line farthest from the location of lightning-arresters. This would indicate that arresters for discharging the line, located say every 25 miles, would be a valuable protection.

Fig. 4—Insulator perforated and broken by lightning bolt

The experience of the last three seasons prompts the writer to offer the following suggestions:

1. Insulators should not be disposed upon poles or towers so that they will be in the path of bolts of lightning going to ground by the supporting structure.

2. A grounded cable, strung above the transmission wires at the highest point of the tower, is certainly more effective than lightning-rods in protecting the insulators and conductors from direct bolts of lightning.

3. Lightning-arresters, for discharging the line in case very high voltages are present on the wires, would be of some value if located along the line at frequent intervals.

4. On steel construction, an insulator should be used that has a high margin of safety against puncture and arcing over.

It seems at present general practice to use insulators for high potentials with practically no margin of safety, and when the conditions are severe there is almost sure to be trouble. Aside from trouble with the puncturing of line insulators by direct bolts of lightning, which was apparently prevented by the use of lightning-rods on towers, nearly, if not quite all, of the trouble on this line has come from the breaking down of insulators by the current going over their sides, or through them, from tie-wire to pin. The writer ventures to assert that, if the insulators had been much better, there would have been little trouble on the line where the lightning-rods were in place. Moreover, as a grounded cable undoubtedly affords better protection than lightning-rods, with a suitable grounded cable strung over the transmission wires, and better insulators so disposed as to be out of the path of direct bolts of lightning, even without the installation of lightning-arresters along the line there would result a line that should be practically free from lightning troubles.

Note.—While personal experience suggests that the use, on iron construction, of insulators with a high factor of safety will greatly reduce troubles from lightning, it was decided to change our line insulators on account of trouble from an entirely different cause. During some months of the year the insulators become covered with condensed moisture just at sunrise, due to a very sudden rise in temperature, from the temperature of about zero centigrade. This often left insulators, on the portion of the line where the temperature variation was most severe, covered with condensed moisture nearly as heavy as hoar-frost, and, during the few moments when this effect lasted, the power current was apt to arc over the surfaces of the insulators. The old insulators were considered by the company's engineers as the best obtainable in 1902, and the insulators decided upon in January, 1906, were the largest commercial insulators on the market. A very much better insulator was desired, but for want of time to develop something better it was necessary to adopt an insulator with a factor of safety somewhat lower than that intended to be used. The apparent freedom from lightning trouble on the part of the line equipped with larger insulators and grounded conductor is due perhaps as much to the use of better insulators as to the grounded cable.

DISCUSSION ON "TRANSMISSION LINE TOWERS AND ECONOMICAL SPANS" AND "LIGHTNING-RODS AND GROUNDED CABLES AS A MEANS OF PROTECTING TRANSMISSION LINES AGAINST LIGHTNING," AT NIAGARA FALLS, N. Y., JUNE 26, 1907.

William Hoopes: The method of treatment of this problem appears so excellent that one is at once interested in its practical application. The first conclusion reached is that the economical span-length is determined, not by the original cost of the line, but by its annual cost.

The annual cost is made up of three items:

1. Interest and depreciation on the first cost.
2. The cost of repairs and patroling.
3. The money damage from interruptions to the service.

If lengthening the span will reduce the number of interruptions and cost of repairs, then the economical span is longer than that which gives the lowest first cost.

Inquiry into the operation of a large number of transmission lines reveals the fact that by far the larger portion of the interruptions of service is due to trouble occurring at the point of support; this applies particularly to steel-tower lines. Reduction of the number of supports does, therefore, reduce the annual cost.

The paper shows that this particular line on 800-ft. spans would cost about $300 more per mile than if on 400-ft. spans. Interest and depreciation on this at 10% would be $30 per year. Halving the number of supports would probably save much more than this.

I believe the subject has not been treated in this way in this or any other paper, so I should like to suggest to the committee that such a paper would open up a very live topic.

However, the province of Mr. Scholes' paper is really to show the least first cost of the line, and the above remarks are not strictly germane to it. Investigation of its practical application leads to the following queries:

1. Is the assumption of a uniform price per pound justifiable?
2. Does the retention of the same geometrical figure permit the design of all the towers for the least cost?
3. It is fair to assume that large foundations for higher towers cost as much per cubic yard as small foundations for low towers.

The cost of a tower to the purchaser is made up of the following items:

1. Cost of steel and transportation.
2. Cost of shop work.
3. Cost of galvanizing.
4. Cost of erection.
5. Manufacturer's profit.

If the cost of the tower is directly proportional to the weight of the steel, then all of the items of cost must vary at the same rate as the weight. The cost of the steel does vary approximately as the weight.

The paper gives the cost of a 34.5-ft. tower as $30, and of a 70.5-ft. tower as $243, which is about proportional to the cubes of the heights. The other costs should therefore be as the cubes of the heights.

Inquiry from a concern which makes a very large number of towers elicited the following opinions:

1. As the number of parts is the same for large as for small towers, the number of shop operations will be about the same; but as the shop operations will be slower on the heavier work, the shop cost will vary about as the height of the tower.

2. The same opinion was expressed with regard to the cost of erection.

3. The galvavanizing cost is approximately proportional to the superficial area, or to the square of the height. The galvanizing was said to be a very material portion of the whole cost.

When it came to a question of manufacturer's profit the source of my information ran dry, but if it increases as the cube of the height, it would seem to afford a considerable opportunity to a resourceful purchasing agent.

From the foregoing it would seem that all the costs which go to make up the cost of the tower, other than the cost of steel, vary at a less rate than the cost of the steel, and that a smaller price per pound should be used in determining the cost of the large towers than is used for the small towers.

It would add to the value of Mr. Scholes' paper if he would answer my three questions, and I should like to ask further if it is actually possible to furnish a 34.5-ft. tower galvanized, for $30? or a 32-ft. tower for $21? the prices given in the paper.

P. H. Thomas: Mr. Rowe has given us valuable data on the effectiveness of the overhead ground-wire for protecting high transmission lines. The only thing that remains is to draw correct inferences from the data, and that is very difficult to do. There are some salient points, however, which seem to indicate the real lesson of the paper.

In the first place, in judging of the performance of a new line, the necessary elimination of weak insulators which occurs during the early operation must be taken into account. Mr. Rowe says that by the use of a series transformer in the ground connection he has discovered a way to get the current off the line quickly enough not to break the insulators, so that the power could be thrown directly back again. This is an important point to consider, for if that is the way the improved operation was brought about it is no credit to the overhead grounded conductor.

Mr. Rowe says further:

> On several occasions grounds came on the lines during lightning storms and the power was immediately cut off in order to clear them. In general, these grounds could not be located, so it cannot be said that

lightning did not go over the surface of the insulators on the section where the grounded cable was in place.

This apparently indicates that, only improvement resulted from the grounded wire.

Furthermore, in addition to the installation of the grounded cable, there was a change in the size of the insulators, largely on that part of the line protected by the overhead cable. This, in itself, is the very best sort of lightning protection. As Mr. Rowe himself intimates that the original insulators were really too small for their work, it will not be safe to infer too much from the increased satisfaction in the operation after the introduction of the grounded overhead conductors. On the other hand, it is probably certain that the overhead grounded conductor does relieve the line insulation a great deal; especially in the way of reducing the severity of the heaviest strains.

Is it not true that too great a risk is being taken in using steel poles, steel cross-arms and pins, relying wholly on the insulator? It is relatively easy for a charge to pass over the insulator's surface to ground at the pin, and it is usually destructive when it does come, starting an arc to ground which breaks the insulator and tends to shut down the plant. Is there not some way to preserve the advantage of the old wooden pin and cross-arm, which prevented many discharges to ground from becoming short-circuits?

W. S. Lee: As Mr. Hoopes has suggested, we should not try to get too economical a tower or too economical a span. In some cases these transmission lines are carried over a rolling country; in other cases over a flat country with no fall for a water power, so we have to span from hill to hill, and from point to point, and the practical erection of the line means irregular spans. We have found that in our service. Now, while one may figure on a fixed-span tower, the chances are that the spans will be regulated by the topographical conditions. The usual practice is to make a profile of the country. If there is to be a tower for a 400-ft. span, and the next span has to be extended to 550 feet or 650 feet, we would need towers of different strength. It would be best to keep the tower standard on the line, in case of repairs, or shipments of parts; and for that reason I would suggest getting stronger towers which could be used for either long or short spans.

Referring to Mr. Rowe's paper: In 1897 I was with the Anderson Water Light & Power Co., Anderson, S. C., and we built an 11,000-volt line for a distance of 10 miles. While the poles were being constructed, and before there was a wire strung on them, two poles at different points were shattered entirely by lightning. The plant was built and has been in operation since that time; it has two lines of barbed wire overhead. Though there has been some trouble with lightning, they have not had a direct stroke of lightning on that line since that time. The Catawba Power Company, of Charlotte, N. C., has a transmission system of 18 miles. When the line was built in

1904 one pole was struck by lightning, but there was no wire on it. There is one grounded wire overhead, and no pole has been damaged by lightning since that time, nor has there been a direct bolt of lightning.

We built in 1905 at this same station, a line 20 miles long. It had 11,000-volt service, built with 40,000-volt insulators. This was a three-phase, single-circuit line, and in order to arrange for equilateral triangle construction one wire was placed on top of the pole. We endeavored to locate a grounded wire above the apex wire, by extending supports up to this point, and curving them so as to keep away from the apex wire. This arrangement did not work. We found that irregularities in the country resulted in a tendency to pull up or down, in some cases to bring the grounded wire close to the apex power-wire. For this reason the grounded wire was left off this circuit. Since 1904, there have been two direct strokes of lightning on this particular circuit; neither stroke interrupted the service, but both damaged poles by splitting them. All the lines are now being equipped with the overhead grounded wire.

F. B. H. Paine: Mr. Thomas suggested a question which is frequently asked, in view of our extended use of steel poles and towers; whether we are not putting too much trust in the insulator, and would we not do better with the added insulation of pole, cross-arm, and pin? For a good while I was in doubt about it, but after an experience of two years I think that Mr. Mershon's judgment has been amply sustained. I have recently visited many transmission plants, and in every instance I found that the annual destruction of poles and cross-arms, that is, the entire destruction of the supporting structure, exceeded our loss of insulators per mile. We can replace the insulators much quicker and cheaper than we can the entire supporting structure, whether it be of wood, steel, or what-not. We have something like 200 miles of 60,000-volt transmission lines on wooden structures using the same insulators cemented on steel pins, the steel pins being carefully grounded. We have had some terrific lightning disturbances in that section, and, although many insulators have been lost, in no instance has any injury come to the wooden structure on account of the pins being grounded, and to all intents the same condition existed as on the steel tower or steel pole. I think we have answered the question as to the desirability of wood as an insulator for high-voltage lines very effectively: use metal pins, ground them, and save the pole and cross-arm.

C. W. Ricker: The experience of a railway transmission line in western Ohio may be of interest.

This consists of about 100 miles of three-phase, 3300-volt line built in 1901 on wooden poles with wooden cross-arms and porcelain insulators designed for use at that voltage by one of the largest American makers. Each cross-arm had two steel braces applied in the usual way, and the insulators are set on steel bolt pins about 9 in. long. The line runs through a country in which lightning storms are frequent but not exceptionally severe. Interruptions of service have occurred during thunder storms, and usually two insulators on the opposite ends of the same arm would be found punctured from the tie-wire to the pin. The interruptions became so frequent that it was necessary to make some change, which had to be done without disturbing the working of the line; this left about two hours each night available for work, and the owners of the line were not prepared to incur any heavy expenses. Accordingly, half the cross-arm braces were removed, leaving on each pole a brace from the pole to one end of the cross-arm only, and wooden pins about 15-in. long were substituted for the steel pins, using the same insulators.

After this change the interruptions of service due to lightning were diminished from an average of two or more a month to about the same number during the season following the change. Several cross-arms were burned off, but caused no suspension of service at that time.

Geo. T. Fielding, Jr.: Incidental to the main subject of Mr. Scholes' paper, I would like to arouse some discussion on one of his assumptions: namely, that of allowing for one-half inch of sleet upon the conductor. As a matter of common interest, it would be profitable to learn if any one here has ever seen sleet upon a transmission line that was carrying power or even charging current, and also if there was any wind at the time this occurred. This is an old question perhaps, but we have had experience enough now to cease basing calculations upon advance assumptions that were made for the first lines erected. The greatest mechanical stresses on transmission lines are due to high winds, and a small increase in the diameter of the conductor, as occasioned by a coating of sleet, results in a considerable increase in the imposed stress. The assumptions made, as regards sleet, therefore very materially influence the allowable sags and tower-heights, and while it is legitimate to favor conservatism, it is questionable if we are not inclined to be over-liberal.

I notice that Mr. Rowe uses a stranded steel cable for the ground-wire. This has been the practice on a number of lines. On account of its short life and tendency to stretch and sag, one of the larger telegraph companies has recently ceased using stranded cable for guy- and messenger-wire service. The old solid No. 3 steel galvanized wire is now being substituted in its place. It seems quite reasonable that the cable should tend to retain moisture, by virture of its strands, and hemp center if it has any. This moisture is not helpful in preserving the metal against rust.

Mr. Rowe seems to have had considerable trouble with puncturing of the insulators. This experience has been repeated on many other transmissions. On steel-tower lines where disturbances cause local and suddenly excessive potentials or frequency, the insulators are often observed to puncture before they will arc over, due probably to the element of time which is necessary for the potential to distribute itself.

Increasing the thickness of porcelain does but very little toward increasing its resistance to puncture. It appears as if the use of larger insulators is not the solution of the problem; that is, it is not enough simply to install insulators of larger dimensions, insuring merely a greater arc-over capacity. It is essential to separate the live conductor and the ground, the pin, by a greater distance than has heretofore been specified to obtain reliable insulation: this has been accomplished by the suspension method, described in the paper by Mr. Hewlett. We shall be compelled to direct our efforts with this principle in view before we can successfully operate at, or above, 100,000 volts.

N. J. Neall: One point in Mr. Rowe's paper is, in my judgment, misleading; that is, the use of a circuit-breaker attachment in the neutral of the transformers. In any three-phase transmission line with grounded neutral, the puncture of even a single insulator is more than likely to result in the fusing apart of the conductors, so that in this particular instance any disturbance of this character would undoubtedly seriously impair the continuity of service. I have seen this fusing take place in suprisingly quick time and realize perfectly what it means on service. Now the conclusion to be drawn from Mr. Rowe's paper is that the additional line protective apparatus, irrespective of the automatic cut-out, has been the chief benefactor in this case, but this seems to me a very doubtful conclusion. In other words, the important result is that a *combination* of these things—overhead ground protection, larger insulators, and automatic cut-outs, has produced the desired improvement.

Ralph D. Mershon: The assumptions as to sleet, wind, and various other things which should be taken care of in the design of a transmission line are questions on which engineers will differ almost as much as on the subject of the use or non-use of choke coils. It seems to me that the general solution presented by Mr. Scholes is a very admirable and satisfactory one. There are some points in it to which exception might be taken, but if all the refinements are gone into, such general solution would become so complicated that its value would be questionable. The value of this general solution is that by sorting general assumptions, one can arrive at a preliminary idea as to what is going to be the best plan, considered from the standpoint of those assumptions, and that this preliminary idea will serve as a guide in adapting the construction to meet other considerations, such as inequalities of the country, the desirability of having fewer points of support, etc.

I shall be interested to hear from Mr. Scholes as to the cost in proportion to weight.

Mr. Rowe's experience with grounded wires does not enlighten me much. It does not seem to me that he has offered any definite evidence that the grounded wires do a great amount of good. In the plant of the Niagara, Lockport and Ontario Power Company, we are trying to avoid the use of the grounded wire on account of the expense of putting it up. We are installing on the top cable—there are only three cables, carried on the tower in the form of an equilateral triangle—what amounts to a horn lightning-arrester, a grounded horn reaching far enough above the tower to serve also as a lightning-rod. During the last few days we have had worse storms than we had last year, and the results, so far as we have been able to analyze them, seem to show that these line structure lightning-arresters, as we call them, have been of great value. Their value could be greatly augmented by increasing their number. They are now spaced at approximately 2200 ft., and are set for a discharge gap of 6 in. This discharge gap will be reduced to 4.5 in. or, perhaps, even to 4 in.

Some of our experiences seem to show that lightning does not travel along the line. During one of the storms the last two or three days, we have had three insulators punctured between two of the line structure lightning-arresters. The lightning chose to puncture an insulator rather than travel 550 ft. to go over the 6-in. gap. Possibly, when we reduce the size of the gap, we can cause the lightning to travel.

I am not much of a believer in the idea of being able to foretell what is going to happen in the matter of lightning, whether the prediction involves the nature and contour of the country or the apparatus concerned. We now have, I believe, about 400 miles of main line; 80 miles of this is in rough country, the rest of it is over country that is practically flat. In the flat country the lightning is at times perfectly fiendish, so that, if there is any connection between lightning and mountains, there is nothing on our transmission line to indicate that such is the case.

We do not transpose our lines. We had some transpositions, but found they could be taken out, and have taken out almost all of them. We intend to confine the line structure lightning-arresters to the top wire, in order that when it operates our service will not be interrupted; since, if there are line structure lightning-arresters on two or more of the cables, and two of them operate simultaneously, a short-circuit will result. Whereas, if the lightning-arresters are confined to one of the cables, and we have a resistance in the neutral of the generating station, the arc will clear itself without necessarily interrupting the service. If we transpose and endeavor to follow out this idea, the line structure lightning-arresters would have to be, in some instances, on the top cable and in some instances on one or the other of the cross-arm cables. It may be that, before we get through, we shall put line structure lightning-arresters on more than one cable; but, judging from the performance of the line structure lightning-arresters with a 6-in. gap and spaced 2200 ft. apart, as is the case at present, this will not be necessary. In the last three severe storms, one of which was worse than anything we ever had before, the present installation of line structure lightning-arresters has done much good.

The sub-station lightning-arrester equipment is the one which Mr. Stott has designated as the "totem-pole" equipment. There are nine horn lightning-arresters to each three-phase circuit, three to each conductor of the three-phase circuit. One of the three is set for a large gap and high resistance, the next for a higher gap and lower resistance, and the next for a still higher gap and that has a fuse. So far these arresters have afforded full protection. They have discharged frequently. There are no choke-coils.

N. J. Neall: In your line arresters do you get a continued arc because of the resistance in the neutral, or is it the customary charging arc which you get if you ground one leg of the railway system?

Ralph D. Mershon: We have the neutral grounded through a resistance, and think the line arresters will behave in a good deal the same way as the intermediate arrester used at a sub-station having an intermediate gap, and which has 1000 ohms in series with it.

D. R. Scholes: It must be borne in mind, in considering this problem, that it is impossible to choose a single set of assumptions which will be satisfactory for all lines. Varying climate, contour of country, and other varying conditions of this nature make it impossible. The making of such assumptions in the paper is incidental to the main object of the paper.

It is to be observed that the method pursued in the paper is first to derive an equation expressing the relation between the weight of a tower of given design and its height and strength. This expression is almost wholly accurate. An example illustrating its application to a practical case is then given. In the example certain assumptions are made use of. It is expected that such assumptions will, in each case, be made to suit the particular conditions that are being dealt with.

Most of the discussion, however, has had reference to these assumptions, and while it is not important that their accuracy be proved, the following may be said in support of them: It is assumed that the towers may be had at a given price per pound. This may not always be the case, but, within the range of ordinary practice, manufacturers are to be found who will contract for such structures at a given price per pound, before the size or strength of the towers has been definitely fixed.

It is assumed that the cost of a foundation will vary directly as its volume. The foundation cost will, of course, largely depend on the local conditions. Inasmuch, however, as the economical span will almost always be between 400 and 800 ft., and since the size of the foundation required will not change greatly between these limits, such an assum tion seems admissible in the present instance.

The builder of steel towers for transmission lines is apt to find that the variety of assumptions regarding wind, sleet, factor-of-safety, etc., with which he has to deal is almost as great as the number of different engineers with whom he comes in contact. Each engineer seems to have a different set of natural conditions to meet. The severity of his assumptions seems to depend, generally, on how much money his company can afford to spend on towers. Now it is manifestly impossible to give mathematical expression, in advance, to factors which vary from causes of this sort. So the paper aims to put in the hands of the engineer in charge of line construction a formula which will show the effect on the tower-cost of any change in assumption he may contemplate, and which will make possible a simple solution for the economical span on the basis of his own assumptions.

Frank G. Baum (by letter): Mr. Scholes finds a shorter span more economical than is generally supposed to be the case. It would be of interest had he drawn two curves showing the cost of tower structures, one using his assumptions of sleet or snow on the cable at time of maximum wind velocity, the other with no sleet or snow. In a large section of the country sleet and snow need not be taken into account in the calculations.

Farley Osgood (by letter): Will Mr. Rowe please say whether with complete overhead grounded wire and lightning-rod installation, the use of time-limit relays on the outgoing transmission lines, is recommended, or whether instantaneous relays are preferred?

It is believed that a lightning-arrester installation about 75 miles from the power-station would help the system to a considerable degree, especially if the proper type of electrolytic arrester is used, which has been proved to be very efficient in cutting off the crests of surge-waves.

Would Mr. Rowe recommend the use of an overhead grounded wire on a wooden pole line, to be grounded at every pole by a suitable ground wire running down the pole?

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

A NEW TYPE OF INSULATOR FOR HIGH-TENSION TRANSMISSION LINES

BY E. M. HEWLETT

Link Insulators. Suspension and Strain Types

The transmission of large amounts of power over long distances has reached such proportions that the voltage necessary to transmit this energy makes the problem of line insulation difficult. The so-called " pin " type of insulator has been enlarged to meet the greater demands until it has approached, if not already passed, the limits of good construction. Mr. Buck has given this matter a great deal of study in his high-potential transmission work, and, being dissatisfied with the mechanical features of a pin insulator, has devised a method of line construction involving the use of " suspension " and " strain" insulators. The suspension insulators support the line from above, hanging vertically beneath the cross-arm (or other point of suspension). The strain insulators are used at turns and at intervals of, say, every mile, to support and " anchor " the line, also as pull-off insulators on curves and to dead-end lines.

It is intended in this paper to give some mechanical and electrical tests and describe a porcelain insulator which the writer has designed to carry out this method of supporting high-potential transmission lines.

Each insulator unit is a flanged, or a petticoated, disc with an enlarged central portion having two interlinked semicircular holes. It is called a " *link insulator* " because it is used to insulate the interlinked tie-wires. The holes in the insulator are so arranged that the tie-wires which pass through them exert a compression strain on the porcelain (Fig. 4). Should the insulator

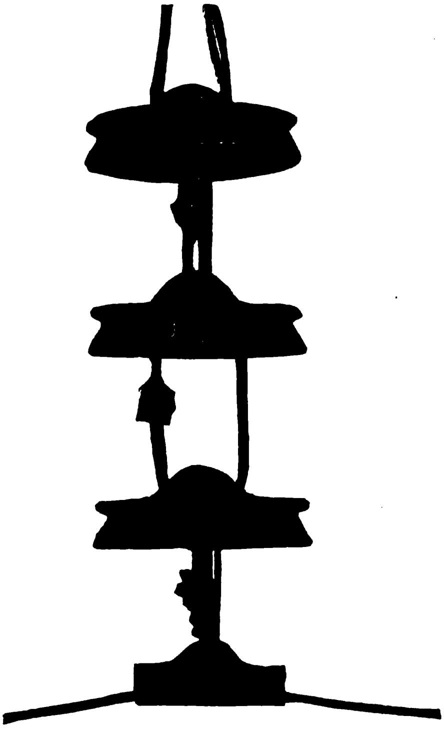


Fig. 1

Fig. 2

break, the tie-wire loops would still be intermeshed (Fig. 5), and as the discs are used in series, with a factor of safety, the remaining discs prevent a ground being formed until the break can be repaired. The link insulator for suspension (shown in Fig. 1) is a petticoated disc, while the strain insulator (Fig. 2) is a disc with a grooved flange. The mechanical and electrical features of the two forms of insulators are essentially the same. The petticoats and flanges are so arranged that one side of the insulator is always protected from rain.

A diameter of 10 in. for both types of insulators has been found by experiment to be most convenient, and such insulators are suitable for a working voltage of 25,000 volts per disc. For higher potentials the disc sare placed in series; for instance, four 10-in. discs are suitable for a 100,000 volt line. As the separate discs arc when wet at approximately 65,000 volts, the rated voltage of 25,000 volt is within safe limits. The 10-in. discs were tested for strength and supported a load of three tons.

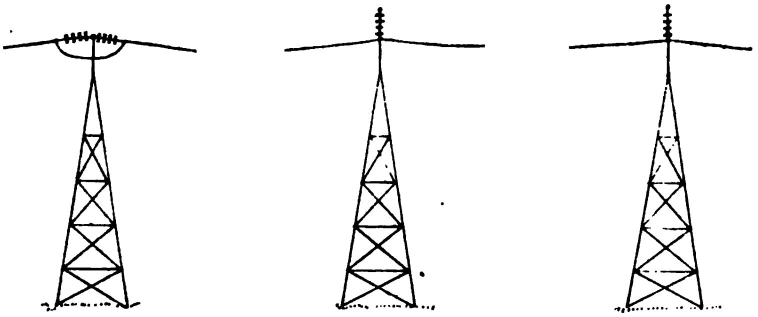


FIG. 3

The insulators described above being made of one piece of porcelain, no cemented fittings or sections are necessary. They are not affected by extreme heat or cold, having stood the test of a severe winter. Tests prove that an insulator with sheltered surfaces stand, a much higher rain test than a much larger insulator which has no dry surface, as for example, a flat disc without the flange or petticoat.

Fig. 3 shows a possible method of line support using ten towers per mile, in which the line is anchored at the end of each mile and at curves, and suspended at intermediate towers. From the cut it will be noted that the conductor is looped around

FIG. 4

FIG. 5

the strain links at the anchorage towers. The use of this type of insulator does away with torsional strain on the cross-arms, giving it a decided advantage over the pin insulator. It is obvious that the link insulator is adaptable to a great variety of conditions.

Fittings have been designed for use with these insulators to fit the conditions thus far presented, but each case should be considered as it comes up, and such fittings designed as are necessary.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26. 1907.

SOME NEW METHODS IN HIGH-TENSION LINE CONSTRUCTION.

BY H. W. BUCK

The great economies in the cost of generating power which have been obtained in the large steam turbine stations and hydroelectric plants, are leading to the general abandonment of small generating stations and the increase in transmission distances in order to distribute power over a large territory. In other words, 100,000 h.p. can be generated in one station and transmitted 100 miles cheaper than it can be generated and distributed from ten 10,000-h.p. stations each near the center of its load. On account of this tendency toward the concentration of generating units, the overhead transmission line has assumed a position of great importance in electrical installations, and the same permanency and reliability is demanded of it as of the generating station itself. The wooden pole line of the past has been practically abandoned and steel construction has been substituted.

The long distances covered by many of the modern lines, the large amounts of power to be transmitted, and the very high price of copper and aluminum—all have combined to force up the transmission voltage to the highest practicable limit. In consequence, the demand for high-voltage overhead line insulators has outgrown the present standard practice, and some new systems will have to be introduced to meet the new conditions.

The method of line construction here described has been developed by the writer and Mr. E. M. Hewlett and is believed to offer a means of operating lines safely at higher potentials than is practicable with insulators of the pin and petticoat type.

Fig. 1 illustrates in a diagrammatic way the arrangements for one circuit. The tower supports shown here are those which were used merely for experimental work and need not be considered as a commercial design. Each span is dead-ended at each support as shown, through a series of insulating units which in this case are plain discs connected together with steel links. The various spans are then electrically connected by jumpers hung below the insulators. The insulators are directly attached to the cross-arms, eliminating all pins. The number of discs linked together in series depends upon the line voltage, the discs themselves being identical for all voltages.

Fig. 2 illustrates a design for a 100,CC0-volt two-circuit line which is soon to be constructed for transmitting 50,000 h.p. 165 miles. The spans in this case will range from 500 to 1000 ft. in length. Here the line is suspended below the cross-arm on most of the towers. The lines will be dead-ended with jumper connection, as shown, only at angles and on tangents at about every fifth tower. This dead-ending will be for the purpose of stopping any creeping of conductors on the line as a whole, to check the transmission of longitudinal waves along the conductors due to wind, and on curves to take the side stress of the conductor due to change in direction. In this installation the lines will not be triangulated, but at suitable intervals along the lines the conductors will be transposed so as to balance up effects of mutual static and magnetic induction. Special cross-arms will be installed at transposition towers.

Fig. 3 illustrates another design for a two-circuit line which is to be built for 80,000-volt operation. The spans in this case will range from 300 to 400 ft. and the conductors will have an approximately triangular relation. The conductors will be susspended by a series of insulators from the cross-arms as in Fig. 2 with occasional rigid attachment, for the reasons given above.

ig. 4 shows a method of assembly of the insulators for suspension under a cross-arm. Fig. 5 illustrates a method of assembly where spans are dead-ended at the cross-arm with jumper connection.

The advantages of this construction, which might be termed "series unit insulation," over the pin and petticoat type may be summarized as follows:

a With the standard type of pin insulator now used the difficulties of construction increase very rapidly at the higher voltages. The cost of insulator for a given margin of safety increases for voltages above 60,000 nearly as the cube of the increase in voltage. Either very large petticoat diameters must be used, or very high insulators with many petticoats. In either case the manufacture of the porcelain parts is a difficult and expensive matter, and with the long pin necessary, the mechanical stresses from the line on insulator. pin, and cross-arm are objectionable. With the series unit system here proposed, the cost of insulator progresses only in direct proportion to the increase in voltage, the only change being in the number of units in series. There is practically no limit to the degree of insulation obtainable.

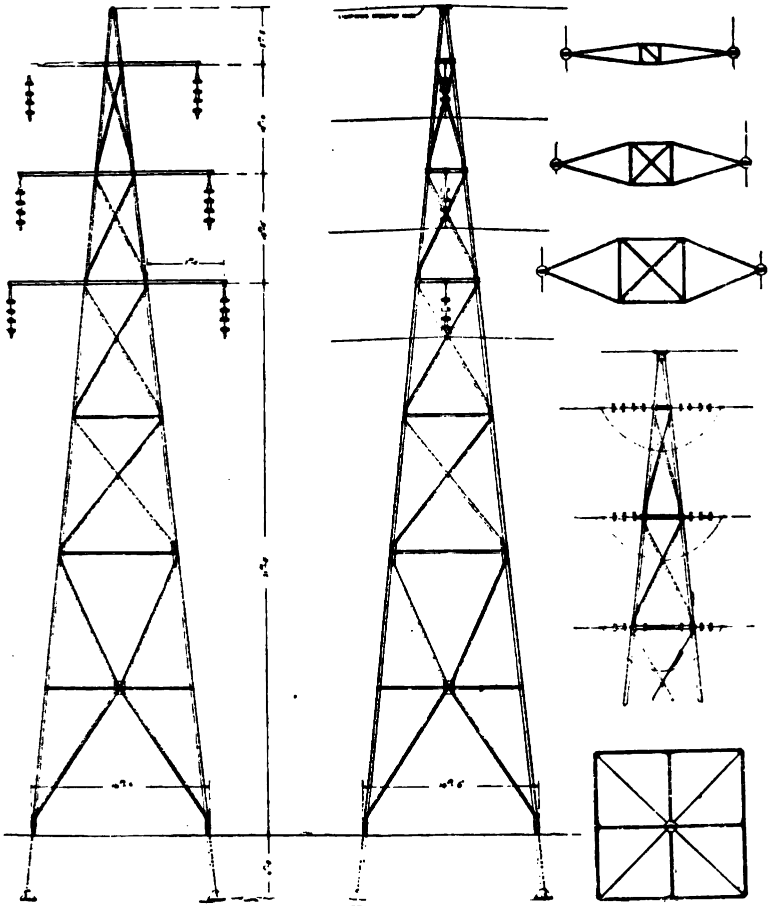


Fig. 2

b One of the most difficult elements of design in a transmission tower, where long pins and petticoat insulators are used, is to obtain a cross-arm which will resist the torsional stresses due to the leverage of the pin. With the pin entirely eliminated, the stresses are directly applied to the cross-arm, this cheapens the construction of the tower.

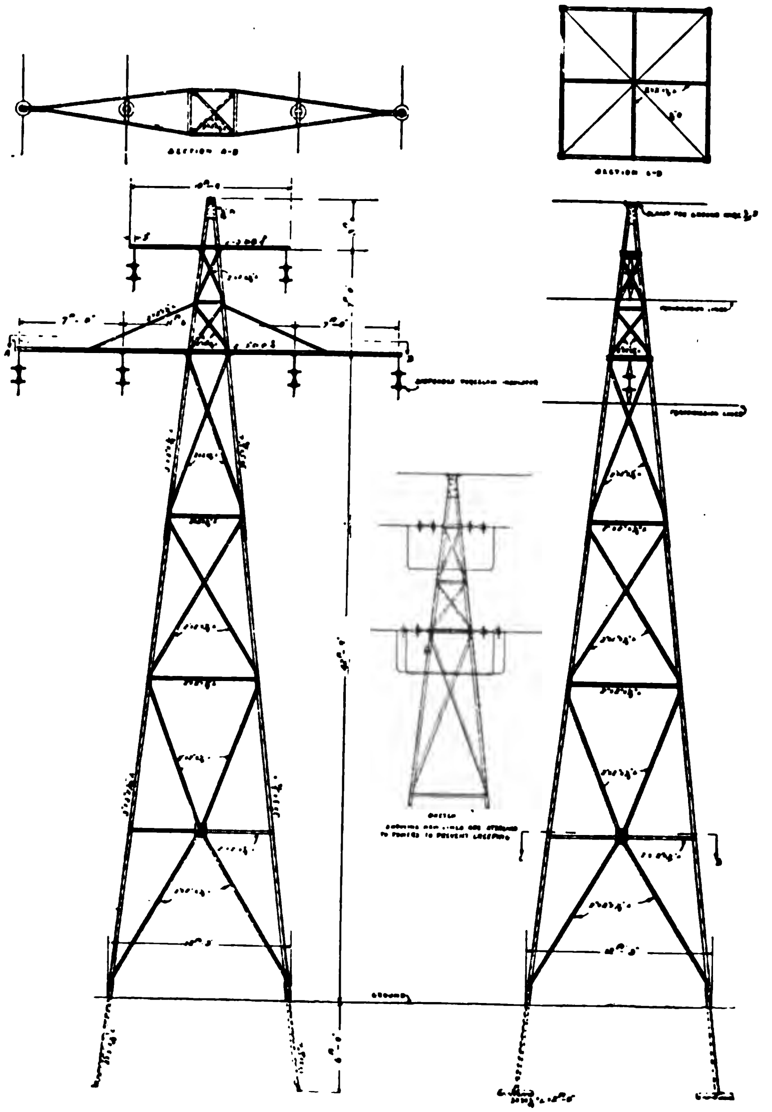


FIG. 3

c In the arrangements shown where the insulating units are attached on either side of the cross-arm, taking the full tension in the line with jumper connection between spans, the insulation can be increased indefinitely by adding discs in series without increasing the space occupied on the tower.

d Where each span is dead-ended, as in (*c*), all faces of the insulating units are exposed to the cleansing action of the rain, so that dirt cannot accumulate thereon. This arrangement also prevents the dripping water from forming electrical communication between units as occurs from one petticoat to another in the pin type of insulator.

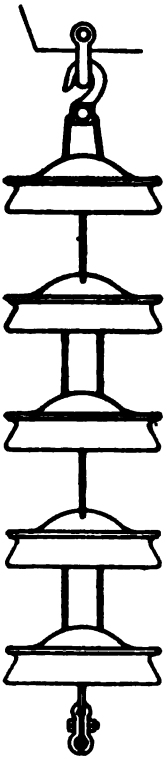


FIG. 4

e A standard insulating unit can be adopted for all voltages, the only variation being in the number linked in series. This simplifies the manufacturing problem.

f If any insulating unit becomes damaged or completely shattered, the insulation of the remainder is not affected. The damaged unit can be replaced without the necessity of renewing the whole.

g If a tower is directly struck by lightning the cross-arms will be likely to take the discharge, since they are above the lines, whereas in the pin type of insulator the line is usually the highest point.

h In long-span installations where the conductor at each end of the span is tied fast to an insulator mounted on a pin, experience has shown that crystallization is apt to take place in the conductor at the tie, due to its rigidity at that point and the vibrations in the span. This frequently results in breakage of the conductor. The flexible connection between conductor and cross-arm afforded by the series of insulators should reduce this tendency to crystallization, and should therefore permit spans of any length to be used without further precautions against this action.

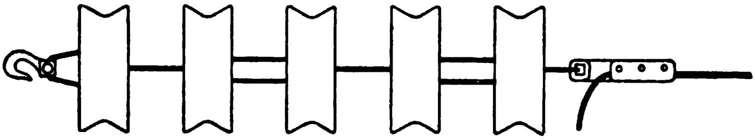


Fig. 5

Fears may be expressed that with the conductor suspended under the cross-arm serious swinging to and fro might take place. From numerous observations it is believed that no such swinging will occur. Long aerial spans under wind pressure take a permanent and steady deflection throughout the span proportional to the average wind velocity along the span, and no indications have been observed of long spans responding to so-called gusts. The towers shown in this paper are designed so that the conductor can safely be deflected by the wind about 60° on either side of the neutral position.

Insulators of a great many forms have been built and tested, but the one which gives the best results electrically and mechanically is the link type developed by Mr. Hewlett and having the grooved or fish-tail periphery. Four of these in series are sufficient for 100,000-volt operation with a liberal factor of safety.

A very important element in this construction is of course the methods of fastening the insulating units together and attaching them to the line and cross-arms. This can be accomplished in many ways and several methods have already been worked out, but these details are beyond the scope of this paper. Further experience in practical line construction and operation under this system will demonstrate the best methods of installation and attachment.

DISCUSSION ON "A NEW TYPE OF INSULATOR FOR HIGH-TENSION TRANSMISSION LINES," AND "SOME NEW METHODS IN HIGH-TENSION LINE CONSTRUCTION", AT NIAGARA FALLS, N. Y., JUNE 26, 1907.

J. B. Whitehead: Have any tests been made to determine the potential over these insulators when placed in series? Is the actual distribution 25,000 volts per unit?

Ralph D. Mershon: The more I consider Mr. Hewlett's type of insulator the more attractive it is from many different standpoints, but I should like to know if Mr. Hewlett has constructed any spans. using these insulators, with the idea of finding out just what sort of mechanical oscillations or waves, or swinging can be obtained. It seems to me that there is a possible chance of these spans swinging so as to arc to the tower. There does not seem to be any chance to use a discharge gap in connection with a line. Any arc close to the insulator has a good chance to destroy the whole insulator whereas if there were a discharge gap, the arc would rise away from the insulator and it could be saved. It would be extremely difficult to install a line using such insulators and more difficult to repair it.

Ralph W. Pope: This appears to be one of the cases where there is a decided improvement in insulators, with some objections due to manufacturing, which may be eliminated as we go along. It is likely that in the course of time, with greater experience with the insulator, these difficulties may be overcome. Is it not the case with most improvements, that in practice the shortcomings are eventually overcome ?

Ralph D. Mershon: For about three years past we have been conducting some high-voltage measurements in Niagara Falls, under all the various conditions we could think of that would approach actual practice. We took a lot of actual loss measurements on insulators of different sizes, dry and wet. I thought that if we assumed a certain thickness of the films on the petticoats of the insulators, and calculated on that assumption the resistance from the neck of the insulator to the pin, perhaps we could get some relationship between the loss over insulators of various sizes. It would not work out. Some of the smaller insulators had less loss than the big insulators. I think that the petticoats become charged and act as a condenser plate with reference to the pin; and the closer they are to the pin the more effectively the condenser acts to increase the loss and make them flash over. We measured the loss from the neck of an insulator to the pin, with a wooden pin and a metal pin. The wooden pin, if dry gives fine insulation, and at first thought one would think the loss would be lower with the wooden pin than with the iron pin; but it was a great deal higher. This surprised me. I thought it over and finally reached a probable solution, and this solution has been confirmed by another experiment. The way I explained the higher loss is this: the insulator is taking a certain charging current; the pin has a straight ohmic resistance; and the voltage taken by it is in quadrature with the voltage of the supply current. You might increase the I^2R considerably, without decreasing the current going over the pin. We got a wooden curtain pole, and stuck the insulator on that, and took different lengths of pin. After the first trial it was found that the loss continually fell off as the length of the pin increased.

F. B. H. Paine: There are some features of transmission engineering which are not altogether electrical. The people along the line are likely to insist on having a method of supporting the cables which will prevent them from falling to the earth, or so close to the earth as to become a menace to travelers on the highway because of the loss of one or more points of support. If the cable is supported from above, it will necessitate some means to catch the cable in case an insulator fails and the cable is lowered. Is this provided for in this design ?

Chas. P. Steinmetz: In multigap lightning-arresters very great inequalities exist in the potential distribution only when very many spark gaps are connected in series across a high-potential circuit. With four or five or even ten spark gaps in series, the distribution of potential under lightning-arrester conditions is still practically uniform. There is to be considered, regarding this distribution of potential, between the successive insulator discs the fact that it is a function of the voltage and that when voltage is raised to a point approaching the breakdown strength of one element, then the distribution of the potential changes and becomes more uniform. So it may well be, if there are, say, four elements in series, you get across the first element 50 per cent. instead of 25 per cent. of the total voltage at normal impressed voltage. If now you increase the potential, as soon as it approaches the breakdown strength of the first element, brush discharges occur over the surface etc., and to increase the effective capacity of this condenser, and then the potential distribution becomes more uniform and may be nearly uniform, when you reach the united breakdown strength of the whole system, at least where the number of sections is not very large.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

THE TRANSMISSION PLANT OF THE NIAGARA, LOCKPORT AND ONTARIO POWER COMPANY

BY RALPH D. MERSHON

On the seventh day of July, 1906, there was put into operation the first of the transmission lines of the Niagara, Lockport and Ontario Power Company. This event marks the inauguration of one of the first undertakings in the matter of distributing Niagara power over a large section of country, and the beginning of an enterprise which is one of the most important, and in some respects the most important, of its kind anywhere in the world.

The plans realized at present and contemplated for the immediate future, in the plant of the Niagara, Lockport and Ontario Power Company, involve a maximum transmission distance of 160 miles. This distance puts the plant amongst the longest transmissions of the world. As regards capacity, the plant of the Niagara, Lockport and Ontario Power Company is now one of the most important in existence, and, in the near future, its capacity will be far in excess of any other transmission system in the world. In addition to these points of importance, there are a number of engineering features somewhat out of the usual line of transmission practice which make the installation of interest from an engineering standpoint. Inasmuch as the description of such a plant is usually more satisfactorily accomplished through pictures than otherwise, they will be mainly resorted to herein, with the aid of only such brief text as may be necessary to cover points which cannot be well shown in illustrations.

The prospective system of the Niagara, Lockport and Ontario Power Company is a comprehensive one for the delivery of power in the United States within an economic transmission radius of Niagara Falls, and especially for its delivery in the northern and western portions of the state of New York. The company expects within the next two years to be transmitting 60,000 horse power, and its present right-of-way purchases are with reference to an ultimate transmission of 180,000 horse power. The plans of the company as at present laid out contemplate the transmission of this power by means of main lines and branch lines therefrom; the contracts for power being, wherever possible, made for delivery of the power at the main-line voltage of 60,000, less line drop. Where, however, the business of a given territory will justify it, the company will install step-down transformer stations for the delivery of power at a lower voltage. Each of the main transmission circuits will be capable of receiving and transmitting 30,000 horse power at 60,000 volts, and it is intended always to provide a sufficient number of spare main transmission lines to insure continuity of service on the main line. Spare lines will be provided in the case of branch lines only when the latter are of considerable importance.

The Niagara, Lockport and Ontario Power Company is only a transmission company; that is, it buys the power to be transmitted and has, therefore, no generating plant of its own. The power for the transmission is generated in the hydraulic power station of the Ontario Power Company, situated on the Canadian side of Niagara Falls. The water for this station is taken from the Niagara River, some distance above the falls, whence it is brought to a point at the top of the cliff, a short distance below the falls, through underground steel conduits, and from this point delivered through underground penstocks to the power station located at the bottom of the cliff, near the foot of the falls.

The power house contains the generating units with their exciters and switchboard apparatus. The generators have a capacity of 7,500 kw. each, and deliver three-phase 25-cycle current at 12,000 volts. From the power station the current is taken at 12,000 volts to the transforming and switching station of the Ontario Power Company located on the bluff above the falls. It is stepped up from 12,000 volts to 62,500 volts, and at this latter voltage delivered to the transmission lines. The transmission lines of the Ontario Power Company extend from its transforming station to a point some six miles farther down the Niagara River, at which point the

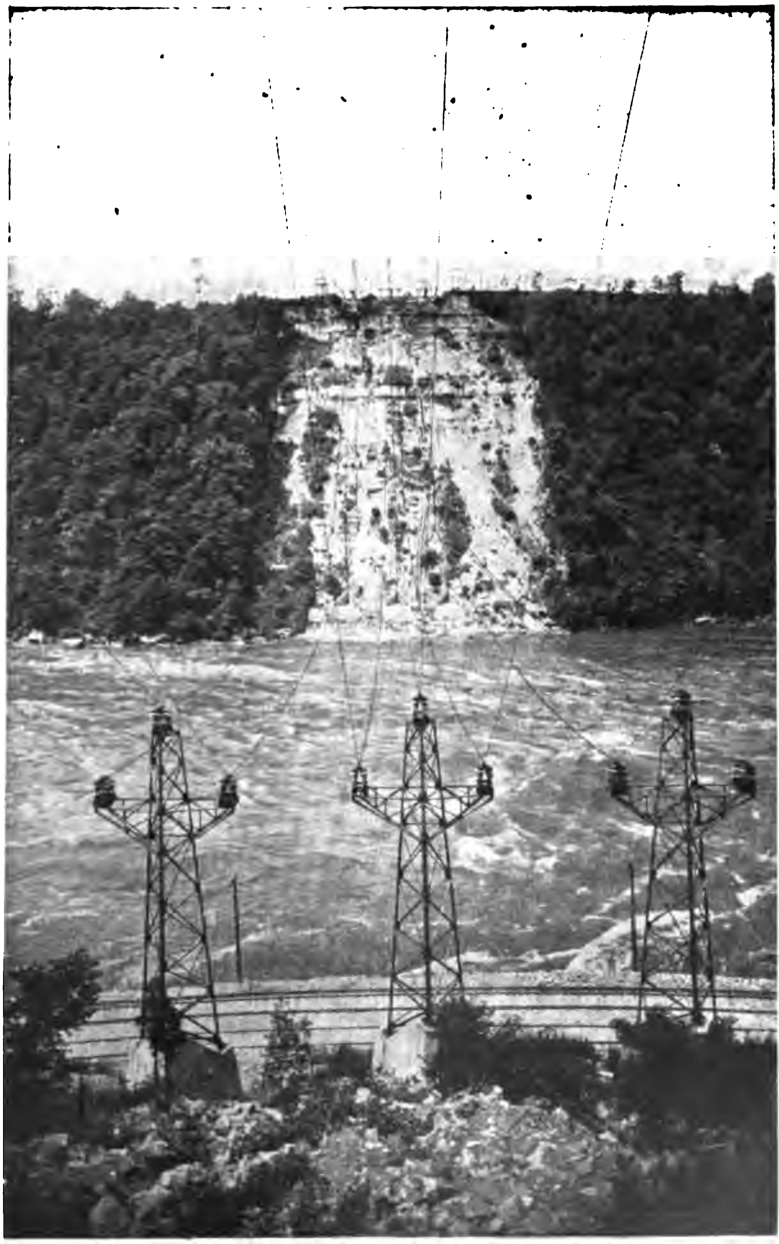


FIG. 1—Niagara crossing, general view

FIG. 2—Niagara crossing, water-edge towers, American side

lines connect to circuits spanning the Niagara River. The Niagara, Lockport and Ontario Power Company takes delivery of the electric power at the international boundary line in the middle of the Niagara River.

At the present time, the Niagara, Lockport and Ontario Power Company has in its possession a private right-of-way 300 feet wide from the Niagara River to the town of Lockport, about 16 miles east; from Lockport east to Mortimer (six miles south of Rochester), a private right-of-way 200 feet wide, a distance of about 57 miles; from Mortimer to Fairport a 100-foot private right-of-way a distance of 10 miles; and from Fairport to Syracuse a private right-of-way 75 feet wide, a distance of 71 miles. From Lockport south, in the direction of Buffalo, the company has a private right-of-way 100 feet wide. In ad-

FIG. 3—Niagara crossing top of water edge towers

dition to this, the company has the right to install transmission lines on the right-of-way of the West Shore Railroad and has acquired the necessary private right-of-way to get from its main private right-of-way to that of the railroad company.

The installation which the company has now in operation is for receiving 30,000 horse power and delivering this amount, less the line loss. The main transmission consists of two lines in duplicate. From the Niagara River to Lockport, a distance of 16 miles, there are two lines on the company's private right-of-way, each capable of transmitting 30,000 horse power. From Lockport to Mortimer, a distance of 57 miles, there is a line on the company's private right-of-way having a capacity of 20,000 horse power. From Mortimer east to Syracuse, a distance of 81 miles, there is a line on the company's right-of-way

FIG. 4—Niagara crossing, cantilevers, American side

having a capacity of 10,000 horse power. From Lockport to a point about 11 miles east, thence south on the company's private right-of-way to the West Shore Railroad, and thence on the West Shore Railroad to Pittsford is a line having a capacity of 20,000 horse-power. From Pittsford on the West Shore Railroad right-of-way east to Syracuse is a line having a capacity of 10,000 horse power. From Lockport south to a point south of Buffalo, there are two transmission lines on the private right-of-way of the company, each having a capacity of 30,000 horse power. These two lines south are tapped into the two lines

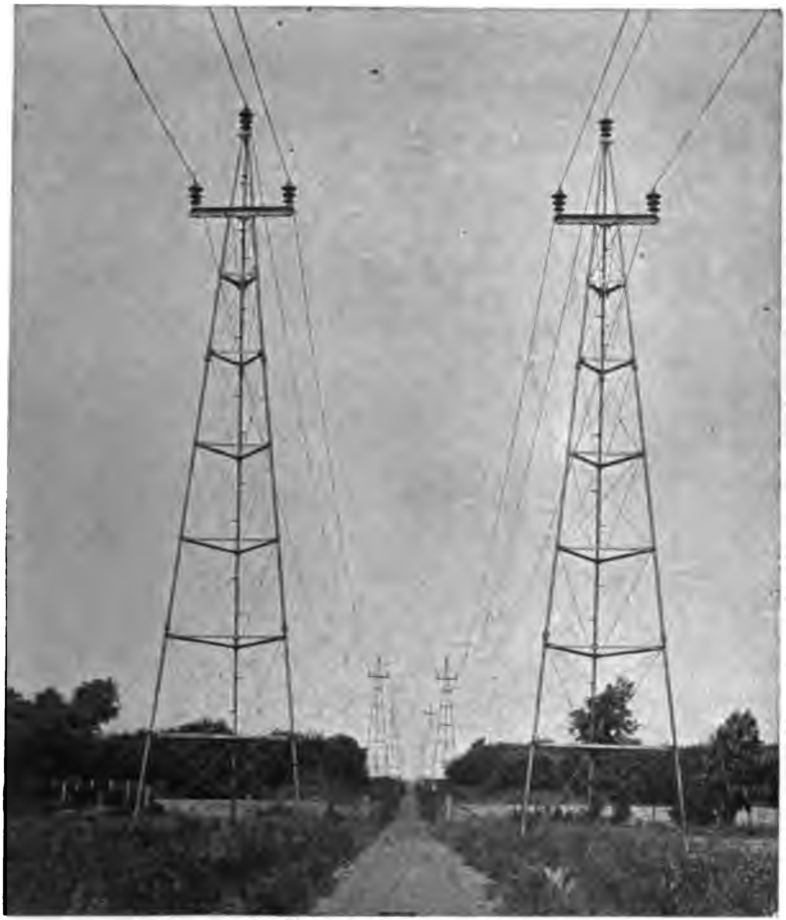


FIG. 5—Pipe towers

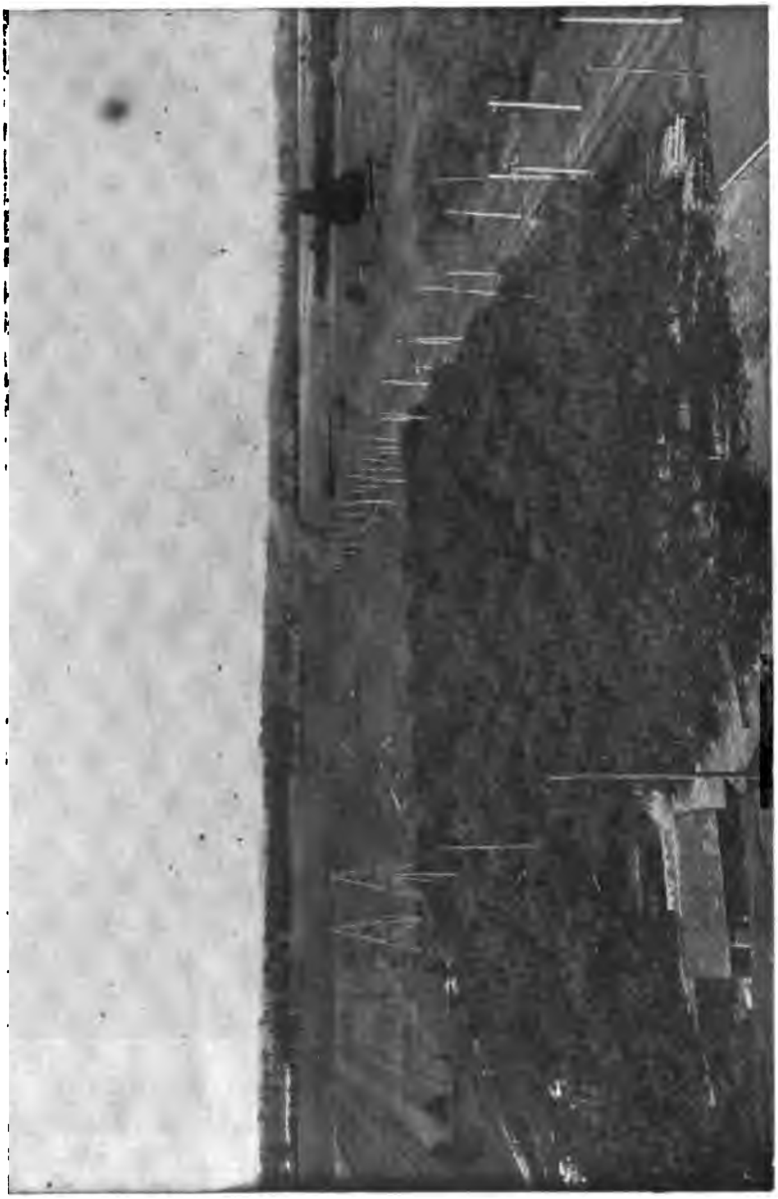


Fig. 6—Transmission lines from Lockport to Buffalo

coming from the Niagara River to Lockport, and constitute, therefore, at present, a branch line; but they will be eventually extended clear through to the Niagara River, and it is in anticipation of this extension that they are constructed with the full capacity of 30,000 horse power. As will be seen from the above, the distance from the Niagara River to Syracuse is 154 miles. In addition to this, the transmission from the transforming station of the Ontario Power Company to the Niagara River has a length of about 6 miles, making, as previously mentioned, a maximum transmission of 160 miles.

Fig. 7—950-foot span over Buffalo creek

It will be seen, therefore, that in delivering power in Lockport, and in the neighborhood of Buffalo, Rochester, Syracuse, and at intermediate points, the company will have transmission circuits in duplicate, each capable of transmitting the full amount of power to be delivered at the several points.

As previously stated, the power is brought across the Niagara River by means of aerial cables spanning the river, and delivery of the power is taken by the transmission company at the international boundary line. The cables are brought across the river in three spans; one span from steel cantilevers at the top of the cliff on the Canadian side to steel towers at the water's edge on the Canadian side; another span from the water-edge towers on the Canadian side to the corresponding towers on the American side; and a third span from the steel water-edge towers on the American side to the steel cantilevers at the top of the cliff on the American side. The use of cantilevers is necessitated mainly by reason of the steep angle at which the cable descends from the top of the cliff. Their use also makes possible the required clearance between the cable and the slope of the gorge, a point of special importance on the American

FIG. 8—1253-foot span over swamp

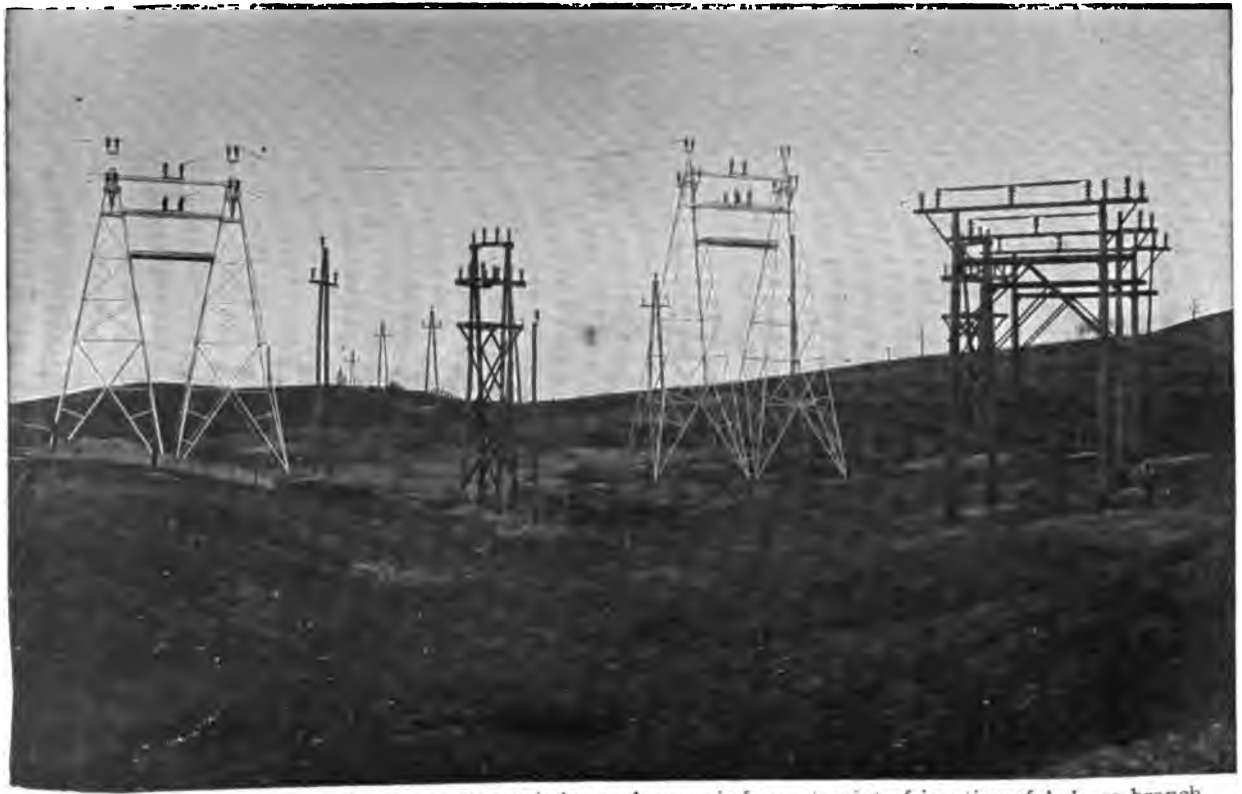


Fig. 9—Cross-connecting and disconnecting switches and open-air fuses at point of junction of Auburn branch line and the main line

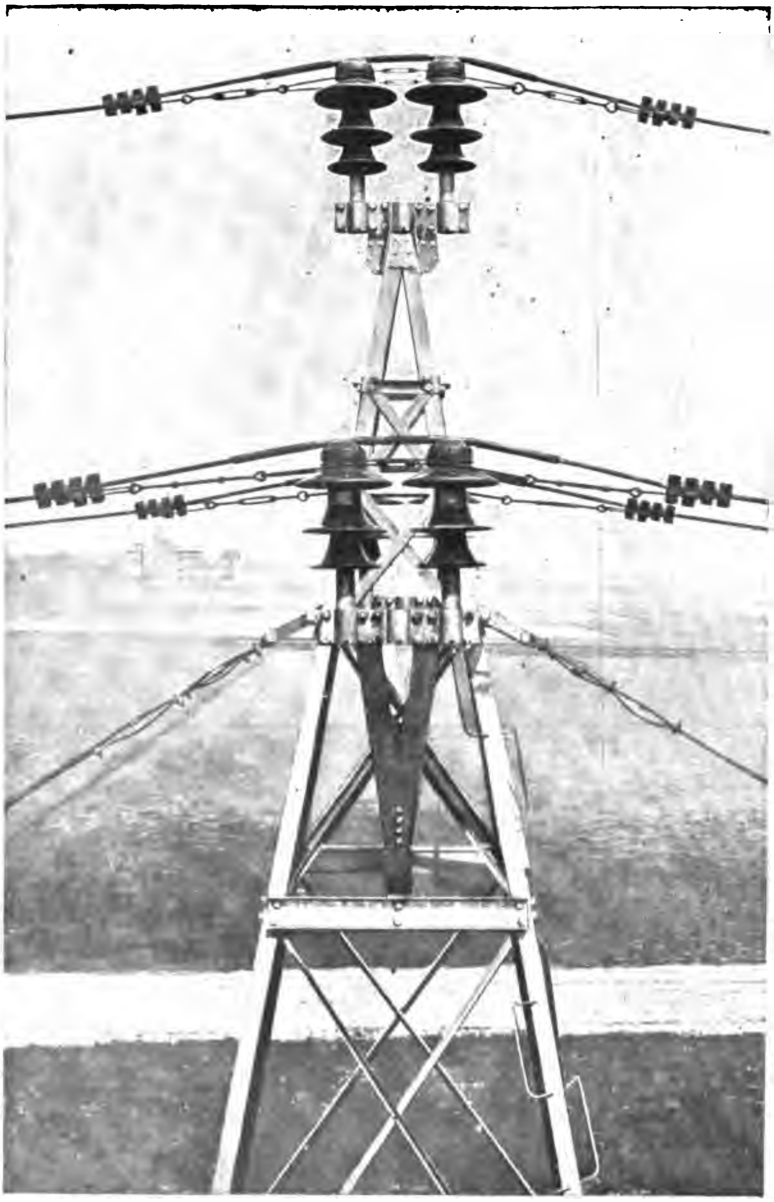


FIG. 10—Top of double-guyed steel tower

side in view of the fact that one of the branch lines of the New York Central Railroad is on the American slope of the gorge. The steep slope of the cable at the cantilevers would make it bear upon the upper petticoat of the insulator supporting it, if the cable were attached to the top of the insulator in the usual way. As will be seen by the photographs of the cantilevers, this difficulty is obviated by attaching the cable to a steel cross-bar supported at each end by an insulator.

FIG. 11—Tower in Montezuma swamp

The steel cantilevers and the river-edge towers are all designed to withstand the most extreme conditions of sleet and wind that will probably ever exist. The requisite mechanical strength of the insulation at the points where the cables are attached to the steel structures is obtained by using a sufficient number of line insulators, and the proper distribution amongst these insulators of the forces which will come upon them is effected by means of malleable cast-iron caps cemented to the tops of the insulators and to which the cables are fastened.

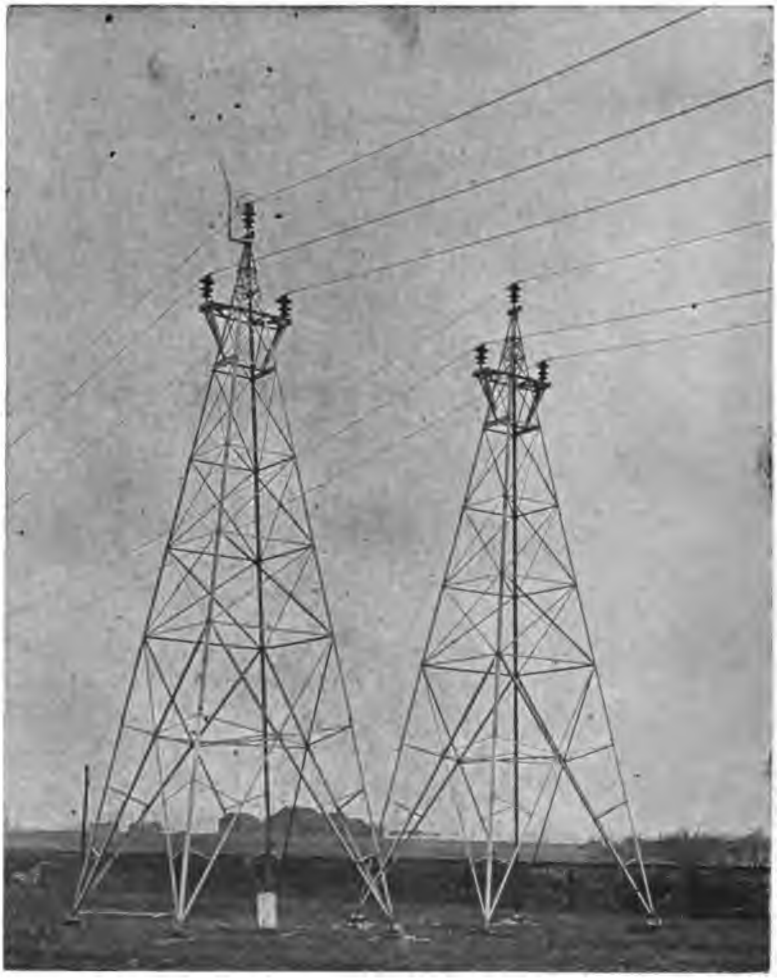


Fig. 12—Line structure lightning-arrester on steel tower

It was originally intended, and provided for in the contract with the Ontario Power Company, that just after crossing the river the 60,000-volt lines should be led into a switching station in which, by means of 60,000-volt electrically operated oil-switches, it would be possible to interchange the circuits coming into and going out of this station. The building itself for this switching station has been completed, but, before the equipment of the station had been installed, arrangements were made with the Ontario Power Company to defer the outlay for such equipment until the use of it should be more necessary than at the present time, when only two lines are in operation.

FIG. 13—Stringing line cable

The main-line construction of the Niagara, Lockport and Ontario Power Company is most substantial. With the exception of that portion of the main line on the West Shore Railroad between Churchville and Syracuse, the main-line structures are all steel towers, and the standard line-span is 550 feet. On some portions of the transmission line, however, much longer spans are used, the longest at present installed being 1,253 feet. In some cases these long spans had to be provided with towers heavier than the standard; in other cases it was possible to put them up with little, if any, modification of the standard tower construction. For a number of reasons, the principal one being lack of the requisite space, it was necessary to use on the West Shore right-of-way between Churchville and Syracuse wooden construction of special design which will be described later on, the standard span being 220 feet. In every case on the 60,000-volt lines, each line of towers or wooden structures carries only one three-phase circuit. The main line conductors installed so far are all of them of aluminum cable, except on a portion of the line between Mortimer and Syracuse where, because of the long spans employed, it is preferable to use copper.

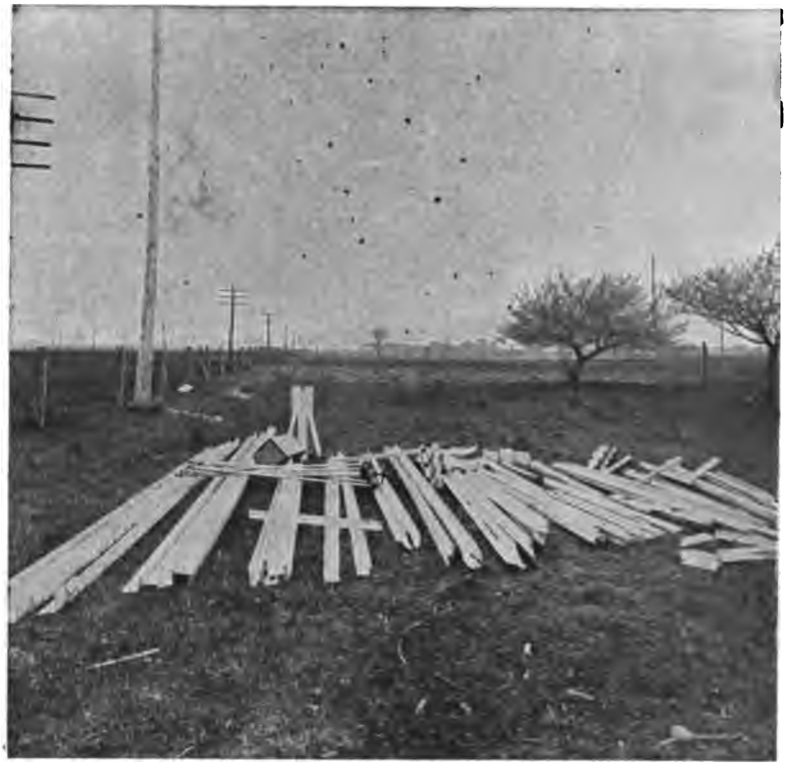


Fig. 14—Tower delivered ready for assembling

The first of the steel towers installed were of the tripod type, made of lap-welded pipe; but the later towers, and those which in the near future will be installed, are of structural shapes and galvanized. The design of these two types of towers is shown in the accompanying illustrations. Two types of the structural tower are shown. The earlier ones were non-interchangeable; that is, the guyed towers differed in construction from the unguyed towers. The later towers are interchangeable; that is, the guyed and unguyed towers are exactly similar except for the guys and double insulators of the former. Contrary to the practice which has heretofore been followed in the matter of steel line towers, the towers of this transmission line are mounted on foundations of reinforced concrete. These foundations are designed to utilize the weight of the earth around them in resisting uplift. The towers and their foundations are capable of withstanding transverse forces which will be brought upon them when the line cables are covered with 0.5 in. of ice all around them and the wind blowing transverse to the line at a velocity of 75 miles an hour. The towers have the same strength in all directions; that is, they are capable of withstanding the same forces in the direction of the line that they are capable of

FIG. 15—Assembling tower (1)

withstanding transverse to the line. To meet the contingency, not likely to occur, of all three cables breaking at once, in which case the full tension of all the cables might be brought upon the towers, there are at intervals along the line certain towers guyed both ways in the direction of the transmission line, and having double fixtures. The strength of these guyed towers is such as would enable them to withstand the forces that would obtain under the extreme conditions outlined above, if all the line cables should break. The guyed towers will, therefore, terminate any progressive failure of the line which might under extreme conditions be instituted by the breaking of cables.


FIG. 16—Assembling tower (2)

As stated above, on the West Shore right-of-way it was necessary to use wooden line structures. The type of construction employed is that which has been designated by the company as " A-frame construction." It is clearly shown in one of the accompanying cuts. By adopting this type of construction, in which each structure consists of two poles instead of one, it is possible to use twice the length of span that would be used in ordinary wooden pole construction. and employ, therefore, one-half the number of insulators. As stated above, the standard length of span of this type of construction is 220 feet. On some portions of the West Shore right-of-way it was necessary to use steel construction, and in such places there were installed galvanized lattice steel poles, such as are shown in one of the illustrations. The span on these poles is the same as that on the A-frame construction.

FIG. 17—Foot of tower, showing method of fastening tower to foundation

In a number of places on the main line, both on the West Shore and on the private right-of-way, it is necessary to cross the Montezuma marsh. Where this marsh was crossed with steel tower construction, the concrete foundations for the steel towers were built by first excavating the swamp through the soft mud until the soft marl, forming the sub-stratum of the swamp, was reached. On the marl was laid a platform of two layers of corduroy, and on this platform was built the concrete foundations, the weight of which was made sufficient to take care of any uplift which will come upon the towers. These foundations were installed, some of them, in cold weather and, so far, they have shown no settlement. Where this marsh was crossed with A-frame construction, it was found in places much too expensive to excavate for the proper foundation for the A-frames. The A-frames were, therefore, installed by laying on top of the ground four line poles in two pairs, the poles of one pair being parallel to the line, and the poles of the other pair being at right angles to the line. These poles were spiked together at the point where they cross, and at the point of crossing the A-frame was spiked to them, the A-frame being further

FIG. 18—Tower foundation dug up for purpose of relocation

secured to the poles by braces. On each end of each pair of poles was spiked a box, built up of planking and filled with stone, in order to give sufficient weight to take the uplift due to any pull at the top of the tower. This structure, while far from beautiful, has, so far, proved very satisfactory. The tower construction and the A-frame construction in swamps are shown in the illustrations.

It will be noted that, in some of the illustrations of the towers and A-frames, there is shown a horn attached to a cap on the top of the insulator and another horn alongside of it fastened to the structure and extending some distance above the insulator. This comprises a combined line-structure lightning-arrester, or spark-gap, and lightning-rod. It has been decided to make a careful trial of this method of protection of the line before resorting to a grounded cable; partly because of the great expense of the grounded cable, and partly because there is no reason to think, so far, that it will necessarily afford complete protection in every case. For the present, these line-

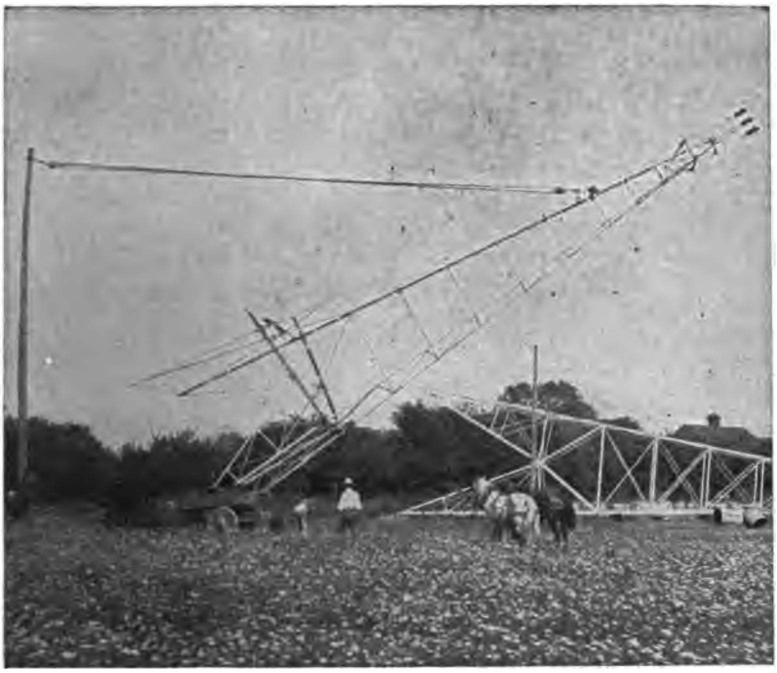


FIG. 19—Erecting 75-foot tower (1)

structure lightning-arresters will be installed only on the top cable, in view of the fact that during the last lightning season, in the course of which a number of insulators were broken by lightning, more than three-fourths of the insulators so broken were top insulators.

The insulator used on all the main-line construction is one especially designed for this plant by the writer. It has probably the greatest factor of safety as regards flashing, etc., of any insulator in practical use to-day, and is considerably larger and heavier than any insulator of which corresponding use has heretofore been made. It consists of three shells nesting in one another and cemented together by means of neat Portland cement, the whole insulator being cemented in a similar manner to a steel pin before attachment to the tower. The insulator is clearly shown in one of the illustrations. The total height

FIG. 20—Erecting 75-foot tower (2)

of it from the edge of the lower petticoat to the top of the head is 19 inches. The diameter of the upper petticoat is 14.5 inches. The insulator used on some of the branch lines is smaller and less expensive than that for the main line, partly because the branch lines receive in general a somewhat lower voltage than the main line and partly because the lines, carrying the small amounts of power they do, are not considered to be entitled to the same insurance as the main line. Each branch line has in series with it, at the point where it is tapped off the main line, 60,000-volt outdoor fuses to cut out the line in case of trouble on it. The fuses consist of lengths of thin copper wire 16 feet long, run through an ordinary small rubber bathroom hose and laid in clips on top of a wooden bar supported at each end and at the center by line insulators mounted on poles.

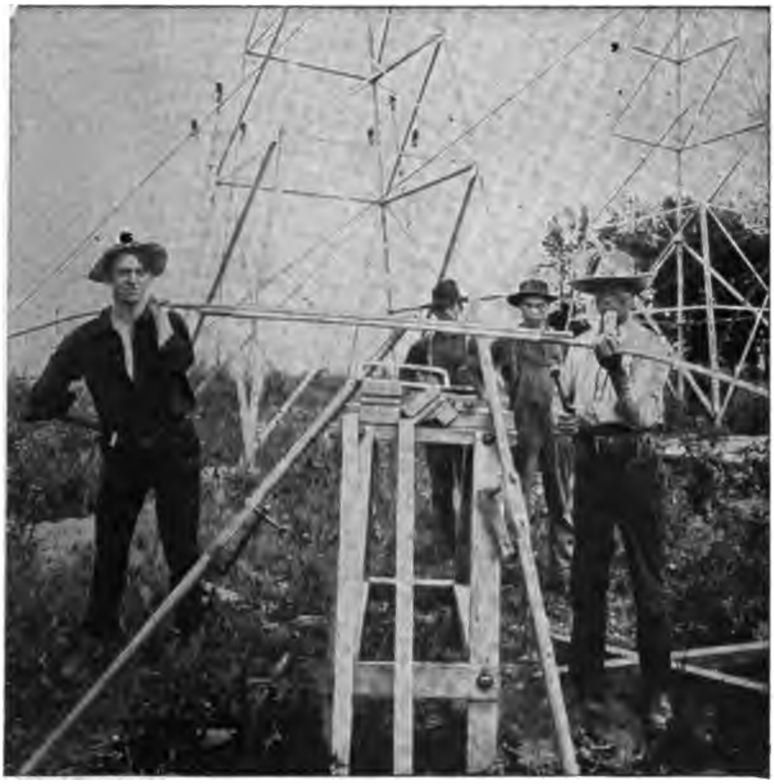


FIG. 21—The making of a joint (1)

The fuses are parallel to each other in the same horizontal plane, and the distance from center to center is about 25 feet. These fuses have so far proved very satisfactory but will probably in time be replaced with fuses of the explosion type. The outdoor 60,000-volt fuses are shown in one of the illustrations.

There are only three sizes of cables used on the main transmission line, designated by the company as 3/3, 2/3, and 1/3 respectively. The 3/3 cable is aluminum cable, consisting of 19 strands, and having a total area of 642,800 cir. mils, being equivalent to 400,000 cir. mils copper. The areas of cross-section of the other cables are respectively two-thirds and one-third that of the large one.

Fig. 22—The making of a joint (2)

In ordinary straight-away work, the cable lies in the top groove of the insulator, and the pull of the cable is taken care of by means of two aluminum wire ties around the neck of the insulator. One of these ties extends each way along the cable. The tie itself consists of a single loop around the neck of the insulator, the two ends of the loop being twisted around the line cable. The result is that the cable is not really fastened to the insulator at all, but simply lies in the top groove. The ties do not, therefore, perform any function, except when there is a pull on the cable tending to slide it in the direction of its length. The advantages of such a tie are twofold: first, the full strength of the tie wire is developed, which is not the case if a tie is twisted or "pig-tailed," since in such case the tendency is for the tie to cut itself in two at the twist; secondly, the tie does not damage the soft aluminum cable, as would be the case with most of the other ties usually employed.

FIG. 23—The making of a joint (3), joint complete

In other than straight-away work, and where it is desirable that the method of fastening to the insulator shall be such as will withstand a pull equal to the full strength of the cable, in case the cable should break, the tie mentioned above is not used, but instead there is employed a cable-clamp and a yoke extending each way on the cable.

In every case the cable near the insulator is protected from possible arcs, so that in the event of an arc there will be a chance for the circuit-breaker at the generating station to open before the cable shall have been burned off. This protection is accomplished in the top groove of the insulator by means of sheet aluminum wrapped around the cable at this point to a thickness of ⅛ inch, and is accomplished on each side of the head of the insulator to a distance of 12 inches from the head partly by the turns of the tie-wire mentioned above, and partly by an additional serving of tie-wire. Where, in the case of the use of cable-clamps, no tie-wire is used, its absence is made up

FIG. 24—60,000-volt main-line insulator with tie and cable protection

for by additional serving. The photographs show very clearly the methods of attaching the cables to the insulators and the methods of protecting the cables from arcs.

The ends of the line cables are connected by means of twisted-sleeve joints. The method of making these joints is shown in the illustrations.

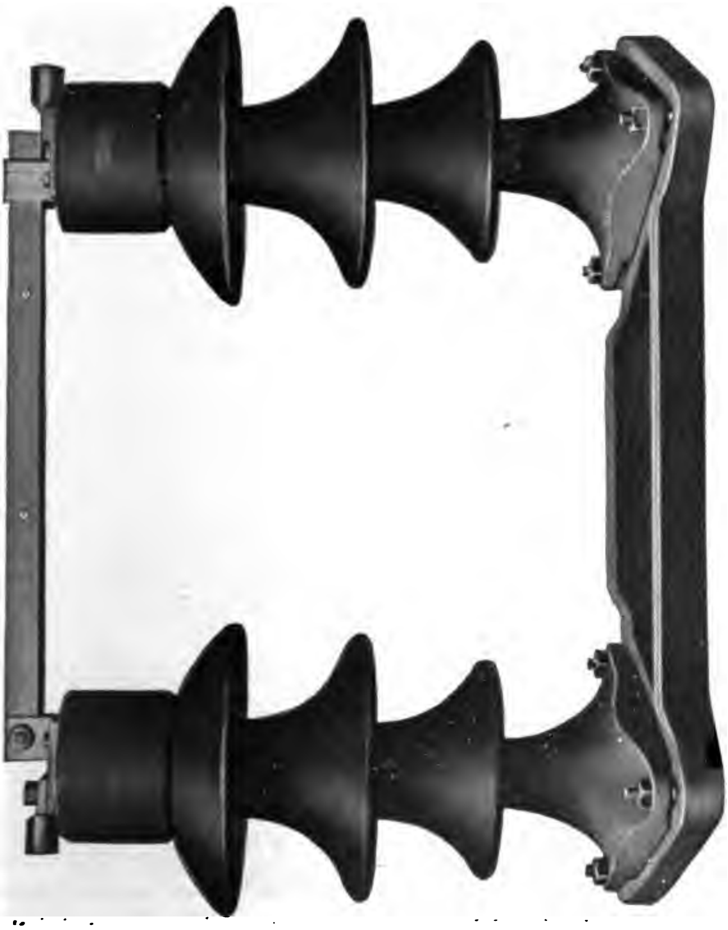


Fig. 25—60 000-volt outdoor line disconnecting switch

At intervals along the line there are provided disconnecting switches for sectioning the line to facilitate testing out in case of trouble, or cutting out any portion of the line which is damaged. There are also provided at certain points, in connection with these disconnecting switches, cross-connecting switches, enabling the interconnection of different portions of the two lines.

On a considerable portion of the company's right-of-way is a wagon road, for use in patrolling the line and delivering material for construction or repair. At certain points along the line there are patrol houses for the storage of material, for taking care of teams, and for the comfortable housing of the patrolmen. Each house has in it a sleeping room, kitchen, and

Fig 26—Standard A-frame construction showing line structure lightning-arrester

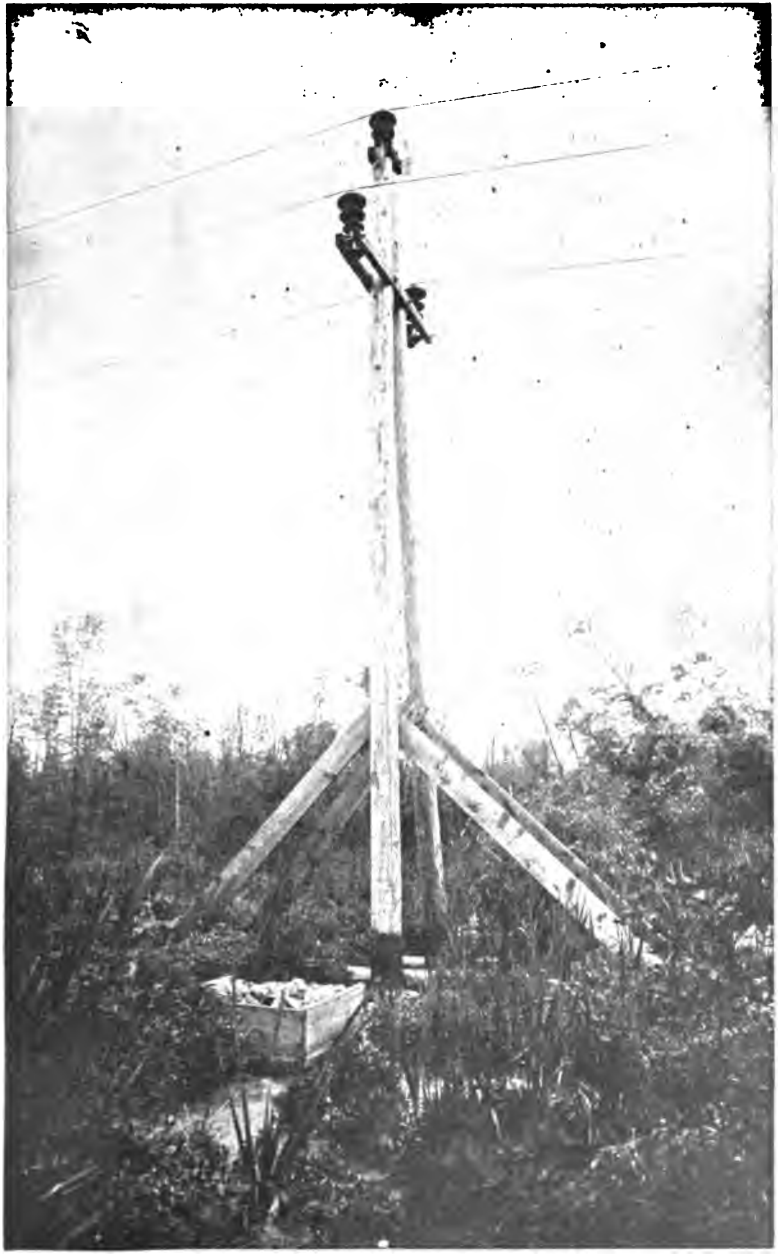


Fig. 27—A-frame construction, Montezuma swamp

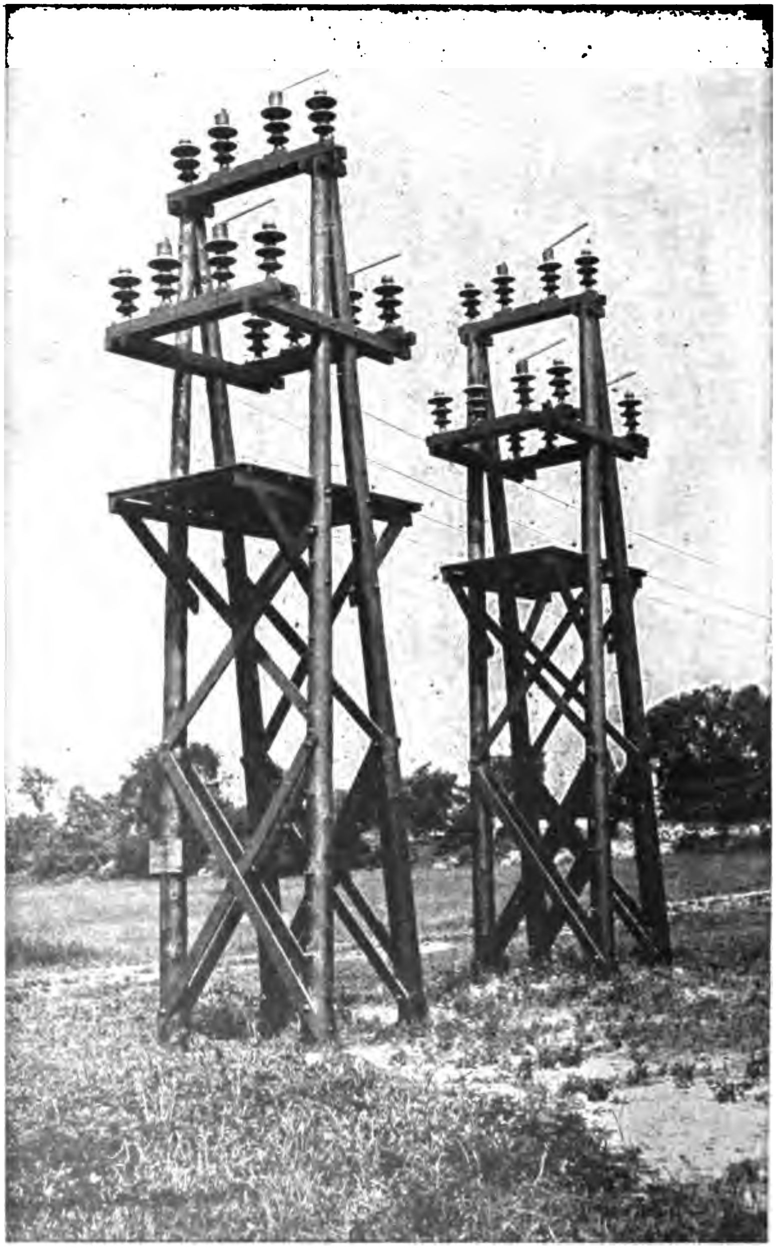


FIG. 28—A-frame disconnecting switches

sitting room. On all of the transmission lines, also, the company has a private telephone line on a separate set of wooden poles. Taps from this line are brought into each of the transmission houses, and in addition to this the line patrolmen have portable telephones which can be connected to the telephone line at any point.

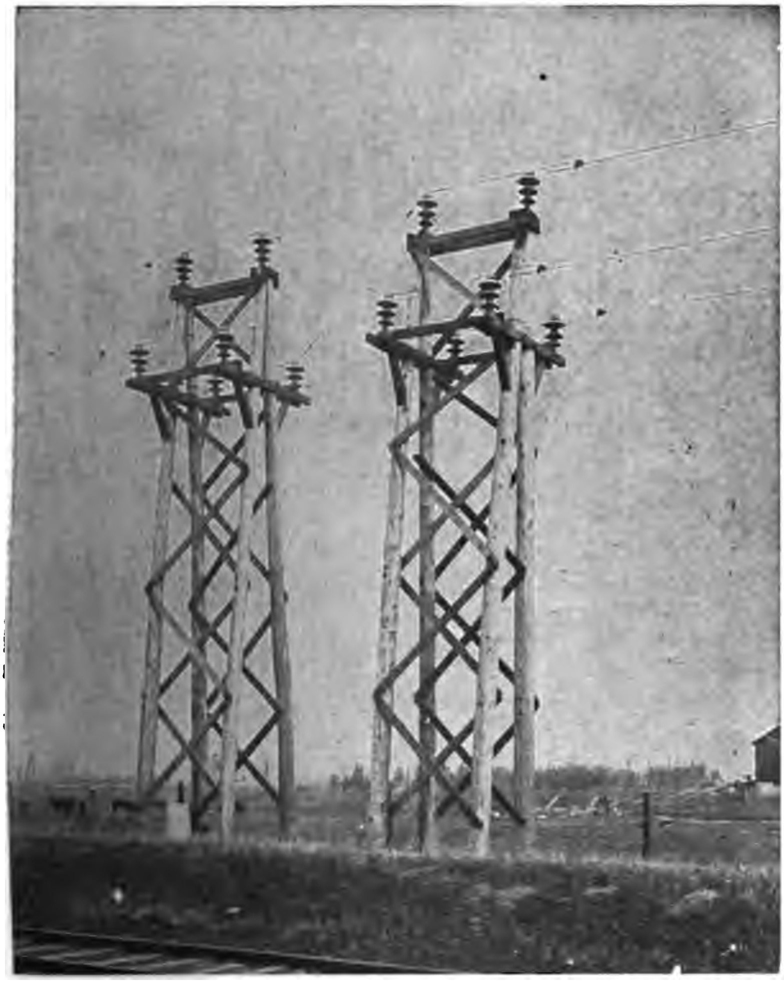


FIG. 29—A-frame transposition

Most of the contracts which the company has for the supply of power cover the delivery of the power at the main-line voltage.

FIG. 30—Galvanized steel poles on railway

Thus far the company has installed only three sub-stations, two of them of considerable size at Lockport and Gardenville, respectively, and one at Baldwinsville, a very small and comparatively inexpensive one. The stations at Lockport and Gardenville have each a normal capacity of 3,000 kw. not including the spare apparatus. They are so designed that their capacity can be indefinitely increased. The Baldwinsville station has a capacity of 750 kw. The station at Lockport has been installed and in operation for some time. That at Gardenville is about complete, but not yet in operation. The accompanying illustrations will, in a general way, make clear the type of construction employed in the Lockport and Gardenville sub-stations; but, as there are a number of features in connection with these sub-stations which are quite different from ordinary

FIG. 31—Lockport sub-station showing 11,000-volt outdoor lightning-arresters

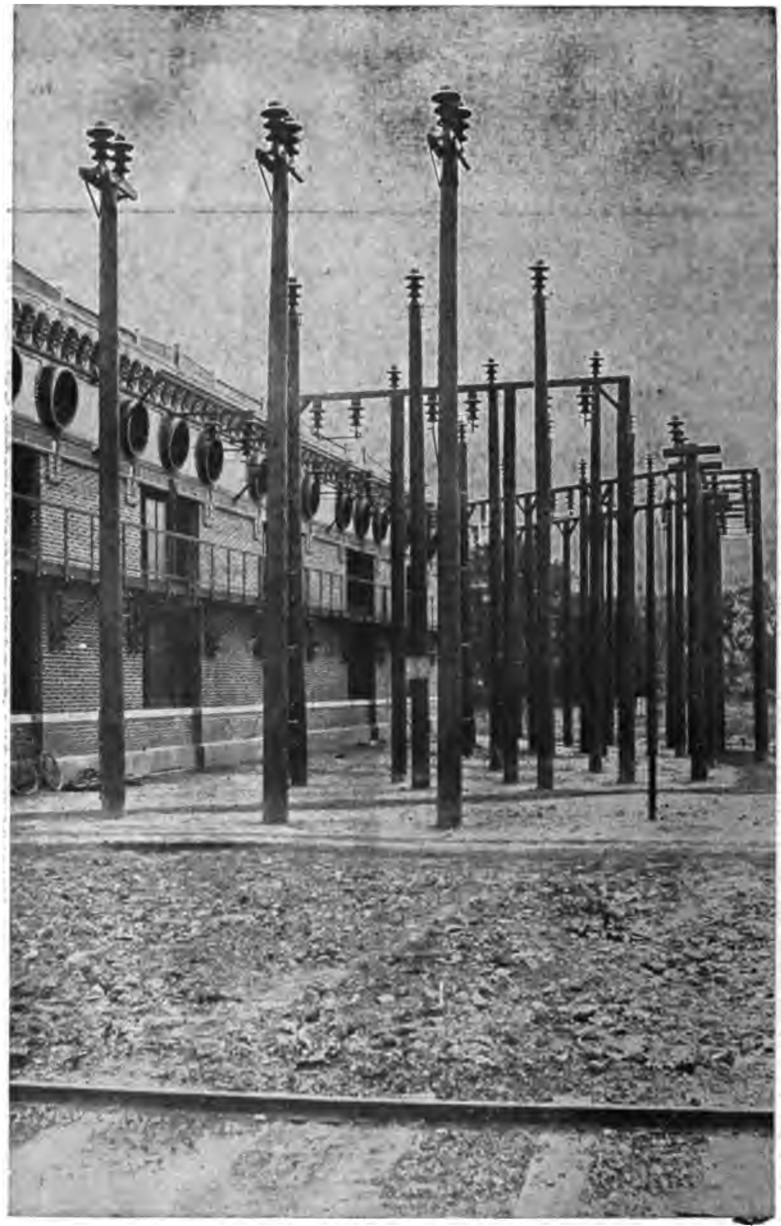


FIG. 32—Lockport sub-station showing outdoor 60,000-volt bus-bars

practice in these matters, a brief description of them will be in order.

The 60,000-volt bus-bars at these sub-stations are outdoors; in other words, these bus-bars have been treated exactly as if they were part of the transmission line and located out of doors in a manner, so far as insulation is concerned, similar to the transmission-line cables. In connection with them are disconnecting switches as shown in the accompanying cut for making various combinations of the apparatus connected to them. Of

FIG. 33—Transformer room, Lockport sub-station

course, the disconnecting switches are not intended to break the working current. When it is necessary to break the circuit under load, it will be accomplished by means of the 60,000-volt electrically operated oil-switches installed in the station which, in the case of the Lockport sub-station, serve also for the control of the two lines to the Buffalo district.

Another feature out of the ordinary in connection with this station is the lightning-arrester equipment. This equipment is also out of doors, and consists of a number of horn-type lightning-arresters mounted on wooden poles in much the same manner as such arresters are ordinarily mounted. The installation differs, however, from the ordinary lightning-arrester installation of this kind, for, instead of there being only one pair of horns for each line conductor, there are three such pairs. One pair is set for a comparatively low striking electromotive

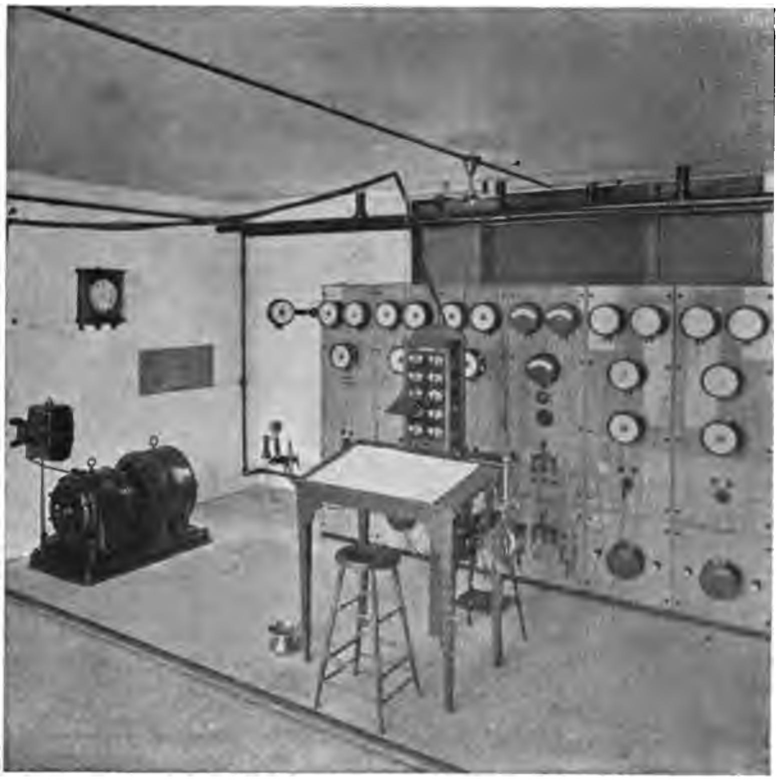


Fig. 34—Switchboard room, Lockport sub-station

force and has in series with it a high resistance; the next pair is set for a higher striking electromotive force, and has in series with it a lower resistance; a third pair is set for very high striking electromotive force and has a fuse in series with it.

The theory on which these arresters are installed is that for ordinary slight static disturbances in the line the arrester having the lower striking electromotive force will discharge, and, since it has in series with it a comparatively high resistance, the resultant disturbance to the system due to the generated current which follows the discharge will be comparatively slight. A more severe static disturbance (whether due to lightning or to any other source), will cause both the arrester having the lowest gap and the arrester having the next higher gap to discharge simultaneously, thus affording two discharge paths to earth, the combined resistance and inductance of which is considerably


Fig. 35—60,000-volt oil-switch and circuit-breaker, electrically operated

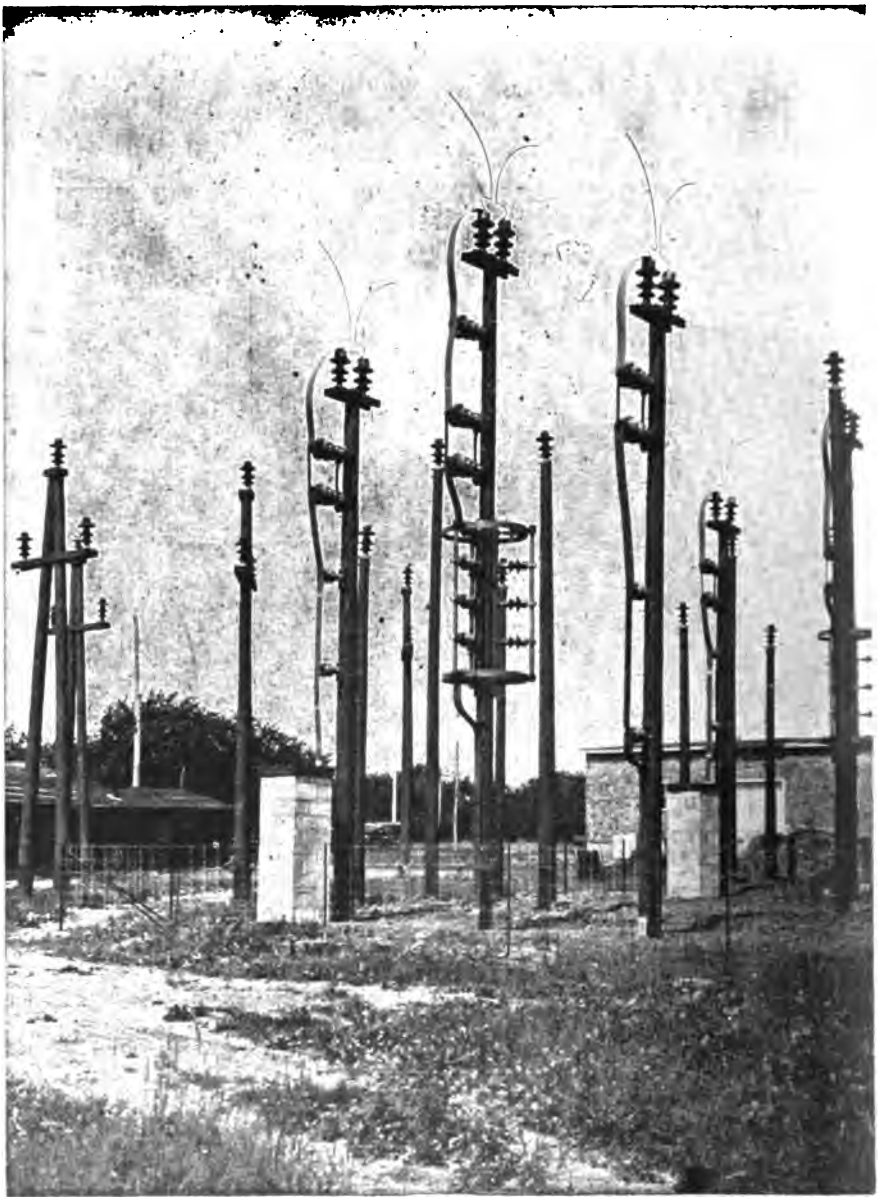


FIG. 36—60,000-volt lightning-arrester equipment; two 3-phase circuits

lower than that of the first path. This will mean a somewhat more severe disturbing effect on the system, due to the generated current which follows. In the case of a very extreme condition; for instance, a direct lightning stroke on the line, the three arresters would discharge simultaneously, the fuse, in the case of the arrester with the highest air-gap, blowing and interrupting the arc upon it, the disturbance of the circuit finally ending upon the other two arresters. Judging from experience in the case of other plants with a much less elaborate arrangement than that outlined, and the experience during the last lightning season with the protection afforded at the Lockport station, the writer believes this method of protection to be entirely effective in the matter of preventing damage to apparatus in the sub-station. Such an installation may, in the case

Fig. 37—Baldwinsville sub-station, showing lightning-arresters

of a very severe discharge, such as that due to a direct stroke of lightning, mean a temporary shutdown of the system, or at any rate of the synchronous apparatus operating upon it; but it does not necessarily follow that this will be the case if expulsion fuses be used on the highest gap arrester. Such fuses as have been experimented with in connection with this work operated very satisfactorily. It may be noted in passing that a lightning-arrester equipment similar to that just described for sub-stations is installed also at each point where a branch line is taken off at the main line.

FIG. 38—Typical patrol house

The other features of this station are very similar to those usually found in such installations. There is a complete system of oil piping for putting oil into or removing it from the transformers and oil-switches, and also for storing oil to replace that in the transformers and switches when it may become necessary. There is also provided outside of the building an oil-storage tank for storing oil that has been damaged until such time as it is convenient to put it through the oil-cleaning apparatus. In view of the fact that there is no other continuous water supply available at this sub-station, it has been necessary to drill wells for the supply of water for cooling the transformers. In connection with these wells there has been installed a pumping plant, a water tower, and a cooling pond, the latter for use in case the wells should not be able continuously to supply all the water required.

There will be installed shortly on the company's system two switching stations, one at Mortimer and one at Syracuse. The one at Syracuse will be for taking care of the two incoming 10,000-h.p. lines and the outgoing lines to the consumers in Syracuse. The one at Mortimer will be for taking care of the two incoming 20,000-h.p. lines and five outgoing lines; two of them being a line in duplicate to Rochester; two of them the line in duplicate to Syracuse; and one the Avon branch line supplying several installations, amongst them the station of the Erie Railroad Company, operating their trolley line between Rochester and Avon. Both these switching stations will be equipped with the 60,000-volt electrically operated oil-switches, reverse relays, and other apparatus necessary for properly manipulating the circuits which they control.

The transmission lines of this company cross the rights-of-way of a number of railway companies, and some difficulty has been had in arriving at a satisfactory arrangement with the railways in regard to these crossings. In general, the attitude of the railways is that of being unduly fearful of the transmission lines, and requiring protective precautions of one kind or another. It is, however, gratifying to note that in every case the railway companies have, on investigation, been so well satisfied with the reliability of the transmission company's type of line construction as to waive the elaborate steel protective bridges which have been insisted upon at times in the past, and in most cases little or no extra precautions have been required.

DISCUSSION ON "THE TRANSMISSION PLANT OF THE "NIAGARA LOCKPORT, AND ONTARIO POWER COMPANY," AT NIAGARA FALLS, NEW YORK, JUNE 26, 1907

E. J. Berg: You have a telephone circuit in connection with the power lines?

Ralph D. Mershon: We have a separate telephone line on separate poles on our own right of way.

E. J. Berg: The following observations made in Mexico about a year ago have some bearing on this. A 500-volt direct-current temporary station was furnishing power for lighting a number of buildings on the top of a mountain. The station was located in the valley about 500 ft. below. The lines were strung on high-voltage insulators and were about 22 in. apart. A short time before a thunderstorm, static sparks were seen between these lines. At the time, a number of lamps were burning so that the circuit was closed between the lines within 50 ft. of the spark. Furthermore, these same lines were placed within about 2 in. of each other in the building, yet the spark chose to strike 22 in. in air. A lightning-arrester within 50 ft. of the disturbance would apparently not have taken the discharge.

Ralph D. Mershon: We have line structure lightning-arresters about every 2200 ft. Two or three days ago an insulator was smashed on the tower within 550 ft. of one of these lightning-arresters, set for six inches.

J. W. Fraser: It seems to me that the concrete foundations we are using at the present time are very expensive. We are figuring on a new line, and putting in a sort of button about 2 ft. in diameter, of cast iron, and putting it down about 5.5 feet in the ground. Throughout the Carolinas we have fairly solid earth. I see no reason why this foundation should not be as effective, and it does not cost as much as concrete.

Ralph D. Mershon: Mr. Scholes has figured on metallic foundations and anchorages two or three times, and each time the cost of metallic foundation is more than the concrete.

J. W. Fraser: They are using buttons 18 in. in diameter, that weigh 106 lb. in the West. I understand that they are perfectly satisfactory.

F. B. H. Paine: The towers used in the West are in places where they are not subject to sleet or any of the enormous strains our lines are subjected to in this part of the country. It is reasonable to suppose that they can adopt the metallic foundation, as they can use a lighter tower than we can.

Ralph D. Mershon: Under the assumptions made for the towers of the Niagara, Lockport and Ontario Power Co., the resultant of the horizontal and vertical component forces is 15,000 lb. Under test, the towers must stand twice that.

J. W. Fraser: Wouldn't it be as satisfactory to make a lighter tower and use one strong tower every mile?

Ralph D. Mershon: These towers would not stand the condition of breakage of all the cables. Every two miles we have a guyed tower that will stop all breakages that occur; that is, under the conditions of sleet and wind. Mr. Paine can tell you something about sleet on telephone wires.

F. H. B. Paine: A couple of years ago Mr. Hammond V. Hayes was good enough to relieve my mind of the thought that Mr. Mershon had provided too great strength in our lines. He showed me some plaster casts of wires coated with sleet, which had been subject to a wind, according to the United States Weather Bureau, of 100 miles an hour, the sleet and wind occurring at the same time. That was on telephone wire, and the construction came down. The three or four samples I have in mind, which he showed me, were either from western Massachusetts or along the Hudson valley, in that section, and they occurred during the two famous blizzards.

Ralph D. Mershon: No two engineers will agree on the subject of sleet and wind. If an electrical engineer who has not done much in the way of designing framed structures, designs a line in accordance with his ideas of the wind he will encounter, and submits his designs to a bridge engineer, the bridge engineer will probably say that the assumptions and factors of safety are entirely too low. The factors of safety and assumptions for our structures have been criticized for being too low and for being too high, but I believe we are very close to being right.

J. W. Fraser: I do not think it advisable to provide against abnormal conditions.

Ralph D. Mershon: It depends on the amount of power; a small amount of power is not entitled to the amount of insurance that a large amount of power is entitled to. If there is 30,000 h.p. going over a circuit, there is more depending on the 30,000 h.p. than there would be with 5,000 h.p. You are justified in taking more risk in connection with a 5,000 h.p. line than you are with a 30,000 h.p. line. The latter serves a much greater territory than the 5,000 h.p. and industries and utilities which in the aggregate amount to a great deal more than in the case of a 5,000 h.p. service.

J. W. Fraser: We decided that the largest amount of power we could carry over one line normally would be about 6,000 kw. Of course that makes a lighter line.

Ralph D. Mershon: Our conductors starting out over the river are larger than they are farther along the line. The cable is 0.9 in in diameter; add 0.5 in. of ice and it becomes a good size conductor.

In regard to the question of wind pressure, I would confirm something Mr. Buck said this morning in regard to long spans. When we were crossing the Niagara River we had extended over the river a light rope used as a messenger rope. It responded of course to every impulse of the wind. I have observed this rope with the wind blowing pretty hard, and its average position scarcely changed at all, but the positions of different portions of the rope varied over wide ranges. You could see waves running back and forth over it, showing heavy gusts of wind in one place, and gusts of wind of lower velocity somewhere else. The behavior of the rope confirmed the results of the tests made on the Forth bridge, that there is a great difference between maximum and mean wind pressure, and that the maximum average wind pressure on a small area will be much higher than on an extended area.

J. W. Fraser (by letter): Recently we have had a test made on the holding-down power of metallic anchors and the attached curves have been calculated from data obtained. Mr. Mershon says that "The resultant of the horizontal and vertical component stresses is, I think, 13,500 lb." If this is the stress at a point 40 ft. from ground, and the base of tower is 15 ft., each anchor would have to withstand a pull of 18,000 lb. Referring to curve B, two 10-in. channels 2 ft. long, spaced 26 in. on centers, would have to be sunk 6.5 ft. in the ground. The extra cost of these anchors per tower would exceed the cost of ordinary anchors by about $18.00. I take it that Mr. Mershon was referring to the extra strong towers spaced two miles apart, and if I am correct much smaller anchors would be ample for the ordinary towers.

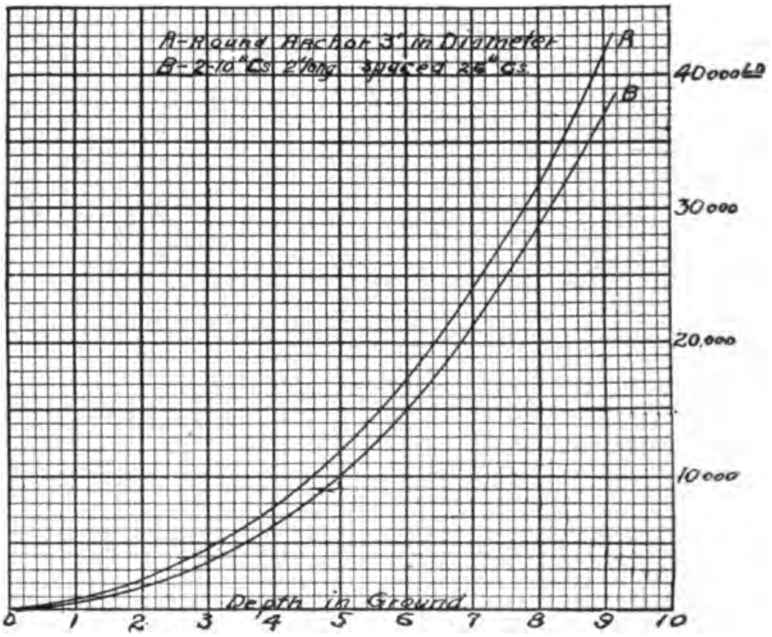


FIG. 1.

It is not only that stone, water, and cement have to be hauled long distances by teams, but the work is delayed excessively, waiting for either the water or the cement or for the foreman to adjust template and set the anchors. In all our line construction we are obliged to provide camping outfits and board for our men, and the delay caused means a great deal more money than the paper estimates of the construction of steel lines.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

LOCATION OF BROKEN INSULATORS AND OTHER TRANSMISSION LINE TROUBLES.

BY L. C. NICHOLSON

Injury to a single insulator, under certain conditions of operation, renders an entire transmission line, many miles in length, entirely inoperative until the faulty insulator be discovered and replaced. The longer the line the more difficult it becomes to find a broken insulator, or to locate other irregularities in operating conditions, and a correspondingly long time is consumed in restoring the line to service.

When long lines are sectionalized by disconnecting-switches spaced at regular intervals, it is possible, by successive applications of voltage to section after section, to determine the particular section which contains the fault, and then to locate the exact point of failure by patroling a considerable length of line. This process is tedious on account of the necessity of manipulating the line-switches upon telephonic advice from the generating station, and by reason of the time required to patrol the particular section containing the fault. For these reasons it is desirable to employ some method of locating faults by means of electrical measurements which shall be capable of a reasonable degree of accuracy, and of being performed in a short time.

There are several well-known methods of locating faults electrically; among these are the Varley and Murray loop tests. These and other ordinary methods operate with low-voltage direct current acting upon a Wheatstone bridge arrangement of resistances and galvonometer, and are readily applied to metallic circuits suffering from a total grounding or short-circuit. If, however, the fault be a partial one, such for instance as occurs on a high-voltage transmission system when an insulator becomes defective by puncture, or otherwise, it is impracticable to apply any of these methods, since a high voltage must act to develop any current-flow under these conditions. It is manifestly impracticable to manipulate adjustable resistances quickly and accurately in a high-voltage circuit, or to use direct-current instruments such as a galvonometer, because alternating current is demanded by the relatively high voltage which it is necessary to employ. It will be appreciated that, for a fault-locating method to be trustworthy, it must be adapted to the normal operating potential of the transmission line, inasmuch as partial faults sometimes develop which will withstand normal voltage for a short time. It is therefore essential and also desirable to employ the generating, transforming, and switchboard apparatus of the generating station for making fault-location tests upon the transmission lines. A simple scheme of connections involving the manipulation of a few hook-switches has been employed for this purpose upon a long-distance high-voltage circuit, and it has been found possible to locate quickly and accurately any fault seriously interfering with operation.

The particular plant upon which such a test has been operated transmits power at 60,000 volts, 25 cycles, three phase, over lines approximately 160 miles long. The line conductors are of aluminum, spaced seven feet apart, and are carried partly on steel towers and partly on wooden structures. In both cases the insulators are supported on electrically grounded steel pins, a ground-wire being used for this purpose on the wooden structures. The step-up sending transformers operate delta-star with neutral grounded. Under these conditions of operation and line construction, it is evident that an insulator becoming disabled flashes and holds an arc between the line conductor and the insulator pin, which constitutes a short-circuit on one of the transformers and prohibits further service until the injured insulator be replaced. Causes other than broken insulators may interfere with operation; for example, branches of trees fouling wires during wind storms, or even malicious interference. However, trouble necessarily appears from one wire to earth, or from wire to wire.

The method of locating faults referred to above, consists in supplying current from a generator and transformer to the fault to earth through a divided circuit or a loop, formed by joining two line conductors together at both ends, one of the wires so connected containing the broken insulator to be located. The total current supplied divides quantitatively between the branches of the loop in a proportion depending upon the ratio of the two impedances to the fault which ratio is determined by, and therefore is determnative of, the location of the fault. Indicating ammeters or integrating wattmeters connected in the two branches of the loop by means of proper transformers show the current or power supplied through the respective conductors. Amperes or watts so measured, together with the known electrical constants of the line under test, serve to determine the geographical location of the fault. Evidently, only the relative currents flowing in the two paths at the same instant, or the relative integrated power delivered during any length of time, need be ascertained.

Fig. 1 shows the scheme of connections which has been employed. The loop consists of wires *A* and *B* which have a metallic short circuit placed on them at the generating station just inside the current transformers, and a similar one at the receiving station just outside the disconnecting switches. It is, of course, necessary for the generating station operator to order a short circuit placed on the proper wires at the distant end of the line when a test is to be made. *E* is the high-tension winding of a power transformer. Its connection to earth is through the neutral which operates grounded. The particular transformer used will depend upon which wire is in distress. *R* is a limiting resistance connected in series with the loop, and is designed to limit the total flow of current to the capacity of the transformer and the measuring instruments. At *V* is represented a fault to earth, which usually takes the form of a broken insulator, over the surface of which current flows through an

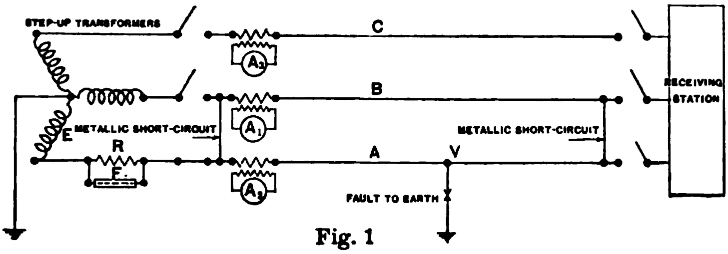


Fig. 1
SCHEME OF CONNECTIONS.

arc. A_1, A_2, A_3 represent indicating ammeters in the secondaries of current transformers.

The limiting resistance R may be connected in either the high- or low-tension side of the transformer. The amount of resistance used, depends largely upon the character of the fault to be located. It must be large enough properly to limit the current flow, and must not be so high that it will interfere with a continuous flow of current through an arc after the fault has developed. Moreover, when testing for a fault which will resist nearly normal voltage on a long transmission line taking a large charging current, there occurs a loss of potential across this resistance on account of the charging current flowing through it, so that the potential operating upon the fault may be less than normal potential of the system and too low to flash over the injured insulator. To obviate the necessity, under such conditions of raising the voltage of the system above normal, an expulsion fuse, F, shunting this limiting resistance has been employed. The capacity of this fuse must be at least equal to the normal charging current of the line. Its use ensures full voltage at the fault and allows the current flow to be properly controlled by the resistance R after the fault has developed and the fuse has burned. Any automatic overload circuit-breaker could be substituted for the fuse.

Since the resistance drop is in quadrature with the condensance voltage, a fuse or its equivalent is necessary only when testing long lines, and then very rarely.

A cheap and entirely satisfactory form of resistance, well adapted to use in the high-tension circuit, consists of ordinary cement concrete columns supplied with expanded-metal terminals. Four columns, 12 ft. long, a square foot in section, each having a resistance cold of about 2000 ohms, have been used in multiple or singly as occasion demanded. The temperature-resistance coefficient of concrete being large and negative, it is an easy matter to arrive at a proper resistance by heating the columns with current. Such flexibility in this resistance has at times proved very convenient.

Experience so far obtained, indicates that, in a large majority of insulator failures, a 1,000-ohm concrete resistance in the high-tension side does not prevent flashing of a broken insulator, nor does it interfere with satisfactory current readings. Occasions do arise when the fuse is necessary, and when a comparatively low resistance must be used to maintain an arc at the fault long enough to obtain current readings on indicating ammeters. It appears that after an arc has once been established it will hold indefinitely, provided the current flow be not too restricted. The more incomplete the fault and the longer the striking distance, the larger the current required. From 50 to 100 amperes has proved an appropriate range of current for general testing purposes. Variations that occur when using this amount of current are usually gradual—being due to decreasing resistance of the concrete—so that there is rarely any difficulty experienced in obtaining satisfactory simultaneous ammeter readings during a period of, say, five or ten seconds.

FIG. 2.

On account of conditions at the fault being unfavorable to a steady flow of current, trouble may be had in reading indicating instruments which are not dead-beat. In such cases, integrating wattmeters may be resorted to, to obtain a comparison between the power supplied to the fault through the two sides of a loop. Only in extreme cases, such for example as disturbances caused by swinging tie-wires or tree branches, is it necessary to use wattmeters.

Fig. 2 shows an insulator broken by a stone in such manner that it withstood operating potential for a few seconds, the striking distance being about seven inches. This insulator was located easily with ammeters which were not dead-beat.

The effect of an arc upon the cable is an important consideration. If it is burned so as to require splicing, considerably more time is consumed in restoring the line to service than if only a broken insulator is to be replaced. This is particularly true with long spans, on account of the weight of the cable to be handled. Under ordinary operating conditions, it is impossible to know how much the cable is burned by the short-circuit current at breakdown and how much by the testing current. Damage to the cable by an arc carrying 100 amperes sustained forty seconds has been found to be insignificant when the striking distance is several inches. It appears that there is some damage if the arc is short and confined, such as would obtain in the case of an insulator punctured through the head. However, during the short period required to read the instruments, the cable does not suffer materially. Where shields are used to protect the cable, there is no damage in any event.

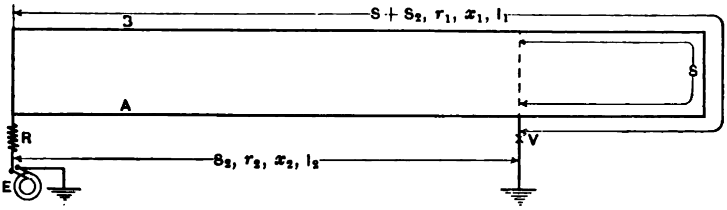


Fig. 3

Since the current through the faulty conductor varies from one half the total current when the fault is at the distant end of the line to the total current when the fault is at the testing station, while the current through the other conductor varies from one-half the total current to zero corresponding to the same locations, it is desirable that the full-scale value of one ammeter should be twice that of the other. For this reason, and on account of their superior accuracy, portable instruments are preferable to the switchboard type.

Referring more particularly to the division of current between the two paths, it has been found that this division takes place in accordance with Ohm's law, or that the currents I_1, I_2 are inversely proportional to the ohmic resistances r_1, r_2 of the two branches.

Assuming the resistance volts of the two branches equal, it is interesting to note how reactance volts are also equal. The two parallel wires constituting the loop, Fig. 3, carry currents in the same direction to the fault, and in opposite directions beyond it. These currents, I_1, I_2, are of the same phase and frequency but of different magnitude, I_2 being larger than I_1. Only that magnetic flux included between the wires need be considered as influencing a division of current, inasmuch as the flux which embraces both wires affects only the total impedance of the entire circuit. The flux included between the wires up to the fault is the resultant of two oppositely acting magnetomotive forces separated in space by the distance between centers of wires. The flux density at any point within either wire is proportional to the current and to the distance from the center, while at any outside point it is proportional to the current but inversely proportional to the distance from the center.

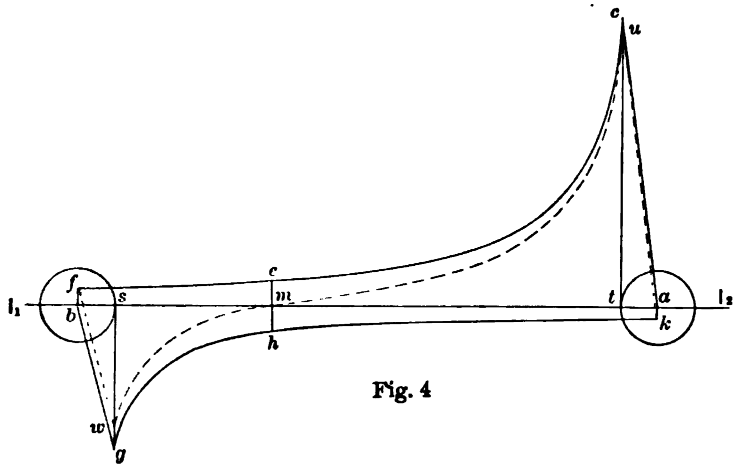


Fig. 4

Fig. 4 is a graphical representation of magnetic conditions existing at any instant. Area *a c f b* represents flux due to I_2 and area *b g k a* that due to I_1, I_2 being in this case twice as large as I_1. At *m*, a point situated so that $\frac{am}{bm} = \frac{I_2}{I_1}$, there is a complete cancellation of magnetomotive forces. If the two currents are in phase, this point remains one of zero flux, and the resultant flux on either side of it caused by the difference between the two magnetomotive forces is that influencing the current flow in the corresponding wires. This resultant, represented by the dotted line *k u m w f*, obtains through a distance S_2, Fig. 3, while the flux in the loop beyond the fault, represented by the area *b g k a*, obtains through a distance S.

So that,

$$\frac{X_2 I_2}{X_1 I_1} = \frac{I_2 S_2 \left(0.25 + \log_e \frac{d}{r} \; \frac{I_2}{I_1 + I_2}\right) - I_1 S_2 \log_e \frac{I_1 + I_2}{I_1}}{I_1 \; S_2 \left(0.25 + \log_e \frac{d}{r} \; \frac{I_1}{I_1 + I_2}\right) - I_2 S_2 \log_e \frac{I_1 I_2}{I_2} + I_1 S \left(0.25 + \log_e \frac{d}{r}\right)} \qquad (1)$$

where, d = distance between wires

r = radius of wire

Assume,

$$\frac{S_2 + S}{S_2} = \frac{r_1}{r_2} = \frac{I_2}{I_1} \qquad (2)$$

$$S = S_2 \left(\frac{I_2 - I_1}{I_1}\right)$$

$$I_1 \; S \left(0.25 + \log_e \frac{d}{r}\right) = I_2 S_2 \left(0.25 + \log_e \frac{d}{r}\right) - I_1 S_2 \left(0.25 + \log_e \frac{d}{r}\right) \qquad (3)$$

Substituting (3) in (1) and expanding, we have,

$$X_2 I_2 = X_1 I_1$$

or the inductance drop is the same over each path. Since the total volts are identical, this result follows directly from equation (2), as does also the assumption that the two currents are in phase.

From a consideration of resistance only,

$$\frac{I_2 - I_1}{I_2 + I_1} = \frac{\frac{r_1 - r_2}{2}}{\frac{r_1 + r_2}{2}} = \frac{\text{ohms from fault to distant end of line}}{\text{total resistance of one wire}} \qquad (4)$$

Either (2) or (4) may be used to compute fault locations, The latter is less influenced by observation or instrument errors and lends itself more readily to graphic representation. If line-structure numbers of a given circuit and the ratio $\frac{I_2 - I_1}{I_2 + I_1}$ be used as coordinates, a chart may be constructed, as Fig. 5, from which the fault location may be readily taken. This chart contains right lines drawn from the point $\frac{I_2 - I_1}{I_2 + I_1} = 1.00$ to the line-structure number at which the loop is closed. The use of such a chart makes it possible to test to any point along the line at which it may be convenient or desirable to place a short circuit, without the inconvenience of computing the resistance to that point. Such flexibility and ease of construction is not true of a chart based upon the relation between

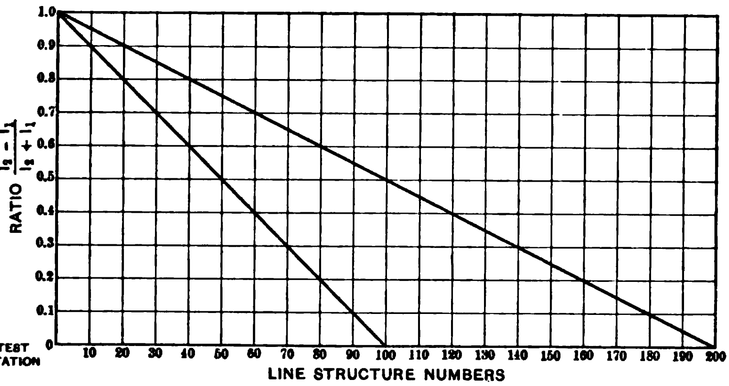


Fig. 5

$\frac{I_2}{I_1}$ and the line structure at which the fault occurs, because this relation is hyperbolic.

When testing lines whose conductors are not of uniform cross-section throughout, the foregoing method is not applicable without modification. Whether large wires be followed by small ones, or the reverse, the current flow will not be determined by resistance only. If the wires are larger near the testing station than farther out, the effect is to locate the fault too far away; to locate it too near if small wires be followed by large ones. The reason for this is evident from a consideration of the relative impedance of the two branches of the loop. The branch having the larger ratio of inductance to resistance, of course takes relatively less current than that indicated by resistance. A comparison of inductances is rendered complex on account of the phase-displacement which takes place between the two currents by reason of the disparity between the ratios of inductance and resistance.

The error involved through considering resistance only is, however, a linear function of the distance from the distant end of the line to the fault, if it be in the region beyond the junction of the two sizes of the cable, and likewise of the distance from the testing station if the fault be nearer than the junction point. Thus it is possible, by making a single test upon a fault placed at the junction of the two sizes of wire, to obtain a correction which is applicable to the entire line. This correction is readily applied to the graphic chart mentioned above. It consists of right lines drawn from the experimentally determined value of $\frac{I_2 - I_1}{I_2 + I_1}$ to either end of the resistance line. A maximum correction of five miles has been found necessary in the case of a line made up of 60 miles of 0.75-in. aluminum cable followed by 70 miles of 0.52-in. cable when testing at 25 cycles per second.

The following are some of the results so far obtained in locating faults by the two-ammeter method:

Length of line	I_1	I_2	Computed location tower number	Actual location tower number	Error
118 miles	1.1	1.125	4472	4479	1000 ft.
118 "	1.53	1.55	4482	4481	200 "
36 "	1.56	2.4	512	513	500 "
23 "	0.4	4.5	151	153	1000 "
60 "	1.36	3.57	512	513	500 "
60 "	0.8	2.00	520	519	500 "
60 "	1.70	2.05	730	731	200 "

This list includes a variety of insulator failures. Some of them were complete grounds, while others withstood high voltage. In only one case was there any trouble in obtaining satisfactory ammeter readings—this being a loose wire swinging in a wind storm.

The time consumed by an experienced operator in making a test under ordinary conditions is about thirty minutes There is sometimes a delay on account of the necessity of communicating with the distant end of the line.

The test is subject to the following restrictions: when several faults are on a single wire, they must be located in reverse order of their insulating values and must be repaired in the order located; when all three wires are in trouble, the one having the highest insulation cannot be tested until one of the others is repaired; if two complete grounds a considerable distance apart occur on a single wire, the localizaton will be in serious error.

These conditions are for the most part exceptional, although entirely possible. None of them has presented itself since this method of testing has been in use.

DISCUSSION ON "LOCATION OF BROKEN INSULATORS AND OTHER TRANSMISSION LINE TROUBLES," AT NIAGARA FALLS, N. Y. JUNE 26, 1907

L. T. Robinson: It seems to me that the method proposed is open to some serious limitations, and that the good results obtained are chiefly on account of the experience of the people who have handled it. For instance, in the table, in the first example given, an error of 1% in the determination of either I_1 or I_2 will make the result practically 2,000 ft. instead of 1,000 ft.

Ralph D. Mershon: I understand that this break, 1760 ft. from the station was located in three-quarters of an hour by an ordinary station attendant. One-third of a mile is a small portion of 100 miles.

L. T. Robinson: I was about to say that the thing involved is the determination of the ratio between I_2+I_1 and $I_2—I_1$. It would seem impossible to develop the method further and get much greater accuracy. An instrument could be made having two windings carrying I_2 and I_1 in opposite directions that would measure $I_2—I_1$ directly, and another instrument with two windings carrying I_2 and I_1 in the same direction which would measure I_2+I_1, and these could be combined into one instrument that would determine the ratio of the two quantities directly. This would be an instrument without spring control at all.

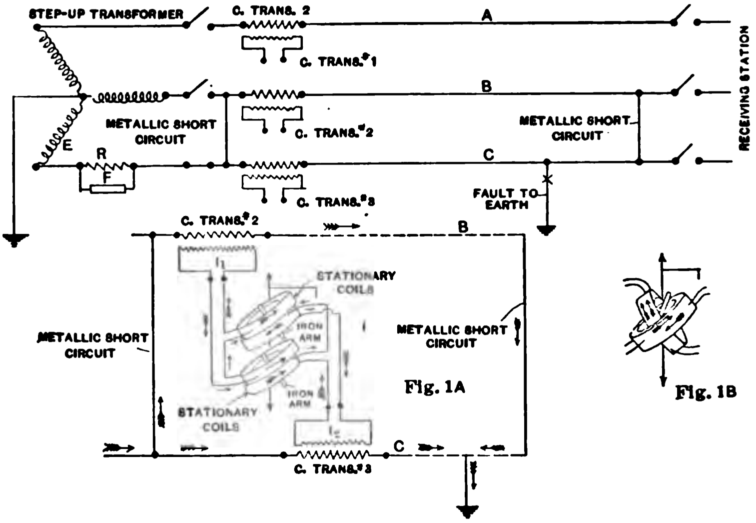


Fig. 1A

Fig. 1B

FIG. 1

In Fig. 1 I show such an instrument connected to a circuit in the same way that the ammeters are connected in Fig. 1, of the paper. In that part of the sketch lettered Fig. 1A the compound windings are shown acting on two separate iron vanes, mechanically connected, and in 1B both the compound windings act on the same iron vane.

Ralph D. Mershon: You would make these windings affect the same core?

L. T. Robinson: Yes; its action is based on the assumption that the two currents are in phase ordinarily, and that the line resistance, inductance, and capacity are uniformly distributed. An instrument, as described, in which the windings are properly placed, and without spring control, would indicate the ratio between the two values, previously referred to, and its indications could be directly applied to the chart, Fig. 5.

Ralph D. Mershon: These instrument coils would have to be so arranged that they would have comparatively little effect on the circuits that feed them.

L. T. Robinson: The elements of the instruments would be connected to the lines through current transformers, and would have no more effect than any ordinary instrument. Being a ratio instrument, it would simply be the torque that would fluctuate for variations in the currents used, and not the torque ratio. It would be an instrument similar to a power-factor indicator or to a frequency indicator.

F. B. H. Paine: I think Mr. Nicholson has given a good deal of consideration to the various means of improving the details. The purpose of the paper is to indicate the possibility of what can be done with the ordinary commercial things he had about him, and to help us in determining faults and enabling us to correct them quickly. He has not quit thinking about the matter. Mr. Robinson's comments simply reenforce the importance of that.

L. T. Robinson (by letter): To the above I would like to add that since this discussion took place it has been pointed out to me that a much simpler instrument, embodying the same general principles, but in which there are only two simple windings, one carrying I and the other I_2, instead of the two compound windings, referred to above, would be satisfactory. This is obviously true and would simplify the instrument without rendering it less useful.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

SWITCHBOARD PRACTICE FOR VOLTAGES OF 60,000 AND UPWARDS

BY STEPHEN Q. HAYES

The idea of this paper is to touch briefly on the salient points of interest in connection with high-voltage switching practice and if possible to bring out in the discussion the opinions of various engineers interested in this line of work, relative to such points as have not been definitely settled by standard practice as being the best solution of the problem.

The reason for limiting this paper to voltages of 60.000 and upwards is that, while the design of stations for voltages up to 60,000 has often been described, but little has been written regarding any for higher pressures. It might be remarked, however, that the switchboard practice for these higher pressures does not differ very materially from that found desirable for voltages from 33,000 to 60,000. In fact. 33,000 volts seems to be the critical point at which it is found advisable to change the type of switching devices, wiring, etc., and most of the remarks in this paper would apply for any installation above 33,000 volts.

In comparing the merits of different types of apparatus, the relative advantages and disadvantages of the conflicting designs have been stated in a manner as free from bias as possible, but the statements are of course the personal opinions of the writer and consequently are open to criticism from others having a different point of view.

The matter of suitable switchboard equipment for any plant may be briefly summarized as follows:

I. *General Scheme of Connections.* Under this heading it is necessary briefly to consider the following matters:

a. Type of plant.

b. Frequency.

c. Transformers.

d. Flexibility versus simplicity.

e. Main connections.

II. *Necessary equipment.* Under this heading should be weighed the relative advantages of the following:

a. Switchboards, panel type.

b. Switchboards, pedestal type.

c. Switchboards, desk or bench-board type.

d. Types of oil circuit-breakers.

e. Types of disconnecting-switches.

f. Types of protective apparatus.

g. Bus-bars and wiring enclosed.

h. Bus-bars and wiring open.

III. *Present design.*

a. Typical station for 60,000 volts.

b. Typical station for 100,000 volts.

IV. *Future design.*

a. Indoor transformer and switching stations.

b. Outdoor transformer and switching stations.

I-*a*. *Type of plant.* Without exception, American plants operated at or designed for voltages of 60,000 or higher employ three-phase circuits and obtain the high voltage by means of transformers. For this reason, this is the only type of plant which will be considered in this paper as being of practical interest at present.

I-*b*. *Frequency.* Nearly all the important transmission systems operate at frequencies of 25 or 60 cycles, although frequencies between these limits are used in Mexico and elsewhere, and a lower frequency has been suggested for large railway work. The switching equipment, however, being independent of the frequency, it is unnecessary to consider this matter here.

I-*c*. *Transformers.* For plants of the type considered in this paper the transformers are invariably oil-insulated and usually water-cooled, and may be built either in single-phase or three-phase units and connected in delta or star. With delta connections it is often desirable to cut out any one transformer, leaving the remaining two connected in *V*; knife-switches or oil circuit-breakers are sometimes supplied for this purpose in addition to the other switches or breakers that would normally be used.

With star connections, if the neutral is grounded, it is often feasible to use smaller switches, breakers, etc., owing to the lower insulation strain. By connecting the instrument series transformers at the neutral point instead of in the main leads a cheaper and better arrangement for supplying current to the meters or relays can often be made. The relative advantages of delta or star connections, being a question of transformers and not of switchboards, will not be taken up in this paper.

I-*d*. *Flexibility versus simplicity.* In settling on the design of a power plant, it is necessary for the engineer to consider carefully the relative importance of flexibility and simplicity, and to determine the relative value of apparatus needed only in emergencies and the saving resulting from its omission. While it is possible to duplicate the equipment of switches, bus-bars, etc., so as to take care of almost every contingency, or to reduce the equipment so that trouble in one or two places may seriously cut down the output of the plant, a happy medium can usually be found.

Although the conditions of each plant have to be carefully examined, and due consideration given to the nature of the load, capacity of station both for initial and ultimate installation, sizes of generator and transformer units available; the general problem for all plants is to obtain the maximum amount of flexibility and safety, with the minimum cost of apparatus and building to house the apparatus. This is particularly true with plants for extremely high voltages, and many ingenious and effective schemes have therefore been evolved for reducing the number of high-tension breakers, switches, etc., to a minimum.

I-*e*. *Main connections.* The paper read by Mr. D. B. Rushmore before the annual convention of the Institute in Milwaukee, May, 1906, on the subject of " Electrical Connections for Power Stations," covered the subject so fully that the writer will not devote much space to it here.

The relative advantages of the single bus-bar system, double bus-bar system, the group system, and the ring system are matters for discussion; the particular system decided on is often a matter of local conditions and a compromise between flexibility and cost.

Except where local conditions of low head or some other cause limit the size of the generators, it is usually advisable to have the transformer banks equal to the capacity of one or two generators, and to have the transmission lines of the same capacity as the transformer banks, to permit independent operation of the outgoing feeders with the minimum amount of apparatus and the maximum amount of flexibility. To obtain this flexibility and ready interchange of units, it is necessary in most instances to install a low-tension and a high-tension bus-bar, although occasionally it is feasible to have the generators connect directly to a bank of transformers or to have the transformer bank feed out directly on the line.

II. *Switchboards.* In practically all high-voltage plants of recent design, the high-tension circuits are controlled by electrically operated oil-switches or circuit-breakers. The devices for use with these oil-switches are usually mounted on a switchboard of the (*a*) panel type, (*b*) pedestal type, or (*c*) desk or bench-board type. Occasionally two or more of these types are used in the same station.

The material of the switchboard panels, the top of the control desk, or the face of the pedestal is ordinarily blue Vermont marble or slate with either oil or marine finish. Blue Vermont marble, in the opinion of many people, presents a somewhat finer appearance than the slate, but it has the drawback of showing oil-stains and scratches, and it is hard to obtain a good match for large switchboards. The difficulty of keeping an exact record of the shade and markings of the marble shipped to a certain customer, in case it is desired to supply additional panels or additional desk sections at a later date, militates somewhat against its use.

The slate, whether marine finish or oil finish, has the advantage of presenting a far more uniform shade and a shade which may be duplicated with almost absolute certainty when additions are desired. While it is almost impossible to remove a deep scratch or bad spots from a polished blue Vermont-marble panel, it is a fairly simple matter with oil-finished or marine-finished slate. The oil finished slate panel can be treated with vaseline, while with marine finish, additional paint put on with an atomizer can be used to cover any spots, scratches, or other imperfections. The dull-black finish of the slate, moreover, causes the instruments, controlling devices, etc., to stand out in bold relief and has no tendency to reflect the light in the eyes of the attendant.

II-*a*. *Panel boards.* Where the panel type of board is used, the panels are simply modifications of those required for lower voltages. The usual equipment of instruments for the generators transformers, feeders, etc., are mounted on the same panels as the controlling devices. This type of construction is used where the number of units is comparatively small and the length of the board will not be too great. It is also employed where the space needed for the instruments is so great that any attempt to reduce the length of the operating board by mounting the controlling devices on a desk, or any more compact arrangement, would result in placing the instruments at such a distance from the operator that it will be difficult for him to see their scales and pick out the meters belonging to any one circuit. The plant of the Canadian Niagara Power Company is equipped with this type of panel board.

II-*b*. *Pedestal type*. This type of control is ordinarily used in plants with voltages lower than those referred to in this paper. and where the number of generators is small in comparison with the number of feeders. In this case the generators are controlled from pedestals while the feeders are controlled from panels. This system is, however sometimes used for high-voltage plants and was adopted for the distributing station of the Ontario Power Company at Niagara Falls. With these control pedestals, it is customary to furnish posts for the instruments.

II-*c*. *Control desk or bench board*. Where it is desired to reduce the length of the operating board to a minimum, it is customary to install a control desk or bench board and to mount on the top of the desk the various controllers for the circuit-breakers electrically operated field-switches, field rheostats, governor motors, etc. Wherever possible, the instruments for the various circuits are mounted in such a position relative to the sections of the control desk as to indicate clearly to the station operator the instruments belonging to particular circuits.

With a control desk, the instruments may be mounted either on independent switchboard panels, on panels forming the back of the control desk, in an instrument frame back of and usually higher than the top of the control desk or on instrument posts. Where independent panels are used with a control desk the panels usually occupy a greater amount of space than the desk, and it is possible for the station operator to become confused in determining the instruments belonging with a certain generator or feeder whose controlling devices are on the desk. As a rule, card-holders or name-plates are placed both on the desk and in the panels, and the grouping of the instruments is made to correspond as far as possible, with the grouping of the controlling devices.

Where the instrument panels form the back of the control desk, the instruments are arranged to correspond in location with the controlling devices for the same circuits. This is the type of desk used by the Electrical Development Company at Niagara Falls.

A modification of this arrangement permits the station attendant to face the generator room and readily observe the operation of the machine he expects to control. An independent instrument frame is provided back of and above the control desk and its height is such that the operator looks over the top of the desk and under the bottom of the frame.

A control desk 18 ft. long and an instrument frame of the type referred to are shown in Fig. 1, which illustrates the equipment being furnished for the control of six 5000-kw. generators, six banks of 88,000-volt transformers, and four 88,000-volt transmission lines.

In the plant for which the desk shown in Fig. 1 is used, each of the six transformer banks is provided on the high-tension side with an electrically operated oil circuit-breaker and a double set of disconnecting-switches, so that a bank of transformers may be connected to either of the two sets of high-tension bus-bars. These two sets of high-tension bus-bars are divided in the middle, but may be tied together through electrically operated junction circuit-breakers. The two sets of bus-bars on each side of the junction breakers may also be connected by means of electrically operated tie-breakers.

The four outgoing transmission lines are each provided with an electrically operated oil circuit-breaker and a double set of disconnecting-switches, so that the breaker may be connected to either of two sets of bus-bars. With this arrangement it is possible to operate the four transmission lines entirely independently, and a very flexible combination of generators, transformers, and lines may be obtained.

The top of this desk is made of marine-finished slate, while the ends, front, and back are made of planished steel plate, which is light, strong and readily removable to permit access to the interior of the desk. The instrument frame is of steel and the unit idea has been carried out to allow for future extensions.

This desk, like most of those where the connections are at all complicated, is provided with a miniature bus-bar system with the usual red and green lamps to indicate whether a breaker is open or closed. As the double-throw system on the high-tension circuits is obtained by means of disconnecting-switches, miniature disconnecting-switches are placed in the mimic bus-bars. The idea is that the station attendant, after closing or opening any of the high-tension disconnecting-switches, will report the fact to the switchboard operator so that the latter may set the miniature ones to correspond. As the arrangement of the disconnecting-switches is not likely to be changed from day to day, it is believed that this scheme will furnish the operator with

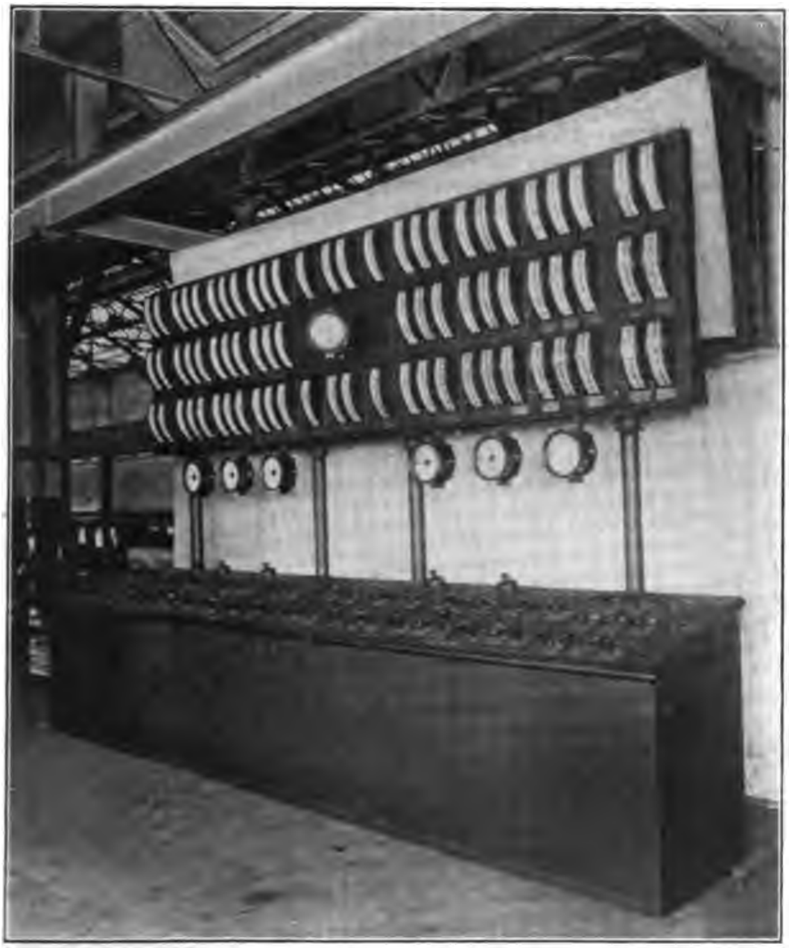


Fig. 1—Control desk for 88,000-volt plant

all necessary information as to the conditions of the high-tension connections.

In this plant the electrical control is extended to the field and exciter circuits as well as to the generators, transformers and lines. All the controllers, etc., are mounted on the top of the desk, the instruments being in the switchboard frame. With the exception of the power-factor meters, where a 360-degree scale was desired, and the synchroscope, where it is necessary for the needle to revolve, all the meters, both alternating current and direct current, are of the same general appearance.

FIG. 2—Switchboard for exciter and field control for 88,000-volt plant.

The motor-operated rheostats and the solenoid-operated switches for the exciters and the field circuits of the generators are arranged to form the panel board shown in Fig. 2.

The four outgoing 88,000-volt lines were each provided with a complete set of graphic recording ammeters, voltmeters, wattmeters, power-factor meters, and frequency meters, as well as polyphase integrating wattmeters.

The control desk for the line and transformer circuits in the receiving station of this plant is very similar to that for the generating station, but some additional refinements are being introduced. Instead of having miniature disconnecting-switches on the desk, small green telephone lamps will be placed in the miniature bus-bar system on the desk. These lamps will be connected in series with a standard incandescent lamp and a snap-switch located in the high-tension room, or in the passage way from which the disconnecting-switches are to be operated. The intention is to have the station attendant, after pulling out the disconnecting-switches, turn on the snap-switch and in this manner light the green lamp on the desk and the standard lamp near the switch. In a similar manner, after closing the disconnecting-switch, the snap-switch is turned to extinguish the light. Failure of the telephone lamps would indicate the danger position; that is, that disconnecting switches were closed.

In this receiving station, as it will be difficult for the attendant in the passage-way near the disconnecting-switches to see whether the oil circuit-breaker is open or closed, red and green lamps will be installed opposite each set of disconnecting-switches. These lamps will be operated by a signal-switch on the oil circuit-breaker in the same manner as the red and green indicating lamps on the control desk.

The synchronous motors of the motor-generating sets, as well as the gas-engine-driven generators for the reserve power, are to be operated from the control desk, while the railway generators and alternating-current and direct-current feeders will be controlled from panels.

II-*d*. *Oil-switches and circuit-breakers.* The terms " oil-switch " and " oil circuit-breaker " are used synonymously in this paper. While in a few cases the oil-switches for high-tension plants may be and are operated by hand, these cases are exceptional, and only the oil-switches or breakers intended for electrical operation will be considered. These are usually one of two distinct types, and the engineer has to weigh the relative advantages of the different designs.

One type of switch is essentially a bottom-connected motor-operated switch intended for mounting in a masonry structure with each pole in a separate fireproof compartment, and each contact in a separate pot with terminals at the bottom of the pot. The other type of breaker is essentially a top-connected solenoid-operated self-contained breaker with the two contacts forming one pole in the same tank. The different features of these two designs will be taken up in order.

Bottom-connected versus top-connected. With the bottom-connected breaker, particularly when made with a wooden pot, considerable difficulty is experienced in making an oil-tight joint where the contact passes through the bottom of the pot. The top-connected breaker does not have this difficulty to contend with. With the bottom-connected breaker, the operating mechanism is entirely separated from the leads, while with the top-connected breaker the operating-rod as well as the leads pass through the top of the tanks and are necessarily closer together than the operating-rod and the leads of the bottom-connected breaker, which are at opposite ends of the pots.

Motor operation versus solenoid operation. On one switch the operating mechanism, consisting of a motor with suitable rods, springs, clutches, etc., is located on a base above the pots and supported by the walls which form the fireproof compartments for the poles. This mechanism is ordinarily at such a height from the floor that it is necessary for the station attendant to stand on a ladder in order to oil the motor or adjust any of the mechanism.

With the solenoid-operated breaker, the solenoid toggles, etc., are located on or near the floor in such a position that the station attendants can readily inspect and adjust them while standing on the floor.

Type of oil tanks. The motor-operated bottom-connected breaker is arranged with the two pots forming one pole of the switch mounted in a common horizontal platform supported at the four corners by wooden legs. This type of switch requires a comparatively small amount of oil and has the advantage that the circuit is opened in two independent receptacles per phase. With this bottom-connected arrangement, however, the sediment of the oil tends to settle on the contacts.

The circuit between the terminals in the bottom of the two tanks forming one pole of the breaker is made through metal plunger-rods attached to a metal cross-piece external to the tanks. A motor-operated mechanism connecting through wooden rods to the metal cross-piece moves it and the plungers vertically upward to open the circuit. The exposed metal parts above the tank and the bare terminals below necessitate the enclosing of the switch in a masonry structure for the protection of the attendant. Doors are provided for each compartment of the structure to permit the ready inspection of the tanks, etc., but the removal or breaking of a door leaves these live metal parts a source of danger.

This motor-operated bottom-connected switch is the type installed in the 60,000-volt circuits of the Electrical Development Company at Niagara Falls and Toronto.

With the top-connected solenoid-operated breaker, metal tanks with insulated linings are used, and the two stationary contacts forming each pole are located under the oil near the top of the tank where sediment cannot settle on them. These contacts are, however, carefully separated by barriers so that the same result is secured as though each contact were in a separate tank.

The circuit between these stationary contacts is completed by plungers connected to a cross-arm and moving vertically downward to open the circuit. These cross-arms are connected through wooden rods to a toggle mechanism operated by a single direct-pull solenoid located on the floor in front of the breakers. All the live metal parts are completely submerged in oil, while the leads brought out through the top of the case are very heavily insulated. As the tanks, mechanism, etc., are grounded for the protection of the attendant, there is no necessity of enclosing the breaker in a masonry compartment.

The tops of the tanks are so made that the terminals, contacts, etc., can be readily got at for inspection, etc. This top-connected breaker is built in two different types, one with boiler iron tanks for very large capacities and the other with sheet metal tanks for smaller capacities.

The solenoid-operated top-connected breaker with boiler-iron tanks is the type installed on the 60,000-volt circuits of the Ontario Power Company and is guaranteed to open safely under any condition of overload or short-circuit that might arise in a plant with 200,000 kw. capacity in generators. The general appearance and over-all dimensions of this 60,000-volt breaker are shown in Fig. 3, while Fig. 4 covers a similar breaker designed for corresponding service at 120,000 volts.

The other type of top-connected breaker, intended for smaller installations and provided with sheet-metal tanks with wooden lining, is shown in Figs. 5 and 6, the former giving the over-all dimensions and the general appearance of the 60,000-volt breaker, while the latter covers the corresponding 88,000-volt breaker.

While the advocates of the different types of breakers naturally favor their own design, and while either type of breaker can be arranged to work in with a scheme of enclosed or open wiring, the bottom-connected switch is essentially designed for in-

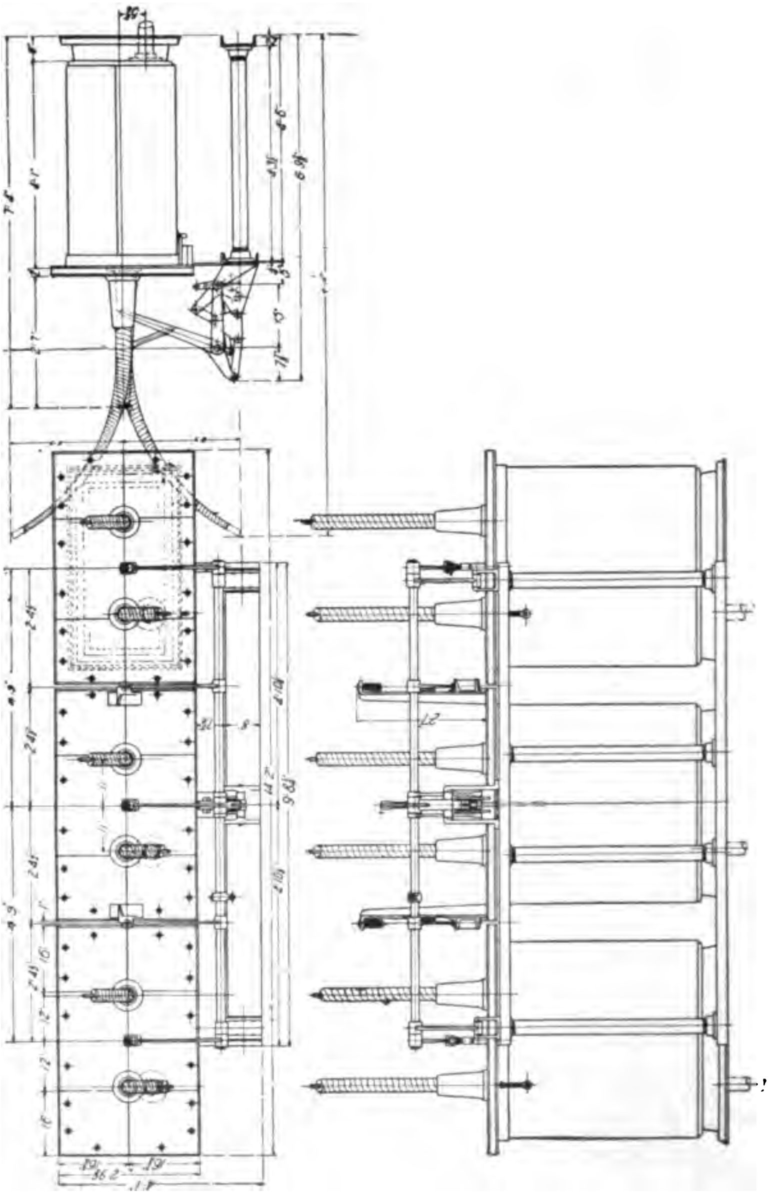


FIG. 3—60,000-volt, top-connected breaker with boiler-iron tanks

stallation where the wiring, bus-bars, etc., are placed in masonry compartments, while the top-connected breaker is intended primarily for plants where the high-tension wiring is overhead and entirely open.

The claim is made for each system that its type of breaker is less liable to get out of order than the other design. Both types are giving satisfaction under actual operating conditions, and the weak points of each breaker are being corrected as rapidly as they are discovered.

Where the control voltage is normal, the speed of operation is practically the same for the motor-operated and solenoid-operated breakers. If the operating voltage is too low, however, the motor-operated breaker closes and opens somewhat more quickly than the solenoid breaker, but with the motor-operated breaker some little time is required after the breaker closes until the motor has wound up the spring to trip the breaker out again.

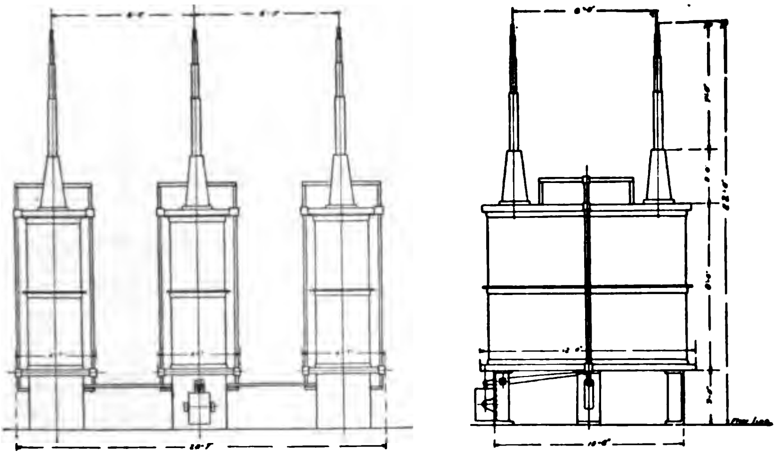


Fig. 4—120,000-volt top-connected breaker with boiler-iron tanks.

Both designs of breakers may be so counterbalanced that in case of ordinary trouble either type will tend to fall open rather than to fall closed. However, if the wooden operating-rods to which the moving contacts are attached should break, the bottom-connected breaker would tend to fall closed, while the top-connected breaker would tend to fall open. Although there is little likelihood of breaking the wooden operating-rods of either type, such an accident is possible. Under this condition the top-connected breaker would have a decided advantage.

Where it is desired to have the breakers automatic, this is done by providing either a series trip-coil, ordinarily located in the tank underneath the oil, or a series transformer. In either case the operation of the series trip or the series transformer closes the direct-current trip-circuit, instead of operating directly on the mechanism of the switch or breaker.

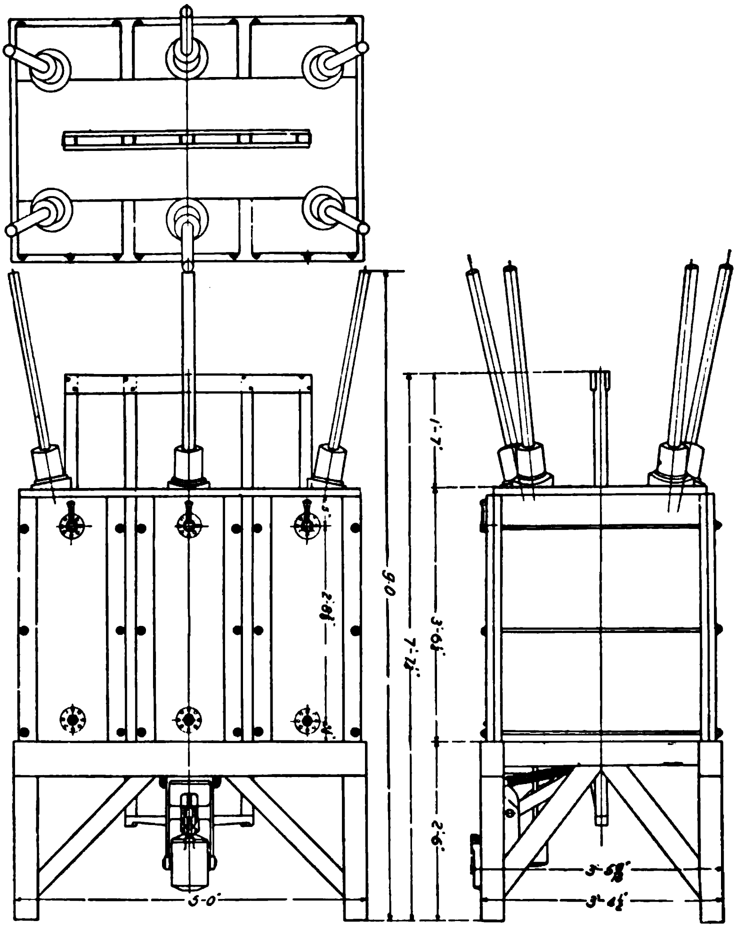


FIG. 5—60,000-volt top-connected breaker with sheet-metal tanks

The advantage of the series trip-coil is largely on account of its being cheaper, while the advantage of the series transformer arrangement lies in the increased insulation obtained and in the fact

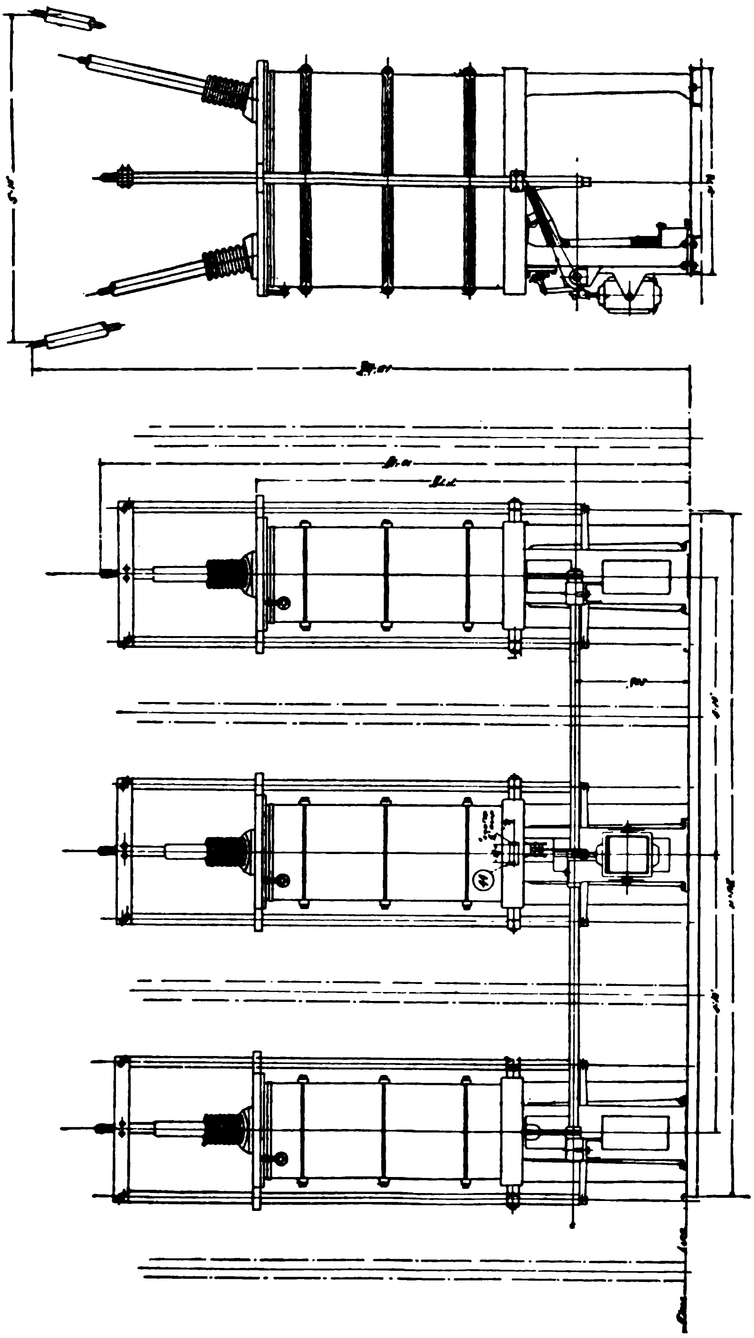


Fig. 6—88,000-volt top-connected breaker with sheet-metal tanks

that series transformers may be needed in case it is desired to operate meters on the switchboard to indicate the current, output, etc., of the lines in which these high-tension breakers are connected.

The two types of breakers previously described may be arranged for operation either with series trip-coils or with series transformers.

While the question of automatic or non-automatic breakers for generators, transformers, and line circuits is often a matter of opinion, the general practice seems to be as follows:

Generator circuit-breakers are usually made non-automatic, although occasionally provided with reverse-current relays. The oil circuit-breakers on the low-tension side of the step-up transformers are usually provided with overload relays. The oil circuit-breakers on the high-tension side of the step-up transformers are usually made non-automatic, although occasionally a differential relay is furnished which operates in case of a local short-circuit in the transformer to cut off both the high-tension and the low-tension breakers.

The breakers for the outgoing transmission lines are ordinarily provided with overload relays. Relays for the different breakers are made instantaneous, definite time relays, or inverse time relays, depending on conditions.

II-*e*. *Disconnecting-switches*. The disconnecting-switches used on high-tension plants consist almost invariably of a plain knife-switch mounted on high-tension line insulators, this switch being operated by means of a pole with a hook in one end. In some plants an operating mechanism is installed for opening the three disconnecting-switches of a three-phase circuit at the same time.

Where the disconnecting-switches are not readily accessible from the operating floor, they are sometimes provided with a projecting arm so that the station attendant may more readily open them by means of a direct vertical pull or push of his operating stick. In some cases where the disconnecting-switches are located in inaccessible positions, it has been proposed to open and close them by means of a solenoid or motor-driven mechanism. These high-tension disconnecting-switches have in most cases been mounted on porcelain insulators, but composition insulators have also been used for this purpose.

The pins for these insulators are made of wood, metal, or composition, depending largely on the individual preference of the designer. The relative advantages of the different kinds of insulators and pins is not a question which comes within the scope of this paper.

II-*f*. *Protective apparatus.* In connection with lightning protection for high-tension plants, choke-coils, either of the open type or of the oil-immersed type, have been largely used. In this work the strain developed across adjacent turns in the choke-coils is so great when the coil performs the function normally expected of it that oil insulation is necessary to obtain the best results.

II-*g*. *Bus-bars and wiring.* As mentioned in the earlier portion of this paper, the bottom-connected breakers are chiefly used with the enclosed system of wiring and bus-bars, and the top-connected breakers with the open system. There is a considerable difference in opinion between the advocates of the enclosed and open systems regarding the relative advantages and disadvantages of the two arrangements.

The enclosed system of bus-bars, wiring etc., for high-voltage plants is an extension of what is acknowledged to be the best standard practice for voltages up to 13,000, and is intended to provide additional safety for the station operator and additional security against a shut-down such as might be caused by something getting across the bus-bars.

II-*h*. Those who favor the open system base their arguments on the following grounds. First, the violence of an arc and the destructive effect of short-circuit depend on the amount of current available at the point of short-circuit, or, for the same amount of power, is inversely proportional to the voltage, so that while fireproof barriers and cellular construction are required on large capacity plants of comparatively low voltage, they are unnecessary for higher voltage plants of the same, or even larger capacity.

Secondly, as the fireproof barriers offer a more or less perfect ground for high-voltage circuits, the striking distance from wire to ground has to be greatly reduced over what could be obtained with open wiring in the same space. The higher the voltage the more perfect the ground.

Thirdly, the use of enclosed bus-bars and wiring ordinarily necessitates several floors or, galleries and a more expensive building than is the case with the open wiring.

Fourthly, it is more difficult to inspect and repair bus-bars, wiring, disconnecting-switches, lightning-arresters, etc., that are boxed in masonry compartments and only visible and accessible by the removal of doors than if everything is in plain sight. Incipient trouble will be noticed far sooner with open wiring than with enclosed, and inspection will be more frequent and thorough if the station attendant in a few minutes' walk can see everything, than if he had to remove several hundred doors and visit two or three floors to examine the condition of the apparatus.

Typical examples of the enclosed and open systems of wiring for 60,000-volt circuits are the transformer houses of the Electrical Development Company at Niagara and Toronto, and of the Ontario Power Company at Niagara Falls.

One of the most striking differences in the two plants, due partly to the use of bottom-connected breakers and enclosed bus-bars in one case, and the top-connected breakers and open bus-bars in the other, is in the location of the disconnecting-switches which isolate the oil-switches or circuit-breakers from the bus-bars.

In the former case they are below the oil-switches and invisible from the switch-room without removing the doors of the switch-compartments, and cannot readily be opened without going down stairs. The station attendant adjusting or cleaning a breaker is on a different floor from the disconnecting-switch, which, if closed through a misunderstanding of orders by a second attendant, will make the oil-switch terminals alive, with consequent grave danger to the cleaner.

In the station of the Ontario Power Company the disconnecting switches are directly above the oil circuit-breaker, can be pulled by the attendant standing at the breaker, and cannot readily be closed without the knowledge and consent of the man working on the breaker.

III-*a*. *Present stations* 60,000 *volts*. In order to give an idea of the relative space required for 60,000-volt and 100,000-volt plants, the preliminary drawings prepared for two different stations of approximately the same capacity and same general arrangement are shown in Figs. 7, 8, 9, 10, 11, and 12.

Figs. 7, 8, and 9 show the plan, elevation, and section of the transformer and switching house to be built on the side of a hill for a plant containing eight 7500-kw. 6600-volt generators, and twelve 5000-kw. 6600- to 60,000-volt step-up transformers, with four outgoing transmission lines. In this station the transformers are delta-connected on both the low-tension and high-tension sides and knife-type disconnecting-switches have

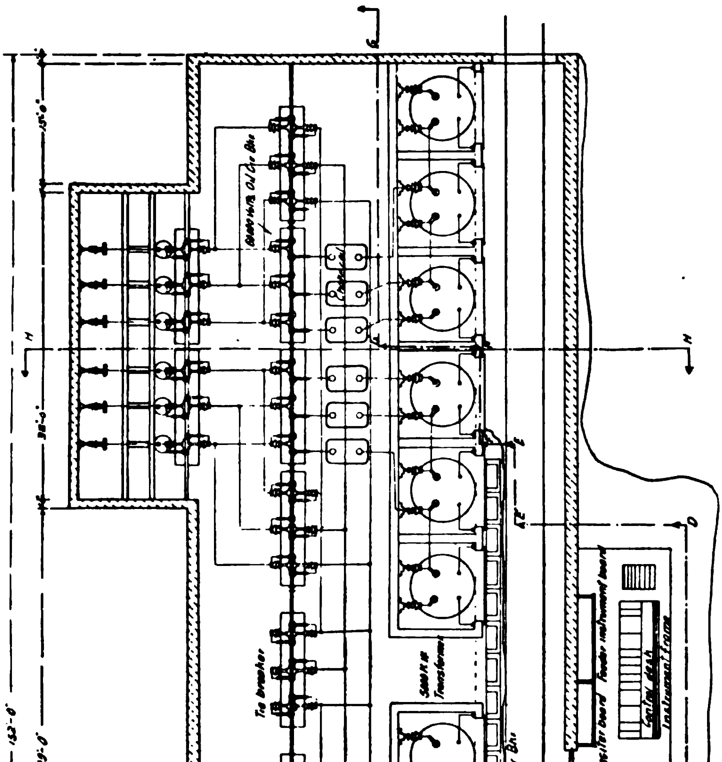


Fig. 7—Plan of transformer and switching house. 60,000-volt plant

been provided for cutting out any one transformer in any bank. The high-tension connections are so made that each transformer bank feeds a short section of bus-bars. This short section of bus-bars can be connected through a circuit-breaker to the main high-tension bus-bar, or through a different circuit-breaker to the outgoing transmission line.

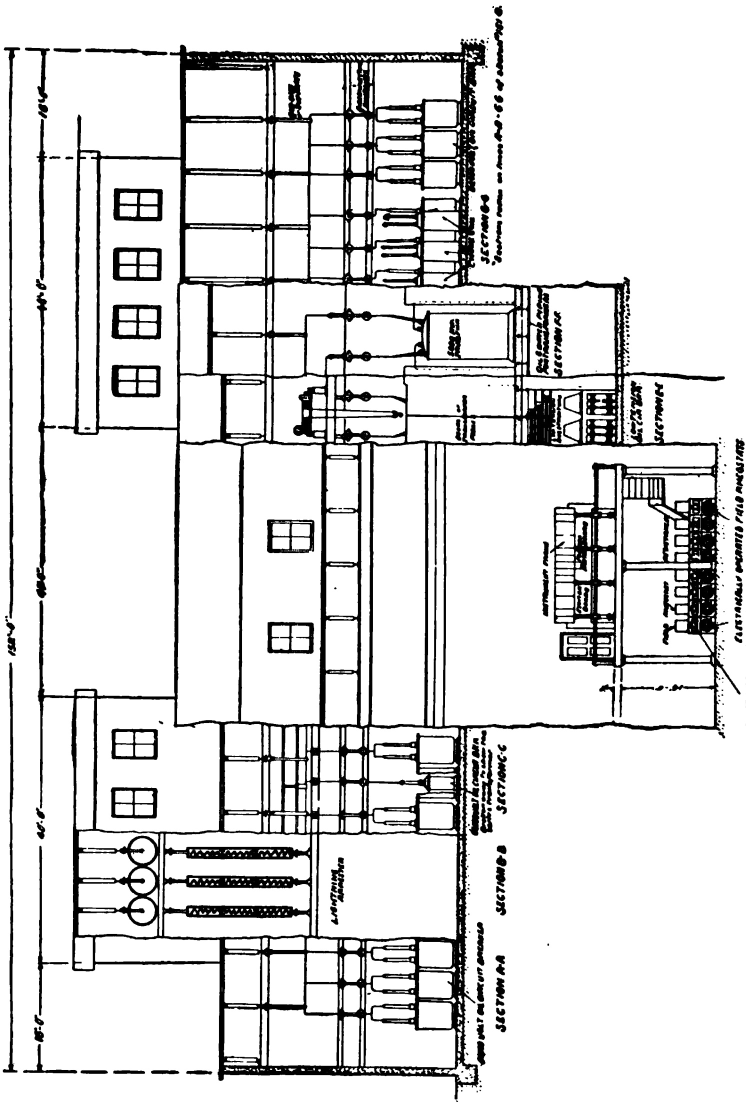


FIG. 8—Elevation of transformer and switching house, 60,000-volt plant

III-*b*. *Present stations* 100,000 *volts*. Figs. 10 and 11 show respectively the plan and section of the transformer and switching house, also on the side of a hill, proposed for the control of ten 5000-kw. 6600-volt three-phase generators, and twelve 4000-kw. 6600- to 66,000-volt step-up transformers. This station will be first installed with the transformers connected in delta both on the low-tension and on the high-tension, and will later be changed over to star connections on the high-tension for operating at 100,000 volts. All the bus-bars, wiring, etc., have been spaced suitably, and all breakers, switches, etc., supplied for this higher voltage.

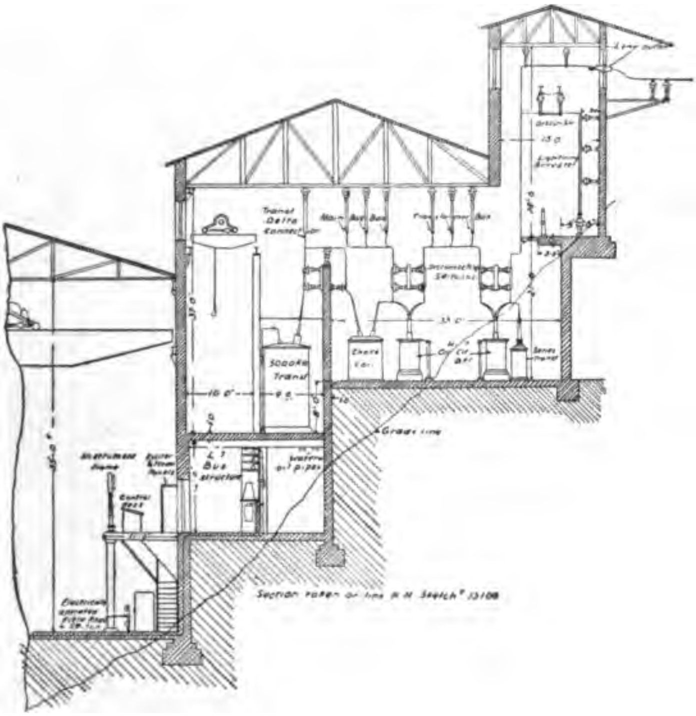


FIG. 9—Section of transformer and switching house, 60,000-volt plant

While operating at 66,000 volts, disconnecting-switches will be used both on the low-tension and on the high-tension side of the step-up transformers for cutting any one transformer out of the bank.

The main connections of this plant will be similar to those of the plant previously described; namely, each bank of trans-

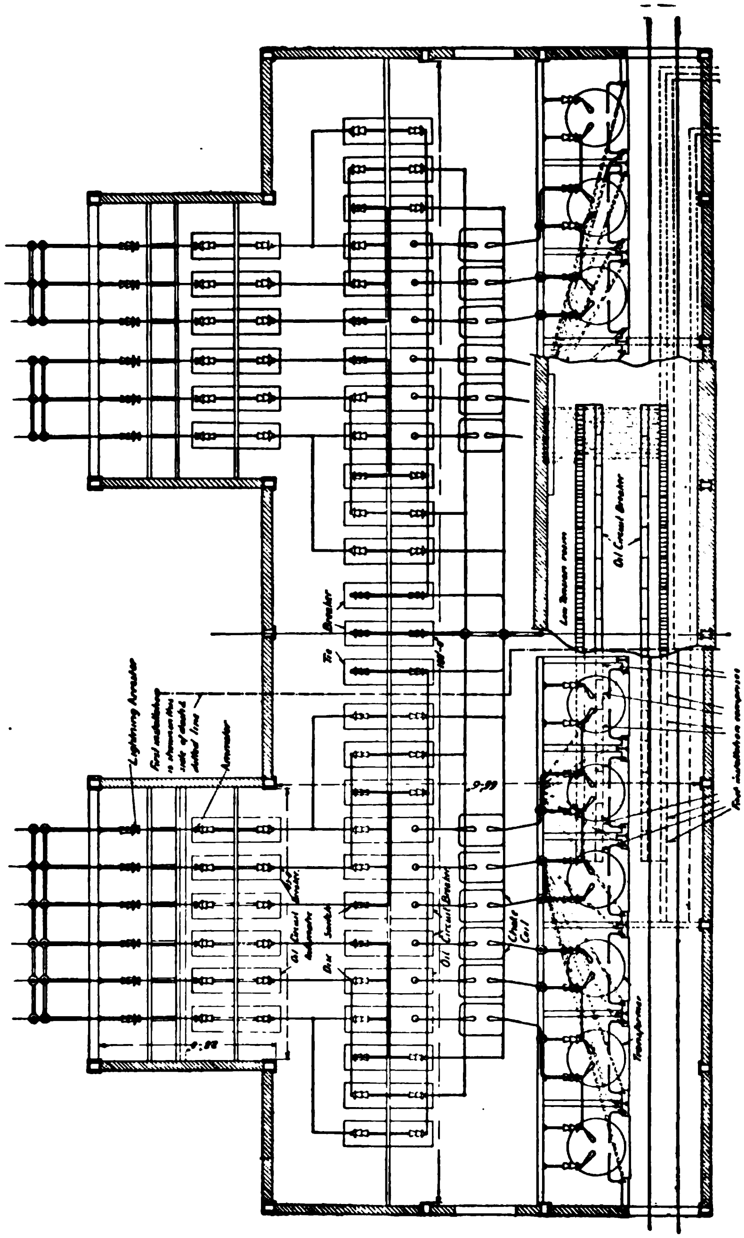


FIG. 10—Plan of transformer and switching house, 100,000-volt plant

formers feeds a short section of transformer bus-bar, which transformer bus-bar can be connected through a breaker either to the main station bus-bar or through another breaker to the high-tension outgoing feeder.

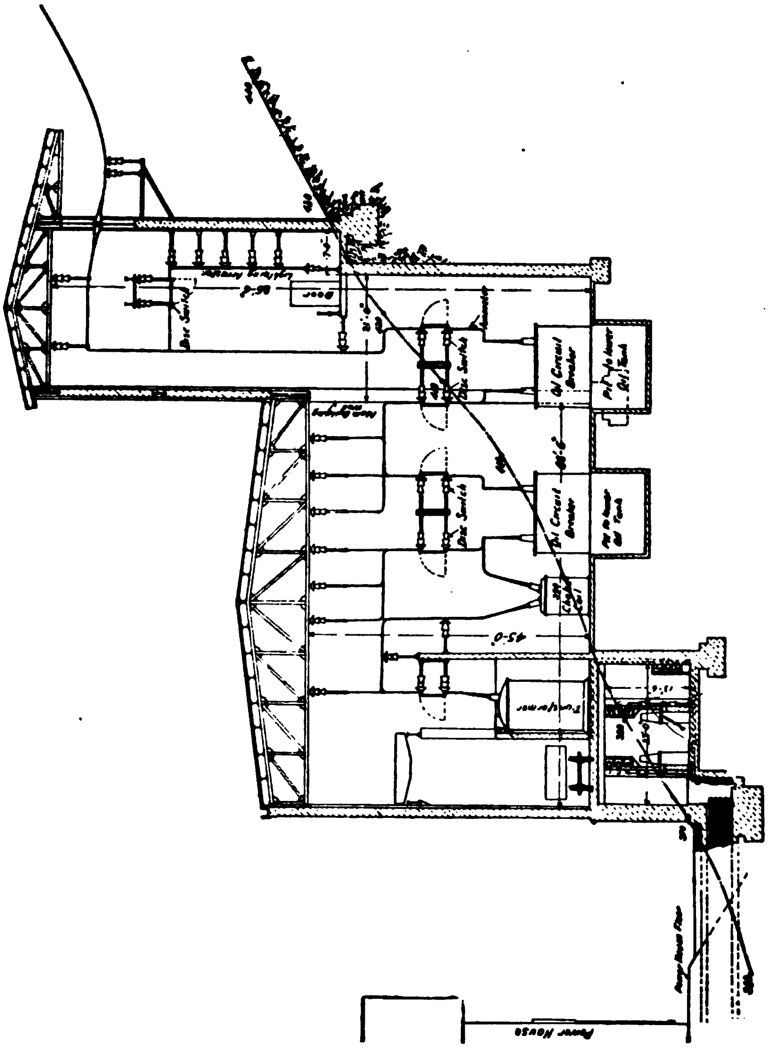


Fig. 11—Section of transformer and switching house, 100,000-volt plant

The low-tension connections are arranged on a straight double-throw system, as indicated by the miniature bus-bar on the control desk shown in Fig. 12, and it may be noted that the entire equipment of this station will not be installed at first.

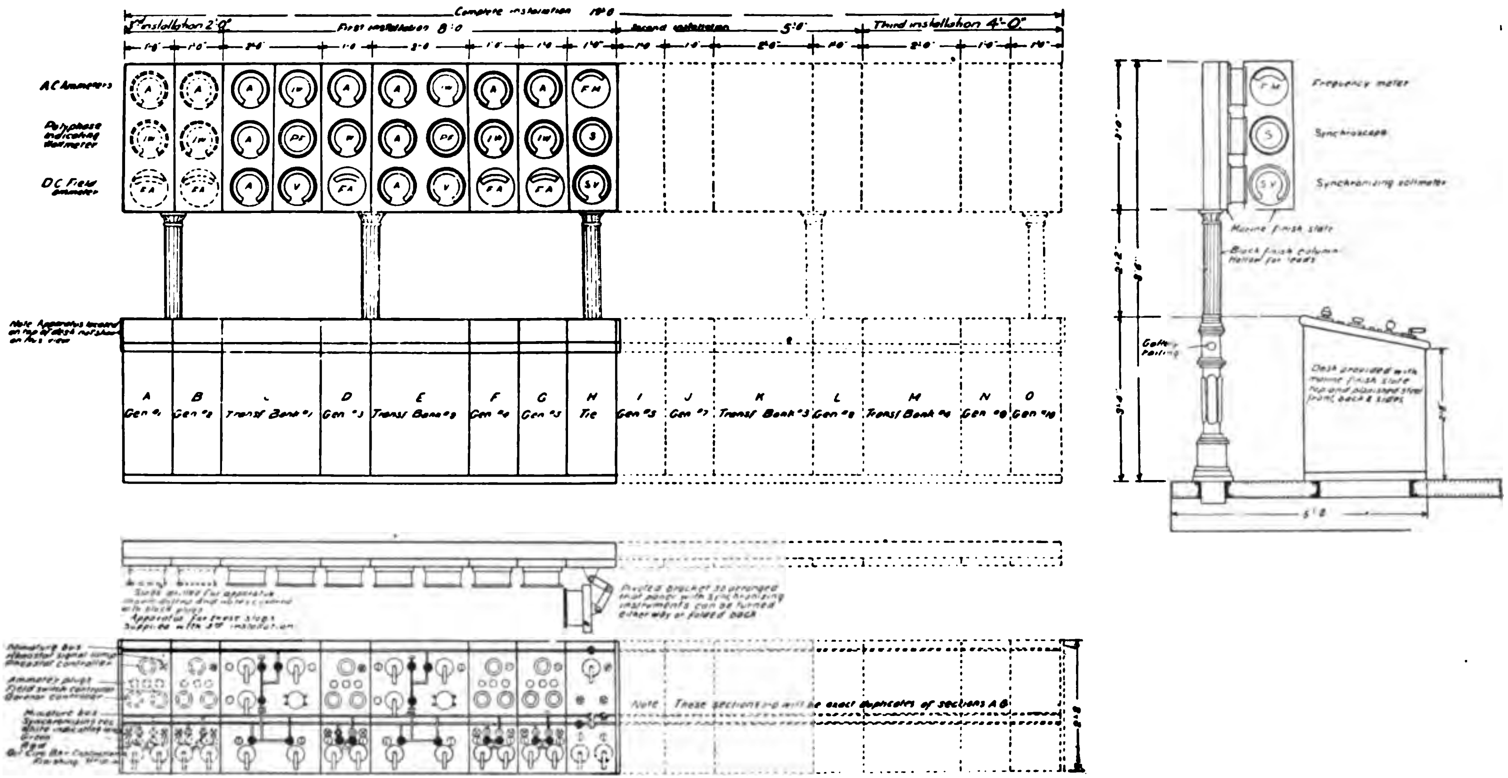


Fig. 12—Control desk for 100,000-volt plant

IV-*a*. *Future stations*; *indoor.* As may be noted from Figs. 6 to 11 the amount of space necessary for the circuit-breakers, switches, bus-bars etc., for a high-voltage transmission plant is comparatively great and it requires a large building to contain them.

IV-*b*. *Future stations*; *outdoor.* It is quite possible that in the not far-distant future where the climate is not too severe, high-tension transformer houses with their breakers, bus-bars, etc., will no longer be used; the transformers, oil circuit-breakers, disconnecting-switches, bus-bars, wiring, and connections will probably be in the open air.

The oil-immersed water-cooled transformers and the electrically-operated oil-switches are well designed to stand out-of-door conditions. Disconnecting-switches have often been used in high-tension transmission lines mounted on the poles, and the use of electrolytic lightning-arresters with the choke-coils combined in the transformer cases will readily permit of this out-of-door operation.

The top-connected circuit-breakers and the open arrangement of bus-bars and wiring are particularly suited for an out-of-door transforming station, and it may not be long before such a station is designed and installed.

DISCUSSION ON HIGH-TENSION TRANSMISSION PAPERS AT NIAGARA FALLS, N. Y., JUNE 26, 1907

P. M. Lincoln: An inspection of some of the illustrations shows that there is a very apparent angle in the cables at the point where they are attached to the tower structures at the bottom of the gorge. This angle would indicate that the strain at that point is downward. I would like to know why this method of construction was used. It surely cannot be on account of relieving the supports at the top of the bank of strains due to a long span, because the strains in the cables must necessarily be increased by the amount of the downward strain at the point where they are attached to these structures.

F. B. H. Paine: The cables drop from the cantilever loosely to the river-edge tower on which they are dead-ended. The cantilevers support the weight, and the water-edge towers simply hold them out of the vertical sufficiently to prevent their hanging too close to the steep hillside.

P. M. Lincoln: It seems to me that exactly the opposite effect would be obtained by this construction, since the curve which would naturally fall would be made more abrupt by pulling down at this point.

F. B. H. Paine: The span across the river is quite independent of the slope-spans, and is dead-ended on each water-edge tower. The crossing is not a catenary into which the water-edge towers are inserted and steady the cables. It is three independent dead-ended spans; two almost vertical and one almost horizontal.

P. M. Lincoln: I do not see why it is necessary to attach to the towers at that point.

F. B. H. Paine: Mr. Mershon divided the crossing into the three spans to avoid the effects of tremendous winds in the Niagara Gorge—blowing both ways at once—and which unusual condition he feared would result in swinging the cables together. He wanted as short a span as possible and as close to the bottom as possible, to avoid the effects of the cross-winds on one span. I believe our experience shows that the effect of these winds was exaggerated by the " oldest inhabitant."

D. B. Rushmore: Some of Mr. Mershon's power consumers get their power from a single line, and I think it is open to discussion whether such a practice is justified. In the line construction shown, some pertinent questions arise; for instance, from the experience given in the paper by Mr. Rowe, it has been found necessary to put the top conductor below the others, and to run the ground wire in its place. I think that a similar change would be desirable here.

The questions at once arise, why are the wires on separate towers? Why is a single tower not used to carry both sets of wires? Under what conditions can one high-tension line near another be repaired while the other is in operation?

Mr. Buck shows a line construction for very high voltage and he puts both lines on the same tower. Can he repair one line if the other is in operation?

The wooden A-poles which Mr. Mershon shows have got to be replaced every eight years, we will say, but not all poles will last eight years. Every time a pole is replaced, the transmission of power is interrupted, and while at first the interruptions from this cause are not many, they finally become so frequent that customers grow impatient and new customers cannot be got. Under these conditions it seems to me that a single line transmission with a wooden pole construction is not economically justified.

H. W. Buck: Regarding the possibility of working on one line with the other line alive: in Fig. 2, with the tower grounded and with the circuit out of service grounded, I see no reason why a man should not safely work on that dead circuit. He would have the whole tower structure between him and the live circuit, and the circuits are quite a distance apart, about 20 feet.

J. B. Taylor: Mr. Nicholson's method of locating breaks, or more properly grounds, on high-tension lines is extremely valuable, the broken insulator being the trouble which is most often experienced. I think that the transmission system on which he has made his tests was fortunate in having a man who could take up work of this sort, possess the proper ingenuity to make the proper application for the particular trouble, and be on the ground when the trouble came; but I doubt if the average transmission plant will install the necessary switches and resistances and have the experts to locate troubles in this manner.

A plant that was started up about five years ago had a fourth wire installed on a three-phase system. The idea was that when one of the three wires got into trouble, a simple system of knife-switches could cut in the fourth wire, and everything would go along as usual. The line has had occasional trouble, but for one reason or another—either because the operating force did not feel sufficiently sure of the conditions to cut in the spare wire, or because they felt that the trouble was of such a nature that it was unsafe to attempt to resume service before knowing what the trouble was—the fourth line has not been used.

I have not checked the mathematical equations in the paper, but offhand it is not obvious why the reactances of the long and short sides of the loop should come out in the same ratio as the resistances. The inductive effect of the return current in the earth does not appear in the analysis, and under some conditions this appears to be an essential factor. However, the accuracy of the test locations shows the method to be right for the average transmission line when the two sides of the circuit are separated by a few feet.

Without doubt Mr. Nicholson has considered other schemes for locating these troubles. I wonder if he has tried to locate a broken insulator by merely passing the current over the faulty wire to ground and measuring the induced voltage in a neighboring wire—one of the transmission wires, neighboring telephone lines, or anything that happened to be handy. Assuming the wires at uniform separation, the induced voltage should be proportional to the length.

William McClellan: It appears as if every essential point had been considered in the design of Mr. Hewlett's insulator. In the long run it should be cheaper, though the first cost would remain the same as for present types. Those of us who have had experience with large 60,000-volt insulators made of cemented shells know what it means to discard an insulator because of a simple broken shell. Another point is the benefit of the full dielectric strength of the material used. We all know that the breakdown potential of a cemented insulator is considerably less than the sum of the breakdown potentials of the separate shells.

Regarding Mr. Hayes' paper, I think emphasis should be laid on the desirability of the open type of wiring for potentials over, say, 25,000 volts. For higher potentials there is a strong tendency among engineers toward outdoor stations, though it must be acknowledged that the last word on this subject will not be said for some time to come. I think that we should cease putting up ordinary knife-switches to be opened with a pole in the hands of a man on a shaky platform 25 feet from the ground. Very simple switches to be opened from the ground have been designed by certain operators in the West and marked attention should be given to this simple but, at times, very important part of the high-tension apparatus.

W. N. Smith: Has the matter of icicles forming between the successive petticoats of insulators of the type proposed by Mr. Hewlett been given due consideration? It would seem as though a chain of insulators, one above the other, might perhaps enable icicles to be formed that would connect from one disk to another. Unless there has been experience to the contrary, I should hesitate to condemn the ordinary petticoat type on account of icicle formation between petticoats, which I think would be fully as difficult to consummate with the petticoat type as with the new insulator proposed by Mr. Hewlett.

L. C. Nicholson: In regard to Mr. Taylor's suggestion as to measuring voltage generated in a parallel wire, I will say that some such methods have been undertaken, but the results obtained were not encouraging, particularly on account of parallel circuits which were in operation at the time, interfering with any measurements of induced voltage in the parallel wire. In case of only one line, I presume some such test could be made, but having more than one line one interferes with the test on the other by electrostatic and electromagnetic induction. In any case, I think it would be necessary to have two instruments; an ammeter to measure the current flowing, and a voltmeter to measure the induction.

S. Q. Hayes: The 200,000 kw. given as the capacity of the oil circuit-breaker is correct; that is, the manufacturers guarantee that that switch will be able to open any overload or short-circuit that will occur on the station having that capacity on the bus-bars. Up to the present time there is no station with that capacity on the bus-bars.

In connection with the troubles in pulling disconnected-switches, it has been proposed in several cases where the disconnecting switches are in rather inaccessible positions to operate, them by means of a soleloid or motor-driven mechanism.

J. H. Finney (by letter): It seems to me that Mr. Mershon's method of tying-in is not so simple as might be employed, although the tie is very ingenious; the chief objection to it is the large amount of tie-wire required, and the fact that the cable is not firmly fastened to the insulator, but simply lies in the top groove.

FIG. 1. FIG. 2. FIG 3.

I would like to call attention to a tie which not only embodies simplicity and a small amount of tie-wire, but has the advantage of holding the conductor firmly on every side, as will be seen by the accompanying illustrations. The tie is made by straddling the line wire and top of the insulators as shown in Fig. 1. Both ends are then carried around the neck of the insulator in the same direction as shown in Fig. 2. Having made a half circle of the insulator, the ends are made off by taking a number of turns around the line conductor shown in Fig. 3. This makes a symmetrical tie, the conductor being held without danger of kinks, and is not subjected to any strains which would tend to cause abrasion and breakage of either tie-wire or conductor. The strain is uniformly distributed around the head of the insulator, the conductor being held firmly in the groove. This tie is decidedly cheaper than clamps, is more easily installed, and, in my opinion is not only more desirable than clamps, but is one of the best designed ties, from all standpoints, of which I have knowledge.

F. G. Baum (by letter): When trouble occurs on a line similar to that considered by Mr. Nicholson, the station operator will try to find the section of line on which the trouble is located. The trouble may be a broken insulator, or it may be more serious, and repeatedly to throw power on a disabled line to test it may at some time cause very serious consequences. Furthermore, having located the section of the line in trouble, the operator will at once start patrolmen from each end of the section. After the point at fault is located it will require one man, and very often two men, to repair the break. Until the men arrive at the break it is not certain what must be done and what materials will be required. Hence, while the test method may be of some advantage in some cases, generally one would have to use the sure way in addition to it. Power should not be thrown on a disabled line more than necessary, as life and property may thereby be endangered.

Ralph D. Mershon (by letter): Replying to the points raised by Mr. Rushmore. Whether or not service from a single line is justified, depends upon the value and importance of the customer. One would be justified in going to the expense of two lines for a large and important customer, but such expense would render the business of a small customer unprofitable. Mr. Rushmore raises the question of the grounded wire. I have never been fully convinced that the grounded wire actually affords an appreciable amount of protection against lightning, or, at any rate, an amount of protection which would justify the expense of installing it. I had hoped that Mr. Rowe would, in his paper, bring more convincing proof of the value of the grounded wire than has been submitted in the past by those defending it, but I must say I cannot see that he has done this. The question of two-circuit towers vs. single-circuit towers is one on which many arguments can be advanced on both sides. In the end, the choice must be largely decided by the conditions to be met. In our case it seemed best, for a variety of reasons, to make use of the single-circuit towers. What Mr. Rushmore says in regard to wooden pole-line construction is true in many cases; it is not true in this case however. Where the A-frames were installed, the amount of space available was not sufficient to allow of tower construction, and steel-pole construction would not only have been more expensive than wooden poles, from every standpoint, but the necessary deliveries of steel poles could not have been obtained.

As regards Mr. Finney's tie, I would say that the tie we used was adopted for the reasons set forth in the paper, and only after an exhaustive series of tests on all the ties we knew of or could devise. If Mr. Finney will make actual pulling tests on his tie with aluminum cable and aluminum tie wire, he will find, I think, that it will not fulfil the conditions which, as explained in the paper, it was desired to meet, and which the tie adopted does meet.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

DEFLOCCULATED GRAPHITE

BY EDWARD G. ACHESON

The subject-matter of this address is not in any sense electrical in character, but the effect described was discovered as the result of electrical work and the products obtainable by it may, with advantage, be used in electrical work and machinery. Such is my excuse for offering these remarks before this Institute.

In the year 1901, I was engaged in a series of experiments having as their object the production of crucibles from artificial graphite. In this work I was led into a study of clays. What I learned may be briefly stated as follows: 1. The American manufacturers of graphite crucibles imported from Germany the clay used by them as a binder of the graphite entering into the crucibles. 2. The Germany clays are much more plastic and have a greater tensile strength than American clays of similar chemical composition. 3. Residual clays—those found at or near the point at which the parent feldspathic rock was decomposed—are not in any sense as plastic or strong as the same clays are when found as sedimentary clays at a distance from their place of origin. 4. Chemical analysis failed to account for these decided differences.

I reasoned that the greater plasticity and tensile strength were developed during the period of transportation from the place of their formation to their final bed, and I thought it might be due to the presence of extracts from vegetation being in the waters which carried them. I made several experiments on clay with vegetable extracts, tannin being one of them, and I found that a moderately plastic, weak clay, when treated with a dilute solution of gallotannic acid or extract of straw, was increased in plasticity—made stronger in some cases as much as three hundred per cent.—required but 60 per cent. as much water to produce a given degree of fluidity, was caused to remain suspended in water, and made so fine in particles that it would pass through a fine filter-paper. Being acquainted with the record of how the Egyptians had the children of Israel use straw in the making of bricks, and believing it was used not for any benefits derivable from the weak fibres but for the extract, I called clay so treated Egyptianized clay.

Having in 1906 discovered a process of producing a fine pure unctuous graphite, I undertook to work out the details of its application as a lubricant. In the dry form, or mixed with grease or oil, it was easy to handle, but I wished it to enter the entire field of lubrication as occupied by oil. In my first efforts to suspend it in oil I met the same troubles encountered by my predecessors in this line of work; it would quickly settle out of the oil. My unctuous graphite was just plain simple graphite, and obeyed the same laws covering the natural product. So things stood until the latter part of 1906 when the thought occurred to me that tannin might have the same effect on graphite that it had on clay. I tried it with satisfactory results. I will now show you the effect and how it is produced.

I will take for the experiment two equal quantities of my unctuous graphite, as produced in the electrical furnace. When in this form, I call it disintegrated unctuous graphite. To one sample I will add plain water, and, after rubbing up in a mortar, I pour it into a test tube. To the other sample I will add water, a little gallotannic acid, and a few drops of ammonia. This last is not always necessary, but I find it improves the results with some waters. I will now rub the mixture in the mortar as in the first case, and then pour into a test tube. I will now shake up both tubes simultaneously and place them in a rack to settle.

Two minutes have now elapsed since the shaking and we find the graphite in the plain water has very completely separated from the water, not being miscible therewith, while the mixture of graphite, water, tannin, and ammonia remains as black as when shaken up. The graphite is miscible with the water in this mixture; it is suspended and would continue so indefinitely, at least I have found it to remain so for months, and I do not see why it should settle or separate the next day, week, month, or year.

While this experiment, as you have seen it performed, shows the effect, the result is much improved by time. I have here a bottle in which there are graphite, water, tannin, and ammonia which have been mixed for some weeks. The graphite is in what I call a deflocculated condition, a condition of fineness beyond that attainable by mechanical means, a condition approaching, if indeed not actually attaining, the molecular state. It is so fine as to pass with ease through the finest filter-paper. Here I have a glass funnel containing one of the finest filter-papers manufactured, and on this paper I will pour a little of the water and deflocculated graphite. See it run through the paper and collect in the tube, as black as ever and apparently unchanged. In fact it remains so black and has passed through so rapidly that a doubt exists in your minds as to its really being a mixture of water and solid matter—water and graphite. I can quickly convince you that such is the case.

Into the test tube containing the black liquid which has passed through the filter, I will now introduce a few drops of hydrochloric acid, and then slightly warm it over this spirit-lamp flame. These acts have caused the suspended graphite to floccluate and when I now pour the liquid onto a second filter paper, you see the water run through clear, the graphite remaining on the paper. Removing a little of the graphite and smearing it on a piece of paper, drying the paper and rubbing the black spot, it is at once recognized as graphite. This effect is obtainable with amorphous bodies generally; I have obtained it with alumina, lampblack, clay, graphite, and siloxicon.

I have successfully used deflocculated graphite in water instead of oil in sight drop-feed oilers and with chain-feed oilers. I have a shaft in my laboratory measuring $2\frac{5}{16}$ in. in diameter, revolving at 3000 revolutions per minute in a bearing 10 in. long that had no oil on it for a month, deflocculated graphite being the only lubricant used, the feed being by chain, and it ran perfectly. On the same shaft is a similar bearing lubricated with oil; this runs much the warmer of the two.

A few days after this test was started a pessimistic friend remarked that just plain simple water would give the same results, that the presence of graphite was unnecessary. We are influenced by the opinions of others even when we know or think they are wrong, so I emptied the oil out of the second bearing on the shaft and substituted plain water. The results during the first twelve hours seemed to support the contention of the friend. The next day after the machine had stood motionless over night things did not look so rosy for the water; it was a lame second on account of rust and was hurriedly removed. I think I shall not recommend clear water as a permanent lubricant.

Deflocculated graphite in water possesses the remarkable power of preventing rust or corrosion of iron or steel. This graphite, even after flocculation, is so fine in its particles that when dried *en masse* it forms a hard article. I have here a cake of dried deflocculated graphite. You can see it has the curvature of the watch glass in which it was dried. No pressure was used on it, but still you see it is comparatively hard, like a sun-dried clod of clay. It is self-bonding.

While, as I have stated, deflocculated graphite in water is an efficient lubricant, it has the drawback or disadvantage of losing its water by evaporation. I also appreciated that much time would be consumed in converting the world to water lubrication from the present one of oil. Therefore I set before me the problem of replacing the water medium with oil. A very great deal of difficulty and many discouraging conditions were met with, but I am pleased to say success was arrived at, and I have here a bottle containing kerosene oil holding about one-half per cent. of deflocculated graphite, that percentage being sufficient for most work. Here is another bottle containing spindle oil with a like percentage of graphite. The graphite has been in these oils for some weeks and shows no tendency to separate or to settle.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907

SINGLE-PHASE VERSUS THREE-PHASE GENERATION FOR SINGLE-PHASE RAILWAYS

BY A. H. ARMSTRONG

The introduction of the alternating-current single-phase railway motor calling for a single-phase secondary distribution system makes it pertinent to inquire into the question of power generation and primary distribution for such systems. While the simplicity of single-phase generation and distribution is unquestioned, it is not always possible or desirable in these days of general power distribution to install a generating station and primary distribution system capable of taking care of alternating-current railway load alone, to the exclusion of synchronous converters and other receiving machinery requiring three-phase input.

As the use of either the single-phase or the multiphase generator seems to be open to certain objections, various methods of distribution are presented herewith, with some of the advantages and disadvantages pertaining to each.

SINGLE-PHASE GENERATION

1. Single-phase generation and transmission makes it impossible to use synchronous converters, self-starting synchronous motors, or induction motors starting under load. Poorly adapted for general power distribution, it is chiefly limited in application to alternating-current railway operation; its use is, therefore, open to grave objections of a commercial nature where there exists any possibility of selling power or in any way utilizing it for general converter and motor work.

2. The single-phase generator has an unbalanced armature reaction which is the cause of considerable flux variation in the

field pole-tips, and in fact throughout the field structure. In order to minimize eddy currents, such generators must, therefore, be constructed with thinner laminations and oftentimes poorer mechanical construction, resulting in increased cost of the generator. The large single-phase armature reaction results in a much poorer regulation than that obtained with a three-phase generator; it calls for increased amount of field copper; it requires more liberal design; it also requires larger exciting units—these make the cost of the single-phase generating unit throughout considerably more than that of a three-phase unit of the same output and heating.

The difficulties of single-phase generator construction appear to increase with decrease in frequency. The adoption of any lower frequency than 25 cycles may therefore result in serious difficulties in construction for a complete line of machines of the single-phase type, especially of the two- or four-pole turbine-driven type, where the field flux is very large per pole.

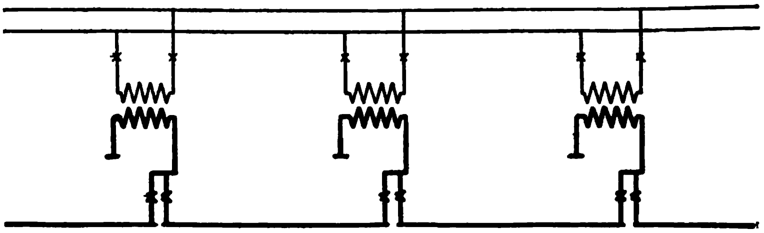


FIG. 1—Single-phase primary and secondary distribution

3. To offset the difficulty of single-phase generator construction, its greater cost and poorer efficiency, there are the advantages of simplicity in the entire generating, primary, and secondary distribution systems for single-phase roads. These advantages are so great that they justify considerable expense; looked at from the railway point of view only, the single-phase system throughout may be considered as offering the most advantages.

THREE-PHASE GENERATION

Three-phase generation and distribution is in almost universal use. Many single-phase railways receive power from such systems. The commercial advantages resulting from the use of such generators may in certain cases justify the complication of single-phase secondary distribution obtained from a three-phase source. As these commercial advantages are in many cases controlling, various combinations of three-phase–single-phase connections are presented herewith.

1. *Three-phase generation and primary distribution to motor-generator sets feeding into the single-phase secondary distribution.* This system has all the advantages of obtaining power from a three-phase distribution which may also feed synchronous converters and a general power load; it is independent of the frequency of the generating system, being equally adapted for 60 or 25 cycles. It is the only system which will give perfect balance on a three-phase distribution system. Its disadvantage lies in the cost of the motor-generator sub-station.

2. *Three-phase generators operating alternating-current railway load on one leg, thus calling for both primary and secondary single-phase distribution.* Commercial considerations of a possible future synchronous converter or power load may justify the installation of three-phase generators designed for single-phase output for railway load and three-phase output for general power distribution. This system is open to the objection of serious unbalancing due to railway load on one phase only, and this unbalancing may be so great as to cause undue heating in synchronous converters, synchronous motors, and induction motors fed from the unequal potentials of all three legs of the three-phase generator. Tests have been made which indicate that receiving apparatus may have its capacity reduced from 30 to 50 per cent. with normal heating with the unbalancing caused by a single-phase railway load fed from a three-phase generator in commercial operation.

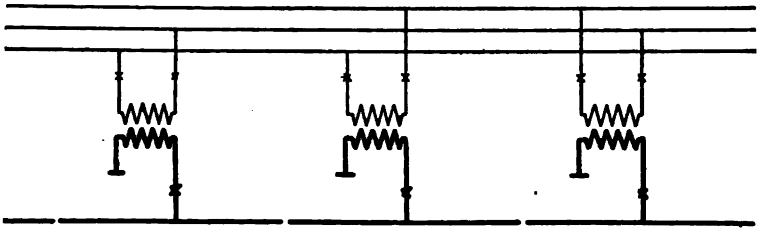


FIG. 2—Three-phase primary and single-phase secondary distribution

A three-phase generator run as a single-phase generator is open to all the objections of excessive armature reaction, poor regulation, and pulsating flux in field structure noted above for single-phase generators. Such generators must be rated single-phase at two-thirds or less of their output when operating on a balanced three-phase load.

3. *Three-phase generation and primary distribution to sub-station, feeding successive trolley sections with separate phases.* Where the length of the road is sufficient to permit sectionalizing the trolley into three sections, or multiples of three, having an equal load on each section, this method provides for balancing the three-phase load, thus securing full output of the generator, non-interference with power load, etc. Each sub-station must contain two sets of transformers connected to separate phases, so that adjacent sub-stations may feed like phases into a common trolley section extending between them. The installation of a single transformer in each sub-station would necessitate the sectionalizing of the trolley midway between sub-stations, hence losing half the effective value of the copper as obtained with the trolley sectioned at the sub-stations and two adjacent sub-stations feeding a common trolley section.

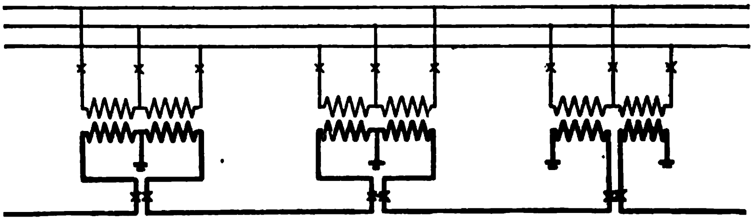


FIG. 3—Three-phase primary and single-phase secondary distribution

This method of obtaining a balanced three-phase load is open to the objection of complication and possible ineffectiveness, with serious disarrangements of schedule such as take place in railway operation during different periods of the day and season.

4. *Two-phase generation, generating station located in center of system and feeding one phase each way.* So long as the load is balanced upon the two primary distribution systems, this method of connection is capable of good results; but operation under the necessities of commercial service shows it to be very difficult to balance the load upon the two phases, thus resulting in considerable unbalancing and extreme voltage variation on the less loaded leg. This same criticism holds true of method 3.

5. *Three-phase generation and primary distribution to transformer sub-stations connected three-phase–two-phase, and*

feeding secondary distribution in such manner that adjacent sub-stations feed like phases into a common trolley section. This method of connecting is capable of giving good results in operation, although occasional serious unbalancing may occur in the primary distribution with a disarrangement of schedule or improperly proportioned trolley sections. Each sub-station must contain two transformers for regular service, and possibly one spare; these, together with the necessary switchboard arrangement, increases the complexity and cost of such sub-stations compared with the simpler arrangement possible with straight single-phase distribution.

There are other methods of connection, such as independent transmission lines to several outlying sub-stations, thus giving the generating station operator the opportunity to balance the load on the several phases of the generators; but the methods outlined are those commonly proposed for single-phase secondary distribution used in connection with three-phase generation and primary distribution.

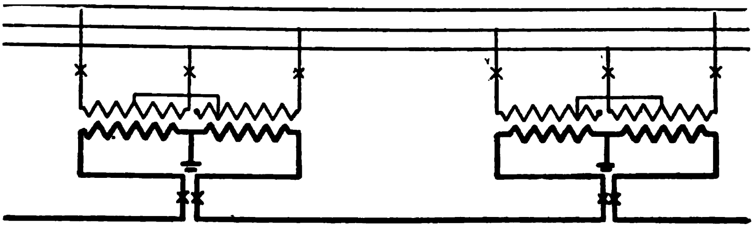


FIG. 4—Three-phase primary and two-phase secondary distribution

GENERAL CONCLUSIONS

The matter of properly selecting generating apparatus for single-phase roads seems to be closely connected with questions of a commercial nature relating to a possible future load requiring a three-phase input. From a purely engineering standpoint, and considered from the point of view of the railway load only, the single-phase system of generation and distribution is to be recommended. The possible installation of generators having a lower frequency than 25 cycles would help this decision, owing to the unfitness of such a low frequency for general power distribution work.

Of the several methods of single-phase combinations proposed, the motor-generator set best protects the three-phase distribution system where power is purchased from foreign distributing systems, and such a method presents many advantages which may outweigh its increased first cost. Where the railway company finds it expedient to generate and distribute its own power from three-phase generators, the use of a single leg for the railway load (3) or the installation of three-phase–two-phase transformer sub-stations (5). Both seem to offer advantages justifying their recommendation, the choice between the two may perhaps be left to the needs of local requirements.

DISCUSSION ON "SINGLE-PHASE *versus* THREE-PHASE GENERATION FOR SINGLE-PHASE RAILWAYS", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

P. M. Lincoln: I agree with the author of this paper, that it is highly desirable to keep power service and street railway service separate if it is at all possible. However, at times commercial considerations may make it essential to supply both polyphase power service and single-phase railway service from the same generating station. When that is necessary, the author of this paper has pointed out several methods by which it may be accomplished. There is one modification, however, which he has not mentioned, but which I believe has considerable advantage over any of the methods mentioned by the author.

The ordinary three-phase system may be represented by an equilateral triangle, in which the three sides of the triangle will be the voltages of each of the three phases, as in (*a*), Fig. 1. When we put a single-phase load on one of the legs, this triangle becomes distorted, affecting both the relative lengths and phase relations of the three phases. It assumes a form something like (*b*), Fig. 1, so that the three-phase triangle is considerably distorted from its original shape. When it is necessary to supply both single-phase and three-phase from the same generating system, we can give the three-phase voltage an initial distortion so that a true three-phase relation shall lie somewhere between the initial distortion selected and final distortion which may be expected due to the single-phase load. By this means the maximum unbalancing that can take place in the three-phase circuit is approximately one-half what it would be if we started with a balanced three-phase. Fig. 1, (*c*) shows roughly in diagram the condition that might be expected. At best the effect on the three-phase circuit is anything but good.

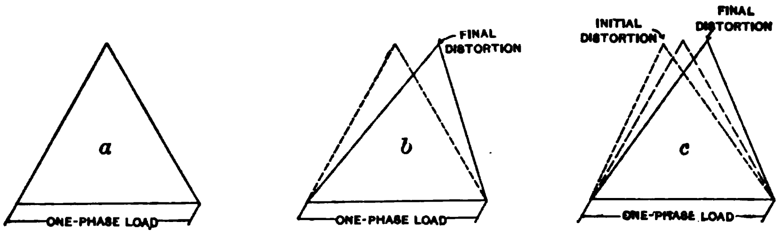


FIG. 1

Therefore, I do not feel like recommending any method or any system where a single-phase railway and a general power distribution are drawn from the same generating system; but, as I have already said, commercial considerations sometimes make it necessary to consider such a system.

Henry G. Stott: One other method, not mentioned in the author's paper, might be brought up for discussion; that is, the method of using the grounded neutral on the three-phase system. Where power is required for general purposes, as well as for single-phase railroad work, this method might be applicable, as, by the use of partly loaded induction motors in different parts of the line, the balance of the phases and also of the voltages would be restored. This makes an extremely simple combination where general three-phase power, as well as single-phase operation, is required.

V. Karapetoff: It seems to me that where difficulties should arise, on account of unbalancing, in cases where single-phase and three-phase lines are fed from the same generators, we would have to regulate the three-phase system by means of induction regulators. It is not necessary to regulate the three legs; only one phase needs to be regulated. The triangle of voltages is originally an equilateral triangle; then it becomes a distorted triangle. It is plain that this latter triangle can be made again an equilateral triangle by moving in a certain direction *one* of the phases, by having in the three-phase system a suitable induction regulator in one leg, so arranged that a vector of any desired direction or magnitude can be added to the line voltage. Therefore, the problem of regulation is not as difficult as it might seem at the first glance.

John B. Taylor: I fail to see how a single-phase induction regulator can be practically applied to a three-phase system in such a way as to compensate for the unbalancing effects of a single-phase load. More important than the drop in voltage due to line resistance, etc., is the distortion due to the reaction in the generator under single-phase load conditions.

All things considered, there will be many cases where the expense of the motor-generator set will be justified. This enables the transmission system to work on balanced three-phase load, at unity power-factor, and also removes the grounds from the transmission system. Where the single-phase load is taken as a part of a large system, unless transformers or motor-generators are introduced, a ground on the single-phase system involves, of course, a ground on the entire system and this in many cases would be decidedly objectionable.

William McClellan: The paper has reference to large systems giving opportunity for sectionalized distribution. So far, single-phase electrification has been over short distances with not more than two sections to be fed. Such a system presents little difficulty where a company is generating its own power. While from a technical standpoint the unbalancing may be inconvenient, it does not affect the coal-pile seriously. When, however, power is bought from a power company and taken from three-phase transmission lines, the effect is more serious. Under modern contracts for power, unbalancing over a certain maximum amount, must be paid for. Under such conditions it is possible to connect the transformers in V which, however, would never give a balanced three-phase load. A better method is to connect the transformers in T and use the 90° phases on the two sections of the trolley. When these two sections are equally loaded, the three-phase load will be balanced and the average balancing of the load will be considerably better. Such a system requires, however, that the three legs at the high-tension side of the transformers be opened nearly simultaneously.

Chas. P. Steinmetz: The problem of taking care of single-phase loads on three-phase systems is rather complicated. I do not believe any induction regulator can take care of it to the extent of balancing the load. The cause of the unbalancing on single-phase load is to be found in the flow of power which with single-phase load is not constant, as it is with the balanced three-phase system, but pulsating. This pulsating flow of power gives a pulsating armature reaction; superimposed upon the fundamental sine wave of the generator it produces the effect of a double frequency pulsation or magnetism due to the pulsation of the flow of power. This results in the production of a strong third harmonic. In some conditions, in extreme cases where the single-phase load is short-circuited, this triple harmonic may reach disastrous values, 250 per cent. of the normal voltage, or even more. This is merely the extreme case of unbalancing.

To restore the equilateral triangle by giving it an initial distortion is open to the objection that the distortion of the triangle is not always the same but depends on the nature and the power-factor of the load. If the power-factor of the load is approximately constant, within a moderate range, as with single-phase railroading, this can be done. But, after all, with any generator of reasonably good regulation, the matter usually is not serious because an induction motor can take care of a very great distortion of the equilateral triangle and still work with no appreciable change in efficiency, no appreciable change of heating. In most cases then we can let the triangle become as distorted as it chooses, and the induction motors and other apparatus will show no difference, except perhaps synchronous converters. Synchronous converters in such systems would necessarily be installed, as they usually are in railway work, with heavy reactances, reactances of ten per cent. or more in the leads. This reactance, by phase displacement of lead or lag, can take care, not only of line drop and control of voltage, but also of distortion of the triangle, and thus supply at the converter the equilateral triangle with a greatly distorted generator triangle, by merely a small change in the angle of lag of the three different phases, one of the three currents lagging perhaps while the other is leading to a small extent. So the converter can also take care of itself.

The main difficulty is where lighting is done from several phases. But even there, if we look at the distortion of the triangle with single-phase load, we find that naturally the loaded phase drops with the ordinary single-phase load. Of the other two phases, one drops more than the loaded phase and the other remains practically constant; that is, of the two unloaded phases the distortion is such as to keep one of the phases almost constant and in that phase through a potential regulator which has relatively little work to do, constant potential may be supplied. That is probably the simplest way of taking care of unbalanced loads. My old scheme, the monocyclic system, was to build the generator three-phase; use one phase for lighting and maintain it at constant voltage, and carry the three-phase load by the auxiliary phases. After all, that was another form of Mr. Lincoln's proposition to start with a distorted three-phase system and use the distortion to distribute the load between the different circuits in the desired manner.

A. H. Armstrong: I am inclined to look at this matter a little more broadly than some of the previous speakers. For instance, the method proposed by Mr. Lincoln can be used successfully in cases where the railway company generates its own power, although in such cases the company would have the privilege of generating and distributing single-phase power, and the simplicity of single-phase distribution would recommend it above all others. We are confronted, however, with the problem of power purchased from foreign concerns, and the tendency of the times seems to be toward establishing large centers of power distribution. The generation and distribution of power is carried on as a separate business by itself. It may be associated with lighting, railway, and power industries, but in any case it is generated and distributed three phase. It is a very difficult problem to connect single-phase railway systems to a three-phase power distribution system without interfering in some degree with other uses of a common power supply. In fact, managers of power distribution systems are very loathe to make contracts which involve the use of single-phase power for railway purposes. In such cases the introduction of a motor-generator set seems almost necessary, aside from the question of frequency supply, if the distribution circuit of the power producers is to be properly safeguarded.

Unfortunately, in a large number of single-phase projects suggested, the margin of profit between installing alternating-current apparatus and direct-current apparatus is rather small. Owing to the inferiority of the alternating-current railway motor, there is no advantage in adopting alternating-current car equipments unless there is a considerable reduction either in first cost or operating expense, or both. The added expense of motor-generator sets oftentimes acts as a serious handicap when considering the installation of alternating current railway equipments fed from a foreign three-phase source of supply. In such cases it will be necessary to use some of the methods proposed for balancing the load on the three phases rather than consider the expense of a motor-generator set.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

THE CHOICE OF FREQUENCY FOR SINGLE-PHASE ALTERNATING-CURRENT RAILWAY MOTORS

BY A. H. ARMSTRONG

Owing to the success attending the several installations of single-phase alternating-current railway motors in this country and abroad, and the suitability of this type of motive power for the electrification of certain steam lines, the questions have been asked as to whether the 25-cycle frequency thus far universally used is the frequency best adapted for alternating-current motor design and operation, or whether the benefits obtained by the use of a lower frequency are sufficient to justify its introduction. This paper is intended to open a discussion on the relative merits of 25 cycles and a lower frequency, and will touch briefly upon the advantages and disadvantages of the present standard of 25 cycles and any proposed standard of a lower frequency.

All the alternating-current railway motor installations thus far made in this country have employed a frequency of 25 cycles, and, with one exception, the service has consisted of the movement of single-car units at maximum speeds of approximately 50 miles an hour at intervals of one-hour headway over a single-track line. That is, all alternating-current roads have been designed to take care of interurban passenger business with the incidental movement of express matter and miscellaneous freight.

It has been found that the alternating-current single-phase commutator motor can be developed to a commercially successful stage at a frequency of 25 cycles; and although some benefits in respect to weight, efficiency, and commutation are to be obtained with the adoption of a lower frequency, the advantages do not as yet seem great enough to justify the standardization of a new frequency suitable to alternating-current commutator motor operation alone. Recognizing the enormous commercial advantage of offering an alternating-current railway motor which could operate from existing power plants, the manufacturers have perfected alternating-current equipments for interurban service for the standard frequency of 25 cycles already universally in use for this class of work.

The introduction of a new frequency calling for the design and establishment of a complete new line of generating, transmitting, and receiving apparatus is a most serious matter; it should not be undertaken without carefully considering all the factors, both commercial and engineering, entering into the case. With the coming electrification of steam roads there is a demand for motors of increased capacity, and the possible limitations of 25-cycle design in large alternating-current motors of certain types is more keenly felt, hence the inquiry at this time into the question of the proper frequency to be adopted when the alternating-current motor is selected as the type of motive power for steam-road electrification.

The various points to be considered may be classed under the following heads:

1. The effect of frequency on design of motor equipment.
2. The effect of frequency on coefficient of adhesion.
3. The effect of frequency on generating and distributing systems.
4. Commercial considerations.
5. Locomotive design and selection of motive power.

The effect of frequency on design of motor equipment. Taking the weight of a direct-current motor as 100 per cent., it is probable that the values in the following table hold approximately true.

COMPARATIVE WEIGHT OF DIRECT-CURRENT AND ALTERNATING-CURRENT MOTORS

Direct Current	25-cycle alternating current	15-cycle alternating current
One-hour capacity 100	150	130
Continuous capacity 100	125	120

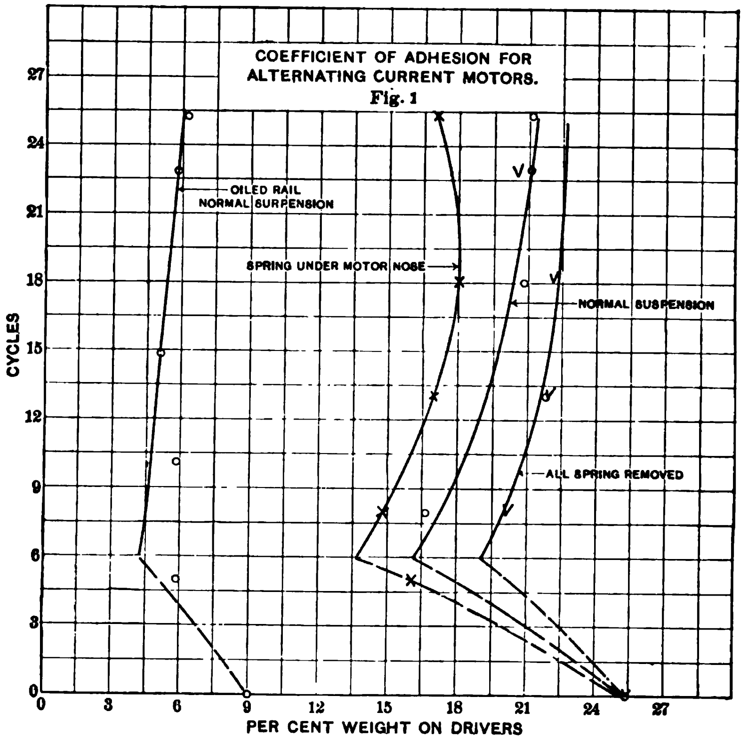
These figures apply to motors designed to give in all cases the same output and heating at the same speeds, but with an admitted superiority in commutation in motors of direct-current commutating-pole design. While the weight of the 15-cycle alternating-current motor is less than that of the 25-cycle motor, this will be partly offset by an increase of 30 per cent. in the weight of the step-down transformer on the car. Although the car transformer weighs but approximately 20 per cent. of the complete equipment, including control and motors, an increase of 30 per cent. in its weight will practically offset the reduction in motor weight when recourse is had to 15 cycles. Therefore, while there are other advantages in superior commutation, higher efficiency, etc., obtaining with the use of 15 cycles, there is no material reduction in weight of the complete alternating-current motor and control equipment.

Until recently the commutation of alternating-current motors has been considerably poorer than that of direct-current railway motors in use. Various expedients, such as high-resistance leads, lower frequency, etc., have been suggested to improve the commutation and reduce the losses and heating at the brushes. Recent improvements in alternating-current motor design have resulted in the production of an alternating-current single-phase motor which compares very favorably in commutation with any of the standard direct-current railway motors now in operation, although inferior in this respect to the commutating-pole type of direct-current railway motor. In fact the commutation of the alternating-current single-phase motor has been so improved and the commutator losses so reduced with a frequency supply of 25 cycles as to make it unnecessary to adopt any of the above mentioned expedients in order to eliminate commutator troubles.

Where it becomes necessary to design motors for the greatest output per cubic foot of space allowable, as in the case of very large motors designed for locomotives under the restrictions of 4-ft. 8.5-in. gauge and reasonable wheel-base, it is possible that the adoption of a frequency lower than 25 cycles permits a greater latitude in design of alternating-current single-phase motors of certain types.

2. *The effect of frequency on coefficient of adhesion.* The torque delivered to the driving-wheels by the alternating-current commutating motor is of a pulsating character, and its effective value is somewhat less than the uniform torque imparted by the direct-current motor. Experiments show that the effective torque is a function of the frequency of motor

supply, and also depends upon the construction of the truck and the method of motor suspension. The values given in Fig. 1, express the relation between tractive effort and frequency for periods from 25 cycles down to zero; that is, direct current. The values given will hold true only with the combination of truck springs, motor suspension, etc., in the test, and the use of stiffer or lighter springs, more rigid or flexibly suspended motor, the use of springs between gear and axle, etc., might give results differing considerably in degree from those submitted herewith.


COEFFICIENT OF ADHESION FOR ALTERNATING CURRENT MOTORS.
Fig. 1

The three curves given represent normal motor suspension, additional spring suspension under the motor nose, and with springs removed, giving practically rigid suspension except for the spring of the armature shaft, gear teeth, etc. While the tests are incomplete, they indicate a slight reduction in the coefficient of adhesion with lower frequency; but so far as can be determined this reduction is not a serious matter in the consideration of 25 cycles or a lower frequency, say 15 cycles.

With normal motor suspension, the coefficient of adhesion as obtained with 25 cycles alternating-current was 82.5 per cent. of the value obtained under the same conditions with the same motor supplied with direct current.

3. *The effect of frequency on generating and distributing apparatus.* The question of generator design at 15 cycles is a serious one and presents many difficulties which can only be partly overcome at an increased cost of the apparatus perfected for 25 cycles. In fact, while certain capacities of low-frequency turbo-generator units may be constructed fairly comparable with 25-cycle units, it is probable that the adoption of 15 cycles or less would seriously handicap the standardization of a complete line of such units; in any case it will increase the cost of those units which it is possible to construct. The steam turbine has shown itself a most excellent prime mover, and the adoption of 15 cycles is seriously handicapped by the difficulties opposing the successful construction for this frequency of a complete line of generator units of all sizes.

Both step-up and step-down transformers are handicapped at 15 cycles by an approximate increase in cost of 30 per cent. over that of 25-cycle design. This applies to step-up and step-down transformers used throughout the low-frequency system.

4. *Commercial considerations.* Perhaps the benefits of standardization to both the customer and the manufacturer have not been appreciated to any greater extent than in the electric railroad industry. The universal adoption of 25-cycle three-phase supply feeding into the distributing system of railway networks constituted so strong a claim in favor of adopting this frequency when developing the alternating-current railway motor as to outweigh certain known benefits to be obtained with a lower frequency supply. The great field for alternating-current motors of 150-h.p. capacity and less is on interurban lines acting as feeders to the surface, elevated, and subway lines of large cities. The ability of such motors to run from the same alternating-current generating and distributing systems without requiring the introduction of frequency-changer sets constitutes a strong argument in favor of continuing the present practice of installing 25 cycles on such lines.

The type of apparatus adopted for new installations must necessarily be largely dependent upon the apparatus already installed for similar purposes in its neighborhood; it is a question, then, when considering the electrification of steam roads in and about large cities, whether engineers can afford to neglect this principle and cut loose from standards already established and universally used. Furthermore, steam railroad electrification often commences in station and signal lighting and car shops, and 25 cycles is already largely in use for such work. Small motors and transformers are much higher in price at 15 cycles; there is no line developed; and station and car lighting is most unsatisfactory at this frequency.

5. *Locomotive design and selection of motive power.* One of the principle arguments in favor of the electric locomotive is that it permits the concentration of a very large amount of power on the driving-wheels. In this respect the electric locomotive equipped with alternating-current series compensated motors does not compare favorably with other types of motors of both alternating-current and direct-current design. Furthermore, the successful exploitation of these other types of motive power does not demand the adoption of a frequency less than 25 cycles, and hence it is pertinent to inquire if, with our present knowledge of the art, the alternating-current single-phase motor of the series compensated type possesses qualifications which make it so superior to other types of electric motors as to justify the introduction of an odd frequency of benefit only to that one type of motive power. The writer feels much gratified at the success attending the development and operation of the various alternating-current roads already completed, but it should be pointed out that this success has been attained with a frequency of 25 cycles.

Admitting the coming of steam-road electrification, we have not had any demonstration or even convincing figures submitted which would prove beyond doubt the desirability of adopting 15 cycles and the alternating-current series compensated motor to the exclusion of direct-current motors of all types and voltages, three-phase induction motors, or even single-phase alternating-current motors of other types which can be built in large capacities at 25 cycles. In the opinion of the writer it becomes, not the choice of the best frequency for the alternating-current series compensated type of motor, but a question of the proper selection of motive power for the exacting demands of locomotive construction designed for hauling trains of any weight at both high and low speeds over roadbeds of any gradient. The question of frequency might well be left in abeyance until the coming of fuller knowledge of the operation of electric locomotives equipped with motors of different types. Considered from the engineering standpoint of alternating-current series compensated motor design alone, the use of 15 cycles offers advantages in the betterment of commutation, efficiency, and output per pound of motor which may justify its adoption, provided that type of motive power it best suited to the needs of the problem in hand. Taking into account, however, the commercial interests involved, and considering the serious claims that may be advanced in favor of other types of electric motors for which a frequency of 25 cycles is well suited, it appears to the writer that much stronger claims for recognition must be brought forth before the adoption of 15 cycles can be seriously considered.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

TWENTY-FIVE VERSUS 15 CYCLES FOR HEAVY RAILWAYS

BY N. W. STORER

At the regular meeting of the Institute, on January 25 of this year, a paper was presented by Messrs. Stillwell and Putnam dealing with the electrification of steam railways and referring briefly to the question of the adoption of a standard frequency for single-phase railways. This question aroused a great deal of interest and was discussed at greater length than any other feature of the paper. The authors, while enumerating the advantages of both 25 and 15 cycles, drew the conclusion that the advantages were greatest on the side of the lower frequency, and this opinion was concurred in by most of those who discussed the matter. Many good points were brought out, but all were more or less general; and while it is obviously impossible for the Institute to standardize at this time a frequency for railways using alternating current, a free and full discussion of the matter can hardly fail to produce good results and to furnish more definite information than was available at the time the paper was presented. The arguments in favor of 25 cycles may be reduced to the following:

1. It is a standard frequency which is in use in a great many plants throughout the country.
2. It is probably better suited for general power distribution and is certainly better for lighting than 15 cycles; therefore any railroad having a 15-cycle plant for operating its road would be somewhat handicapped in power for lighting and shop purposes.
3. The higher frequency is better suited for speeds of steam turbines of small size, it being at present uneconomical to build

turbo-generators for less than 2000 kw. at 900 rev. per min., which is the maximum available for 15 cycles.

4. Transformers are lighter and cheaper for 25 cycles.

The principal arguments in favor of 15 cycles are:

1. An increase of from 30 to 40 per cent. in the output of a motor of a given size and a consequent reduction in the total number of motors required to operate a railway, and in the cost of equipment.

2. Better performance of the 15-cycle motors, including higher efficiency, higher power-factor and better commutation.

3. Less dead weight to be carried on cars and locomotives.

4. Lower line losses.

The first argument in favor of 25 cycles; namely, that it is a standard frequency in use in a great many plants of the country, is certainly a good one. It is undoubtedly a very serious matter to consider the introduction of a new frequency for any purpose whatsoever. There are, as is well known, a number of frequencies in use at the present time for which there is no justification except that they are in use, and there is no class of service of which we know that cannot be handled with equal efficiency by one of the standard frequencies, with the exception of the alternating-current railway systems. Railway electrification, if developed as every electrical engineer hopes it will be, will mean an undertaking of such magnitude as to make it practically independent of other electrical interests, so that if a frequency differing from the standards now in use will be advantageous it should be adopted.

The second argument in favor of 25 cycles; namely, that it is better suited for power and lighting purposes than 15 cycles, may be granted without admitting that it is a particularly valuable point. Satisfactory lighting can be obtained with 15 cycles by using a low-voltage lamp having a large filament with high thermal capacity. This will be entirely suitable for ordinary railway lighting. While not having as wide a range of speed as is possible with 25 cycles, 15-cycle induction motors can undoubtedly be used to accommodate practically any class of service required of them. The fact that the single-phase commutating motor is more satisfactory on the low frequency may make the low frequency even more satisfactory for shop purposes than the high frequency. In the discussion of the Stillwell-Putnam paper one speaker called attention to the fact that railway companies would probably sell a large amount of power along their right-of-way to consumers for various purposes, and stated that 15-cycle current would be unsuitable for such service. In reply to this it is only necessary to call attention to the fact that the voltage on any railway circuit is so variable as to make it absolutely unsuitable for lighting purposes, and it would therefore be necessary to introduce a motor-generator set in order to get good results. This might just as easily be made a frequency-changer to supply current at either 25 or 60 cycles, as might seem best for that particular locality. While this unquestionably destroys some of the simplicity of the scheme, it is undoubtedly what would be necessary in order to give satisfactory service, even if 25 cycles were in use on the railway, unless a separate generator were used for the lighting circuits. It seems therefore that the 15-cycle current would be little or no handicap to the railway company in this respect.

The third argument; namely, that the higher frequency is better suited for speeds of steam turbines is undoubtedly true, but it affects a very small proportion of the work. Heavy railroads will require in practically all cases larger generators than 2000-kw. units. In cases where they do not, high-speed turbines can be used and frequency-changers employed. At the same time we must admit that the last word in regard to steam-turbine design has not yet been spoken, and it may shortly be an easy matter to make comparatively small units for use with 15-cycle generators.

The fourth argument, that transformers are lighter and cheaper for 25 than for 15 cycles is undoubtedly true. There will be a difference of probably 25 per cent. in the cost of the transformers for any given service. This difference must be offset by the difference in the cost of the motors.

The meat of the entire argument for the lower frequency is in the greater output of the motors for a given size and weight. It was well shown in the Stillwell and Putnam paper that the cost of car equipments and locomotives would far overbalance the cost of power houses and transformer stations; and while I do not wish at this time to give a mass of estimates as to the saving, I will adhere to the statement previously made that the output from a motor of a certain size will be increased from 30 to 40 per cent. by the use of 15 instead of 25 cycles. This has been proved by tests on several different motors.

A well known 100-h.p., 25-cycle motor operates with full load at a speed of 620 rev. per min., and in the regular one-hour test on the stand has a temperature rise of 89° cent. in commutator and 75° cent. in armature, other parts of the motor being well below 75° cent. Operated at the same speed on 15 cycles, this motor carried a load of 113 h.p. with a maximum temperature rise in commutator of 76.5° cent. and in armature of 72.5° cent. It is safe to say it is good for 115 h.p. with the limiting temperature of 75° cent. in armature. This same motor with a larger number of turns on the field and run on 15 cycles carried at the same speed of 620 rev. per min. a load of 135 h.p. with a temperature rise in commutator of 76° cent., in armature of 75° cent., and in field-coils of 76.5° cent. It is quite safe to rate this motor at 135 h.p. on 15 cycles.

A larger motor carried a load of 255 h.p. with a temperature rise of 71° cent. in commutator and 76° cent. in armature. other temperatures being well below 75° cent. This motor, operated at the same speed under identical conditions on 15 cycles with a load of 300 h.p., rose 73° cent. in commutator and 81° cent. in the armature. With new field-coils having more turns, the motor will carry at least 325 h.p. and probably 340 h.p. with a rise in temperature not exceeding 75° cent.

While these results are all based on the one-hour test, the continuous capacities will have the same increase on 15 cycles. The inference to be drawn from these results is, of course, that the temperature rise being the same for both frequencies, the losses must be approximately the same; and since the output is greater on 15 cycles, the efficiency must therefore be much higher. Further, the tests are all based on 25-cycle motors modified only in field-coils. If the motors are designed especially for the low frequency, the results will be still better.

A comparison of the weights of car equipments for 25 and 15 cycles indicates that there will be an advatnage in favor of the lower frequency, even with the same number of motors. For instance, a four-motor equipment of 100-h.p., 25-cycle motors, with oil-insulated transformer, will weigh approximately 30,000 lb. Such an equipment for 15 cycles would weigh approximately 28,500 lb. The difference is small, but it is in favor of the lower frequency. If two 15-cycle motors of 200 h.p. each, such as are now building, be furnished, the weight of equipment will be reduced to approximately 23,000 lb., or a reduction of 23 per cent. in the weight of the car equipment. While it is perfectly practicable to furnish two motors for a 400-h.p. equipment for operation on 15 cycles, it will be necessary to furnish three or four motors for 25 cycles on account of the great increase in the size of the motor. It is therefore absolutely necessary that the 25-cycle equipment weigh considerably more than that for 15 cycles. In the case of smaller motors aggregating 280 h.p. it is possible to furnish a two-motor equipment operating on 25 cycles. There would, however, be a difference in weight of at least 1500-lb. in each motor in favor of the 15-cycle equipment of the same capacity. This would offset the increased weight of the 15-cycle transformers by at least 1000 lb. In every case, therefore, even where the same number of motors are in use for both frequencies, the 15-cycle equipment will be lighter. On account of the smaller motors the motor trucks will also be lighter, the amount of saving here depending upon the size of the motor.

The greatest gain from the use of 15 cycles is to be found in heavy railroading where locomotives are used. In building locomotives it is desirable, on account of the weight, cost, and maintenance charge, to concentrate the power in as few motors as possible consistent with weight on the drivers and the tractive effort desired. We have found that in virtually all cases the weight of useful apparatus on the drivers, even with 15 cycles, is sufficient to give the necessary adhesion without adding dead weight; therefore the use of 15 cycles means that in practically all cases for the locomotive a smaller number of motors can be used than is possible with 25 cycles. It is frequently the case that three motors which are sufficient with a certain size of driver for 15 cycles would have to be replaced by four motors having the same dimensions. It would sometimes happen that three motors necessary for 25 cycles could be replaced by two of the same dimensions for 15 cycles. In the case of locomotives of very high-speed the extra weight entailed by the use of higher frequency motors, and consequently heavier mechanical parts, would increase the weight of the train to such an extent as to call for a considerably larger output from the motors, simply to haul the extra weight. Such a case we have in mind in a high-speed passenger locomotive that has recently been built.

This locomotive is designed to haul a 400-ton train both on heavy grades and at high speeds on a level track. The locomotive as built for 15 cycles weighs approximately 140 tons, and has four motors each with a nominal rating of 500 h.p. With a 400-ton train behind it, this locomotive would thus have to handle a total of 540 tons. A 25-cycle locomotive built to handle a 400-ton train at the same speeds and on the same grades would require six motors of approximately the same dimensions, and these extra motors together with the extra weight of mechanical parts would bring the total weight of the locomotive up to approximately 185 tons. The total weight of train would thus be 585 tons, or an increase of about 8 per cent. The capacity of these motors would be in the neighborhood of 375 h.p., which would be just about sufficient to handle the extra weight. It must be seen at once that the motors for this locomotive would cost 50 per cent. more and the mechanical parts also considerably more. The only parts of the equipment which would cost less would be the transformer and preventive coils, and the control equipment would be enough more expensive to counterbalance this.

In this connection it may be of interest to give a brief description of the locomotive as built. It is of the articulated type, each half of which has two pairs of drivers and a four-wheel truck similar to the standard American type of steam locomotive, the two halves being coupled back to back. The drivers are 72 in. in diameter with 7 ft. 6 in. between centers of axles. On each axle is mounted a gearless motor having a nominal rating of 500 h.p. and a continuous capacity with forced ventilation of about 375 h.p. The motors, weighing approximately 19,500 lb., are spring-supported, mounted, and connected to the drivers in exactly the same way as the motors on the single-phase locomotive for the New York, New Haven & Hartford Railroad. This feature has been described so many times that it is unnecessary to repeat it. The frame of the locomotive is of the standard steam-locomotive type placed outside of the wheels. It is of cast steel connected at the front and rear and at three places between the ends by heavy cast-steel girders. The truck, which is of the standard steam-locomotive pattern, has 36-in. wheels, with a wheel-base of 6 ft. 2 in.

The electrical and other equipment in the cab is mounted on a raised platform which is about 2 ft. above the floor-line and occupies the middle of the cab, allowing for a passageway on either side. There are numerous windows along the sides of the cab which afford excellent light for the inspection of the apparatus. The equipment is extremely simple and accessible. The main transformer, which is designed for 11,000 volts, is mounted above the truck, with the top just below the platform in the cab. Directly above the transformer is located the electropneumatic switch-group to which the various taps in the transformer are carried. Back of the switch-group are the preventive coils used in passing from step to step on the transformer, and from these preventive coils runs a single lead to the reverser switch-group, which is placed directly above the main motors. On this raised platform are also placed the motor-driven air-compressor, the motor-driven blower for furnishing air for ventilation of the motors and transformer, and the air reservoirs. Suspended from the structural work between the platform and the Z-bars in the roof of the cab are the oil circuit-breaker in the high-tension circuit leading to the transformer, the small switches used in connection with the auxiliary motors, and the 20-volt battery which is used for operating the valve-magnets in the controller. The high-tension current is collected from the overhead wire by the standard type of pantagraph trolley. On account of the large drivers and the comparatively high position of the apparatus in the cab, the center of gravity of the locomotive is higher than is usual in electric locomotives. The riding qualities of the locomotive are exceptionally good. The weight of the locomotive, as stated, is 140 tons, there being 50,000 lb. on each driving axle and 40,000 lb. on each truck.

In the case of geared locomotives for heavy freight service, there is still the advantage in favor of 15 cycles. Where the same number of motors is used for both frequencies, it will be necessary to use larger wheels for the 25-cycle locomotive. Low-speed locomotives are especially at a disadvantage with 25 cycles. It is possible to make a geared motor with a capacity of 400 to 450 h.p. for slow-speed freight service with 15 cycles, while with 25 cycles a 300-h.p. motor is as powerful as it is practical to use. This means that in the freight service there is virtually the same condition as in passenger service; namely, that about one-third more motors will be required to perform the service. The locomotive will weigh from 10 to 35 per cent. more.

An examination of the efficiency curves for 15-cycle motors compared with those for 25 cycles will show differences in the losses in the motors alone which will mean a considerable difference in the capacity of the power station. This, when added to the power required to haul the extra weight, and the increased line-loss due to the higher frequency, will make a difference of from 5 to 15 per cent. in favor of the 15-cycle equipment. Without giving estimates or long tabulated statements, I leave it to the judgment of the members of the Institute to decide whether it is not advisable, with these facts in mind, to recommend a new frequency.

It is well known that when the advent of the first successful single-phase railway motor was announced by Benj. G. Lamme in his historic paper before the Institute in 1902 the frequency which he advocated was 2000 alternations per minute, or 16⅔ cycles per second. It was believed at that time that this frequency was best suited to meet the many requirements of power plants for railway apparatus. However, owing to the experimental nature of the undertaking, it was deemed advisable to use the standard frequency of 25 cycles until the commercial success of the system was assured. At the same time it was realized that the practical difficulties to be overcome in the single-phase system would be much greater with the higher frequency. Moreover, in the first equipments sold the motors were of comparatively small size, so that the space occupied by them was not limited. Furthermore, the number of motors in an equipment was fixed by conditions other than dimensions and weight, four-motor equipments being selected in nearly every case, partly on account of the prevailing fad for four-motor equipments and partly because most of the equipments were built for operation on both alternating current and direct current. At any rate, aside from the greater difficulties met with in the design of the high-frequency motor in order to get good performance, the question of frequency was of comparatively small importance. Since that time some 15 or 20 roads have been put in commercial operation with single-phase current at 25 cycles. It has been proved beyond doubt that the single-phase motor is a thoroughly practical and commercial machine. At the same time, as was anticipated, all our experience goes to show the advantage to be gained by the use of a lower frequency. This frequency need not be fixed at exactly 15 or 16⅔ cycles. As far as the motor operation is concerned, a variation of one or two cycles either way will have comparatively little effect; but we believe, for the sake of using proper ratios between this and existing frequencies, that 15 cycles, which is one-fourth of the standard 60-cycle frequency, or 16⅔ cycles, which is two-thirds of the standard 25-cycle frequency, should be adopted for use, especially on heavy railroads. While this will undoubtedly make it necessary for the manufacturing companies to keep a larger variety of apparatus in stock (as there is no doubt that 25-cycle railways will be operated for a long time to come) the advantage to be gained from the lower frequency in the wider use of apparatus will far outweigh any slight disadvantage of this kind.

The mistake made by the blacksmith when he made the template which fixed the gauge of the standard railways at 4 ft. 8.5 in. is a matter of tradition. It is recognized as being one of the most far-reaching mistakes ever made, inasmuch as it has ever since placed a limit on the capacity of the railroads of our country, both by limiting the capacity of steam locomotives and the size of cars, and last but not least, the capacity of electric railway motors and locomotives. What an enormous benefit would be gained from even a paltry increase from 4 ft. 8.5 in. to 5 ft. What powerful machines could be built for a gauge of 6 ft.! But the mistake has been made, and it will cost so much to rectify it, that the boldest of our railway magnates is staggered by the suggestion.

Electrical engineers have an enormous responsibility in deciding upon matters of detail, such as frequency, which will have an effect that will far outlast anyone who has a voice in the matter; and it certainly behooves us as engineers to consider carefully before recommending the continuance of the present standard frequency of 25 cycles, where it imposes such a handicap on the capacity of our transportation systems.

DISCUSSION ON "THE CHOICE OF FREQUENCY FOR SINGLE-PHASE, ALTERNATING-CURRENT RAILWAY MOTORS", AND "TWENTY-FIVE *versus* FIFTEEN CYCLES FOR HEAVY RAILWAYS", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

H. G. Reist: With engine-driven generators the problem is a comparatively simple one, since not much difficulty is experienced in building machines for 15 cycles. The cost of the generators will be increased somewhat, perhaps 30 per cent. With turbine-driven generators the increased difficulty is very much more serious. As has been pointed out by one of the speakers, in smaller size generators, about 2000 kw. capacity, the increase of steam consumption on account of the limit in speed becomes serious, and undoubtedly there will be many places where generators of that size, or smaller, will be needed for long distance railway work. On larger sizes, the speed is more favorable for the turbine, but the generators have to be built with two poles only, which makes it a difficult designing problem. The machine becomes massive, the magnetic circuits become exceedingly long, and the weight of the machine must be greatly increased over that of the 25-cycle machine. Roughly, probably the weight and the cost would be increased fifty per cent. over a similar 25-cycle machine. The efficiency would also be a little less, although that is probably not a very serious matter; it might be one per cent. less at full load than with the higher frequencies.

C. W. Stone: If the design of turbine-driven generators is to be complicated by a combination of lower frequencies and single-phase operation, the generator becomes almost prohibitive unless 450 revolutions instead of 900 are used on the large capacity machines. On machines of 8,000 or 10,000 kw. capacity, 450 revolutions is very bad from the steam end. All the recent 25-cycle machines of large capacity have been run at approximately 750 revolutions. To increase the speed from 750 to 900 rev. per min. and make the generator both single-phase and 15 cycle is not to be considered.

E. J. Berg: While I do not believe that it will be necessary to resort to a frequency lower than 25 cycles, I think that some of the objections raised against the lower frequency are not well taken. A so-called half-frequency generator was invented several years ago, a generator with a given number of poles giving half the frequency of the regular generator operated at the same rotative speed. In construction, this generator was similar to the induction motor; in its action, to the well-known frequency-changer. Instead of exciting the field by direct current, alternating current of a given frequency was used, and the magnetic field made to rotate in the same direction as the armature but at half its speed. By this scheme, the frequency corresponding to one-half the speed could be obtained, not only from the stationary, but from the revolving member. Obviously, the exciting current had to be delivered at the lower frequency, but this was not objectionable, as the actual power supplied was slight and therefore the inefficiency of the low-speed turbine of little consequence.

L. B. Stillwell: I am much pleased to find a question of such transcendent importance as this, of the best frequency for railway work, receiving the serious consideration of the engineers of our manufacturing companies.

The electric railway fraternity now for the first time is undertaking the electrification of railways operating heavy traffic and employing steam locomotives. This work presents a problem more important commercially than any we have hitherto attacked. We are dealing with people who are not of the type that we had to deal with in the early days of electric lighting. The railways of the United States are managed by men whose education in most instances is largely an engineering education. They have their own excellently prepared and thoroughly experienced engineering staffs who will pass upon these questions. Therefore, it is of especial importance in considering such questions as this, that we should take a broad view, saving money for our clients by fighting out differences of opinion on paper and on the floors of these conventions, and, if possible, agreeing among ourselves upon all necessary fundamental standards.

The paper which Mr. Putnam and I had the honor to present before the Institute in January last, raised this question of frequency in railway service. Our feeling was that a mistake in all probability was being made. The figures which we worked out were intentionally broad, probably broader in application than any we shall see in our time, but it seemed advisable to look at the entire railway field and attempt to realize the magnitude of this problem. We therefore followed out our analysis of the comparative costs of operation, by figures showing the total cost of electrifying the railways of the United States. Some of the technical journals, whose specialty is steam railway practice, have ridiculed the idea of considering even the possibility of the electrification of all the steam railways in the United States. Probably no one here expects that this will be done in the near future, if ever; but it is significant to find that if we consider the average railway in the United States upon which there are but seven trains in each direction per day and apply to its operation single-phase alternating current, using a transmission voltage equal to that which is to-day in use transmitting power from Niagara Falls to Rochester and Syracuse, it would be possible to save approximately 18% of the present operating costs. This conclusion has not been assailed in respect to anything that is material. Even if we admit every exception to our total figures which was noted in the discussion, we still have a saving of at least 15%. This is a very important and a surprising fact. It indicates not that all of the railways in the United States will be electrified in the next ten years, but it does indicate strong probability of a more rapid extension of the application of electricity to the operation of trunk-line systems than has been generally realized, even by electrical engineers.

In calculating the reduction in operating costs, it is hardly necessary to say that we recognize also what several of our critics have kindly pointed out; namely, that the principal object in view, when the management of a railway decides to electrify its lines, is not reduction of operating expenses but increase of earning power. This fact is well known and has been referred to in many previous papers and discussions. The two reasons undoubtedly constitute an argument operating powerfully to induce railway electrification. The point which I wish to emphasize is that this electrification is in all probability coming at a rate which greatly emphasizes the importance of early standardization of everything essential to interchange of traffic.

A recent bulletin of the Census Bureau of the United States, prepared by Mr. Martin, shows that from 1900 to 1905 the products of companies manufacturing electric apparatus were more than doubled. In the year 1900 few would have dared to predict such an increase.

When we take the broad view and realize the probability of a more rapid extension of the use of electric equipment in trunk-line railway service, the suggestion that it is of utmost importance to adopt a standard frequency especially adapted to this work appears less radical than it does to the factory engineer who is interested primarily in the problem of designing a complete line of turbo-generators.

The total cost of electrifying a railway, is in general not less than $200 per kilowatt of generating capacity installed, and in considering the effect of 25 versus 15 cycles the difference in the cost of the average turbo-generator might easily be $5 one way or the other without materially affecting our conclusion. Moreover, in dealing with the problem of trunk-line electrification we may as well throw aside all of the smaller generators, as this service will rarely, if ever, call for a generating unit of less than 3000 kw. A single freight train, such as is hauled over some of our trunk lines, would require one 3000-kw. generator.

There is another field the limits of which, while not clearly defined, are sufficiently understood; that is, the interurban. Much argument has been presented at various meetings of the Institute this year bearing upon the question of the possible use of a 1200-volt direct-current system as a substitute for the high potential alternating-current system. This system, perhaps, has its field in the interurban service. I think it can have no proper application in the broad service of trunk-line railways of which I am speaking. A potential of 1200 volts on the trolley or third-rail will never be satisfactory for the operation of freight trains. We must go radically higher. Anything less than 6000 volts in single-phase service is out of the question, and the question for us to decide is: " What frequency shall be adopted for alternating-current railway operation "?

The paper which Mr. Storer has read is one of the exceptionally valuable papers of the year. It contains precisely the kind of information which is needed in dealing with the very important question of frequency; and a half dozen pages of facts, such as he has given us, are worth any number of pages of general speculative opinion. In the discussion of my paper in January, the engineers of both the great manufacturing companies engaged in single-phase work, who had to do with the design of the motors and their application to trucks within the limits of space available, testified unanimously to the effect that at given cost 15 cycles secures one-third more draw-bar pull than does a frequency of 25 cycles. The people who will buy electrical apparatus to equip trunk-line railways will buy draw-bar pull. Recognizing this, it seems to me that we must recognize also the fact that, in view of the evidence set forth in the Institute papers and discussions this year, 15 cycles should be adopted in general for heavy railway work. I do not mean to say that a resolution to this effect should be passed, but I do say that unless evidence in favor of 25 cycles not hitherto presented can be brought forward, 15 cycles should be chosen by consensus of sound engineering opinion and should be introduced into practice as promptly as possible.

At the meeting in May when Mr. Sprague's paper was read some interesting facts were brought out in the discussion, especially the statement that one of the great manufacturing companies since January had produced a new single-phase motor of remarkable characteristics which operated substantially as well at 25 cycles as at 15 cycles. This is a very interesting statement, and it suggests information which I hope will be promptly and conclusively disclosed because some of us in the consulting field are now confronted by the problem of frequency for railways which at the present time are considering only the equipment of a terminal or a short division, but which by reason of the saving effected in operation and of increased earning power are morally certain to extend that electrification over much greater parts of their existing systems.

W. N. Smith: I cannot escape the conclusion that the question of electrification of steam railroads is so extremely broad that, as has been indicated by both Mr. Storer and Mr. Stillwell, we should not deliberately tie ourselves down to any existing commercial frequency which was developed primarily for lighting and stationary power.

If the steam railroads want draw-bar pull, which is unquestionably what they need to get the maximum amount of tonnage over a given track in a given time, they will not wish to be handicapped by the facilities offered by some local power company, no matter how large it may be, which may have 25 cycles to offer, if 15 cycles is going to be the best thing for them to use. Great as is the power development here at Niagara Falls, I doubt if there would be enough 25-cycle power generated to supply the commercial demands of this region, now developing so rapidly, and at the same time supply the railway power required by such wholesale electrification as it is conceivable that large railway systems might eventually undertake. I do not believe that there is sufficient power capacity at present installed in any one plant anywhere in the country which would justify the undertaking of the wholesale electrification of a large steam railroad in its own vicinity, in addition to its own commercial load. It appears to me that the problem will without doubt result in the railway companies either having their own power stations, and getting developed for themselves the kind of machinery that they need the most, or calling into existence commercial power companies which will do it for them, developing coal mine power or large water power in such units and by such methods of distribution as the railway companies, their biggest customers, may demand.

William McClellan: If we examine these papers carefully, we shall find a decided agreement between the two authors as to facts, though the opinions and conclusions given are somewhat different. Apparently there is no uncertainty as to the weight-efficiency. Variable adhesion is eliminated as having no practical bearing. As far as the difficulty of generating 15-cycle power by turbines is concerned, Mr. Berg has anticipated me. We had a paper a year or two ago on a type of generator excited with alternating current. It was suggested that such a machine could be built self-exciting, in our case for 15 cycles, and run at double speed, thus making it possible to drive it efficiently by a turbine.

Apparently, the chief argument against 15 cycles is the difficulty of changing present commercial standards; this is certainly entitled to most serious consideration. Nevertheless, it should not be forgotten that great advances have been made in the past by discarding what seemed at the time as fixed practice. This was one of the arguments against the adoption of the metric system. Notwithstanding this, it was announced a few days ago that the Baldwin Locomotive Works had built a locomotive with its regular workmen and had used the metric system throughout. The engineers and workmen were well pleased with the system, and the arguments against its adoption were apparently refuted.

It has also been stated that a low frequency would not be suitable for other purposes than motive power. In this connection it should not be forgotten that it is probable that large lighting and power loads will not be worked from the same busbars as traction loads. It is also worth noting that the present tendency of economic progress is to limit transportation companies strictly to the transportation business, and it is not likely that they will go into the business of selling power. Lighting and power for their own shops, stations etc., is relatively unimportant.

The important point noted in the Stillwell-Putnam paper was that the cost of the motive power equipment is by far the greater part of the expense of electrification. This brings us directly to the motor and its efficiency.

A short time ago there seemed to be a decided unanimity of opinion that the compensated-field single-phase motor was the type which the manufacturers had found to be most advantageous. It was expected that it would be greatly improved but the type would remain standard. With this motor, much would be gained by using 15 cycles. The engineer with the facts before him, and if not limited by local considerations, would necessarily hesitate a long time before refusing to adopt this motor.

Recently, however, we have had public notice that another type of motor is developing rapidly and is said to be nearly as good as the direct-current motor without commutating poles. From the standpoint of both weight and efficiency, this motor will perhaps not offer increased advantages when adjusted to a circuit of lower frequency than 15 cycles. If so, the whole matter is uncertain, and it would be exceedingly unwise to make any decision whatever until we have more definite information in regard to this motor.

It is worth repeating that the whole argument centers around the motor, or motor capacity, if you will, and no decision should be made to standardize frequency until the type of motor is standardized first.

Chas. P. Steinmetz: Probably the railways will generate their own power. At the same time it is a serious matter to depend on one power house only, or even two power houses, and if in an emergency power can be derived from some other station it is a great advantage.

The amount of power which would be required by the steam railways after electrification is frequently vastly overestimated. I understand some investigation on this subject has been made by Mr. Ferguson of Chicago, which I hope will be communicated later.

I believe the conclusion was that if all the railways entering Chicago received their power from Mr. Ferguson's steam-turbine station, the railway load would by no means be the largest load on the system, but probably within the overload capacity of the station.

The question before us is: first, whether the adoption of the lower frequency is necessary; secondly, whether this lower frequency should be 15 cycles or any other frequency. At present we have two standard frequencies, 25 cycles and 60 cycles, but the spectres of sundry other abandoned frequencies still haunt the electrical engineer—125 cycles, 133 cycles, 50, 40 and 30 cycles. It appears to me, and probably to everybody who remembers and still sees the difficulties due to the existence of these odd frequencies, that it would be disastrous to introduce another frequency and then after a year or so find it was not necessary and have to abandon it. Therefore, we should be extremely careful to see whether a lower frequency is necessary. If it is necessary, which frequency should be chosen?

I do not believe 15 cycles is a suitable lower frequency. If we have to use a lower frequency it would be because the alternating-current railway motor is practically inoperative, at least in larger units, at 25 cycles. If that is the case, then 15 cycles probably is not yet the most suitable frequency; but the most suitable frequency is far lower than 15 cycles, and 15 cycles would perhaps be a compromise frequency. The experience of compromise frequencies and compromise designs has been disastrous, and would better not be repeated. If it seems wise to adopt lower frequencies, we should probably have to adopt not 15 but 12.5 or even 10 cycles.

In considering lower frequencies we must realize that, with the single exception of the series alternating-current motor, every part of the system, from the steam turbine generator to the incandescent lamp lighting the cars, the lower frequency is a handicap. This brings us to the need of a lower frequency. We must consider that every type of electrical apparatus has a frequency at which its design is most economical, most satisfactory, and most reliable. For small apparatus usually a somewhat higher frequency and for large apparatus a somewhat lower frequency is best suited. For instance, economically the most efficient frequency for the induction motor is 40 cycles; as a result, induction motors are built for 60 cycles or 25 cycles, both frequencies being sufficiently near the economical frequency for practical purposes. The 60-cycle frequency is mainly used with smaller motors, and 25 cycle with larger motors; and the maximum economy for smaller sizes shifts upward, and for larger sizes downward in frequency.

In the transformer we find the maximum economy is beyond the commercial frequencies. The 125-cycle transformer is better and more economical than the 60- or the 25-cycle transformer. Where the maximum economy lies we do not know; there must be some definite frequency, because we know that the alternating-current transformer is not well suited for 10,000 cycles; it is difficult to design; not economical; that is, 10,000 cycles is too high a frequency, but within the range of available frequencies, the higher the frequency the better for the transformer.

The maximum economy of the synchronous converter is at 25 cycles. A converter designed for a frequency higher than 25 cycles, or lower than 25 cycles, is, as a rule, inferior to the 25-cycle converter.

In the alternating-current series motor the maximum economy is at the lowest possible frequency; the lower the frequency the better the motor. The best series alternating-current motor would be the motor designed for zero frequency; that is continuous current. In that, I agree with Mr. Sprague. In any other apparatus, the larger the size the more urgent the need of lower frequency, and, while good results have been obtained with 25 cycles on moderately small motors in interurban service, for large units, as heavy locomotives, 25 cycles seem almost impracticable for the series alternating-current motor.

It is evident then that the frequency must be lowered so as to approach that of maximum economy, or the type of the motor must be changed. There is no reason to assume that the series motor is the final development of electric railroading. I have really never felt satisfied that the series commutator motor is the solution of the problem and have repeatedly said so. There are other kinds of motors in which the maximum economy is not at the minimum frequency, but is, as near as we can judge at the present time, not far from 25 cycles. If then we adopt the lower frequency, we might find that we have handicapped ourselves in designing alternating-current commutator motors of different types.

Mr. Ernst Alexanderson has succeeded in devising a type of motor in which it appears that the maximum economy of the alternating-current commutator motor is not at zero frequency but probably is in the neighborhood of 25 cycles, and for this motor that would be the best frequency. In this respect, I disagree with Mr. Armstrong in the data on the relative comparison of 25-cycle and 15-cycle motors. I believe that his statements rather represent a period which is past, but still influenced by the experience with the series motor. As far as our present experience goes, the two frequencies, 25 and 15 cycles, in railway-motor design at the present time seem to be equal in economy, and for all I know 25 cycles may be the better frequency. That necessarily means that 15 cycles has no right to exist.

The great and only difficulty with the alternating-current motor is the commutation; all other troubles are secondary, and merely results of the limitations imposed upon the design by the attempt to make the sparking at the commutator least destructive. During the operation of the motor electromotive forces are induced in the short circuited coil under the brush, which lead to more or less disastrous sparking and heating of the commutator, destruction of the brushes, energy losses by parasitic currents, etc. To reduce this effect we can either reduce the electromotive forces induced in the short-circuited coil, by reducing the frequency—and that is after all the gist of the desire to lower the frequency: to get lower electromotive forces induced in the short-circuited coil at commutation—or we can attempt to reduce the currents produced by these electromotive forces by inserting high resistance commutator leads. This is beneficial to some extent, although it introduces the great difficulty to protect these high resistance leads against self-destruction by excessive local heating. But the benefit is limited, because while we reduce the current the insertion of resistance raises the voltage. The solution of the difficulty is to modify the type of the motor so that no electromotive forces are induced in these short-circuited coils, and that is what Mr. Alexanderson has done and concerning which I believe he will give us a paper in a very short time.

Peter Junkersfeld: Considering passenger trains only, and assuming for the sake of argument that it would be physically possible to electrify all the steam railroads centering in the city for a distance of 25 miles from the respective passenger stations, within the next year, we have estimated that the total power demanded by these various railroads would probably not exceed 20 per cent. of all the power generated in Chicago by all the various companies. This figure of 20% would even then be true only for the next year. After that, the proportion of power demanded by the steam railroads would decrease, due to the fact that the amount of power required for all other purposes increases in a much faster ratio. The large amount of industrial power and the very large amount of interior lighting not yet supplied electrically and that still to be developed in Chicago would justify the opinion that at the end of five years the total steam railway demand would not exceed, possibly would be less than ten per cent. of the total electric power generated in the city. This applies to Chicago and to the railroads for a distance of 25 miles radiating outward from their passenger terminals, so that, as Dr. Steinmetz has said, the proportion of power which will be demanded by the electrification of the steam railroads is not nearly so much as we might imagine.

Gano S. Dunn: How would it work out if freight were included ?

Peter Junkersfeld: We made no calculations on that, and it is a hard thing to estimate.

The most optimistic speakers on this subject of railway electrification have said that they hardly expected to see all of the railways electrified within their lifetime; in other words, it is largely a problem of the next generation. We all agree that we should look out for the next generation, but in doing so we should not neglect the present. The electrification of steam railways at and near their terminals, however, is particularly important, in fact that problem is a live and pressing one now.

In the electrification of such terminals the question of direct current or alternating current has by no means yet been settled. There is still a great deal of controversy on this point, and the probabilities are, in my mind, that ultimately the direct current will perhaps be largely used in electrifying terminals. This does not apply to the electrification of long steam railroad lines, trunk lines, etc., but it does apply to the electrification of terminals, not only because of the present state of the railway motor art, but also because of agitation against overhead high tension wires and things of that sort particularly in large cities.

We seem in this country to be passing into an era in which public regulation will perhaps have quite a great deal more effect on electrical development than in the past, and we are confirmed in that impression if we observe the experiences in other countries. In many of these, the electrical development has not been so great as in this country, not because they are less ingenious, but because they have had certain handicaps. These handicaps may appear here, there is already some evidence that they will appear, and may work somewhat against the operation of terminals with high tension overhead trolleys, but may not work against future similar single-phase operation of the long railway lines.

Coming now to the question of power supply for terminals, and even admitting for the moment that possibly single-phase motors could be used for that purpose, we should be extremely careful before recommending an odd frequency, because on the crowded tracks of the terminals the question of reliability and continuity in moving the trains is of primary importance; of much greater importance than the moving of the trains between the large cities. In order to secure the best results it should not only be possible for the railway companies to buy power, when this can be done more economically, but at least to be in a position to readily interchange power with other power supplying companies. Otherwise, the railroad companies will have to make large investments in reserve power equipment to protect their business. The greatest factor in economical electric power generation is a diversified demand, which means a very large number of peaks, and as a result non-coincident peaks. One of the greatest factors in electrical development in a community is low cost of electric power. That can only be secured in the ultimate by having an arrangement so that the interchange of power can be made readily and quickly between the different power consuming systems whether owned or operated by one or by several companies.

The selection of the frequency for any given service should be based on the predominating demand. In a number of the larger cities in this country the predominating demand has been in favor of 25 cycles. That condition still exists to-day, and Dr. Steinmetz has told us that for synchronous converter work, which is 75 per cent. at least of the total demand in three or four of the larger cities, that 25 cycles is the best frequency. For that additional reason, we should be careful before recommending any odd frequency if we want to conserve the best interests of the various companies or clients we represent.

Henry G. Stott: I think that the question of supplying power for railroads has been looked at from a slightly different standpoint than it is by those who are accustomed to the conditions obtaining in most of the large companies that are developing their own power. I wonder which power plant in the United States could give an emergency supply equal to 25% of its rated capacity. Railroad plants and lighting plants have to be designed for a peak load. In a lighting plant the peak load will last not to exceed 400 hours per annum. That means an enormous investment for a short time. The railroad plants have practically a peak load of from 800 to 1000 hours per annum. How can we expect either our lighting plants or railroad plants to carry a reserve of 25% above their peaks for the purpose of guaranteeing a supply to anyone else, and if they do it, at what price can they do it?

The question seems to me to be one which will be solved by the location of a number of plants along our railroad lines. These plants will be able to give a much more reliable service, which, after all, will ultimately be the criterion applied by everyone to the question, rather than the cost. Imagine, for example, a transmission line from Niagara Falls to New York, and our railroads depending upon it, and subject to every thunder storm that comes up. I have no data at hand to show what the average interruptions of such power would be, but I know this—it would be greatly in excess of the interruptions which would obtain in a number of smaller plants distributed along the line. In other words, we can get better insurance by carrying our power in the shape of coal on freight cars than we can by carrying the power on high-tension wires. The insurance given by a number of distributed plants is going to be infinitely greater than we can obtain in any other way.

A. H. Armstrong: From the discussion it would appear that certain advantages in motor design can be taken advantage of at 15 cycles which are not possible with higher frequencies. The problem now becomes one of weighing possible advantages of motor construction against the handicap of using 15 cycles for the generating and distributing system, and seeing if these advantages are sufficiently great to warrant the introduction of an odd frequency with all its engineering and commercial complications. The history of alternating-current distribution has been a constant tendency toward the adoption of lower frequencies as the demands of new apparatus became pressing. Up till now the question of low frequency has been governed by the performance of converters. A frequency of 25 cycles has been sufficiently low to satisfy all the needs of the situation. With the advent of the alternating-current single-phase motor, we have a type of apparatus calling for low frequency, but the greater advantages of 15 cycles must be great indeed to warrant a departure from the standard 25 cycles now in universal use, especially as the single-phase motor is not in any sense inoperative at the higher frequency. It is not a question of the adoption of 15 cycles in order to make alternating-current motor installations possible, as the recent inventions of Mr. Alexanderson and others have given us a motor which is thoroughly commercial at 25 cycles.

I agree thoroughly with Mr. Junkersfeld that the electrification of steam railroads is not to be considered entirely from an alternating-current standpoint, and, instead of steam road terminals presenting a problem calling for a change in the frequency of supply in order better to accommodate the limitations of alternating-current motor design, I would suggest that this class of railroad electrification presents a problem of alternating versus direct current with a decided preference for direct current.

While recent improvements have made the alternating-current motor a thoroughly commercial piece of apparatus with a frequency supply of 25 cycles, due weight must be given to the further consideration that any continued development of this type of apparatus must show further improvements which will make 25 cycles still more desirable; in other words, having a successful 25-cycle alternating-current motor to-day, we can look to the future with the confident hope that any continued development will still further minimize any possible advantage which 15 cycles may enjoy over 25 cycles. At such a short period as two months ago, it appeared that a frequency of 15 cycles was necessary in order to make possible the construction of large alternating-current single-phase motors giving good commutation. The improvements made in two months, however, have made the adoption of 15 cycles less attractive, and it is fair to assume that we have not heard the last from alternating-current motor designers and that the future holds bright promise of still further developments. If we can get a motor just as good at 25 cycles, or even nearly as good, there is no reason to adopt low frequency. In fact, there is every reason to adhere to a frequency so universally in use as 25 cycles.

N. W. Storer: I have only a few words to say in conclusion. Mr. Steinmetz raised the point in regard to suitability of 15 cycles for railway work. He insists that the lower the frequency the better the motor will be. On this point, I cannot agree with him. There is much more to be considered in building a single-phase motor than simply to reduce the short-circuit current to a minimum and thus obtain good commutation. If the frequency is reduced much below 15 cycles, the pulsations of torque will cause considerable trouble. Everything considered, I regard 15 cycles as the best frequency for railway purposes. It is a simple matter to obtain very satisfactory commutation in a 15-cycle single-phase motor. Within the last few days we have been testing the locomotive of which I speak and I have seen the motor carry 100 per cent. overload in current for several minutes at a time when hauling a train with the brakes set, and there was practically no sparking at the commutator, the commutation being much better than almost any of the standard direct-current series motors could do under similar circumstances.

So far as commutation is concerned, we have not regarded that as the main reason for recommending a lower frequency than 25 cycles for railway work. Our desire has been simply to increase the capacity of the motors. If this Alexanderson motor which has been mentioned by so many speakers is able to give the same capacity at 25 cycles that the compensated series-wound motor gives at 15 cycles, I should say by all means stick to 25 cycles, unless there are some other defects in the motor of which we are not aware. No one wishes to add another to the standard frequencies any less than I do. We should cling to the standards as far as possible. I believe that, if in future development it is found that the installation of 15-cycle current for the electrification of a large system can be done more cheaply and operated more cheaply than the same work can be done with 25 cycles, the 15 cycles will certainly be used. As I have said before, it is solely a matter of dollars and cents.

Now, in regard to power distribution, I am much gratified to learn that the power required by the steam railroads entering Chicago is such an insignificant amount compared with that required for other purposes. For this very reason, there should be practically no interference in that case with the systems now in operation. The steam railroads certainly will require enough power when they electrify their terminals in and about Chicago, or any other large terminal, to build their own power houses and furnish their own power throughout. I do not believe it would be at all feasible for the company to draw, even to a very limited extent, from the lighting companies for power to operate their railways.

I agree with Mr. Stott that it is impossible for the various industrial plants to carry sufficient reserve capacity to take care of 25 per cent. or 20 per cent. of their normal load to provide for railway emergencies, particularly as the biggest railroad loads will come just as they do in street car service, at the hours of the day where the lighting load is heaviest and all the people want to travel at the same time. Steam railways must work out their own salvation. In electrifying their lines they must provide sufficient reserve capacity to take care of the entire system.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

COMMUTATING-POLE DIRECT-CURRENT RAILWAY MOTORS

BY E. H. ANDERSON

General. In order to appreciate the development and reasons for the existence of a commutating-pole railway motor, it is well to discuss in some degree some other developments. In the beginning, railway-motor designers had many difficulties to contend with.

1. The question of gearing was possibly foremost, whether it should be single or double reduction or possibly gearless. All these were tried with more or less success. The pendulum swung back and forth from this point, but it has settled partly and is still settling. The small motor (automobile) is now more usually double reduction; however, in some cases, single reduction is used where weight is not of importance. The usual railway motor has settled down to single reduction. In the larger railway motor, where the work approaches that of a locomotive, it is often questionable whether single reduction or gearless should be used. When powers are small, as in the case of single-car units, the motor is naturally provided with single-reduction gearing. Then again, for large locomotives and high speeds, obviously the motor should be of gearless construction, this being especially true in the light of what may be done with gearless bipolar motors of direct-current design.

2. Possibly, insulation is next in order, various methods having been tried. The conductors have been covered with a variety of materials, but double or triple cotton-covered insulation has practically become standard. The slot insulation has been through various changes; for wire-wound machines it has settled down to a good varnished cambric with a protecting tape

of cotton, although an all-asbestos insulation of armature coils is promising.

Where bars are used as armature conductors, it is possible to insulate them entirely with mica. This type of insulation has been fully developed and may be considered as standard.

The field insulation has long been in a state of evolution, but is pretty well standardized on a basis of mica in metallic shells for the larger ribbon-wound field-coils, and varnished cambric for the smaller fields wound with wire. Here also an all-asbestos insulation is promising.

3. The present method of lubricating the bearings with oil has resulted from a process of elimination; many forms of grease-cups, oil-cups, wicks, etc., having been tried; in fact, the preferred lubrication at one time was grease.

With the advent of interurban trolley roads came greater speeds, giving rise to many more car-miles per day, and complaints arose of short life of bearings, injury to armatures, etc. The methods of lubrication underwent many changes, but are now well established as wool-waste and oil; no doubt a good solution of a difficult and important problem.

4. During this period of development, the armature was changed from a smooth to a slotted core, and much thought was given to the size of commutator, number of segments, turns per coil, etc., in the effort to produce successful operation of the commutator.

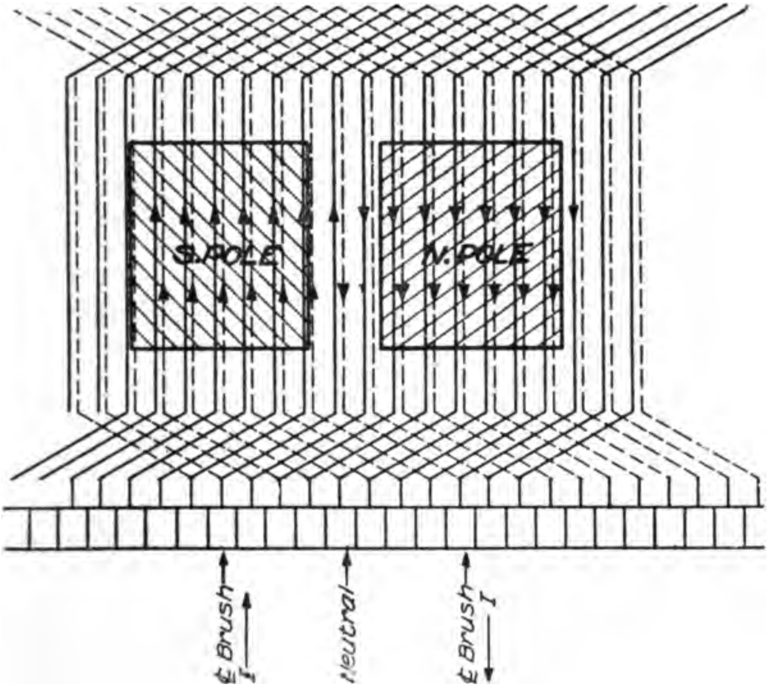
With all forms of copper brushes there was most destructive sparking and enormous local currents in coils short-circuited by the brush during commutation.

The carbon brush was tried and found to be the greatest improvement yet discovered in producing successful commutation. The greater contact resistance decreased the local currents to reasonable values, yet the energy lost by the greater contact resistance in the main circuit was small. The carbon brush thus opened up possibilities in design not before thought of.

The inductance of coils was reduced by placing two in one slot instead of one, thus saving insulation and reducing the diameter of the armature. Later came the three coils per slot armature, this being the standard for many motors to-day.

As motors had to be built to fill a restricted space, not only for large power and small diameters, but with good commutation at higher potentials, it gave rise to the four and five coils per slot armature. Many coils per slot necessarily increased the slot-width, and this in time called for a laminated-field pole structure in order to limit eddy-current losses. In the meantime the operator was demanding higher potentials, more work from the motors, and better commutation, and the commutation had not kept pace with other developments, in fact, was becoming more troublesome as compared with other difficulties, largely on account of higher operating potentials. Some means had thus to be adopted for radically improving commutation, and the following pages deal more particularly with this subject.

Fig. No. 1 D.C. Series Drum Armature
33 Slots 1 Coil per Slot

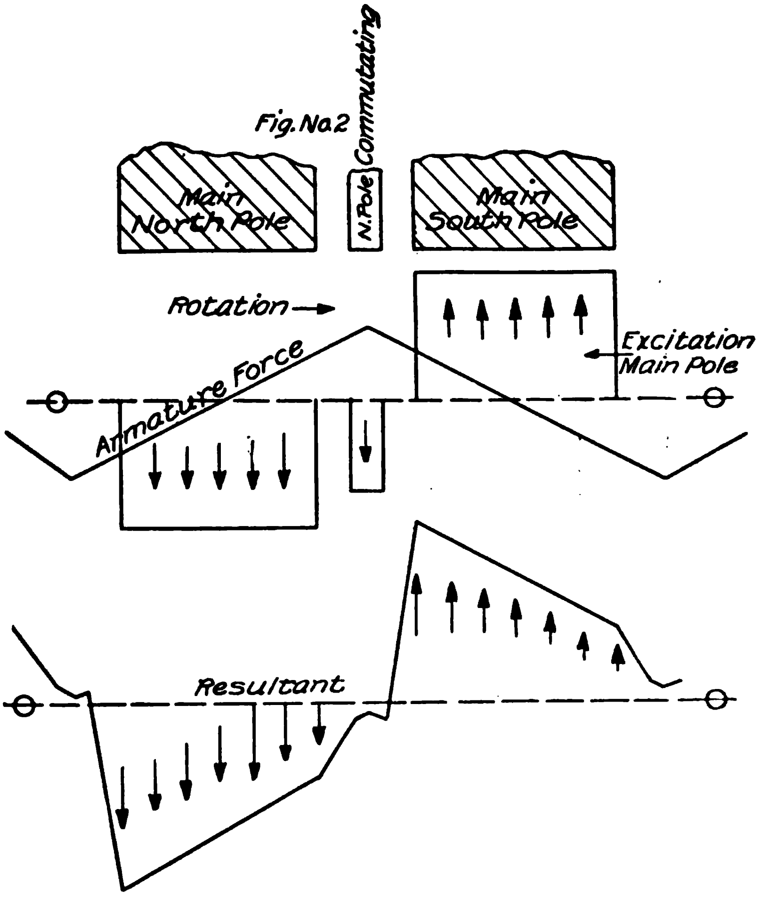


Armature forces. The armature in its simplest conception is a drum, divided into four sections for four poles; under a north pole is a broad distributed sheet of current running parallel to the shaft; under a south pole is also a broad distributed sheet of current, but in reverse direction.

This distributed armature current produces a magnetizing force which changes the distribution of the main flux in the pole-faces, as shown in Fig. 2. It will be seen that in the center of the pole there is no distributing effect, but in the center between poles there is the maximum magnetizing effect from the armature. This is where the conductors are commutated by the brush and the direction of the current reversed in passing from the zone of one pole to the zone of the next.

The magnetizing effect of the armature, being a maximum

Fig. No. 2



midway between poles, produces a flux through the air-space to the frame. The conductors in motion cut this flux, producing a voltage in the coil to be commutated.

The combined result of armature and field magnetizing effect is to cause a flux to leak from the pole-tip over into the armature just where the conductors are being commutated.

The two leakage fluxes are alike and add to produce voltage in the coil which is being commutated. Thus there is a potential between commutator-bars, and when these are short-circuited by the brush a local current is caused to flow in the coil under commutation. This local current adds to the line current already there. Any conductor carrying current has lines of force interlinked about itself caused by the current in the conductor. The conductors, imbedded in and surrounded on three sides by iron, have a good opportunity of surrounding themselves with a lot of leakage flux. The interlinkage of leakage flux is similar to the inertia in mechanics.

The combined current (line and local) has still greater interlinkage of leakage lines and becomes more difficult to reverse. The reversing has been done heretofore by the increasing resistance of contact between the brush and the commutator-bar as the latter is passing out under the brush, the rate of change of current ever increasing. This causes the reactance or kicking voltage to become higher and higher. As the bar leaves the brush, the change in current in the coil becomes so rapid that an appreciable voltage is induced and arcs through the air from the bar to the brush, or vice versa, thus producing what is commonly known as sparking.

The object is, then, to remove the sparking by counteracting one, or all, of its causes. Should we place midway between the main poles another coil, having the same magnetizing power as the armature, but so connected as to magnetize in the reverse direction to the armature, there would be nothing to cause a leakage flux from the armature to the frame. Then, again, should we further excite this coil so as to overcome and balance the combined effect of armature and field forces, commonly known as distortion and leakage of the main flux from the pole-tip, we would annul this troublesome cause of sparking. After the above two effects are taken care of, there remains a force necessary to produce a potential sufficient to reverse the current in the armature coil.

In order to produce this potential there must be such a density of flux as will generate this required voltage by the conductors cutting the flux in revolving. The width of such magnetic density should be sufficient to embrace the conductors commutated by the brush when running in either direction of rotation.

The commutating voltage produced by the flux of the commutating pole is the accelerating force required to change the direction of current in the armature coils one by one as they come under the brush. It must be sufficient to accomplish this in the time that the coil, being connected to two adjacent commutator-bars, is under the brush. When the commutator-bar leaves the brush, the current is already reversed, flowing in proper direction, and is of the proper amount, so there is no tendency to spark. Commutation may then be said to be perfect.

As stated before, an armature coil imbedded in iron is surrounded by a leakage flux, which is caused by the current in the coil, and may be said to have magnetic inertia or momentum. This is similar in mechanics to a revolving shaft bearing a mounted flywheel. The voltage induced in the coil by the flux from the commutating pole may be likened to a constant counter torque; this counter torque serving to slow down the revolutions, stop, and cause an increase in speed in the opposite direction.

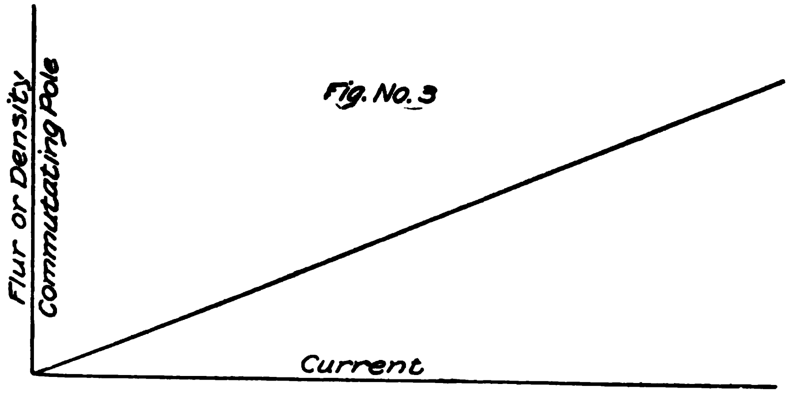
It is evident that there may be a particular armature current, speed of motor, and flux from commutating pole wherein the above described conditions will obtain. It will also be appreciated that the voltage induced by the commutating-pole flux will vary directly as the speed; furthermore, the time that the coil is under the brush is shorter as the speed is higher, and vice versa; also that the time required to reverse a current is inversely as the voltage. The conclusion is that the action is entirely automatic throughout the entire range of speed with the particular condition of current and commutating-pole density.

The next question is: can the action be automatic for varying current as well as speed? The commutating pole may be excited by the main current of the motor, being connected permanently in series with the armature. The commutating-pole flux will then vary almost directly as the current, which is the desired result. When the current is half, the commutating-pole flux is half, and the commutating voltage corresponding thereto. Thus the action is entirely automatic for variation in current or speed, or both.

Fig. 3 shows that the relation between commutating-pole density and current should be a straight line, rising and falling directly with the current.

It is well understood that an absolutely straight line between current and density cannot be obtained when a more or less saturated iron circuit carries the flux, but it can be approached sufficiently close for all practical purposes by careful design and experience in these matters. In a series motor the density of the whole iron circuit increases as the load comes on, and there is an increasing stability in commutation which serves to offset, partly, if not entirely, the lack of commutating-pole density on a heavy load. The combined effect is to produce perfect commutation at all loads.

Since the commutation is automatically taken care of for variations in speed and current, it is possible to change the voltage impressed on the motor through quite a range without sparking. This is thoroughly borne out by motors of 50 to 250 h.p., recently constructed in this country.



The only limitations in raising the voltage are:

1. Armature speed and strength of binding wire.
2. Volts between bars.
3. Insulation.

This brings us naturally to the question: what effect will this commutating pole have on designs for voltages higher than are now general for railway service?

Railway-motor commutators before being connected to the armature winding are tested from bar to bar with 400 to 500 volts, alternating current, which means a maximum of 40% more, so that actual jumping of current from bar to bar on a clean commutator would not occur at less than 500 volts per segment. An ordinary commutator of 111 segments and four poles would, under these conditions, be good for 13,000 volts between brushes. The actual jumping of current across side micas of a clean commutator is not the limiting condition.

The limiting condition is the voltage per bar which will maintain an arc already established. The allowable voltage per segment is largely dependent upon the condition of the commutator. The condition of the commutator depends upon the deteriorating tendencies, such as sparking and other causes, like poor carbon brushes, hard side micas, etc.

If the sparking is eliminated, the etching of the commutator-bars is largely reduced. The carbon brushes are required to carry only the line current, instead of the line and a large amount of local current; therefore the brushes are not disintegrated so rapidly. The carbon brush has less mica to wear off, because the bars are not burned away. The result is that the carbon brushes work better, and the commutator stays in a very much better condition. The conclusion from the above is that much higher average volts per segment may be used with commutating-pole motors than with motors not having commutating poles.

The usual non-commutating pole railway motor, 40 to 50 h.p., has a commutator about 9.5 in. in diameter, with 111 to 125 segments. The average potential between segments is approximately 18 volts. Large motors, operating on 650 volts normal, have 155 to 165 segments, and the average potential between segments is approximately 17 volts. If the average volts between segments on commutating-pole motors be assumed as 24, and the number of commutator bars per inch of circumference as 5, we have the following possible voltages on various sizes of motors and commutator diameters.

Horse power	Diameter of commutator	Maximum volts motor
40	9	850
75	11	1040
100	13	1230
150	14.5	1370
200	16	1510
250	18	1700

The above may be said to apply only as far as tendencies are concerned. Not all these various voltages would be practical. It would be better, for various reasons, to adopt 1200 volts as the higher standard.

The propositions requiring higher potential than 600 volts, are usually 30- to 50-ton cars with speeds of 40 to 60 miles per hr. These call for a motor of 75 h.p. or larger, so the sizes naturally fall where 1200 volts can be made with reasonable cost.

The commutating-pole motor, on 600 volts, makes possible commutation and general operation in service many times better than that of the non-commutating pole motor. On 1200 volts, the commutation is decidely better than with a non-commutating pole type motor on 600 volts.

The 1200-volt motor requires proportionally more insulation than the present 600-volt motor. This extra insulation requires more diameter and more external dimension.

Theoretical possibilities of voltage. We have the possibility of 1200 volts per motor, the motor having four poles. Should the motor be bipolar and the speeds high enough to make the design possible, we may have 2500 volts per motor. Then again, if there should be two windings on one core, a commutator on each, and these windings connected in series, we have the possibility of a 5000-volt motor. Then again, should we have a double-track railway and the rail neutral, we might have 10,000 volts direct current between the two trolley wires.

It will be appreciated that more voltage means more insulation, more space, and more cost. It will also be seen that the control, car lighting, and operation of auxiliary apparatus require special consideration.

Service capacity. The non-commutating pole motor has inherently a higher iron density, which serves as a compensating feature, improving commutation. The commutator-pole compensates for armature reaction and takes care of troubles due to lack of compensating features; a lower iron density may therefore be utilized and lower iron losses obtained.

The absence of sparking makes the commutating losses very much less. The rating on the hourly basis may not be much greater than with the non-commutating pole motor. On account of core-loss and commutator loss being considerably less, and these prominent features in heating, the commutating-pole motor has naturally a higher continuous rating; it is not only capable of taking large fluctuations of voltage and current, but will have a greater all-day service capacity. This latter feature becomes more pronounced as the distance between stops is greater.

There are several ways of making use of higher direct-current potentials. The most prominent of these are the following:

1\. *a.* City service, 600-volt trolley.
Maximum speed 25 to 30 miles per hr.
Stops and schedules incident to city service.

b. Interurban service, 1200-volt trolley.
Maximum speed 50 to 60 miles per hr.
Few stops and high schedules.

The motors would be wound and insulated for 1200 volts.

Two motors would be connected in multiple, and the two groups of a four-motor equipment handled in series and in parallel.

2\. *a.* City service, 600-volt trolley.
Maximum speed 25 to 30 miles per hr.
Stops and schedules incident to city service.

b. Suburban service, 600-volt trolley,
Maximum speed of 30 to 60 miles per hr.
Stops and schedules incident to suburban business.

c. Interurban service, 1200-volt trolley,
Maximum speed 50 to 60 miles per hr.
Few stops and high schedule speed.

The motors would be wound for 600 volts with a relatively low armature speed and insulated for 1200 volts.

On a 600-volt trolley two motors are connected in multiple. and the two groups handled in series and parallel.

On a 1200-volt trolley, two motors are connected in series, and the two groups of four-motor equipment handled in series and parallel.

The armature speed and commutating features should be so designed that if one wheel slips and one motor has 1200 volts or so across its terminal, its armature speed will be reasonable and the commutation good.

Interurban cars with four axles and four motors usually accelerate at 1 to 1.5 miles per hr. per sec.; this requires about 100 to 150 lb. per ton, which is 5 to 7.5% coefficient of traction. These are low coefficient values for interurban roads and are seldom met with; however, should slipping occur, the motor design should be such that no damage to equipment will result. In the city a dirty street may give a low condition of traction, but under these conditions, the motors may be used in multiple or operated as any four-motor equipment is now operated.

ADVANTAGES OF COMMUTATING-POLE RAILWAY MOTORS AS COMPARED WITH NON-COMMUTATING POLE TYPE

1. Sparkless commutation even on heavy overloads.
2. Flashing at commutator largely reduced and probably eliminated.
3. Less wear on commutator.
4. Cleaner and safer motor because of reduced carbon and copper dust from brushes and commutator.
5. Marked reduction in heating of commutator.
6. Greater current density in brushes.
7. Increased life of brushes.
8. Increased efficiency and free running capacity because of lower core and commutator losses.
9. Possibility of successfully using higher voltages.
10. Greater facility in design of large motors, especially as regards commutation.
11. Possibility of increasing service capacity of motors by blowing.

DISCUSSION ON "COMMUTATING-POLE DIRECT-CURRENT RAILWAY MOTORS", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

Gano Dunn: I see a tendency to hail the commutating-pole motor as the direct-current motor of the future. I heartily appreciate Mr. Anderson's paper, and the facts it brings out with which I am in substantial agreement; but I think it illustrates that we are liable to fads, and that the great success that has attended the introduction of the commutating pole so far has led some of us to attach to it too much importance. I regard the commutating-pole motor as applicable to certain classes of machines or conditions of design, such as low voltage, very large size, very high speed. These are found in direct-current turbo-generators, variable-speed motors, such as are known as field-weakening motors, railway motors where the space is crowded—in short, all machines where the commutating limit of capacity is reached before the heating limit. There still remain other classes of machines where none of these conditions applies. We have not yet exhausted our ingenuity in designing motors, so perhaps we may soon be able to equal in weight, cost, and efficiency, the commutating-pole motors, and without their complication.

It should be borne in mind that the commutating pole adds considerable complication. One of the principal advantages of direct-current motors in the past has been their simplicity, and simplicity is of first importance in electrical design.

It may be said that in a four-pole motor we need add only two commutating poles, and we may modify in one way or another the general type of the commutating-pole motor to make it more simple; but, when all has been said and done, we have a motor that has several more poles and considerable additional complication in its windings and connections.

J. C. Lincoln: Have these 1200-volt motors ever been used in practice?

E. H. Anderson: I do not know that there are any 1200-volt motors in this country in railway service. There are some contracts, however, which have been taken, and motors are building for 1200 volts. These motors have been tested on testing stands as high as 1800 volts for commutation.

W. N. Smith: Does the commutator require any more room, any more air-space around it, than with the older type of motor in order to prevent flashing-over to the frame in actual service.

E. H. Anderson: On the 600-volt motor there is usually about 1.25 in. flashing distance, and on some motors as low as 0.5 in. Dirt, copper, and carbon dust affect the flashing distance very materially. If we have a commutator which runs very much cleaner, does not have the copper and carbon dust, we do not need as much flashing distance. However, in order to improve in that direction, 1⅜ or 1½ in. creeping distances are allowed on 600-volt motors and 2 to 2½ in. on 1200 volts. The commutator does not need to be as long on 1200 volts as on 600 volts, because of less current to be carried.

A report presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y. June 27, 1907.

PROPOSED CODE OF ETHICS.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS COMMITTEE ON CODE OF ETHICS.

Ampere N. J., May 17, 1907.

To the President and Board of Directors of the American Institute of Electrical Engineers.

Gentlemen: Your committee, appointed at the annual convention at Milwaukee in June, 1906, to consider the advisability of preparing a code of engineering ethics, and, if thought best, to prepare such a code, has to report as follows:

While we do not consider it practicable at this time to formulate a code of ethics covering explicitly all the conditions which the electrical engineer may meet in his work, we do consider it both practicable and desirable to record some of the general principles of professional conduct that should be a guide for the electrical engineer, leaving it to him to make specific application to the cases which he may meet. We therefore submit and recommend the following, to be printed and distributed to the membership, with a view to its discussion and adoption at the approaching Annual Convention in June, 1907.

Respectfully submitted,
Charles P. Steinmetz,
Harold W. Buck,
Schuyler Skaats Wheeler,
Chairman.

PRINCIPLES OF PROFESSIONAL CONDUCT FOR THE GUIDANCE OF THE ELECTRICAL ENGINEER.

A. General Principles.

B. Relations of the electrical engineer to his employer, customer, or client.

C. Relations of the electrical engineer to the ownership of the records of his work.

D. Relations of the electrical engineer to the public.

E. Relations of the electrical engineer to the engineering fraternity.

F. Relations of the electrical engineer to the standards of his profession.

A. GENERAL PRINCIPLES.

1. In both his professional and his business relations the electrical engineer should follow strictly the same ethical principles that are recognized in the social relations of every-day life. He should consider himself personally responsible for the character of the enterprises and the persons with which he is associated professionally.

2. Before entering into professional relations, it is therefore the duty of the electrical engineer to satisfy himself that the enterprises with which he connects himself are of a legitimate character. If, after becoming associated he finds them to be of a questionable nature he should sever his connection as soon as possible. It should not be considered an excuse that his connection extends only to legitimate engineering work.

3. An electrical engineer permitting the use of his name in any enterprise or exploitation becomes morally responsible for the character of the latter. He should therefore not allow the use of his name in connection with anything upon which he is not qualified by training and experience to exercise competent judgment.

4. The electrical engineer should take care that credit for engineering work is attributed to those who, as far as his knowledge of the matter goes, are the real authors of such work.

5. The electrical engineer should incline toward and not away from standards of all kinds, since standardization is peculiarly essential to the general progress of the profession. This applies to construction, measurement and expression, or nomenclature as well as to conduct, or ethics. Even the tendency to give individuality by providing special construction may sometimes be avoided with advantage.

B. RELATIONS OF THE ELECTRICAL ENGINEER TO HIS EMPLOYER, CUSTOMER, OR CLIENT.

7. The electrical engineer should consider the protection of his client's interests as his first obligation, and therefore should avoid every act that would be contrary to this duty; if any other consideration such as professional obligations or restrictions interfere with his so acting, in accordance with the expectation of his client, he should inform him of the situation.

8. He can honorably accept compensation, financially or otherwise, from one side or party only, interested in the same matter. The electrical engineer, whether consulting, designing, or operating, may therefore not accept commissions, either directly or indirectly, from other parties dealing with his principals.

9. Electrical engineers in a position to decide on the use of inventions, apparatus, etc., should not be financially interested in their use, as by receiving a royalty, etc., unless the matter is clearly understood by the client.

10. Electrical engineers should not accept employment while financially interested in a rival concern except upon the express permission of both parties. An electrical engineer may be employed by more than one party, as in the case of a consulting engineer, when the interests of the parties do not conflict and it is understood, as is usual in such cases, that he is not expected to devote his entire time to the work of one party

but is free to enter into other engagements. A consulting engineer permanently retained by a party should notify other prospective employers of this affiliation before entering into relations with them. A consulting engineer when not exclusively retained by one side may advise rival concerns, with the full knowledge of all of them and upon taking care that the interests of the parties do not conflict in the particular matter handled.

11. Operating engineers should consider themselves responsible for defects in apparatus or dangerous conditions of operation, should bring the same to the attention of their employers and urge remedial action. If the causes of the danger are not removed they should withdraw.

12. An electrical engineer should in general be considered directly responsible to his employer or client for the successful fulfilment of the work upon which he has been engaged and for its satisfactory performance as a whole. It should therefore be clearly understood at the outset just what the extent or the limitations of responsibility of the engineer are to be. Whether he has been employed merely as designer or whether he is retained to design and to superintend construction; whether to design only the chief features or to pass as well upon all details of the apparatus that is to be installed. Attention should be directed to the fact that defects in the manufacture of material or apparatus is a matter distinct from the matters of design or installation. An engineer should not be held responsible for the unsatisfactory performance of a plant resulting from defective apparatus furnished, unless he has undertaken to include this subject.

C. RELATIONS OF THE ELECTRICAL ENGINEER TO THE OWNERSHIP OF THE RECORDS OF HIS WORK:

15. The following general principles should be recognized:

If in executing his work, the electrical engineer uses data or information which are not common and public property, but which he receives, directly or indirectly from his employer, or if the problem solved by the engineer is met in the pursuit of his work for his employer, and is not of such character that his attention would have been directed to it regardless of his relations to his employer, the products of his work, in the form of inventions, plans, designs, etc., are not his private property, but the property of his employer, though the engineer may be entitled to special remuneration for such inventions, etc.

16. If in the execution of the work the engineer uses only his own knowledge or data or information which are public property by prior publication, etc., and receives no engineering data from his employer or customer, except performance specifications, the results of the work, such as inventions, plans, designs, etc., are the private property of the engineer, and his employer or customer is entitled to their use only in the specified case.

17. All the work done by the engineer in the form of inventions, plans, designs, etc., which are outside of the field of engineering for which his employer has retained him, are the engineer's private property.

18. When an engineer or manufacturer builds apparatus from engineering designs supplied to him by his customer, the designs remain the property of the customer and should not be duplicated for other cus-

tomers without express permission. When the engineer or manufacturer and his customer are jointly to work out designs and plans or develop inventions, a clear understanding should be arrived at before the beginning of the work regarding the proportionate rights of ownership in any inventions, designs, etc., that may result, since in such case both parties should be considered to have rights therein.

19. Any engineering data or information which an electrical engineer obtains, directly or indirectly, from his employer or customer, or which he creates as a result of such information, must be considered by the engineer as confidential; and while the engineer is justified in using such data or experience in his own practice as going towards his education, the publication thereof without express permission is improper, as is also its use in producing for other parties, work that is characteristic of the original customer or employer.

20. Designs, data, records and notes made during his engagement by an engineer employed under permanent engagement, and referring to his work, are his employer's property. The same matter in the case of a consulting electrical engineer are the property of the consulting engineer.

21. A customer, in buying apparatus, does not acquire any right in its design beyond the use in the apparatus purchased. A customer of a consulting engineer does not acquire any right to the plans made by the consulting engineer except for the specific case for which the apparatus was built or the plans made.

D. RELATIONS OF THE ELECTRICAL ENGINEER TO THE GENERAL PUBLIC.

22. The electrical engineer should endeavor to assist the public to a fair and correct general understanding of engineering matters, spread the general knowledge of electrical engineering, and discourage wrong or exaggerated statements on engineering subjects published in the press or otherwise, especially if these statements are made for the purpose of, or may lead to inducing the public to participate in unworthy schemes.

23. Controversies on engineering questions, however, should never be carried on in the public press, but should be confined to the technical press and the engineering societies.

24. First publication of inventions or other engineering advances should not be made through the public press but rather through the technical press and the engineering societies.

25. The publications which an electrical engineer is justified in making through the public press should therefore be of a historical, educational, instructive or similar character and should not relate to controversies between engineers or on engineering questions, to new inventions, etc., nor contain technical criticisms of fellow engineers, and it should be considered unprofessional to give opinions without being fully informed on all the facts relating to the question, and on the purpose for which the opinion is asked, with a full statement of the conditions under which the opinion applies.

26. In giving expert testimony before judicial bodies, the electrical engineer should confine himself to brief and clear statements on engineering or historical facts. He should not give personal opinions without so expressly stating, and should avoid pleading on one side or the other.

E. RELATIONS OF THE ELECTRICAL ENGINEER TO THE ENGINEERING FRATERNITY.

30. The electrical engineer should take interest in and show due regard for the electrical engineering societies and the technical press.

31. He should assist his fellow engineers by exchange of general information, experience, instruction, etc.

32. He should not take a position left by another electrical engineer without satisfying himself that the former has left voluntarily, or for proper reasons.

33. Where engineering work is in charge of an electrical engineer, no other electrical engineer should undertake the work except on request of or in coöperation with the electrical engineer who had charge of the work before, unless the latter's connection with it has already terminated.

34. An electrical engineer in responsible charge of work should not permit other engineers or non-technical persons to over-rule his electrical engineering decisions. If this is done and persisted in, he should as soon as is practicable withdraw.

35. In engineering work in charge of a board of engineers, the respective limitations of the authority of each should be decided at the outset, and each electrical engineer should give full and complete information on his part to the other engineers and insist on this being reciprocated.

F. RELATIONS OF THE ELECTRICAL ENGINEER TO THE STANDARDS OF HIS PROFESSION.

40. The title " electrician " should be applied to those having practical training sufficient to enable them to carry on intelligently certain classes of electrical work, such as the installation of electric lights, signaling systems, and the operation of small electric plants.

41. The title " electrical engineer " should be applied only to graduates from the electrical engineering schools of universities of recognized standing, and such men as possess an equivalent knowledge of electrical engineering.

42. The title " consulting electrical engineer " should be applied only to those electrical engineers who possess such knowledge and experience in electrical engineering as would qualify them to full membership in the American Institute of Electrical Engineers.

Signed,
CHARLES P. STEINMETZ,
HAROLD W. BUCK,
SCHUYLER SKAATS WHEELER.
Chairman.

DISCUSSION ON "PROPOSED CODE OF ETHICS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

Schuyler S. Wheeler: The report I have to present represents the work during the last year of a special committee of three consisting of Charles P. Steinmetz, Harold W. Buck, and myself. The committee was appointed at the last annual convention to take up questions that were raised by the presidential address of last year on the subject of engineering honor. This address brought up the subject of ethics and the professional conduct of engineers. A committee was appointed to look into the matter and see if any kind of a code should be prepared.

I am happy to say that our committee has been most harmonious in all of its conclusions. We have not disagreed over a single feature in the entire report. Another matter that I want to mention is that we have no idea that the present report is right throughout. We look upon it as a mere starting point, and we think that it will be very useful to us all, because it will at least furnish us what engineers call a datum line; and taking this we can go on with it and make improvements, and constantly make our list of principles better as time goes on.

The report was presented to the Board of Directors and accepted and ordered to be printed and sent to all of the members of the Institute in order that they might examine it so as to pass upon it intelligently at this convention.

William McClellan: I think that all of us at times have found the need of some such code as this. Questions come to us of more or less importance concerning which we should like to know just how other men of our profession would think. I believe that if this proposed code is examined carefully, it will be found that we are not limited or constrained by minor details but are given broad principles which may be interpreted according to the facts of the particular case. No doubt some of us would write such a code differently in details and would, perhaps, desire to have certain changes. This, however, should not prevent it from receiving favorable consideration from every member of the Institute.

Henry G. Stott: I think that the committee has done very admirable work in bringing together for the first time a code of ethics for the American Institute of Electrical Engineers, but there are some individual rules with which I do not agree at all. Take, for example, No. 11, which reads as follows:

> 11. Operating engineers should consider themselves responsible for defects in apparatus or dangerous conditions of operation, should bring the same to the attention of their employers and urge remedial action. If the causes of the danger are not removed they should withdraw.

Now, that is purely academic. Is there in this room any operating engineer who would do a thing like that? I for one would not, because the conditions may be such that it is absolutely impossible for the employer with all the resources at his command to overcome these defects. The operating engineer would not be doing his duty if he should withdraw; his duty is to stand by the apparatus and his employer until such time as the defects can be remedied.

I also take exception to the following rule, No. 12, which states among other things that,

> 12. It should therefore be clearly understood at the outset just what the extent or the limitations of responsibility of the engineer are to be.

Personally, I would not have a man work for me who started out with such a conception of his duties. I would want a man who would agree to accept responsibilities beyond what I ask him to accept at first, and I think every employer would feel the same way. I would not want to have it understood that an engineer is responsible up to that particular bolt or this particular plate and not any further, and the next man who comes along is responsible for what follows. If there is something wrong, is it not our duty, as engineers, to report it ?

I think the rules are altogether too specific, and I would like to see them recast so as to make them broader.

Rule 20, states that designs, data, records, and notes obtained by an engineer employed on salary, are his employers' property; while the same matter in the case of a consulting electrical engineer paid by fee or by commission, are the property of the consulting engineer. I do not see the fine point in that distinction.

Then, again, Rule 26 as follows:

> 26. In giving expert testimony before judicial bodies, the electrical engineer should confine himself to brief and clear statements on engineering or historical facts. He should not give personal opinions without so expressly stating, and should avoid pleading on one side or the other.

The man who is on the stand giving expert testimony does not get a chance to express himself. It is entirely up to the lawyers as to what the man says. He usually says " Yes " or " No ", and he does not get a chance to express his opinion.

Rule 32 provides:

> 32. He should not take a position left by another electrical engineer without satisfying himself that the former has left it voluntarily, or for proper reasons.

That is a perfectly correct attitude, but it may be there would be such a condition as that a man has been ill, or has absented himself from duty for some reason or other, and he cannot be reached. Under these conditions should we say that the employer has not the right to ask some one else to take up his duties if the man has absented himself ? I think not.

H. W. Buck: Mr. Stott thinks that some of the rules are too specific. It was with the full knowledge of the committee that some of the rules were made very specific, and it was the belief of the committee that by only making them so radical and specific could general criticism be brought forth, by attracting attention to the various questions at issue. The committee realizes that many changes will have to be made, but I personally feel that if it is the sentiment of the meeting to have such a code at all, the best way is to recommend its adoption as offered by the committee. If it is allowed to lapse and further criticism is called for by correspondence or vote, I think it will simply result in the gradual disintegration of the proposed code through excessive criticism.

Charles F. Scott: I think that we should accept the report and have it published to the membership, with the strong endorsement it has in the names of the committee; that our Board of Directors should be asked by this meeting to continue a committee of this kind for consideration of suggestions which may be made to the committee and that the committee be asked to present a redraft of the report.

At the beginning of the next session, on Friday morning, June 28, 1907, **President Sheldon** said: The Chair will entertain a motion to the effect that the report of the Code of Ethics Committee be referred to the Board of Directors for their consideration.

[The motion was made by Henry G. Stott, seconded by **Lewis B. Stillwell**, and adopted by the convention.*]

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* For revised Proposed Code of Ethics as considered by the Board of Directors and submitted to the membership for suggestions, see Appendix, page 1789.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

THE ATTITUDE OF THE TECHNICAL SCHOOL TOWARD THE PROFESSION OF ELECTRICAL ENGINEERING.

BY HENRY H. NORRIS

Introductory. The technical school is primarily an educational institution. The purpose is not to teach trades of any order, nor is it directly to produce business or professional men. The technical school sustains a vital relation to the profession of electrical engineering, and it cannot succeed without an understanding of that relation. On the other hand, the profession cannot use technical graduates efficiently without a knowledge of the purpose underlying their training. That both school and profession are coming to understand their relation is made evident by many signs. Among these may be mentioned the development of graduate-apprentice courses by manufacturing and operating companies, the reduction of manual training and the increase of scientific training in the schools, the formation of employment committees by both companies and schools, and the cordial relations existing between practitioners and teachers. From the first the technical school has stood for the encouragement of useful studies with a scientific foundation. At first undoubtedly too much emphasis was laid upon the practical features of the curriculum, and the attempt was made to do in the laboratory what can only be done in the factory. This and other faults are being corrected by the study of industrial conditions, and the work of the school is being increasingly appreciated by the profession generally.

The purpose of the present paper is to examine the methods of instruction in technical schools in order to ascertain how the requirements are being met, and to note the progress made and the prospects for improvement. Instructors in engineering realize that they are engaged in a most important business, that of preparing men for practical usefulness. In any industrial undertaking men are more necessary than money or machines, therefore the technical school works upon the most important element in commercial success. In many ways such a school is like a manufacturing establishment. It secures its raw material from the preparatory schools in the form of boys with crude ideas of practical life, with little conception of the purpose of a technical education, and with a fair preparation in several lines of study. During four years it endeavors by means of separate and assembling processes to produce men who can " do things." Thus the finished product of the technical school forms a most important part of the raw material of manufacture, construction, operation, and commerce.

Resumé of 1903 *convention papers on education.* At the Niagara Falls Convention of the Institute held in 1903 a profitable session was devoted to the discussion of technical education. Messrs. White, Gherardi, Osborne, and Jackson presented papers dealing with various aspects of the subject. The consensus of opinion expressed in these papers is that the personality of the technical graduate is of more importance than any information which he may have acquired. Professor Jackson emphasized that the function of a technical school is to produce a capacity on the part of the students for becoming engineers. It is the duty of a college to learn how to do this, the inference being that the teaching of special subjects is a means rather than an end. Professor Jackson's synopsis of the ideal engineer states that he is one who is competent to conceive, organize, and direct extended industrial enterprises. Mr. White selected a number of elements of a young man's personality which are important in business, and he summarized the results of a successful education as: (*a*), the satisfaction which results from possession; (*b*), the ability to enjoy good society; (*c*), the practical use which may be made of the training; (*d*), the ability properly to know any subject; and (*e*), the higher rank which will be taken as a result of this training. The employer inquires as to the business judgment, the mental capacity, and other similar characteristics of an applicant for a position. Mr. Gherardi separated the natural ability of a student from his school training. He does not believe that the training of a telephone engineer should be especially different from that of other electrical engineers, the training of any engineer properly consisting of such studies as will convince him of the necessity of getting facts, teaching him the best method of doing so. Further, these studies should train in the interpretation of engineering data and in reasoning from them. Mr. Osborne dwelt particularly upon the function of shop work in a technical training and pointed out that the training, as then conducted, tended to emphasize the importance of business rather than manufacturing. He argued for a knowledge of accounting, contracts, and other matters of direct importance in engineering.

Magnetic analogy of technical training. The effect of a technical training on a student may be considered as analogous to that of a magnetomotive force upon a piece of steel The latter possesses the ability to be magnetized on account of the inherent magnetism of its molecules. Before being subjected to the influence of a directive magnetomotive force, these molecules are grouped in such a way that no external effect is produced. When brought into a magnetic field the molecular magnets tend to arrange themselves in the direction of the applied force. The steel then becomes a magnet ready for any one of a number of practical uses. The external magnetomotive force has put nothing into the steel, but has merely supplied the incentive necessary to render available its inherent qualities. In a similar manner the young men entering technical schools possess certain elements and qualities of personality. The young men differ even more than do various samples of steel. The studies and the personality of the teachers supply what is needed to bring out and develop the natural aptitude of the students, and they can do no more. The student gets little that is new from his college course, and if the attempt is made to impart more information to him than is necessary to stimulate him to his best endeavors, his training will be to that extent a failure. Excess training produces saturation in the mind as does excess magnetomotive force in magnetic material. Like most analogies this one cannot be pushed too far. It emphasizes the fact, however, that the efficient training will be the one which aims most carefully at the development of the students' intrinsic qualities.

Problems of technical instruction. The difficulties encountered in technical education are not met in the delivery of certain courses. They result from the attempt so to coördinate these courses as to develop accuracy, quickness of perception, common sense, and such qualities. Leading engineers who are employers of technical graduates place greater value upon the personal qualities of the young men than upon their mere ability to produce designs and superintend construction. They expect the schools to turn out men of character as well as attainments. To meet these demands successfully requires attention to the following items: (1), the attraction and retention of desirable students and the exclusion of those not qualified for technical work; (2), the selection of such studies as will stimulate and direct mental activity; (3), the conducting of all courses in such ways as will tend to bring out the desirable personal qualities in the students; and (4), the recommendation to the students of those lines of engineering practice for which they are best suited.

Not a little of the success of all schools depends upon the quality of men who enter and upon the requirement of severe and continuous application. The results of the training depend very largely upon the personality of the student before he enters the institution. They are affected also by influences not directly resulting from study; for example, athletics and social activities. The direct mental effect of the studies is, therefore, not the only result, and possibly not the most important result of the training.

TECHNICAL SCHOOLS.

Historical notes—general. Technical education in this country may be said to have begun with the founding of the United States Military Academy in 1802, although no technical courses, in the modern sense, were given there. After its reorganization in 1817, an excellent system of mathematical and scientific instruction was given, forming a basis for practical army work. The first technical school, Renssalær Polytechnic Institute, began instruction in 1825. A course in civil engineering was gradually established to meet the demand of that time. The object of this school was to teach the application of science to industry, especially to agriculture, domestic economy, the arts, and manufacture. It is evident that the desire of the founder was to elevate the practical arts by a study of the principles underlying them. In 1845 the United States Naval Academy was founded, and another institution was added to the short list of those in which scientific and mathematical instruction was given with a practical end in view. The far-reaching effect of this discipline was noticeable in the early development of electrical engineering by the number of Annapolis and West Point men who were attracted to it. This occurred when the technical courses in electrical engineering were in the formative period. The demand of the time was for soundly trained and practical men, and these soon learned enough of electrical applications to enable them to take leading positions. Among these may be mentioned F. J. Sprague, (Annapolis, 1878), Louis Duncan, (Annapolis, 1880), W. D. Weaver, (Annapolis, 1880), S. Dana Greene, (Annapolis, 1883), and O. T. Crosby, (West Point, 1882).

As the demand for scientific and practical instruction increased, schools were established in connection with universities and upon private foundations, but it was not until after the passage of the Morrill Act of 1862 that a great impetus was given to them. The object of this act was particularly to encourage scientific and technical instruction. The results have been far reaching. Previously established schools were strengthened and many new ones were established, each having for its object the training of young people in practical arts. These schools are accomplishing and have accomplished a great work because their instruction has a definite end in view, that of producing independent, useful, and intelligent citizens.

The practical development of the telephone, the generator, the motor, and the electric light between 1870 and 1880 created a demand for technical instruction in electricity. By this time there were at least twenty-five institutions giving practical and scientific work, some like the Worcester Polytechnic Institute giving especial prominence to shop work, others combining the practical and scientific. The best example of the latter class was the Massachusetts Institute of Technology. In 1871 the Stevens Institute of Technology was organized and at once took a leading place through the prominence given by it to experimental engineering. A third class of schools was more purely scientific, being affiliated with the older classical colleges such as Yale, Harvard, Dartmouth, and Union. All of these schools became interested in the applications of electricity and the beginnings of electrical engineering study were made about 1880. The technical instruction in electricity lagged only a few years behind the industrial beginnings.

Historical notes—Sibley College. Among the land-grant colleges one of the most radical and least trammelled by tradition was that of New York State. Founded in spite of the opposition of every college in the state except Columbia, Cornell University was always ready to undertake anything that appeared promising.

The mechanic arts formed an important part of the curriculum from the start in the fall of 1868. In 1870 the Honorable Hiram Sibley of Rochester, N. Y., provided means for erecting a suitable building for the department and for purchasing the necessary equipment. The first degree of bachelor of mechanical engineering was conferred in 1873. The work in mechanic arts was administered by the late Professor John L. Morris from the beginning until his retirement in 1904. When early in the seventies William A. Anthony, then professor of physics, began experimenting with the "dynamo", the arc-light, and other novelties he received encouragement from President Andrew D. White. Professor Anthony, assisted by Professor G. S. Moler, designed and built in 1875 a Gramme machine and instruments for experimenting with it. Still earlier he had a telegraph line about the campus; this was transformed into a telephone line as soon as the telephone appeared. An arc-light system with underground cable was also operated. All of these electrical applications impelled him to give instruction in physics with special reference to electricity. In the spring of 1883, while visiting the physical laboratory, President White was impressed with the interest in electrical matters manifested by the students. From his association with Ezra Cornell he was familiar with the development of the telegraph and he had also noted the work done with the electric motor in Germany. Among the experiences which he remembered with pleasure were the rides taken in 1879 upon the Siemens train at the Berlin Exposition of that year and upon the Lichterfelde road. He was also pleased with the Jablochkoff candle in Paris. While talking with Professor Anthony about the rapidly developing art, he suggested that there might be occasion for a new course of study, that of electrical engineering. Professor Anthony agreeing with this suggestion, immediately prepared a plan for a course and presented it to the trustees on March 22, 1883. The trustees referred the matter to the faculty and on March 26 authorized the announcement of a course in electrical engineering.* The announcement was made and several students were attracted by it. The register for the following year states:

> The rapid development of the application of electricity has created a demand for thoroughly trained engineers conversant with electrical

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* An electrical course had been begun during the previous year at the Massachusetts Institute, but President White had not heard of it, nor had he received any applications for electrical instruction.

science, especially by companies carrying on telegraphy, electrical lighting, electrical supply and transmission of power, electroplating or the manufacture of electrical machinery and apparatus. Recognizing this demand, at the beginning of the past academic year the trustees of Cornell University began to receive students desiring to fit themselves to enter this new and constantly extending field. While the general studies of the new course are mainly those of the departments of Civil Engineering and Mechanical Engineering, the special studies of the course embrace the theory of electricity, the construction and testing of telegraph lines, cables, and instruments, and of dynamo-machines, and the methods of electrical measurements, electrical lighting, and the electrical transmission of power.

The electrical course proved popular and developed rapidly. Upon the transfer of the late Robert H. Thurston from Stevens Institute to the directorship of Sibley College in 1885, the electrical course was transferred to Sibley College and became a division of the mechanical engineering course, as it is to-day. The change was based upon the necessity for a thorough foundation of mechanics in the study of electrical engineering. As the major part of the work was given in Sibley College it was natural that the students should come under the jurisdiction of that faculty. The test of time has amply demonstrated the wisdom of this arrangement.

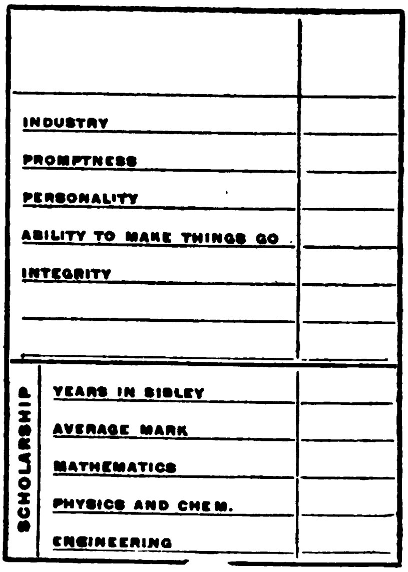
Present curriculum at Sibley College. The present curriculum of Sibley College is the result of a continuous attempt to give a practical education upon a scientific foundation. At first much attention was devoted to manual training, but this has given way to the principles of manufacturing. Experimental engineering has had an increasingly large place. The "backbone" of the course in mechanical engineering is mechanics, theoretical and applied. Analytical geometry and the calculus in the first year lead to the mechanics of engineering in the second. The physics and chemistry of the first and second years give a scientific basis for their practical applications. The descriptive geometry of the first year prepares the way for mechanical drawing. In the second year this takes the form of elementary machine design and kinematics, followed by the more advanced machine design in the third year. A limited amount of shop work is given in the first, second, and third years with accompanying lectures on shop administration and kindred topics. Engineering work begins in the third year with the principles and practical applications of steam and electrical machinery. Experimental work in the electrical and mechanical laboratories continues throughout the third and fourth years. During the first three years the instruction in mechanical and electrical engineering is identical, Considerable specialization is allowed during the fourth year, the student taking, as a division of general mechanical engineering, electrical, railway, marine or power engineering, machine design, or naval architecture.

Electrical engineering is taught as an application of mechanics, the only difference from other branches of mechanical engineering being in the source of the forces and the methods of transferring and transforming energy. The alternating current is studied from the start upon the ground that it gives a simple, general, and logical application of the laws of mechanics. The students appear to grasp the applications most readily in the following order: transmission lines, transformers, induction motors, alternators, synchronous motors, synchronous convertters, continuous-current generators and motors, and special machines and devices. In connection with each of these topics the auxiliaries are discussed in their logical places; for example, with transmission lines; switches, fuses, and lightning protection.

The electrical instruction is three-sided; experimental, analytical, and graphical. In the laboratory numerous experiments are conducted upon various types of machines, and data (facts) are collected. In the class room the performance of the same machines is predicted from the physical laws underlying their operation. In the computing room the theory and the facts are brought together in graphical form and are thus compared and verified. No designing of electrical machinery forms part of the required course, as this is largely empirical, depending upon the judgment and trained instinct of the practical engineer. Instead, the student is taught to predetermine the characteristics of machines from the dimensions and arrangement of their electric and magnetic circuits, each machine being reduced to an equivalent electric circuit. The computing room is a useful adjunct in this work. While it is not possible to have all of the laboratory reports prepared and problems solved under instruction, a beginning is made, the reports being completed at home. The work of the fourth year is not wholly electrical, but a course in power engineering is taken by all. The mechanical laboratory also tends to prevent undue concentration upon the one subject. A course in political economy also draws attention to important phases of business and social activities.

In addition to the required courses, a considerable part of the senior year is available for elective work in engineering subjects. The electrical elective studies comprise electric railways, telephone engineering, electrical machinery design, and power generation and distribution. These are given in the second half of the senior year, after the major part of the routine work is complete Thesis work may be taken as an elective when a suitable subject presents itself for investigation.

The course described is essentially that given in all technical schools, although details and arrangement differ with environment. Sibley College is fortunate in being connected with a large university which undoubtedly tends to interest the technical students in matters outside their specialties and thus broadens their horizons. On the other hand, the university acknowledges the stimulus received from the technical school through the energy displayed and the practical nature of the studies.



	INDUSTRY	
	PROMPTNESS	
	PERSONALITY	
	ABILITY TO MAKE THINGS GO	
	INTEGRITY	
SCHOLARSHIP	YEARS IN SIBLEY	
	AVERAGE MARK	
	MATHEMATICS	
	PHYSICS AND CHEM.	
	ENGINEERING	

Results of technical education. It requires no further argument to prove that in importance personality precedes scholarship in the makeup of the technical graduate. Some years ago Professor Harris J. Ryan devised the foregoing form to be filled in when an estimate of a student's characteristics was requested.

This form is still in use by the Employment Committee and it is of great service in making recommendations. The words "excellent," "good," "fair" and "poor" are used in grading the students for the purpose. Proceeding upon the assumption that the personality is of prime importance, the writer, for the purposes of this paper, requested a large number of Sibley alumni of from four to twenty years' standing to state whether or not the training affected honesty, thoroughness, initiative, perseverance, accuracy, conciseness, energy, self-confidence, address, alertness, and loyalty. Practically all testified that these items are affected and as a rule favorably. Further the alumni were asked to arrange these elements in order of importance. The combined result of the recommendations placed them in the following order: 1, honesty; 2, perseverance; 3, accuracy; 4, thoroughness; 5, energy; 6, initiative; 7, address; 8, loyalty; 9, self-confidence; 10, conciseness; and 11, alertness. It is unnecessary to discuss the ways in which these elements are affected by a technical training. Employers are justified in expecting them in the technical graduates and the schools must and do recognize their importance.

Incidentally, the alumni were asked to state which part of their courses, classical, scientific, or technical, was most beneficial. The majority think that the technical studies benefit them most but there is a recognition of the necessity for a scientific basis for the applications. In response to a query as to improvements needed in technical courses, the impression seems to be that the attention of the students should be directed to the purposes to which the principles are to be applied. A few advocate the introduction of cost-accounting, contracts and allied subjects, which are undoubtedly desirable when time permits. A fourth question asked was, "In what particulars have you found your technical training useful?" This elicited many interesting opinions. *Practically none referred to any technical information which had been received in college.* Instead the opinion was that the greatest gain was the habit of scientifically and practically attacking and solving problems as they arise. General adaptability and the faculty of securing information when needed along any line were also mentioned as important.

After all, the best test of a training of any kind is the use made of it. To determine what the Sibley alumni are doing a canvass of the entire number was recently made. From partial returns the following table has been compiled.

TABLE OF PRESENT OCCUPATIONS OF ALUMNI OF SIBLEY COLLEGE.

(Includes over 80% of the alumni up to 1904)

	Occupation.	Number.	Per cent.
1.	Mechanical engineer	298	23.20
2.	Electrical engineer	170	13.23
3.	Designer or draftsman	140	10.90
4.	President, vice-president, secretary, treasurer, or member of firm, manufacturing	127	9.88
5.	Teacher	114	8.88
6.	Sales engineer	107	8.33
7.	Consulting engineer	43	3.35
8.	Manager or superintendent, operating	41	3.19
9.	Non-engineering occupations*	39	3.03
10.	Manager or superintendent, manufacturing	32	2.48
11.	Foreman	31	2.41
12.	Manager or superintendent, constructing	25	1.94
13.	Insurance engineer	19	1.48
14.	Attorney	18	1.40
15.	Army or navy officer	17	1.32
16.	Editor or publisher	15	1.17
17.	Assayer, geologist, or mining engineer	15	1.17
18.	President, vice-president, secretary, treasurer, or partner, constructing	13	1.01
19.	Patent examiner	8	0.62
20.	President, vice-president, secretary, treasurer, or partner, operating	7	0.54
21.	Civil engineer	4	0.31
22.	Irrigating engineer	1	0.08
23.	City engineer	1	0.08
	Total	1285	100.00

Comments. The first three items may require some explanation. By the term " mechanical engineer " is meant those who are rated as such or who are doing general mechanical engineering work. Designers, draftsmen and those engaged in administrative work are classed separately. The same remark applies to electrical engineer. The word ' designer " covers those engineers, however prominent, who are primarily engaged in preparing or superintending the preparation of drawings and designs. It is interesting to note the large number engaged in actual engineering work. There is, however, a great tendency on the part of young engineers to enter sales departments.

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*The non-engineering occupations are as follows: Bankers 4, car agent 1, chemist 1, dairy farmer 1, dentist 1, druggist 1, flour miller 1, healer 2, hotel manager 1, jeweler 1, librarian 1, mechanics 4, merchants 7, paper hanger 1, photographer 1, physician 1, postal clerk 1, real-estate agents 3, secretary department of public charities 1, stock broker 1, sugar planter 1, time-keeper 1, tobacco dealer 1, tobacco planter 1.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

ON THE CONCENTRIC METHOD OF TEACHING ELECTRICAL ENGINEERING

BY V. KARAPETOFF

Introduction. The aims in teaching electrical engineering must be in accord with the demands of the electrical industry, and with the needs of the country, broadly understood. The details of electrotechnical pedagogics should properly be discussed among the teachers themselves, but the principles and the aims should be established through close coöperation with national technical bodies, such as the American Institute of Electrical Engineers.

The manufacturer of machinery learns from the user in how far his product has been successful; so the teachers of electrical engineering turn to the representatives of the electrical industry at large for advice and direction. The teacher of engineering wants to know what product is desired, and what faults are found in present technical graduates.

The concentric method of education outlined below is one which it is thought will supply the needs of industry better than the present method. *From theory to practice is the present motto*; *from practice to theory is the new principle proposed.*

SOME REMARKS ON THE PRESENT METHOD

The established educational custom is to begin the teaching of every technical subject with *theory*, gradually turning to *practice*, as based on theory. That this method is the only logical one has seemed to be almost self-evident, it being generally understood that practice cannot be taught without theory. But the question is, can theory be successfully taught without previous practice? Is teaching engineering merely the filling of a man's mind with detached facts, or does it mean developing his ability, to the end that he may think logically in his profession, getting correct results by correct processes? If the latter, the coöperation of the student must be secured at the very start and maintained throughout the course. The immature mind of eighteen years is entirely blank so far as the theory and practice of engineering are concerned. Can this coöperation be secured more easily by teaching him abstract auxiliary sciences, like mathematics, mechanics, and physics, as is now done, or by hurrying him into his profession at the very outset?

The writer's principal objection to the present method of teaching engineering is that student is burdened with abstract *auxiliary* sciences during the first two years of his college course, before he has had even a taste of his profession. The conscious coöperation of the student is not assured. Rather, he follows the prescribed courses blindly on the supposition that he is being properly cared for. It always reminds me of going to a dentist or to a barber, where we pay a specialist and passively submit to an unpleasant but inevitable operation.

It is perfectly evident to us that mathematics and mechanics, physics and chemistry, constitute necessary correlatives for engineering courses, just as history and economics are necessary for the study of the law. But this is not obvious to the beginner; he is all at sea in studying subjects without knowing their application. *All auxiliary subjects of study must follow the principal study and not precede it, as is the case with the present system.* I know this would mean to reverse entirely all the present plans of instruction, but what is right ought to be done at any cost.

No subject should be taught in which an interest can not be aroused. This means, do not begin with the elements, because they are not interesting; "*begin from the end.*" In teaching Latin do not give in the freshman year dry grammar and other dead stuff. Begin by reading the best examples of Roman literature in English translations. Then let the boys decide whether it is worth while for them to spend several years in studying the language in order to enjoy these same monuments of human genius in their original form. Is not a great mistake committed continually in making our young people study dead languages for years, only to find in the end that ninety-nine per cent.

of them cannot then read Latin and Greek authors well enough to enjoy them.

The same mistake is made in mechanic arts, by beginning the course with elementary operations, forging, filing, etc., which arouse very little interest. Let the freshman begin his work by making a simple but complete piece of apparatus, wherein all the essential operations enter in their simplest form; let him discover himself the necessity of all these operations, then begin to study them in detail. If a student cannot be interested in making a piece of machinery where he has to perform all shop operations, this student is not fitted for the engineering course, and should be advised to change his specialty. *But if he is interested, then his coöperation is assured* and it becomes an easy task to teach him the details of his profession.

A great problem before technical educators is the evil of early specialization. But teaching mathematics and physics is no remedy; a true broadening effect is exerted only by a study of actual life, of practical economic conditions. Explain to the freshman the significance that various branches of engineering possess for the welfare of the country; this will have a much more broadening effect than studying the equation of an ellipse or the properties of barium. This is exactly what the proposed concentric method has in view, as may be gathered by reference to the schedules in the appendix to this paper.

In colleges of applied science all courses of instruction should consist, in the freshman year, in explaining the practical side of the profession and the social standing and opportunities of men in them. The engineering colleges should demonstrate the operation and application of all kinds of machinery; the practical side of building bridges and constructing railroads, etc. The college of law should have popular lectures on the practical work of lawyers, judges, and other men engaged in preserving justice among men. The college of medicine should give practical demonstrations in different specialties of medical work, and so on. A freshman should be offered an opportunity to go to all these lectures and to see what specialty he likes best. Let him even lose (?) a year if he has not selected any profession; for this is much better than to study three years under the present system, and, after coming to his senior year, to the practical side of his profession, to find himself sadly mistaken in his expectations.

Let us begin from the end, then, let us exchange the freshman and the senior years; let us first give the student the fruits of knowledge; then, if he likes them, he will be interested to learn of their theories and foundations. Of course, freshmen cannot be taught engineering or law in the same way that these subjects are taught to juniors and seniors; but who would venture to say that these subjects could not be taught in a more popular and interesting manner than at present?

What the Concentric Method Is

The method of instruction for which the author stands may properly be called the " concentric method," and is represented

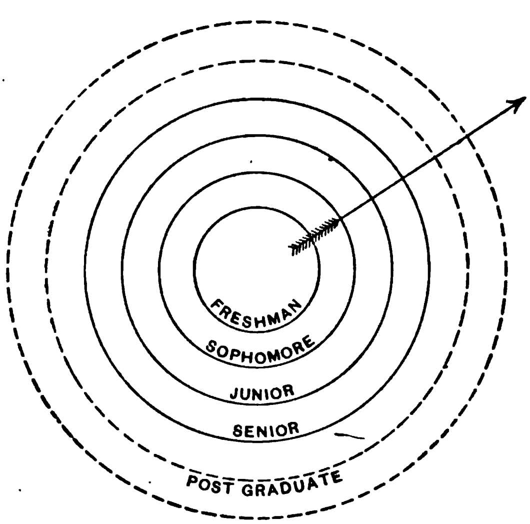

Fig. 1—Concentrically widening the student's mental horizon

graphically (Fig. 1) by a series of concentric circles; each zone comprises as far as possible the whole scope of a given specialty. The knowledge represented by different zones differs only in the degree of specialization.

During the freshman year (inner circle) the student is introduced to the whole scope of his profession, though in a very elementary, popular manner. The next year (second zone) he studies the same subjects from a somewhat more special point of view. The third zone represents the same subjects still more advanced, etc. For example, in applying this method to the study of history, the first zone would represent a broad sketch of the destinies of different nations; the next zone would be a more detailed treatment of the most important historical periods; the third zone might include a critical study of original sources and actual remains: and the fourth, the philosophy of history. Or, in studying the steam engine, the first circle corresponds to a purely descriptive sketch of the operation—handling and troubles—the second a more detailed study of the parts and an experimental investigation of the accompanying phenomena; the third year would comprise the theory of these phenomena from the standpoint of thermodynamics, mechanics, strength of materials, etc. The outer zone would represent design and special investigations. The dotted circles on the diagram represent advanced post-graduate work and symbolize infinity of knowledge.

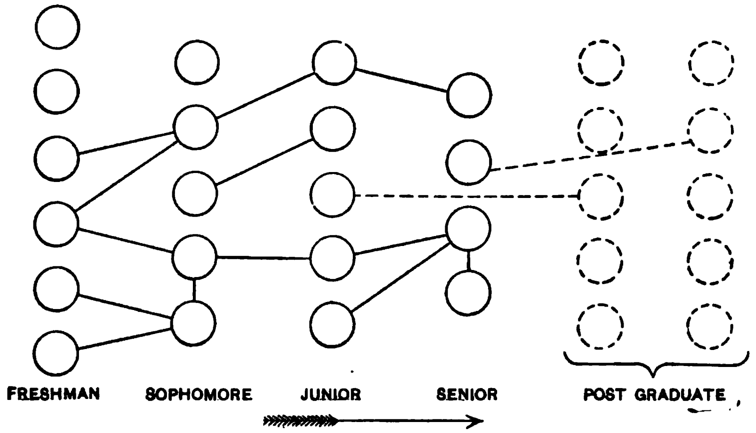

FIG. 2—Lack of system in the present way of instruction (subject method)

In contradistinction to this system, the method now in vogue, or the "subject method," is represented in Fig. 2. Here the student begins his freshman year by studying several subjects of an abstract character, subjects having no relation whatever to each other. They are in part auxiliaries for consecutive studies, in part are supposed to develop logical thinking and imagination. The subjects introduced the second year are based partly on the studies of the previous year, partly represent new departure; but again their relation to the principal subject of study is not sufficiently evident to the student, so that he blindly and reluctantly follows the program, instead of coöperating actively.

In the third year, the professional studies begin, based on the sciences absorbed during the first two years. But these studies are again of too academic a character, too abstract, since the whole underlying idea with the present system is that practical applications must follow the general theory. Thus only in his senior year does the student come to the practical side of his profession. This method is probably the easiest for the teachers, because they also were educated in this way; but unfortunately it contradicts the very nature of man, and stands in contradiction to the educational aims of our times. The method has a distinct stamp of old scholastic culture based on the authority of precedent, rather than on free progressive thinking.

Some of the courses of study in the scheme shown in Fig. 2 are indicated separately from any consecutive courses, or are connected only to advanced problems (dotted connecting lines), which hardly one student out of a hundred takes; and still all students are required to take these preparatory courses in the freshman or sophomore year.

It is particularly sad that the student does not realize the necessity for many of the studies during his college years, and the significance of some of them remains an enigma through his entire life. What a difference between the natural development of a farmer boy and the artificial cramming of a student with knowledge, The boy learns the surrounding world in a purely "concentric" manner; the student is taught according to the "subject method." The farmer boy begins at once with botany, zoology, law, mechanic arts, and enlarges his knowledge gradually as he feels the need for it; and he is more and more interested in the results of such knowledge or experience. The student begins with the most abstract knowledge, or fragmentary practice, which he cannot connect with his life. The farmer boy lives to-day; constantly he applies his knowledge or at least realizes its use; the student lives with the expectation that some day he will understand the use of the dry stuff he is forced to imbibe, or perhaps be allowed to forget it. How can any great success be expected under such circumstances?

We are beginning to understand that true preparation for an activity consists not in mechanical ability to perform simple operations, or in knowing abstract elements. The mind of the man must be made receptive by impressing him with the important or interesting side of his subject; this can be done only by showing him the result before he begins an extensive study.

It seems that with our present system we are preparing students, not for ordinary commercial work which ninety-nine per cent. of them take up, but for special research work, which hardly one per cent. ever follow. In doing so we are involuntarily tempted to make of the students what we ourselves to some extent are—men pursuing more or less original research rather than regular commercial work. *Let us remember that we are supposed to prepare, not future professors, but men for industrial work, and that our first aim should be to comply with the needs of the industry.*

Our democratic and industrial times call for infinite stages of knowledge and ability. A man who thoroughly assimilates, say, two concentric circles of study is of more use to himself and to the nation than a man filled with useless undigested knowledge, though in his pocket he have a diploma from our greatest university.

Courses of Study According to the Concentric Method.

We will suppose now that the reader agrees with the above contention, that the best method of education is that in which the student gets first a bird's-eye view of his profession, and then improves and specializes in it. This method is in accord with our nature, permits everybody to go just as far as he can or wishes; an element of interest is introduced into the study; a hastily selected vocation may be easily changed, etc. The question arises: is this method practicable? Can courses of study be arranged according to the above principles? As an answer the writer gives below an outline of a complete four- or five-year course of study of electrical engineering according to the concentric method. It seems to him that any other subject could be arranged just as well, since electrical engineering is no exception.

The present course in mechanical and electrical engineering may be called " from abstract to concrete"; that is to say, the course begins with mathematics, mechanics, and physics, then passes through an intermediate stage of machine elements, strength of materials, drawing, etc., and finally advances to the electrical and mechanical engineering proper. The courses in engineering proper are also arranged somewhat from abstract to concrete, so that general theory precedes the experimental and empirical side of study. The proposed courses, arranged according to the concentric method, follow the opposite way, "from concrete to abstract", the idea of each year being characterized as follows:

Freshman. Introduction into electrical engineering (bird's-eye view).

Sophomore. Experimental electrical engineering.

Junior. Elementary theory of electrical engineering.

Senior. Advanced theory of electrical engineering.

Freshman year. The fundamental course of this year should be "Electricity in modern life," or "Cyclopedia of electrical engineering." This course should comprise the following divisions:

1. A popular outline of applying electricity to lighting, railways, telephones, signaling, metallurgy, chemistry, medicine, etc.; popular experiments must make it perfectly plain and intelligible to everyone, so that students of all departments could easily and with interest follow the course. This is in accordance with the idea that during the freshman year the student is not supposed to have definitely selected his specialty.
2. Talks on the general character of engineering work, on opportunities and social standing of engineers, on necessary qualifications for different kinds of work, etc.
3. A historical sketch of the development of the electrical industry, and its present state in this country and abroad.
4. Explanation of the concentric method pursued during the four years, and an outline of the consequent work during this course. This is desirable in order to insure the conscious cooperation of the student in his future work.

A similar course should be given in mechanical and possibly in civil engineering; these three courses constituting the most important part of the freshman year. If the student feels that he cannot yet decide to become an engineer, or what kind of engineer he wants to become, let him spend the rest of his time in going to similar popular lectures in other departments of the university. But if he has already decided that he is going to become an electrical engineer, he may be given some work in the shops and the laboratory. This should be not the so-called *elementary* work, consisting of filing, or measuring specific heat and resistances, but *practical* work, consisting of assembling and dismantling of apparatus, handling machinery, electric wiring and connections, etc., so that he may feel that he is already started in his profession. This consciousness would give him pride and satisfaction, and arouse his interest for further studies. *This purely psychological element of technical education is almost entirely lost sight of with the present system.*

Freshmen should not have more than, say, 12 hours a week of engineering work, and should be induced to take a few courses of a general character in other departments, rather than allowed to specialize in one kind of work. Experience may show that there will be some demand for mathematics and physics on the part of the students themselves; should such be the case, the corresponding courses could be easily provided.

The writer wishes to emphasize the fact that he by no means belongs to that class of " practical men ' who sneer at any theory, and do not consider physics and mathematics as a part of engineering education. He himself is very fond of these sciences and preferably spends his hours of leisure in studying them. Yet he firmly believes that for engineering purposes physics and mathematics are of an auxiliary character and should be given the students only as such Moreover, these sciences should be taught so that the student may clearly see their importance and necessity in his profession. Later on, during his senior year, or after graduation, a student who feels an academic interest in these sciences may specialize in them; but *his first duty during the freshman and sophomore years is to study engineering, and not physics and mathematics.*

Sophomore year. Electrical engineering should be treated during this year purely experimentally, keeping in mind that while the underlying phenomena are unchangeable, all our theories and explanations are rather poor excuses for our absolute ignorance of the true nature of electricity and magnetism. Thus the electrical engineering courses during this year should comprise construction and operation of electric machinery, lamps, street-car equipments, telegraph and telephone apparatus, etc., going more into detail than was possible during the freshman year, where it was necessary to establish in the first place the very possibility and scope of applications of electricity.

Hand in hand with this course should go electrical laboratory work, not in the sense usually applied now, that is to say for the purpose of getting some numerical results, but simply for the purpose of handling all kinds of electrical apparatus. This should impress the student that the apparatus studied is something real and substantial and not mere fiction or schemes drawn on the blackboard. Lectures in mechanical engineering and mechanical laboratory should be of about the same character; it is not at all necessary or important for an electrical engineer to know much about thermodynamic calculations, but he must be sure that, if necessary, he can take care of boilers, steam, and gas engines, pumps, etc.

Shop-work must again consist in making pieces of simple apparatus comprising as many different operations as possible; no "single" operations should be allowed at this stage, because it would immediately lower the interest in the work. As a novel feature, some electrical work might be introduced, such as making blade-switches, simple measuring instruments, and spark-coils. In building such apparatus the student will meet with most of the shop operations and will get the necessary preparation for taking up regular shop theory and practice during the next year.

The study of mathematics, physics, and mechanics can be profitably begun during the sophomore year, provided they be taught *by an engineer and from the standpoint of engineering applications*, rather than abstract theory. Moreover, in order to link this course with engineering and with the mathematical knowledge required at the entrance examinations, this course should begin with applications of elementary mathematics to engineering problems, the students being tactfully brought to seemingly elementary problems, where analytics and the calculus become necessary. In this way the mind of the student is brought to an understanding of the practical importance of considering infinitesimal parts of time, length, volume, etc.; and thus partly by intuition, partly by application, he is introduced to analytics and the calculus.

Drawing, both freehand and mechanical, must be taught, not as an art by itself (unless the student desires it), but simply as a matter of necessity in shop work and in laboratory reports; the same holds true of descriptive geometry. The laboratory work, the shop practice, and possibly some class exercises should be so arranged that the students may *naturally* come to use drawings, both those given them and those made by themselves. Thus they will gradually recognize the necessity of plan, elevation, cross-section, perspective, schematic representation, and other technicalities. In the opinion of the writer, drawing should be taught in engineering colleges just as writing is taught in good primary schools. There the child is skillfully brought to an understanding of the advantages of putting down its needs on paper, and of reading the ideas of other people.

Junior year. Now comes the third year. With the present system the student begins dimly to realize at this time the very first principles of his specialty. With the system here proposed the student begins his third year with a more or less definite idea of the whole scope of his specialty; he knows that he is going to study the details of the work of the previous years and that he was lacking last year such auxiliary sciences as mathematics, physics, and chemistry. Now he is prepared to appreciate their significance; even more, he is already absolutely sure of their necessity, and is willing to accept the teacher's word even though he does not see its immediate application. Thus the work of the junior year should include a study of mathematics, physics, mechanics, chemistry (auxiliary sciences) with particular reference to electrical and mechanical engineering; at the same time a deeper insight into the specialty is made possible, assisted by these sciences.

The study of engineering may now be taken up with numerical relations. It is not necessary to go at once into higher mathematics, but merely to establish such relations as may be deduced from experiments, and which may immediately be applied to the solution of practical problems. With the training of the two previous years, the educator need not fear to go into details, since the student is already able to understand the significance and the place of a particular problem in the general field of electrical engineering.

To expect a student to investigate numerically this or that property of an electric machine the first time he sees the machine in the laboratory, as is the case under the present system, does not seem very rational. The purely qualitative and constructive side is of much more importance than any precise measurements. But if he has already had electric machines before him for two years, as with the proposed concentric method, he certainly can be made interested in numerical relations during the third year; and these measurements will be of a much better quality because he already knows how to handle machinery, apparatus, and measuring instruments.

Shop-work at this stage should consist in a systematic study of different operations: machining, forging, making castings, wood-work, etc. The work of the two previous years has shown the student *the necessity* of all these operations, and the relative positions they occupy in the processes of manufacturing. Now he will find interest in going into the details of each operation. Of course, it should be understood that the final purpose is to know how to direct and specify shop-work, rather than merely to acquire manual skill. This work should be supplemented by lectures on the subject, which would unify the methods taught in the shops, extend them beyond the possibilities of college shops, and also treat of cost of production and of methods of accounting.

Senior year. With the present system a senior hears for the first time the most elementary things in practical engineering; at the same time he knows (or is supposed to know) all about many theoretical laws and abstract relations studied during his junior and sophomore years. With the proposed concentric system he would already know a good deal about construction and operation of machinery from his three previous college years, but would lack the theoretical knowledge necessary for independent original work and design. The senior year is supposed to give him this, on the basis of the practical knowledge acquired during the previous years. Let us begin from the end.

The senior year should be devoted mostly to the theory of electrical and magnetic phenomena on the firm basis of previously established experimental relations. The educator may now boldly go into the very depths of mathematical analyses, for a senior understands their significance, whereas our present freshmen and sophomores merely get a chronic mental indigestion from the sight of mathematical formulas—an indigestion that often lasts a lifetime. It is a truism that the average technical graduate instinctively dodges differential coefficients and the symbol of integration.

In addition to pure theory, special elective courses should be given, such as electrical design, electric railways, telephony, etc. Such electives are given with the present system, but they are more of an elementary character, because the student is introduced into his profession too late.

For those theoretically inclined, an opportunity should be offered for studying mathematics, physics, and chemistry beyond the scope necessary for ordinary engineering practice.

The Concentric and the Present Methods Diagrammatically Compared

The following two diagrams show the difference between the present schedules of instruction and the schedules arranged according to the concentric method. Lighter portions signify the practical side of the subjects, the darker portions refer to the theoretical side.

With the concentric method (Fig. 3) the student begins with the practical side of electrical engineering and with an elementary description of other branches of engineering activity. A considerable portion of time is allotted to general subjects, but practically no time to auxiliary sciences, such as mathematics, mechanics, and physics. As the course progresses, more and more time is devoted to electrical engineering, and less time to other branches of engineering and general culture. The studies themselves gradually become more rigid and theoretical. This naturally requires more and more time to be devoted to the auxiliary sciences. The small light portion in the senior year refers to practical elective studies (specialization).

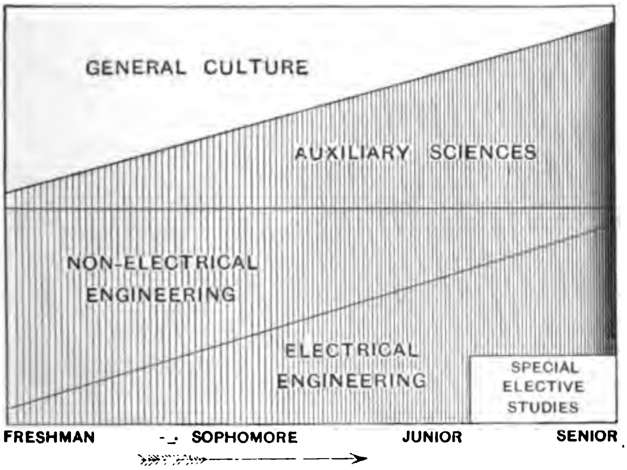

Fig. 3—Arrangement of subjects of study with the concentric method (from practice to theory)

In contradistinction to this scheme, the method now generally adopted is represented in Fig. 4. Here the first two years are practically filled with dry auxiliary studies, and the student does not get even a glimpse of his future profession until his junior year. And when he gets to his profession, the studies have again a theoretical character and only gradually become more and more practical.

A comparison of the two diagrams will clearly indicate the points of difference, and they do not require any further explanation. Those particularly interested in the subject will find these principles incorporated in the schedules printed below.

CONCLUSION

1. The study of engineering should begin in the freshman year and be carried throughout four years.

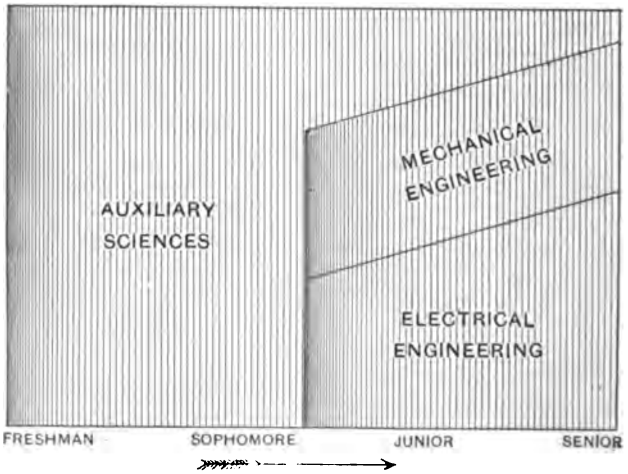

FIG. 4—Arrangement of subjects of study with the present method (from theory to practice)

2. Engineering instruction should be taken up with first giving a bird's-eye view of actual practice, and not with theory.

3. Auxiliary sciences, such as mathematics, mechanics, physics, and chemistry, should not be required further than is necessary for the understanding of engineering, and should be given later in the course.

4. Each year of study should be as much as possible self-contained, the mental horizon of the student being gradually and *concentrically* widened (Fig. 1).

APPENDIX

Proposed schedules of study according to the Concentric Method. The numbers signify the number of hours per week for first and second term.

Freshman year

(Suitable for all engineering students)

	Hours	
Cyclopedia of electrical engineering		2
" " mechanical "	2	
" " civil "	2	
" " mining "		2
Handling machinery	2	2
Making simple apparatus	2	2
Physical culture—one hour every day		
Electives.		
Law, medicine, history, economics, philosophy, languages, painting, music, etc	6	6
Recitations in at least three subjects	3	3
Total hours	17	17

Sophomore year

(For mechanical engineers and electrical engineers)

	Hours	
Descriptive course in electrical engineering		3
" " steam "	3	
Principles of manufacturing		3
Mechanical laboratory	2	2
Electrical laboratory	2	2
Shop	2	2
Mathematics of engineering	3	3
Drawing in connection with laboratory and shop	2	2
Electives (non-engineering)	3	
Physical culture—one hour every day.		
Total hours	17	17

Junior year

(Electrical engineers only)

	Hours	
Electric lighting	2	
Generators and motors		2
Electrical transmission		2
Electrical measurements	2	
Electrical shop-work		2
Electrical laboratory	2	2
Power engineering		4
Machine design	4	
Mechanical laboratory	2	

Mathematics	4	
Mechanics		3
Physics		3
Chemistry	2	
Total hours	18	18

Senior year

(Electrical engineers only)

	Hours	
Electric and magnetic circuits	3	
Alternating currents		3
Theory of electrical machinery	2	2
Laboratory	3	3
Electrical calculations	2	2
Theoretical electives:		
Mathematics Physics Mechanics Chemistry — two subjects to be taken		8
Practical electives:		
Electric railways Telephony Design Power plants Hydraulics, etc. — three subjects to be taken	8	
Total hours	18	18

DISCUSSION ON "THE ATTITUDE OF THE TECHNICAL SCHOOL TOWARD THE PROFESSION OF ELECTRICAL ENGINEERING" AND "ON THE CONCENTRIC METHOD OF TEACHING ELECTRICAL ENGINEERING", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

V. Karapetoff gave an abstract of his paper and said in conclusion: I appear with this paper before the Institute, because of my conviction that the Institute is competent, as a body, to dictate to the technical schools the requirements which their graduates ought to possess. I hope to see the day when the management of the Institute will appoint a committee on technical education. We now have thirteen committees—not a very lucky number—I wish this number could be increased to fourteen and the committee I have suggested be appointed.*

F. B. Crocker: Professor Norris says:

> Electrical engineering is taught as an application of mechanics, the only difference from other branches of mechanical engineering being in the source of the forces and the methods of transferring and transforming energy.

I object to that expression, because it is not true. Mechanical engineering is a fine profession, no one has greater respect for it than myself, but electrical engineering won its independence some years ago, and I think it is a little late to speak of electrical engineering as being a branch of mechanical engineering. Another reason why I object to it is that it leads to unpleasant feelings. Taking another step backward, we find that the civil engineer considers that every engineer who is not a military engineer is a civil engineer. I presume that Professor Norris used that expression in a general way, meaning that we are dealing with mechanical problems; but in the Engineers' Building in New York the mining engineers, mechanical engineers, and electrical engineers are certainly on terms of equality, and I cannot see any reason for subordinating one to the other. It has usually been the custom in the education of electrical engineers in this country to consider electrical engineering as part of mechanical engineering or physics. Nearly all courses of electrical engineering were grafted on, or formed parts of a course in mechanical engineering, or a course in physics. Columbia University, with which I am connected, started a course of electrical engineering in 1889 which was not part of mechanical engineering or of physics. It was as distinct as any other course in the university. We took that stand 18 years ago and have had no occasion to recede from it. I think there is a strong tendency for others to take the same position.

Professor Norris, in his history of the development of electrical engineering education in this country, overlooked the fact that we have courses which are specifically electrical engineering and not appendages to mechanical engineering or physics.

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* Such an Educational Committee has since been appointed.

In Professor Karapetoff's paper, what he advocates is not only very radical, but opposed to the whole history of education, which from the very beginning has dealt first with the simple and later with the complex. When I say " simple ", I do not mean necessarily the most easily understood, but the idea involving the fewest things to think of at one time; that is, principles should precede practice. I think this is natural in education. It certainly is the historical method. Furthermore, we have experience bearing upon that point. Take an institution like the Troy Polytechnic, which for many years taught theory almost exclusively with very little laboratory or other practical work, that institution has been successful and has turned out a number of eminent engineers. While it may have modified its course somewhat recently, this experience shows that it is possible to turn out successful engineers on this plan. Perhaps that is going a little too far, but it shows it is possible to do that. On the other hand, the trade-school, which deals with practical matters almost entirely, is very well in its way, but it does not produce the highest intellectual results.

Furthermore, we must have some sort of a *pons asinorum* for weeding out the incompetent men. I think that we should not make it too easy, or too pleasant, to get into the electrical engineering profession. At West Point, for example, the cadets are made to do exactly what they don't want to do. That is what a man should be taught to do. This leading a man by the hand to pleasant places does not meet my approval; in professional education a student cannot learn electrical engineering by sitting in the park and looking at beautiful scenery. That is too easy. A student must be capable of abstraction; he must be capable of self sarcifice; he must do the very thing he does not like to do, and do it well. I consider West Point the best technical school in the world, and in itself a very strong argument in favor of technical education.

I do not agree with the contention that subjects like chemistry, physics, mathematics, and mechanics, should be taught by engineers, especially electrical engineers. I do not object to a teacher having an engineering interest, a man with a high opinion of engineering, but if he is an electrical engineer and teaches chemistry, mechanics, or physics, he will teach those portions which he *thinks* are important. He may be right at the time, but perhaps five years from then the whole situation changes. I believe in teaching chemistry, physics, mechanics, and mathematics for themselves, and not picking and choosing; if properly taught these subjects, the student will be well equipped and can talk on equal terms with other men who have been taught these general subjects.

Gano Dunn: I wish to express satisfaction with the policy of the Institute, developed in recent years, of devoting so much attention to the subject of engineering education. It has been said that the civilization of a nation may be measured by the height of the plane upon which it places its women; it is equally true that the proficiency and accomplishment of a profession is in direct proportion to the attention it gives and the respect it has for its educational influence; to the importance it attaches to its universities and colleges. It was a refreshing address that President Hadley of Yale delivered at the dedication of the Engineers' Building in New York. He said if there was any thing that made the nineteenth century different from all the centuries that had preceded it, it was the accomplishment of the engineer—never before in the history of the world had human beings had so much control over the materials and forces of nature, and the result of that control was transforming all human activities. He went so far as to imply that before long the most successful merchant would be the merchant-engineer; the most successful mayor of a town the mayor-engineer; the most successful statesman, if you will, the statesman-engineer. There is something in the method of an engineer's mind that is direct, that goes straight to the truth, and, although we have been discussing a code of ethics to-day which implies that engineers are not honest, I believe that they are naturally honest because their contact with nature has led them to expect the truth and, when they do not find it, to put the blame on their own methods of investigation. They proceed further with confidence that what they are dealing with is absolute truth, and that if they persist the truth will be revealed. The influence of the engineer is extending to all other callings, and the engineer in the future will exert an influence that he has never dreamed of exerting in the past. Consequently, if we are to grasp the glorious future which has been outlined for us, many of us believe we cannot give too much attention to the methods by which we educate our engineers.

Professor Karapetoff's paper interested me extremely because of his concentric method of instruction. I have little cause for complaining of the methods under which I was instructed, but I feel with Professor Crocker that the plan Professor Karapetoff outlines is too radical. I think, however, that our existing methods could be profitably modified to include many of his ideas. For instance, it would have helped me enormously while I was a student if I had had some person in the capacity of a kind friend at college to give me the relations which the studies I was pursuing bore to other studies and to the activities of the world. Instructors are supposed to do that, but, because each man is devoted to his specialty, very often he does not do it. I really think we could profitably establish in our universities a course on the correlation of the student studies, to which might be given a very small portion of time, but that portion of time would be highly efficient. A student could then know it would be worth while for him to study calculus, for the good it would do him. He could have a promise given, on the strength of which he would work hard.

I believe in America we are ahead of Great Britain in technical education. Conversation with the manager of a correspondence school over there revealed that many of his students were obliged to keep secret the fact that they were studying technical subjects. Many of the industrial managers, I have been told, have not had theoretical educations, and they prefer to employ men who have grown up in the ranks of their business, rather than men who have received a technical training. I even know of one Oxford man who wanted to go to Cambridge to take a technical course, and the superintendent preferred he should go straight from Oxford into the factory, feeling that he would do better than if he took a technical training. I can hardly believe it, but it is true.

I should like to expose my ignorance of the law by giving it a dig in passing. I believe that engineers have set the pace for progressive training, and, as a result the engineering mind, as President Hadley described it, has a great future. We come into contact a great deal with the law in the direction of patents, and in many other directions. It seems to me that progress in medicine, in the arts generally, in all commercial industries, in engineering, and in science has been very great, but that progress has not been as great in the law. The law to-day is more complicated and less satisfactory than it was many years ago, and, while it is perhaps idle to discuss the question here, I feel if the engineer uses his influence, whenever he has a chance, to urge the simplifying of legal processes, and expresses his disapproval to lawyers of the complicated processes which they now pursue, and which many of them advocate, some good may be done.

As between a broad general training in a technical school and a specific training which, of course, must be limited to a few subjects, I prefer the former, and this supports Professor Karapetoff's ideas. A man is better equipped for life if he knows the scope of his field, even though he does not know many specialties in it, than if he is made an extreme specialist in a particular portion of the field which he may not have occasion to use. Not only is he better equipped, because he can realize on his time spent at college, but because his general training has broadened him as a man in a way that the special training would not do. I hope every convention will have some educational papers, and that we will all take pleasure and pride in supporting our universities in every way we can.

William Esty: A number of the subjects brought out at this session seem to me to warrant the adding of some papers on technical education to our convention programs. I agree with Professor Karapetoff that in dealing with young men, say at the college age of eighteen, there is necessity for giving them something concrete to take hold of on which to build up the theory. I think that is the natural order of development in the child; and with college students some attention must be paid to the natural order of their development. Professor Crocker, in discussing this matter, spoke of beginning with principles because they were simpler than the concrete cases. It seems to me that his idea contradicts the view of Herbert Spencer, who speaks of principles as being a conglomeration of concrete things and of a principle or law being essentially more complex therefore than any one of the concrete facts on which it is based. It seems to me that that is a valid definition of a principle—an aggregation of concrete facts which have finally been formulated into principles from experience. Principles then are more difficult to teach to a freshman than isolated concrete facts: so I think we should have something of the concrete to give him also.

I am going to outline briefly how at Lehigh University we try to accomplish the object of giving the students an idea of some of the concrete facts on which engineering is based, and at the same time give them some theory also. At the end of the freshman year the mechanical and electrical engineers take what we call our " summer school in constructive elements of mechanical and electrical apparatus ". The summer school lasts only four weeks, and the students are at work for three hours in the morning and three hours in the afternoon. In that rather brief time we attempt to acquaint them with the elements of mechanical and electrical engineering. For instance, in the electrical end of it, in which I am especially interested, we have them dissect circuit-breakers, rheostats of different types, disassemble motors and generators, lightning-arresters and transformers, and sketch the circuits. We do not attempt at first to teach them the complete theory on which all this apparatus is based, but rapid progress results by having them acquainted with the actual things. We find this plan very advantageous. We have tried it now for six years, and if there is anything in the old adage that, "the proof of the pudding is in the eating ", we can show that this pudding has proved good with us. We find, as a matter of fact, that the mechanical and electrical engineers who have taken this supplemental course in concrete facts, with a little theory mixed in on the side, are much better able to grasp the theory of the dynamo and of the transformer later on in their course than are, for example, the civil engineers who do not have this summer school work. We find it saves time in the long run. Our object is to concentrate in that four weeks an experience with the things themselves that these young men might take a year or more to acquire without it. I am not sure whether we are unique in this respect among colleges and universities, but if there are any others that have had similar experience I should like to hear from them.

In summing up this controversy of theory versus practice, it strikes me that it is after all another phase of the old question as to whether we should have classical education or technical education and as to which does the most for the young man. We have heard this thing wrangled over now for twenty or thirty years, and the end is not in sight. I think both sides of the controversy can certainly come to a common ground if we conclude that what after all is the object of education is the training of a young man to think for himself, and that implies, of course, a knowledge of how to solve problems when they arise. We cannot possibly teach all problems to a young man in college, but we must ground him in fundamental principles, giving him theory even at the expense of practice, so that when he leaves college he will have training which will enable him to solve almost any problem. That, I think, is the aim of technical education.

G. W. Patterson: As a member of the committee of the University of Michigan on reorganizing our course, I have taken part in a great many consultations as to what a technical school course should include. I must admit that the trend of the work by our committee has been entirely away from what Professor Karapetoff has given us to understand is his notion of the proper thing. We feel that a man who goes to a technical school is a crude product, and that there are many things which he ought to study to make him an educated man before he takes up engineering as a specialty. Without modern languages, without drafting, without a thorough grounding in mathematics, physics and chemistry we feel no man is competent to understand the elements of any kind of engineering, to say nothing of electrical engineering. I am of the opinion that there are some germs of truth in what Professor Karapetoff has told us, but if we examine his paper closer we find that if we adopted his ideas we would in my opinion make a sort of plaything of engineering. Instead of a real training, which should be given to men who are to occupy these important positions, the actual training would fall far short. The engineer should be an educated man; he cannot be educated in a specialty that ignores the elements which go to make a broad education. With us the trend is rather toward a six-year course than to cut off the things which we find necessary to teach in the first year or two under the present plan. In the University of Michigan we have six-year combined courses in which a man registers in the department of literature, science, and the arts, and also in a professional department. At the end of four years he receives the degree of bachelor of arts, and at the end of two years more either that of doctor of medicine, or bachelor of laws. In the engineering department the trend is toward the same thing; that is, a longer course in which we do not cut out the modern languages, or reduce the amount of physics and chemistry in the period of training, but put them in earlier and put in other things. There should be no opportunity for a man to learn engineering without a proper foundation. Omitting the foundation, is like trying to build a mansard roof first and put on the foundation the last thing.

If Professor Karapetoff's paper be taken seriously, it would, I think, tend to destructive rather than to constructive teaching.

Lester W. Gill: I am interested in this subject, because I have been endeavoring for the past few years to develop a course in electrical engineering in one of the Canadian universities. I am in sympathy with a number of the opinions expressed, but I do not think that it is practicable to introduce the radical changes suggested by Professor Karapetoff. Referring to his proposed schedule, it is noted that mathematics is omitted entirely from the work of the first year, and very little is set down for the second year. My experience has been, not only in my own case but in the case of students in my classes, that if mathematics is dropped even for one year before the student is acquainted with its practical applications, he loses his grasp and consequently his interest in the subject. To most students mathematics is a dry subject unless it is presented in an interesting way; but even admitting that many find it uninteresting, it involves a certain amount of discipline which is quite necessary.

I quite agree with President Sheldon that the greatest difficulty lies in the presentation of the subject, and in my own work I have endeavored to make the elementary subjects practical as well as theoretical. This results in a compromise between the standard college schedule and that proposed by Professor Karapetoff. In this way the elementary subjects—mathematics, physics, and chemistry—can be made as interesting as the purely engineering subjects. As a student I found mathematics the most interesting subject of the whole course, because the teacher knew how to make it interesting. To make these subjects interesting the student should be given examples of the practical applications of the subject as he proceeds, and these examples should deal with things with which he is familiar. This arouses his interest in the theoretical side of the subject and he at once realizes its value. As an illustration, take the case of a student in physics trying to master Ohm's law. If this is presented to him merely as an abstract natural law, he will not find it very interesting, and will consequently get only a superficial conception of it; but give him an illustration of its application; ask him to calculate the voltage at the end of a given trolley line, given the distribution of current, and it will be found that after solving this problem he will look upon this law from an entirely different standpoint.

The above illustrates what I mean by making the elementary subjects of a practical nature. My own opinion is that the weakness in our engineering schools lies in the method of teaching rather than in the arrangement of the schedules. The aim of the teacher should be to develop the student's ability to reason for himself, to think logically rather than to memorize rules. When a student can take the initiative and reason things out for himself, the technical school has done all it can to make him efficient from a technical standpoint.

L. D. Nordstrum: Referring to Professor Karapetoff's paper —this proposed method is in a sense radical, but I cannot help but agree with him in part. I do not think that the students should have mathematics and physics and kindred sciences taught by engineers. It is well if we can have mathematicians introduce as far as possible the engineering subjects, so as to make them interesting to the student, but for the teaching of these subjects thoroughly we must have a professor of mathematics and a professor of physics, etc., who are, so to speak, specialists in that line. The time is here when the trend is towards specialization, and no man can hope to have the strength of a thorough mathematician, a thorough physicist, a thorough engineer, etc., all in one. The student must get these from individual instructors who devote their entire time to their particular subject.

I believe that we can not expect to turn out a finished engineer from our universities. I think all that we can hope to do is to take our student as he enters the college and direct and train his mind properly in the fundamental principles, giving him a good foundation upon which to build. I think it is too much to expect a student in a four years' course to gain all that is gained and can only be gained in the practical pursuits of his profession. It is my opinion that a man has never finished his education; his entire life is that of a student. His university years are merely the starting or foundation years.

V. Karapetoff: In reply to Professor Crocker's remarks, I would say that, of course, the instruction should proceed from simple to complex; the point at issue is what to consider as simple and what as complex. This to my understanding varies with time. Twenty years ago it would not have been simple to begin the freshman year with instruction in street-car propulsion and incandescent lamps; but now this is much simpler for the student than an instruction regarding the properties of magnetic poles. We now see street cars and electric lights much more than magnetic poles. Professor Crocker mentioned trade-schools, and I understand him to favor the opposite, or the theoretical courses. I am not in favor of the trade-school idea, or of a theoretical-school idea. I am in favor of the *psychological* idea. Our president and some other speakers compared the student with raw material; there is however a great difference between raw material in a manufacturing sense, and a man. A man is a thinking being, and if you try to make a machine out of him, he kicks at first, and then withers intellectually. The analogy to a machine should not therefore be carried too far.

Mr. Dunn said that my method is very radical. Perhaps it seems radical for electrical engineers, but it is not considered radical at all among our best educators. It is an already acknowledged fact among our primary and secondary schools. I simply transplanted the psychological ideas that are in use in the primary and secondary schools in this country, schools of which we have good reasons to be proud. With me it is primarily the question of assuring a coöperation of the student. If you do not agree with teaching electrical engineering in the freshman year, there still remains this point—that the cooperation of the student is not secured with the present method of instruction. Hence, you must change your method so as to secure his coöperation. He is a thinking being, he is supposed to enjoy his life while in school, and not simply live in expectation of the things which may come after he has left the school. Professor Crocker thinks that unpleasant things must be connected with the education of young men. I agree with him, and wish to assure him, that even with the concentric method there will be enough left to make the life of a student more or or less unpleasant. Professor Crocker objects to mechanics, physics, mathematics, and chemistry being taught by engineers from the engineering standpoint. Surely they should not be, at the *advanced* stage, but at the elementary stage, in order to connect them with the engineering profession. In the courses of studies which I give in my paper, I propose that mathematics and mechanics should be taught in the second year by an engineer.

Expository ability and the raising of salaries of professors have been said to be more needed at present than a change in methods of instruction. I do not quite see how the concentric method could prevent a raising of salaries, or affect the necessity for expository ability on the part of the teachers.

Professor Patterson thinks that I am opposed to general culture. On the contrary, if you will kindly look into my courses of instruction you will find a considerable amount of time devoted to general culture in the first two years. I do this not only for the sake of general culture in itself, but also in order to give the student an opportunity to select intelligently his profession, before he goes into the details of it. This is more important than the general culture, as now understood. It is time to stop calling a study of mathematics and mechanics or even languages in their dry, abstract form, as "general" culture.

In presenting this paper I had in mind two purposes: to criticize the present system of instruction, and to give a new, improved method. Even if the concentric method is no good, there still remains for you to answer the criticisms against the present system, and to develop a better system.

Charles F. Scott: There are some dozen points which I had in mind to bring up, but I will forego doing so at the present time. I will refer to one point, however, the statement made a little while ago that the method proposed by Professor Karapetoff would be opposed to the whole history of education. Is not that one of the best recommendations it has? Has not the history of education for the last fifty years been one of advance? Not long ago new sciences were proposed instead of old languages. Then science was degraded by being applied to engineering. Then engineering ceased to be theoretical, and laboratories and machine shops found their way into colleges. Educational ideals and methods have been changing. We have not reached perfection. Engineering methods must be applied to the teaching of engineering, and that means development. Possibly, therefore, one of the best recommendations of this proposed system is that it is radical and is opposed to old ideas. If it is not quite the right thing it is getting closer to it and it merits careful consideration.

I wrote down two words on this slip of paper a moment before Professor Karapetoff mentioned the same words "educational committee." Accepting the suggestion of Professor Karapetoff as a motive, I am very pleased to second that motion; namely, that the Board of Directors of the Institute be requested to consider the advisability of the appointment of an educational committee.

V. Karapetoff: I shall be very glad to make such a motion. (The motion was put and carried.)

J. J. Carty: A few years ago I would have been quite ready to submit a number of criticisms on our technical schools. But the more information I get upon the subject and the more attention I pay to it, the more difficult it seems to be and the less ready am I to criticize. During the past twenty years I have received into my office a very large number of graduates from the principle technical schools in America, and from this experience I am able to make two generalizations. They are these:

1. That the best men do not all come from one school. The personal equation is so overwhelming that so far as my experience goes, the efficiency of the school from which the men graduate cannot be determined by the relative efficiency of the men themselves after graduation.

2. As a rule, the men are well trained technically but are very often defective in respect to that broad and liberal training which should underlie the technical education of every professional man. This defect is a serious one and very difficult to overcome. I have almost come to the conclusion that it is hopeless to attempt to give in the technical school the necessary broad and liberal foundation studies, and at the same time keep up the arduous work required of the student in connection with the strictly engineering studies. I am coming to the state of mind where it seems to me that the introduction of these so-called broadening studies into the curriculum of the technical school might fairly be likened to the introduction of such studies into a medical school.

As the general scheme of education in this country stands at present, I think that the electrical engineer, for the foundation of his liberal education, must depend solely upon the scientific studies themselves, or pursue his broad studies either before or after his technical course. Helpful as the scientific course is in the development of the student when forming part of a liberal education, it alone is not sufficient if the engineer is to take his place in the world, as he should, with cultivated men of affairs, whether they be physicians, lawyers, or men of business. The engineer should be so equipped that he may attain those ideals so well set forth by President Hadley in his recent address at the dedication of the Engineers' Building, in which he says:

> We have outgrown the day when a little common sense was sufficient for managing the affairs of the nation. They are become too complex, and this complexity gives the engineer—if he will add to his training in mathematics a training in ethics and political economy and the fundamental principles of the law—an opportunity such as never before existed to claim and receive the position which rightfully belongs to him.

Further on in his address, President Hadley says:

> We celebrate to-day and we are justified in celebrating the recognition of science as a necessary guide in the conduct of the material affairs of each man's business. Half a century hence, when our descendants shall meet in this building, or some yet greater building, I am confident that they will celebrate a yet greater thing—the recognition of the right of men of science to take the lead in enlightening the thought of the people on public affairs and the responsibility of filling the higher positions in the service of the commonwealth

President Hadley says elsewhere in his address that the course of our technical schools tends to have a narrowing effect upon the student, instead of a broadening one. This is in my judgment often the case. The narrowing effect of this technical training, it seems to me, is a negative one, not due to the technical course *per se*, but due to the fact that technical training is given, to the exclusion of liberal studies. I am hopeful that ultimately our entire scheme of school, college and university training will be modified so as to permit the student to graduate from his professional school at a sufficiently early age, and at the same time have received the necessary liberal education. At present I do not see how this can be done.

How to provide this broad and liberal education and at the same time not encroach upon the legitimate work of the professional school is what I consider to be the problem of engineering education to-day. Until this is settled, I have very little heart in any discussion, such as that pertaining to the relative number of hours which the engineering student should spend in the laboratory, at shop work, or at lectures. Once the engineering student has a proper educational foundation to build upon, his professional studies can no longer be said to be narrowing, for these studies would, in the light of a proper philosophy, take on a new meaning. They would become an absorbing, intellectual pursuit rather than a hard and disagreeable task. They would become to a high degree broadening.

With this large question out of the way, I am satisfied that the problem of the make-up of the curriculum of the engineering school could be satisfactorily solved. If these views which I have expressed should prove to be correct, we would still have before us the most difficult question as to what broadening studies should be specified, and that perhaps equally difficult question as to where and when these studies should be pursued.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

REGENERATION OF POWER WITH SINGLE-PHASE ELECTRIC RAILWAY MOTORS.

BY WILLIAM COOPER

The conditions necessary in order that an electric motor may operate successfully in regenerating or restoring power to the supply circuit are:

1. The counter pressure generated by the motor must be greater than the impressed pressure of the supply circuit.
2. The value of this excess counter pressure must be under control and maintained in suitable relation to the impressed pressure.
3. There must be at the time other power-consuming devices connected to the supply circuit.

There is no difficulty in producing the first condition the second is the one that is difficult to fulfil. There are two methods of regulating the counter to the impressed pressure; one is to increase the counter pressure and the other to reduce the impressed. The third condition, except in isolated cases, will be taken care of by the operating load.

Practically all variable-speed railway motors are of the so-called series type, and as this type of motor is the only one having the proper characteristics for general railway work it alone will be considered. The operation of a series dynamo electric machine as a series generator on a constant-potential circuit is a problem which many have grappled with, but none has solved. The machine must be given a shunt characteristic of a greater or less degree in order to make such operation possible. A machine having the shunt characteristic predominant is unfit for use as a railway motor, and as this characteristic must be predominant to operate successfully as a generator it is at once evident that the motor must be changed in some manner before it can be used as a generator. But this is not the only condition which the motor must fulfil in order to operate successfully as a generator in restoring power to the supply circuit; the motor must operate satisfactorily while the armature current is varied through a wide range with a constant field. This is evident from a very casual observation of the conditions.

Assume that the car or locomotive being driven by the motor under consideration has attained a balanced or free running speed under the conditions. The motor is then developing only sufficient torque to overcome the train resistances. The motor, being a series machine, has the same current in the field and armature. Under these conditions a very slight increase in the field current would increase the counter electromotive force of the armature to a value greater than the impressed electromotive force of the supply circuit.

Now assume an ordinary series motor in which the armature current cannot be increased materially above the corresponding field strength without disturbing the commutating conditions; it follows that the motor acting as a generator can only give a retarding force approximately equal to the train resistances. This added to the train resistance would give a total retardation so small that it could not be called a braking effect. From this it is obvious that the armature current must exceed the field current at times in order to produce a retarding effect which can be utilized in bringing the train to rest, or in holding the train on a grade. This, then, is another condition which the ordinary series railway motor does not readily fulfil.

From the foregoing it would seem that a motor to operate successfully as a regenerator of power must have the following characteristics:

1. It must be capable of operating through a wide range of variation between field and armature current, and

2. It must be provided with some means of producing a shunt characteristic.

The first characteristic exists to the fullest extent in a motor having some means of compensating for armature reaction, as well as a means of maintaining a constant commutating condition. This characteristic also exists to a limited extent in a motor having either one of these functions.

The second characteristic is not so easily provided. In the direct-current motor it can be obtained by providing the motor with both a shunt and series winding, either of which has sufficient capacity to operate the machine either as a shunt-wound generator or as a series motor.

Another method of furnishing the shunt characteristic is to provide a means of separately exciting the motor field independent of the line or motor voltage. There are several ways of doing this. In the case of four-motor equipments, one method is to use one motor as a generator to excite the other three motors which will operate as generators, being connected to the supply circuit.

Storage-batteries may also be used to excite the fields, but this arrangement has its disadvantages in being complicated.

The great difficulty encountered in operating direct-current motors as regenerators of power is that the impressed pressure is a constant, and the means at hand for meeting it are very limited. As the ordinary series motor will not permit of any very great variation of armature current with a constant field, and as only a very limited number of combinations of the motors is possible, the range through which an equipment can be operated regeneratively is, under the most favorable conditions, very limited.

In the single-phase, alternating-current motor of the series type these necessary characteristics are inherent. Without entering into a description of this motor, the design of which is well known, it is sufficient to say that the machine is provided with a compensating winding to neutralize the armature reaction, and also has preventive leads between commutator and armature windings which assist in commutation. This construction yields the first characteristic; the second is easily obtained in connection with the transformer used in the voltage control of the motor.

The method of producing this result is to use one of the motors of the equipment as an exciter for the others. By providing the transformer with suitable voltage taps, the value of the field current of the exciter may be varied through a wide range, as well as the generated voltage of the restored power. In this respect the conditions are very much more favorable than in the case of the direct-current motor, in which the only variations that can possibly be made are in the series-parallel combinations of the motors that are being used as generators.

The exact arrangement of the motors and their connections are shown diagrammatically in Fig. 1.

Assume the car or locomotive upon which the motors are mounted to be in motion, the armatures turning at a corresponding speed. If the field of the first machine be connected to the transformer, an alternating electromotive force will be generated by its armature, the value of which will be directly proportional to the speed. If the field of the other motor be connected to the exciter armature, an alternating current will pass through it, and the second armature will in turn generate an alternating electromotive force the value of which varies about as the square of the speed—the excitation of the first machine remaining constant.

The electromotive force generated by the second armature will bear a very close phase-relation with the electromotive force of the transformer, for the reason that the current in the field circuit connected to the transformer lags approximately 90°, as does the current in the field-circuit of the second machine. This combination throws the generated electromotive force of the second machine approximately 180° back of the transformer electromotive force, or, by reversing the connections, in the same phase-relation.

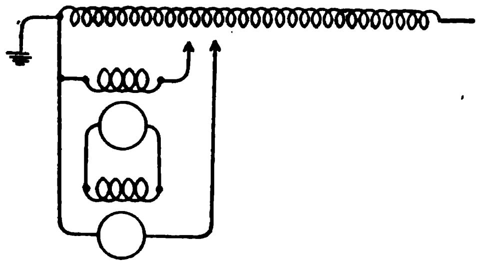

FIG. 1

The phase-relation between the generated and transformer voltages is shown in Fig. 2.

This record shows that the two electromotive forces are in exactly opposite phase. Under these conditions the current flowing after the circuit is closed with the connections reversed, will be displaced from the electromotive force, due to the impedance of the armature circuit. Fig. 3 shows this displacement when the armature is carrying about 100% current overload.

This is at a power-factor of 80%. The power-factor varies between this and 100% as the load decreases to zero. The obvious method to improve the power-factor is to shift the phase-relation of the generated to the line electromotive force. The result of this is shown in Figs. 4, 5, and 6.

Fig. 4 shows approximately the relation of the generated to the transformer electromotive force as it would be on open circuit, as the current in this case is small.

From these records it is evident that there is no difficulty in restoring power with a single-phase, commutator-type motor at practically 100% power-factor, the machine operating as a non-synchronous, alternating-current generator.

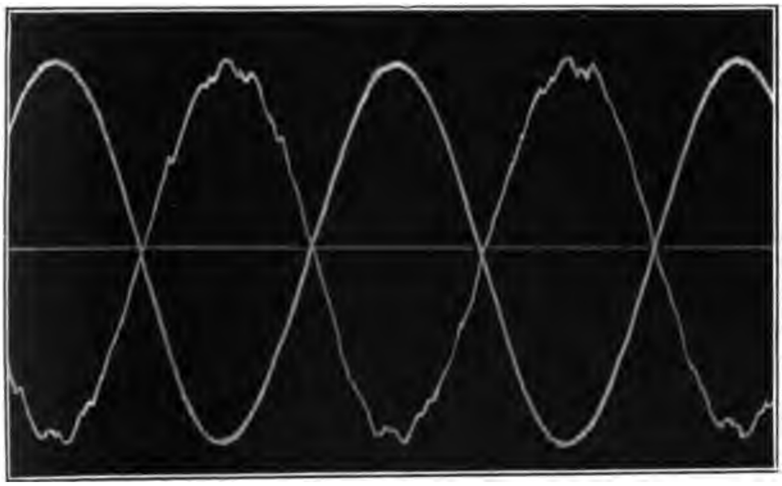

FIG. 2—Oscillogram of generated and transformer electromotive forces. The generated electromotive force is the curve with the irregular top

This condition being established, the next step is to see how it applies to actual operating conditions. From the foregoing it is evident that one of the motors of the equipment must be set aside for use as an exciter for the others, or a separate motor-generator set must be provided. If a separate source of excitation is provided, all the motors can be used to the fullest extent for regeneration of power, in which case the total capacity for regeneration will be increased over the capacity of the machines as motors by the increase in the power-factor. If the regenerative function is to be used for braking in making frequent stops, it might be desirable to supply the separate excitation; but if it is to be used in holding the train on grades it is unnecessary, as the remaining motors, if the equipment consists of three or more motors, will have ample capacity to do the work.

Assume a 2% grade of considerable length. The motors, all working, have sufficient capacity to haul the train up the grade. Assume the equipment to consist of four motors. Assume train resistances at six pounds per ton. The total tractive effort will then be 46 pounds per ton in ascending.

To hold the train at the same speed in descending, a retarding force of 34 pounds per ton must be supplied. The retarding force necessary is then approximately 75% of the force necessary to haul the train up the grade. It is evident from this that three of the four motors have ample capacity to exert the necessary retarding force, even if the power-factor of the machines as generators is no better than when they are operating as motors. It has been shown that the power-factor when operating as generators can be made better than when operating as motors; therefore, there is a surplus of capacity in four-motor equipment, and in three-motor equipment about an equal capacity.

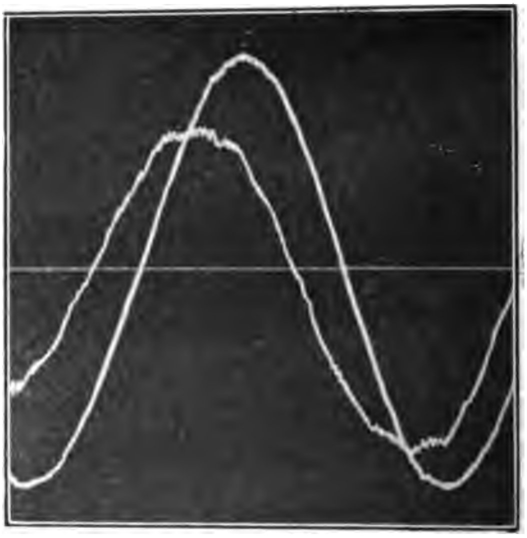

FIG. 3—Oscillogram of current and electromotive force of generator. The lower curve is the current. Power-factor 80% lagging current

The characteristics and capacity of the machines being

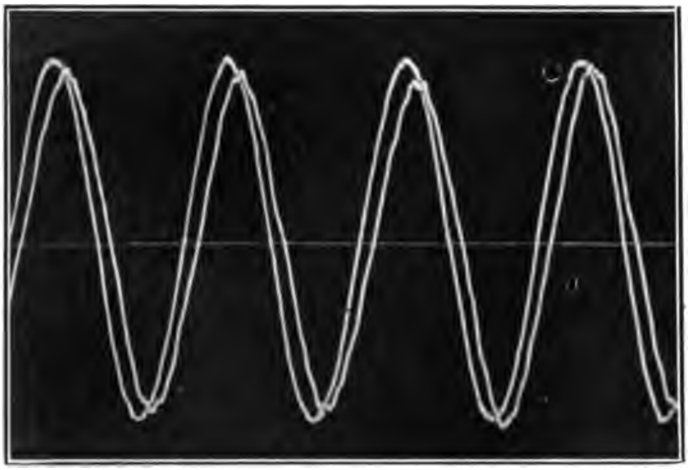

Fig 4—Oscillogram of current and electromotive force under light load. The lower curve is the current. Power-factor 98% leading current.

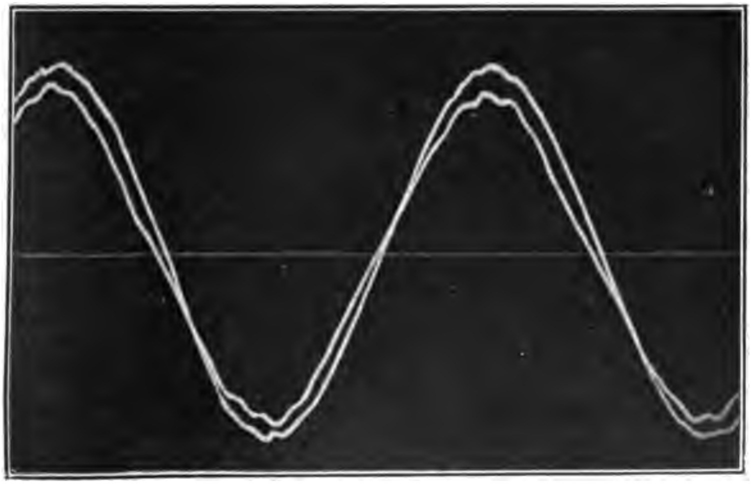

Fig. 5—Oscillogram of current and electromotive force under normal load. Conditions same as Fig. 4 The lower curve is the current. Power-factor 99.5% lagging current

correct for the work, it only remains to provide suitable means for manipulating the circuits to adapt the apparatus to the conditions. This is accomplished by providing switching apparatus to connect the motors in the proper relation and for furnishing and controlling the field current of the machine used as an exciter.

Fig. 7 shows diagrammatically the main circuits and connections for a four-motor equipment. From this it is evident that the switches used must have a current capacity the same as the motors, for there are four in parallel on the transformer and the switches used for reversing carry the current for one motor only. As shown, 36 switches are required for the entire control of the motor equipment.

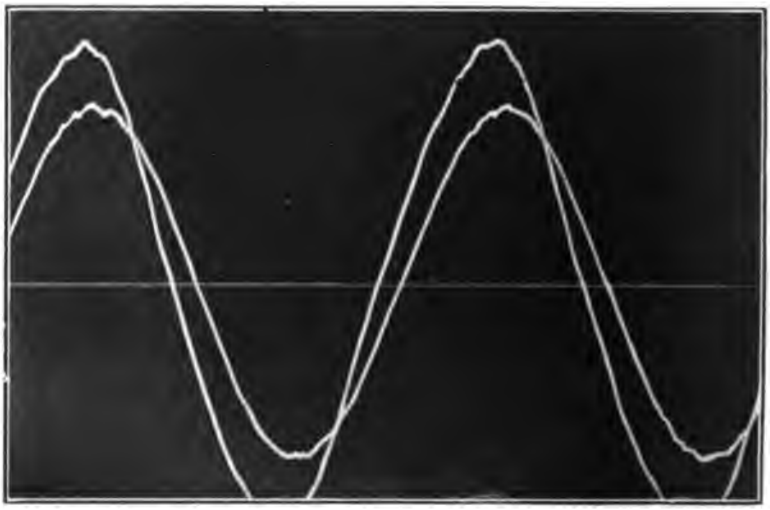

FIG. 6—Oscillogram of current and electromotive force under 100% overload. Conditions same as Figs. 4 and 5 .Power-factor 97% lagging current. The current is the upper curve.

Fig. 8 shows diagrammatically the same motor equipment arranged for regeneration in addition to the regular motor control. As shown, 54 switches are required of the motor-current capacity, and 16 of one fourth that capacity. Of the added switches of the motor-current capacity, 10 have been added to the transformer to enable slow speeds on regeneration to be obtained, and 8 are required to change the combinations of the motors. Besides the added switches, three small preventive coils and a few additional transformer taps are required. From this it is seen that the amount of additional apparatus required is insignificant compared with the result accomplished.

The curves shown in Fig. 9 give the relative tractive and retarding effort, both continuous and maximum, of a four-motor equipment.

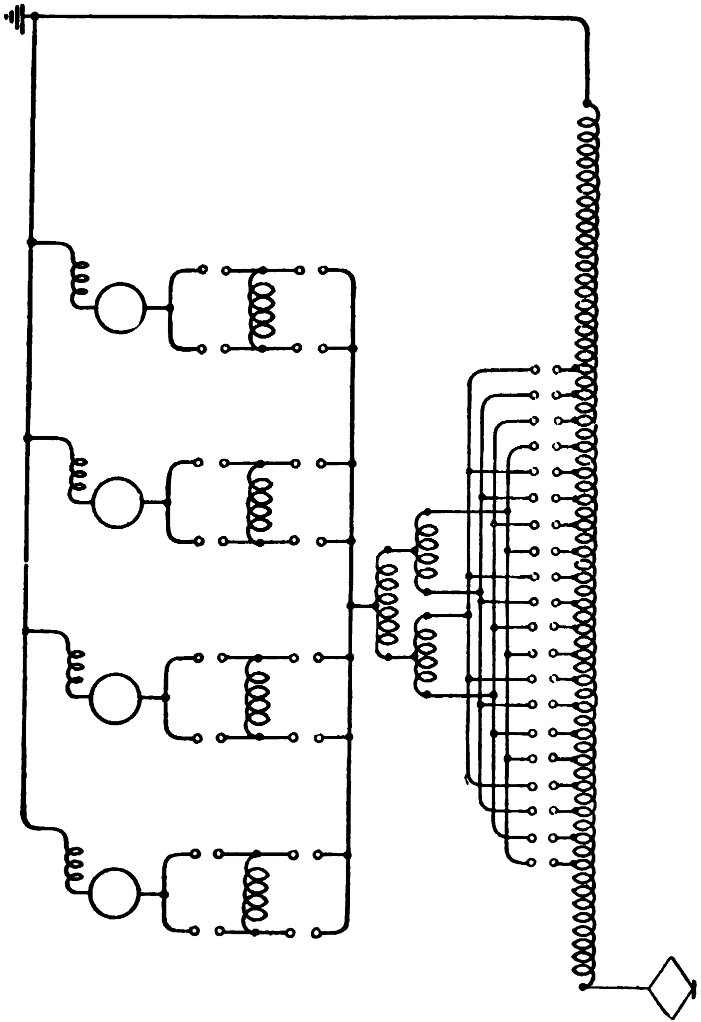

FIG. 7

As shown by the curves in Fig. 9 the three motors of a four-motor equipment acting as generators restoring energy to the line will let a train down a 2% grade at any speed from 9 miles per hr. to 30 miles per hr., that the motors have capacity to haul up the same grade at any speed up to 18.5 miles per hr. This is for continuous duty. At maximum duty for short periods the

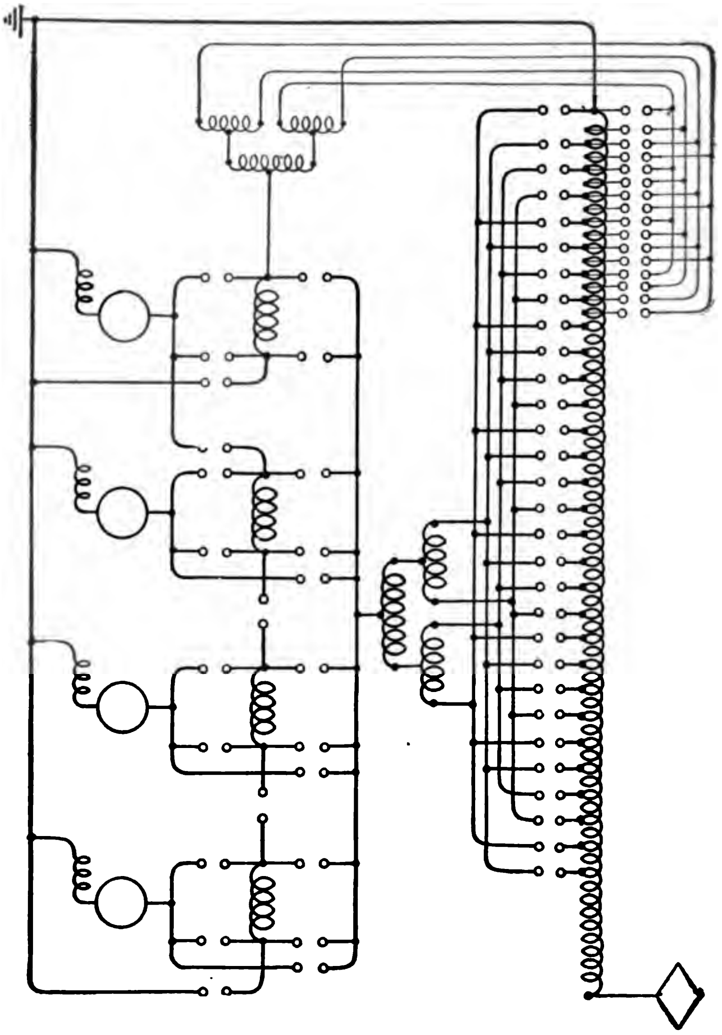

Fig. 8

capacity is increased about 60%. Between 9 miles per hr. and 30 miles per hr. there are 40 operating speeds, the gradations from one to the other being such that at no time will there be any variation exceeding 10% in torque. This necessitates, of course, a rather large number of switches being used, but it seems to be a very desirable condition to fulfil in heavy freight traffic.

Efficiency of this system of regeneration. The efficiency of the system when the motors are operating as generators and restoring energy to the supply circuit is about the same as the efficiency when operating as motors, there being perhaps a slight advantage in the case of the generator, due to the improved power-factor conditions. This, of course, assumes about the same load conditions on the machines in either case. However, the actual saving in power-house output can never be a very large percentage. If the entire road consisted of 2% grades and there were no switching to be done, the saving in power consumption might be as high as 50%; under ordinary conditions it could not be made to exceed one half of this, while under unfavorable conditions or with a level track and long runs, using the regenerative function only for braking, the saving could not be more than a few per cent.

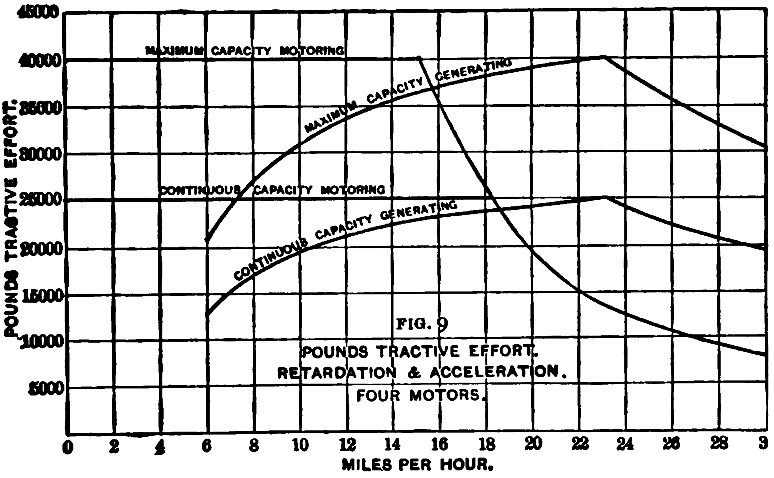

FIG. 9
POUNDS TRACTIVE EFFORT.
RETARDATION & ACCELERATION.
FOUR MOTORS.

The value of this system of regeneration is not to be found so much in the saving of power as in the saving in wear and tear and the ability to operate over a wide range of speed, as well as the comparative safety of operation. In the case of running heavy trains down long grades, the braking apparatus of all cars in the train can be held in reserve, it being necessary to use it only in emergency or in making the final stop. Under these conditions the number of accidents due to the failure of the brakes would be very much reduced.

This is the only system of regeneration yet developed which can be operated at maximum efficiency over a wide range of speed. In the case illustrated, forty speeds between 9 miles per hr. and 30 miles per hr. are obtained. This number can be increased if desired simply by the addition of a few switches.

The three-phase system is the only other one in which the regenerative function has been developed to any extent, but at most there are only a few widely separated speeds at which it can be operated efficiently. Generally there is but one.

A system of electric traction in which the trains must go up-grade and down-grade at one fixed speed in order to operate efficiently is certainly at a disadvantage when compared with one in which the trains can be operated at *any* speed *below* a certain maximum speed up-grade and at *any* speed within safe limits down-grade, at all times, whether taking energy from the line or restoring it to the line, the apparatus operating with maximum efficiency.

It will be noted that in this system the impressed voltage is changed to adapt it to the generated voltage, while in the direct-current or the three-phase system there is but one impressed voltage available.

This wide range of working voltage, with the ability to vary the armature current with respect to the field through a wide range, gives to the single-phase series motor the extreme flexibility as a regenerator of power that it has as a motor.

One other point that is worthy of note in connection with the operation of this system is the absolute safety and stability of the combination. While the machines being operated as generators are normally series machines, it will be noted that no one of the armatures is connected in series with its own field, and under no condition can there be any surging or building up of load. In case of momentary interruption of the supply circuit, the circuit again being restored the system will again operate exactly as before the interruption, there being no surging or violent action of the machines.

The system of regenerating power here described has been used in testing locomotives to give a dead-load condition under a wide range of speed.

Numerous stand-tests have also been made, so that the operation of the motors under the conditions is well established and there is no doubt about the scheme doing all that is claimed for it.

DISCUSSION ON "REGENERATION OF POWER WITH SINGLE-PHASE ELECTRIC RAILWAY MOTORS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907.

W. I. Slichter: The possibility of regenerating power with single-phase motors is one of the valuable features of the single-phase system and one which will be of great assistance in bringing the motor into the field of heavy railway work. The possibility of regenerating at various speeds is well illustrated in Mr. Cooper's paper, but it is interesting to note that there are two points in the system at which the speed can be varied; first, by changing the tap on the transformer from which the exciting motor obtains its excitation; secondly, by changing the tap on the transformer to which the generating motors are connected. These two actions may be independent, giving twice as many steps as there are taps. With this arrangement a very large number of taps on the transformer is not necessary.

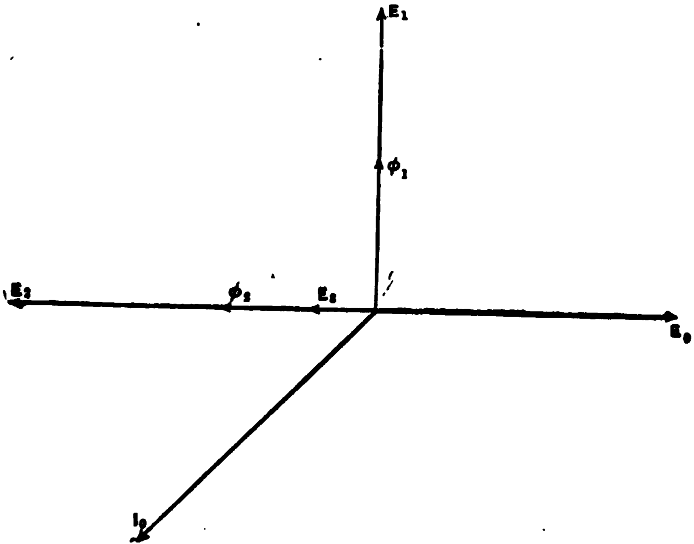

FIG. 1

With regard to the phase of the current which is returned to the line, there is liable to be a low power-factor, due to the inductance in the motor, the line, and the steel rails. This can be improved by a compounding effect in the motor which is acting as a generator, as shown in Figs. 1 and 2.

E_0 represents the electromotive force of the line, or at the secondary of the transformer, which is impressed on the field winding of the motor that is acting as an exciter. The flux which is set up in these fields will be displaced approximately

90° behind E_0, as at ϕ_1. The armature of the motor used as an exciter revolves in this flux and produces a voltage in phase with ϕ_1, as shown by E_1.

This voltage being impressed on the separately excited fields of the power motors, produces a flux in their fields displaced 90° behind E_1, as shown by ϕ_2.

The electromotive force generated by these armatures is in phase with ϕ_2 as E_2, which is nearly in opposition to the line voltage E_0, giving a resultant electromotive force E_3.

This resultant forces the current I_0 through the windings of the motor and transformer, in which there is a considerable amount of inductance, and the current will lag behind E_3 an amount depending upon the inductance of these circuits.

If, however, in addition to the magnetizing current caused by E_1, we force through the fields of the power motors a certain portion of the current from the field of the exciting motor having the phase of ϕ_1, then will ϕ_2 and E_2 be advanced in phase considerably, as in Fig. 2, and the resultant E_3 will lead E_2 and the current I_0 flowing may lag considerably behind E_3, and still be nearly in phase with E_2 or E_0, assuming a position between the two giving a good condition for returning power instead of volt-amperes to the line.

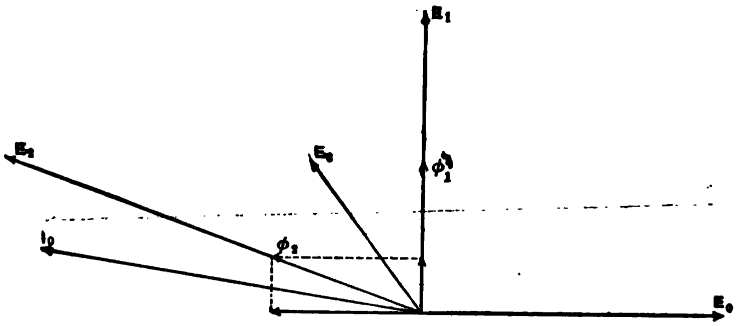

FIG. 2.

L. B. Stillwell: The importance of recuperation has not been recognized adequately by American railway engineers. Its importance, as Mr. Cooper states, is primarily due to the fact that it assists powerfully in reducing wear and tear of rolling stock equipment. The average cost of renewals of rolling stock of the railways of the United States to-day exceeds $250,000,000 per annum. Of that total, a large proportion, probably at least one-half, is due to the destruction of rolling stock by loss of control on heavy grades and by excessive wear and tear of wheels and brakes and strain of draft-gear. A number of years ago when the late Judge Cowan was president of the Baltimore & Ohio, this wear and tear of rolling stock loomed up in the road's cost of operation as so formidable an item that he and some of his assistants very seriously considered the problem of utilizing electricity to operate the heaviest of their mountain grade divisions. Messrs. Duncan & Hutchinson made an investigation and report at that time, and I recall that subsequently Judge Cowan expressed to me the opinion that the saving in cost of maintenance which could be effected by using the three-phase system on this division was of the greatest importance.

In this connection, the work that Mr. de Kando and his associates of the Ganz company have done is of great interest. The argument which Mr. de Kando uses in meeting the opposition of the railway operator, who is of the opinion that it would be quite impossible to operate up grade and down grade at uniform speed, is interesting. Mr. de Kando takes the position that the true limitation of speed, either in climbing or descending a mountain grade, is the curvature of the road, the limiting curves properly fixing the maximum speed. He argues that instead of climbing a grade at a speed of 20 miles an hour and descending it at 40 miles an hour the same result is attained in crossing the mountain if the locomotive be run at the average speed of 30 miles an hour. If 30 miles an hour be the permissible speed with reference to limiting curves nothing is lost, so far as schedule is concerned, and much is gained in assuring the safety of the train in going down grade by adopting a system that absolutely holds the train to the speed that is predetermined as a safe limit.

Anyone who travels over mountain-grade divisions in this country and looks out of a car window usually sees the remains of at least one freight wreck, and the argument which Mr. de Kando makes is not fully met, in my judgment, by saying that it is necessary to operate at widely varying speeds in going down grades in order to attain the necessary average speeds. Undoubtedly this is the practice. The engineer will " let her out ", as he says, when he has a short tangent and will go downgrade at what he considers a safe speed, but the results are shown by the wrecks. It would be far safer, as far as the maintenance of rolling stock is concerned, to fix the limit speed for him in the office of the superintendent and provide a system which does not permit him to exceed the limit established.

As regards the interesting system of recuperation of power which Mr. Cooper has presented, I would suggest that the attempt has been made to go too far in obtaining variation of speed at the price of complication of switching apparatus. In my judgment it would be better to establish a narrower range of speeds for operation on mountain grades, and eliminate a considerable proportion of the switches illustrated in the diagrams. A tendency of single-phase equipment is toward an inordinate use of switching gear.

Recuperation involves, in general, an increase in the output of motors, since they are worked down grade as well as up grade. Probably in practical operation the difference would not be very material in respect to this point. It is customary now to add a second engine when a train reaches the foot of a mountain grade, and in general it would not greatly handicap mountain operation if the second locomotive were to accompany the train over the entire grade, being used to assist in holding back the train and restoring energy to the line in descent. Substantial compensation for the additional locomotive mileage involved would be obtained in the saving of power.

J. C. Lincoln: Has Mr. Cooper made experiments to determine how much more wear there is on the gears of this regeneration system than with the ordinary method now used in operating railroad motors, where the motors are used as motors only and never as generators?

William Cooper: As to the wear on the gears—of course that is purely a mechanical matter and it is self-evident that if the gears do work they will wear. The best example of that, I think, would be the traction brake on street cars, where the electric brake is used for traction purposes. In that case, of course, we find that the gears wear out faster than they would if only used as motors. They are bound to do that from the nature of the case. The amount of wear would be proportional to the amount they are used for regenerating purposes.

Mr. Stillwell's comment about the number of switches involved as shown in the diagrams needs a reply. Of course there are some other considerations which will determine how many switches are necessary, but from the standpoint of making assurance double sure, and having a system to operate without a hitch of any kind from a designer's standpoint, I incorporate a sufficient number of switches to cover any condition. Probably a case would arise where a very much smaller number would answer the purpose.

In regard to Mr. Slichter's point about shifting the phase relation of the generated electromotive force, I ask how he would produce the displacement of the electromotive force on the exciter field? It is simpler to displace the current in the exciter armature circuit than it is to displace the current in the field circuit of the exciter. That can be done by methods well known to the art of shifting the current in an alternating current system, by increasing resistances or inductance to get any predetermined relation.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28. 1907.

FRACTIONAL PITCH WINDINGS FOR INDUCTION MOTORS

BY C. A. ADAMS, W. K. CABOT, AND G. Æ. IRVING, JR.

For several years past some of our large manufacturers have used fractional pitch windings, for induction motors to a considerable extent, and for alternators to a lesser extent.

It was the original purpose of this investigation to develop by theory and experiment a method by means of which the effects of such windings may be calculated; and although this purpose has been successfully carried out as far as time allowed, there is still a very interesting part of the subject which must be left for another time; namely, the relation of fractional pitch windings to squirrel-cage motors.

THEORY

The theoretically ideal induction motor would have a very large number of symmetrically placed phase windings of full pitch on both primary and secondary structures, the primary windings being supplied with the same number of equal, symmetrical, simple harmonic electromotive forces. In this case the flux density across the air-gap, the primary current, and the secondary current would be distributed sinusoidally around the gap periphery at any instant, and these distributions would revolve smoothly around the periphery at synchronous velocity.

The chief difference between this ideal machine and the actual is that the number of phases in the latter is small and there must, therefore, be several adjacent conductors or slots carrying the same current at the same instant, thus forming what may be termed a *belt* of conductors in which the current increases and decreases as a unit. On either side of this belt is another, the current in which differs in phase from that in the first by a considerable angle, 60° in a three-phase and 90° in a two-phase motor. Thus the current varies from point to point around the periphery by jumps or steps rather than gradually, as in the ideal motor.

It is a well known fact which has been demonstrated both theoretically and experimentally that even an ordinary induction motor, if it have a low-resistance squirrel-cage secondary, and be supplied with simple harmonic electromotive forces, will have a gap flux whose peripheral distribution is approximately sinusoidal at each instant, the effect of the slot openings being neglected.

Even in the case of a phase-wound secondary, the most satisfactory common ground for calculation is the assumption of a sinusoidal peripheral flux distribution, for although it may be claimed that such a distribution does not exist in fact, the results of calculations based upon this assumption are sufficiently close to the observed facts to render its use quite warrantable.

Differential factor. When an harmonically distributed flux sweeps round the gap periphery it causes to be induced in the conductors of any given slot a simple harmonic electromotive force. If this slot is one of three per pole per phase of a three-phase motor, there will be induced in the conductors of these three slots of the same phase, three harmonic electromotive forces differing in phase by 20°, and these three electromotive forces will add together vectorially to form a resultant whose magnitude is about 0.96 of their numerical sum. This slight loss of effectiveness in electromotive force generation, which is due to the fact that different conductors of the same phase belt are at certain periods experiencing electromotive forces of opposite sign, may be termed *differential action,* since it consists in the differential cutting of flux by conductors of the same phase belt. Similarly the factor (0.96 in this case) by which the total numerical electromotive force must be multiplied to obtain the actual resultant electromotive force, may be called the *differential factor.* But differential action in these phase belts is not confined to electromotive force generation; it also appears in a similar manner in the production of an harmonically distributed magnetomotive force by currents in these belts. This means that a larger current per phase is required to produce a given magnetomotive force than in the ideal motor. If the secondary is supplied with an ordinary phase winding, the belts of this winding will be subject to the same differential action, both in the generation of electromotive force and in the production of torque by the reaction of the current belts on the gap flux. Moreover, in this latter case the overlapping of a secondary phase belt by parts of two primary phase belts, (or vice versa), results in local fluxes crossing the gap, which have components in phase with both primary and secondary currents and thus give rise to quadrature electromotive forces* which may be

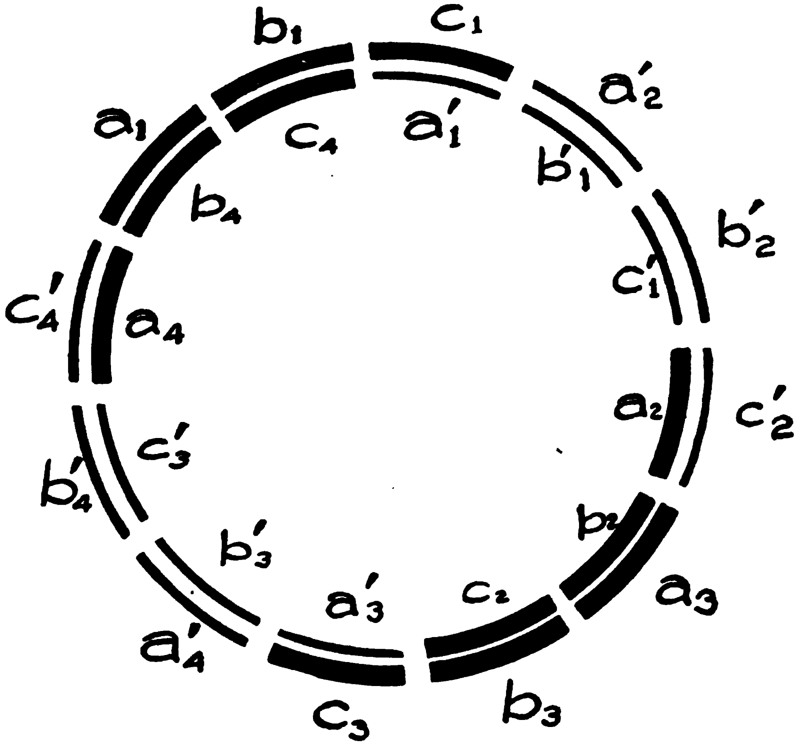

Fig. 1.

considered as another aspect of the belt effect or differential action.

The phenomena introduced by fractional pitch windings are largely of this same type, and may in most cases be treated as an

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*This subject has been treated by one of the writers under the head of *Belt leakage*. Proceedings International Electrical Congress, St. Louis, 1904, Vol. I, page 706.

extension of differential action. Thus if coils having a *pitch* or *throw* of less than 180° (electrical) be used for the winding of an induction motor, the effect will be to shift one of the layers of the winding around through a certain angle from its full pitch position, see Fig. 1, where a four-pole, three-phase winding with a two-thirds pitch is shown diagrammatically. The positive or backward connected belts are shown in heavy lines, and the negative or outward connected belts in light lines; the two sides of each phase coil are similarly lettered and numbered. The overlapping of currents of different phase in the same slots is here quite apparent.

Slot leakage. The reactance due to that part of the leakage flux which crosses a slot, linking with more or less of the conductors in that slot, may be expressed as follows:

$$x_s = 2\pi\, n\, \phi_s\, N^2_{cs}\, l \frac{N_t}{p'}\, 10^{-8} \qquad (1)$$

where n is the frequency, ϕ_s the flux per ampere per unit length of slot, N_{cs} the conductors per slot, l the length of the core, N_t the total number of slots, and p' the number of phases. None of these quantities is affected by a change of coil-pitch, except ϕ_s. This change will therefore be a measure of the effect produced upon the slot leakage by the fractional pitch.

Designate by θ the pitch of the coils in electrical degrees, and by β the angle of pitch deficiency = 180°-θ. Then if the machine in question has a very large number of phases, the two coil-sides located in any given slot will in general carry currents which differ in phase by β degrees, and the component of one of these currents in phase with the other will be proportional to cos β. If the product of the inductances of these two coil-sides is equal to the square of their mutual inductance, *i.e.* if there be no relative leakage flux between them, the ratio of the average leakage flux linked with one, to what it would be with full pitch winding and no phase difference between the two currents, is $\frac{1+\cos\beta}{2} = \cos^2\frac{\beta}{2} = \sin^2\frac{\theta}{2} = k_p$. This may be called the slot-pitch factor, under the two above mentioned conditions. But neither of these conditions exists in practice.

Consider first the relative leakage between the two coil-sides in the same slot. Referring to Fig. 2, the flux linked with coil b per inch length of slot for one ampere in b is

$$\phi_{bb} = \frac{3.2}{w}\left(\frac{d_1}{6} + \frac{d_1}{2} + d_2\right)$$

The flux linked with *b* per inch of slot for one ampere in *a* is

$$\phi_{ab} = \frac{3.2}{w}\left(\frac{d_1}{4} + d_2\right)$$

But the current in *a* differs in phase from that in *b* by an angle β, and the component of ϕ_{ab} in phase with ϕ_{bb} is $\phi_{ab} \cos \beta$. Then the total in-phase flux linked with *b* per slot inch and for one ampere distributed uniformly over the whole copper section of the slot, is,

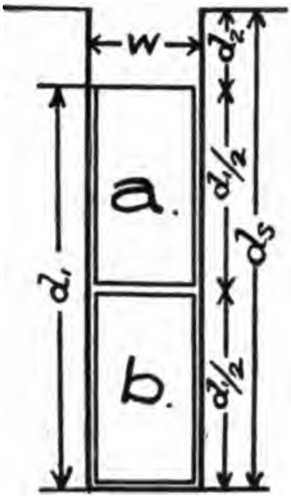


Fig. 2.

$$\phi_b = \frac{\phi_{bb} + \phi_{ab} \cos \beta}{2} = \frac{3.2}{w}\left[\left(\frac{d_1}{3} + \frac{d_2}{2}\right) + \cos \beta\left(\frac{d_1}{8} + \frac{d_2}{2}\right)\right]$$

Similarly

$$\phi_{aa} = \frac{3.2}{w}\left(\frac{d_1}{6} + d_2\right)$$

$$\phi_{ba} = \frac{3.2}{w}\left(\frac{d_1}{4} + d_2\right)$$

and $$\phi_a = \frac{\phi_{aa}+\phi_{ba}\cos\beta}{2} = \frac{3.2}{w}\left[\left(\frac{5}{24}d_1+\frac{d_2}{2}\right)+\cos\beta\left(\frac{d_1}{8}+\frac{d_2}{2}\right)\right]$$

Then since each coil has one side in the bottom and the other in the top of a slot, the average flux linkage per ampere inch of slot will be

$$\phi_s = \frac{\phi_a+\phi_b}{2} = \frac{3.2}{w}\left[\frac{d_1}{12}+\left(\frac{d_1}{4}+d_2\right)\left(\frac{1+\cos\beta}{2}\right)\right] \qquad (2)$$

or $$\phi_s = .267\frac{d_1}{w}+\frac{3.2}{w}\left[\frac{d_1}{4}+d_2\right]\sin^2\frac{\theta}{2}.$$

There is thus a small portion $\left(0.267\frac{d_1}{w}\right)$ of the slot leakage which is independent of the coil-pitch; it is obviously that part which lies between the two coils, and would disappear if the latter were placed side by side in the slot rather than one on top of the other.

With this correction, the slot pitch-factor becomes

$$k_p = \frac{\frac{d_1}{12}+\left(\frac{d_1}{4}+d_2\right)\left(\frac{1+\cos\beta}{2}\right)}{\frac{d_1}{12}+\left(\frac{d_1}{4}+d_2\right)} \qquad (3)$$

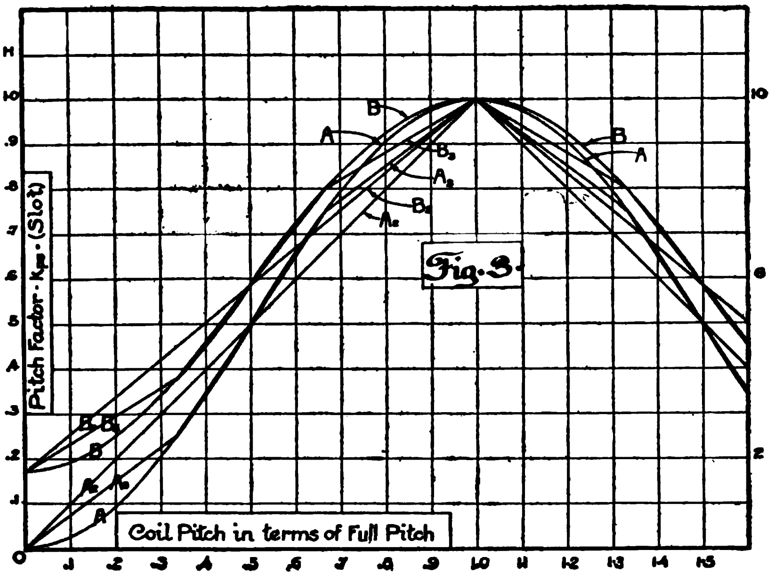
If the slot is partly closed, the resulting increase in ϕ_s is common to both coils and would involve a change in only that part of formula (2) which is affected by the coil-pitch.

In Fig. 3, curve *A* gives the values of $\frac{1+\cos\beta}{2}$ corresponding to different values of the coil-pitch, and curve *B* gives the corresponding values of k_p from equation (3), for a motor with open slots, in which the coils occupy about 80% of the slot depth. If the slots be partly or wholly closed, the constant part of equation (2) decreases relatively and the corresponding k_p curve will drop down, approaching more nearly to curve *A*.

In all this a very large number of phases has been assumed. Consider now the effect of a small number of phases. Take for example a two-phase motor with ¾ pitch. $\beta = 45°$ and k_p taken from curve *B*, Fig. 3, is 0.88. The two layers of the winding will be as in Fig. 4, where the relative phases of the currents in the several belts are indicated. Consider the 0° belt in the upper layer; half of it overlaps a 0° belt in the lower layer and the pitch-factor for this half is therefore 1; the other half overlaps a 90° belt in the lower layer, with a corresponding pitch-factor of 0.585. Thus the average pitch-factor for the belt is 0.792 in place of 0.88 as given by curve B or equation (3).

If the coil-pitch is deficient by one or more whole belts, the conditions will be exactly the same as those for which the curve B Fig. 3, was calculated. Therefore that curve will give the correct pitch-factor of a three-phase motor for a $\frac{1}{3}$ and for a $\frac{2}{3}$ pitch, and of a two-phase motor for a $\frac{1}{2}$ pitch winding.

A little consideration will show that between these points the actual pitch-factor will follow a straight-line law.



In Fig. 3 the lines B_2 and B_3 show the variation in k_p for two and three-phase motors respectively. A_2 and A_3 show the same factors when the relative leakage between the two coil-sides in the same slot is neglected.

Tooth-tip or "zigzag" leakage. The expression for the tooth-tip leakage reactance is of the same form as that for the slot leakage;

$$x_{tt} = 2\pi\, n\, \phi_{tt}\, N^2_{sc}\, l\, \frac{N_t}{p^1} 10^{-8} \qquad (4)$$

where ϕ_{tt} is the tooth-tip flux per ampere inch of slot, for both primary and secondary.

As far as the fractional pitch effect is concerned, this element is exactly on a par with that part of the slot leakage which crosses the slot above the conductors, since it is wholly common to both coil-sides. The *tooth-tip pitch-factor* will therefore be that shown by lines A_2 and A_3 Fig. 3.

Coil-end leakage. The coil-end reactance may be expressed as follows:

$$x_f = 2\pi n \phi_f p \left(\frac{N}{2p}\right)^2 l_c 10^{-8} = \frac{2\pi}{4} n \phi_f \frac{N^2}{p} l_c \qquad (5)$$

where ϕ_f is the flux per ampere inch of the whole phase belt bundle of coil ends, p the number of pairs of poles, N the conductors per phase and l_c the length of the two ends of one coil, usually about three times the coil-pitch. There are two terms in equation (5) which vary with the coil-pitch, l_c in a comparatively simple manner, and ϕ_f in a manner not so obvious.

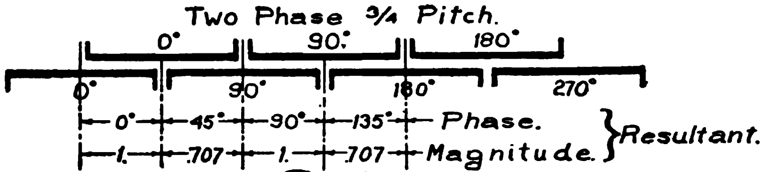


Fig. 4.

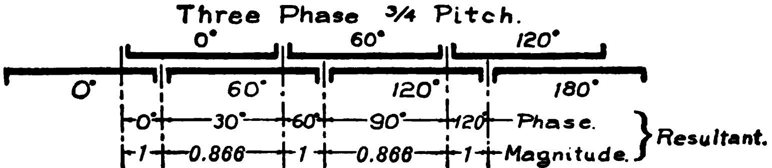


Fig. 4a.

For a circular coil in air, ϕ_f, the flux linked with one inch of the coil as a whole, per ampere distributed uniformly throughout the section of the coil, is proportional to the logarithm of the ratio of coil diameter to the diagonal of its cross-section, provided this ratio is large. For coils such as are used on induction motors this relation holds only in a general way, especially when the mutual inductive effect of neighboring coils is taken account of, and when the pitch is fractional. However, within practical limits ϕ_f would increase in approximate logarithmic relation to the coil-pitch, were it not for the mutual inductive effect of adjacent phases, and the curve representing this relation would tend toward a zero which is not that of the pitch.

Consider now the mutual inductive effect of adjacent phases. For pitches less than unity, this decreases in about the same ratio as the self-inductive effect and thus does not much change the general shape of the curve. But for values of the pitch greater than unity, the mutual inductive effect of opposing phases begins to count and to reduce considerably the otherwise value of ϕ_f. Thus the curve showing the relation between ϕ_f and the coil-pitch should be logarithmic in its general character, tending toward zero at some small (not zero) pitch, and falling increasingly below the logarithmic curve for pitches greater than unity. This, in fact, is approximately the shape found by experiment.

Belt leakage. The belt reactance may be expressed:

$$x_b = 2\pi\, n\, \phi_b\, 2\, p \left(\frac{N}{2p}\right)^2 l\, 10^{-8} = \pi\, n\, \phi_b \frac{N^2}{p} l \qquad (6)$$

where ϕ_b, the flux per ampere inch of the belt, is inversely as the reluctance of the belt magnetic circuit, and proportional to the $\sin^2$ of $\frac{1}{2}$ the angle of phase difference between the currents in the two opposing belts. ϕ_b is thus proportional to the belt-pitch and inversely to the air-gap.*

In the analysis of the effect of fractional pitch upon belt leakage, each case is a law unto itself, and requires a special quantitative analysis, which is not always short. The results, however, are in some cases most interesting, and can best be considered in conjunction with the experimental data.

Exciting reactance. In the case of fractional pitch, a higher flux density is required in the gap in order to produce the same resultant electromotive force, because the electromotive forces in the two sides of any given coil differ in phase by β degrees. The electromotive force differential-factor is then $\cos\frac{\beta}{2}$ or $\sin\frac{\theta}{2}$ where θ is the coil-pitch angle.

Not only is the exciting current higher because of the increased gap density, but it is still further increased because of the overlapping of currents of differing phase and the consequent reduction

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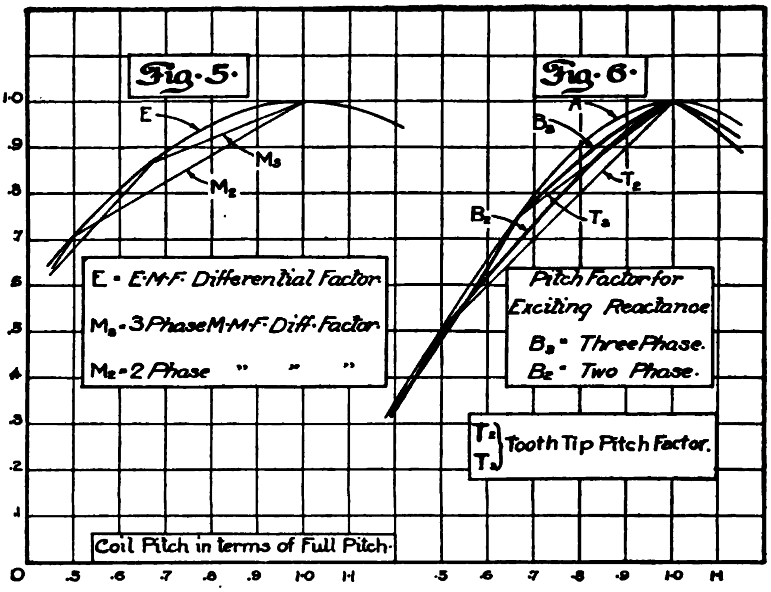
*See the paper referred to in note at bottom of third page of this paper.

in effectiveness for magnetomotive force production. The magnetomotive force differential factor is cos $\beta/2$ only when the coil-pitch is an exact multiple of the belt-pitch. For example, take the two-phase motor with 0.75 coil-pitch, Fig. 4, the average of the resultant currents is $\frac{1.707}{2} = 0.853$, but $\cos\frac{\beta}{2} = 0.96$. In Fig. 5, curve E shows the electromotive force differential-factor, M_3 the three-phase and M_2 the two-phase magnetomotive force differential-factor. The pitch-factor for the exciting reactance is then the product of E and M_2 or of E and M_3 and is shown in curves B_2 and B_3 of Fig. 6.



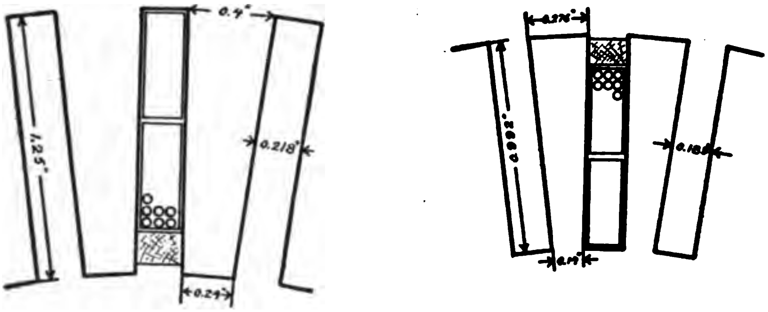
RESULTS OF EXPERIMENTS

The motor tested had 48 slots, (see Fig. 7) on stator and rotor and several sets of coils were used in the same core. Short-circuit tests were made at 300 and at 60 cycles, and open-circuit tests at 60 cycles. The latter were made with rotor stationary. Each set of coils had the same number of conductors per slot, as had the rotor and stator coils.

Coil-end reactance. The core was removed except for two plates, just sufficient to support a set of short coils. Short-circuit tests with this arrangement were practically useless owing to the relatively large exciting current; so the primary and secondary were connected in series, phase for phase, and the opposing belts set opposite each other. Then, since there were the same number of turns in primary and secondary, no flux crossed the gap, and the total impedance was accurately determined. Moreover, by measuring the drop across primary and secondary, the two impedances were separated. The very small slot reactance due to the two core discs was then computed and subtracted from the total, leaving the coil-end reactance alone.

Two sets of coils were employed in these tests. One set with a pitch of twelve slots was connected for three phases; two poles and four poles; half and full pitch respectively; both primary and secondary being connected in exactly the same manner

Fig. 7.



Stator—48 Slots

Rotor—48 Slots

The other set with a pitch of nine slots was connected for three phases; two poles, four poles, six poles, and eight poles; ⅜ pitch, ¾ pitch, 1⅛ pitch, and 1½ pitch respectively; making in all six combinations with the short coils.

From the reactances obtained from these tests, the corresponding values of ϕ_f were computed by means of equation (5), in which l_c was taken as the total length for both primary and secondary. The results were plotted in the curves of Fig. 8. The difference between ϕ_f for the twelve-slot coils and the nine-slot coils is due to the fact that in the latter case the primary and secondary coil ends were bent farther back, thus leaving more room for leakage between them.

The upper curve of Fig. 8, shows both sets brought together by plotting each set in terms of its full pitch value. The curve of Fig. 9 shows the total coil-end pitch-factor for a special case where l_c is taken equal to 5 in. + 2.8λ_c, λ_c being the coil-pitch in inches. The pole-pitch was taken as 10 in.

The coil-end pitch-factor is then:

$$k_{pc} = (\phi_f \text{ in terms of that for full pitch}) \times \frac{5+2.8\lambda_c}{5+2.8\,\lambda_p}$$

If all the coil-end leakage be charged to the primary, the corresponding full pitch value of ϕ_f for the first set of tests is 1.14, and 1.35 for the second set. The first of these corresponds more nearly to a normal induction motor.

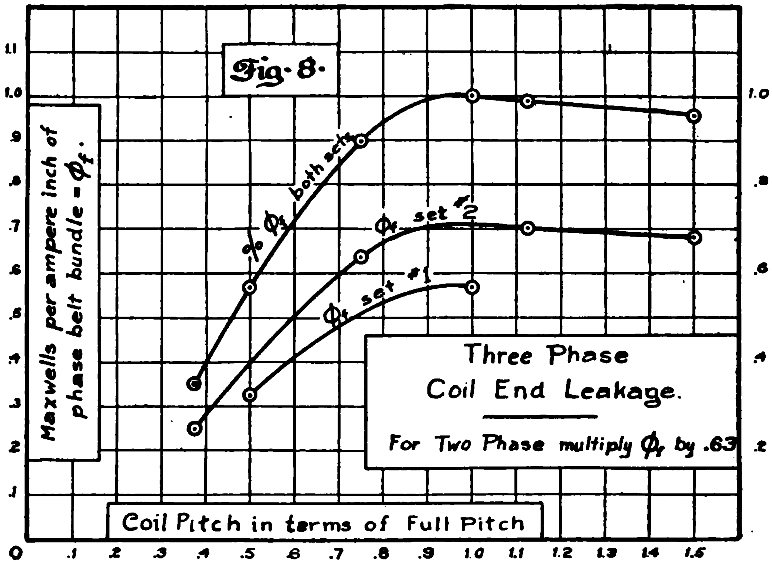


Fig. 8.

For a squirrel-cage motor with bars extending well out from the core, the value of ϕ_f (all charged to primary) is known to be about one or a little more, which is very close to the value given above for a wound rotor. No experiments of this sort were made in the present investigation; but many instances are at hand where a considerable change has been made in the reactance of a squirrel-cage motor by altering the disposition of the end-rings. The writer hopes to investigate this matter in the not distant future.

Slot reactance. Following the above described coreless tests, the normal core of length l = 3.2 in. was replaced and tests were made with two different sets of coils; one set having a coil pitch of twelve slots and the other nine slots. The first set was connected in four combinations, two-phase two-poles; two-phase four-poles; three-phase two-poles; and three-phase four-poles; the second set was connected in five combinations, two-phase four-poles; three-phase, two-poles, four-poles, six-poles, and eight-poles. In the second set the wires were placed in the slots without taping and were depressed as much as possible, see Fig. 10.

Series tests were first made with the secondary belts directly opposite the corresponding primary belts, thus eliminating both tooth-tip and belt reactance.

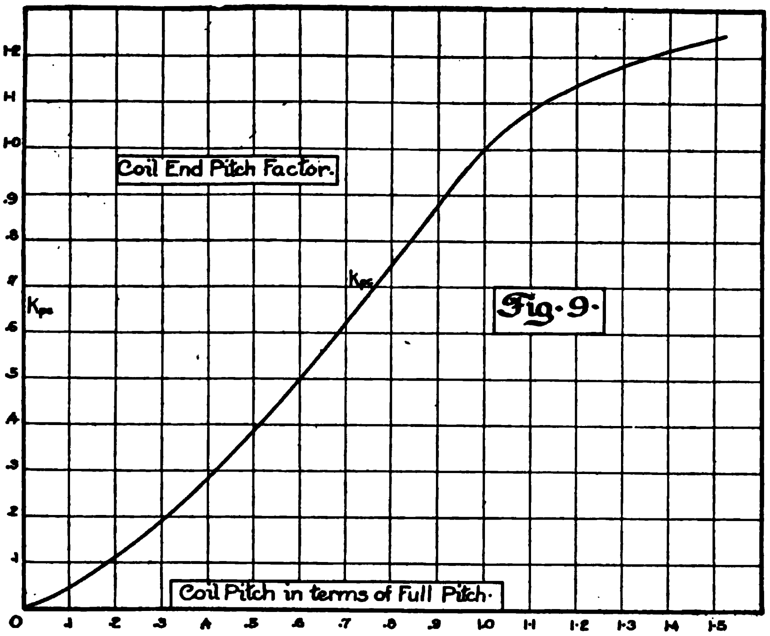


Fig. 9.

Ordinary short-circuit tests were then made, (*a*) with belt opposite belt as in the series test, (*b*), one half of the tooth-pitch beyond position "*a* ", where the tooth-tip leakage is a maximum, and (*c*) one half belt beyond position " *a* " where the belt leakage is a maximum.

Tests were then made with the secondary open circuited to determine the exciting reactance.

The short-circuit tests " *a* " gave reactances uniformly two or three per cent. lower than the series tests, as was to be expected.

From the reactances obtained from the series tests, the coil-end reactances, (as calculated with the aid of the coreless tests) were then subtracted. The remainders are the slot reactances. The full pitch values of ϕ_f used in calculating x_f were 0.66 for the first set, (the twelve-slot pitch coils), and 0.70 for the second set, (the nine slot pitch coils). In both these cases, the coil-ends were bent well back in order to make room for the temporary between-coil connections which had to be changed several times. At first 0.70 was chosen for both sets, but it was found that 0.66 gave more consistent results for the slot leakage in the first set. This is also what might have been expected since, in the second set, the primary and secondary coil-ends are farther apart where they come out of the slots.

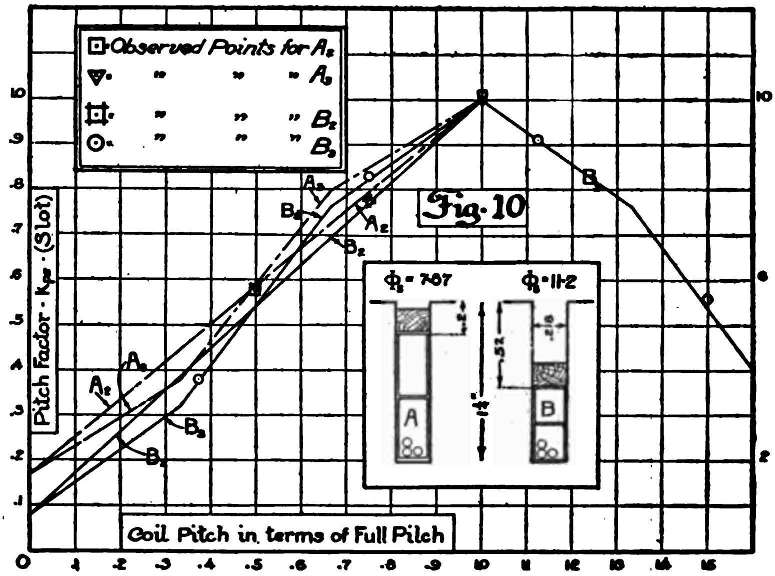


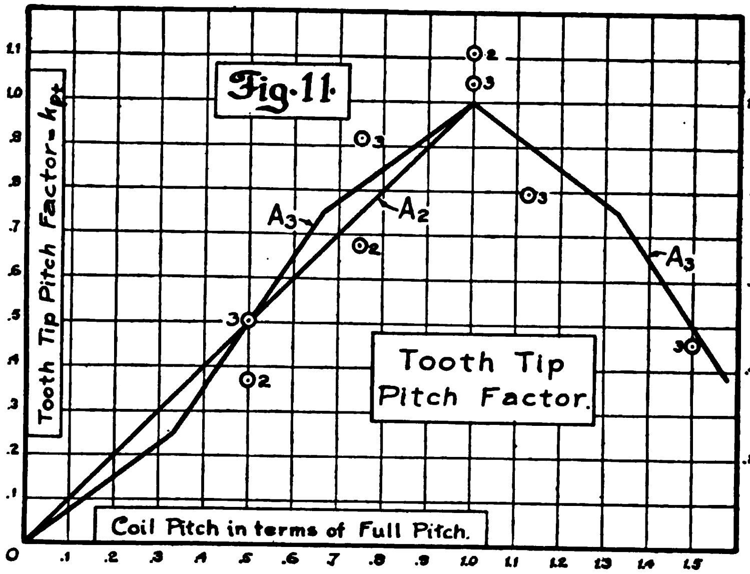
Fig. 10

From the slot reactances obtained above, ϕ_s was calculated from equation (1). The slot pitch-factor is then $k_{ps} = \phi_s \div \phi_{s1}$ where ϕ_{s1} is the value of ϕ_s for full pitch.

The values of k_{ps} thus determined are plotted in Fig. 10 where the calculated curves from Fig. 3 are also shown. It will be noted that the deviations of the observed points from the calculated curves to which they belong, are within the reasonable errors of observation and calculation, particularly when it is remembered that owing to the comparatively large values of x_f, which were subtracted from the series test reactance x to get x_s the slot reactance, a moderate change in ϕ_f will shift the relative values of k_{ps} so that when plotted they appear to have little relation to the theoretical curves.

Tooth-tip or "zigzag" leakage. The difference between the "b" and the "a" reactances gives the maximum tooth-tip reactance x_{tt}, but it gives in addition a small portion of the belt reactance.

From this difference, ϕ_{tt} may be calculated by equation (4) and thence the tooth-tip pitch-factor. The results are plotted in Fig. 11, together with the theoretical curves A_2 and A_3 for two- and three-phase respectively, taken from Fig. 3.



These results may seem rather wild, but there are several reasons therefor. First, the tooth-tip leakage is, in this case, a comparatively small part of the total reactance, and a small error in either the "a" or the "b" reactance makes a large percentage error in their difference; secondly, it is not likely that the rotor was set each time in exactly the position of maximum tooth-tip reactance, since the maximum is a narrow one owing to the open slots on both sides of the gap; thirdly, because of the inevitable presence of the uncertain and variable amount of belt leakage mentioned above. Taking these things into account, the results are in very fair accord with the theory. There is every reason to believe that this element of the leakage follows the theory outlined, quite as closely as does the slot leakage.

Belt leakage. The maximum belt reactance was obtained from the short-circuit tests by subtracting the " *a* " reactance from the " *c* " reactance. The experimental results are given in Table I, and a few typical cases will be considered. In column x_{B_3} the two-phase belt reactances are reduced to two-thirds of their actual values for comparison with the three-phase reactances.

TABLE I

			No.	Pitch.	x_B	x_{B_3}
12-slot pitch	2 phase	2 poles	1	0.5	11.32	7.52
		4 poles	2	1.	6.02	4.01
	3 phase	2 poles	3	0.5	1.38	1.38
		4 poles	4	1.	0.846	0.846
9-slot pitch	2 phase	4 poles	5	0.75	0.81	0.54
	3 phase	2 poles	6	0.375	0.535	0.535
		4 poles	7	0.75	0.24	0.24
		6 poles	8	1.125	......	......
		8 poles	9	1.5	0.175	0.175

First compare the two-phase and three-phase belt reactances; No. 1 and No. 3 are alike in all other respects, but the two-phase is nearly 5.5 times the three-phase value; similarly with No. 2 and No. 4. The theoretical ratio of two to three phase is 5.1 for the same number of slots per belt; when the above results are corrected on this latter score, they compare still more favorably with the theoretical ratio.

Compare No. 1 and No. 2, the only difference between which is the number of poles and the fractional pitch. In No. 1 ϕ_b* is twice as great because of the increased belt pitch and p is one half; therefore x_b should be four times as great were it not for the pitch-factor which is thus, 0.53, about the same as for the slots.

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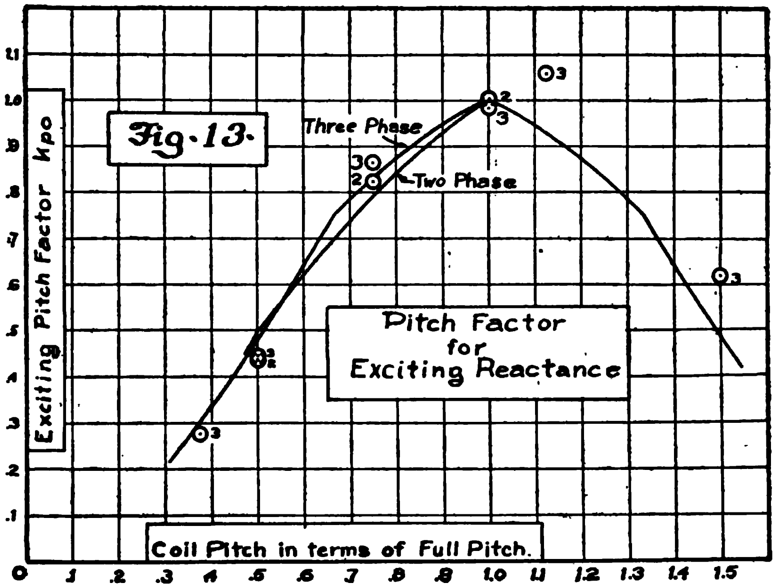
*See equation (6.)

Compare No. 2 with No. 5, the only difference being in the coil-pitch. The reason for the great reduction will appear from an inspection of Fig. 4, which represents the two layers of the ¾ pitch winding of No. 5. The effect of the overlapping of the two layers is to double the number of resultant belts and to decrease the phase difference between them to one-half. There is still an unbalancing of the magnetomotive forces due to the different magnitudes of the resultants, but this cannot be analyzed by means of equation (6).

Comparing No. 5 and No. 7, which differ only in phase, we find no such contrast as between No. 1 and No. 3. The reason for this will appear from the belt diagram of No. 7 shown in Fig. 4a; namely, that the maximum belt width is here reduced to only ¾ of its original value, whereas in No. 5 it was reduced to onc-half. In fact, the maximum belt width is the same in No. 5 and No. 7, although they are two and three-phase respectively.

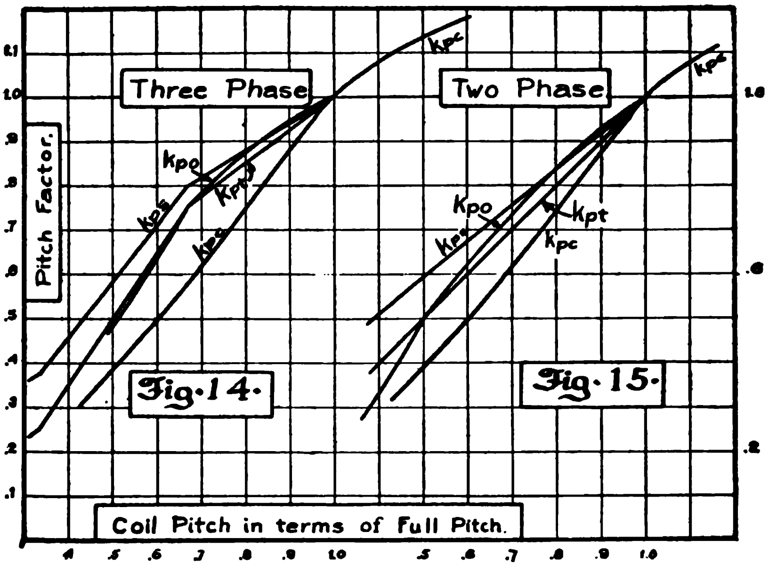

Fig·13·

The result of this analysis is to show that the fractional pitch effect on belt leakage is largely dependent upon the relation between the coil-pitch deficiency and the belt-pitch, and that a proper choice of this relation makes a relatively very large reduction in the belt leakage, especially in a two-phase motor.

Such a choice also smoothes out the large kinks of the current distribution, and has much the effect of doubling the number of phases.

Exciting reactance. The exciting reactance was determined from the open-circuit tests made with rotor standing in the position of maximum reactance, namely, with the rotor teeth opposite the stator teeth.

In order to make the results comparable and thus be able to determine the pitch-factor, the exciting reactances were all reduced to a three-phase two-pole basis by multiplying by $\frac{p' p^2}{3}$. In addition to this, the two-phase reactances were multiplied by 1.10 in order to eliminate the difference between the differential-factors of the two and the three-phase motors at full pitch.



In Fig. 13, the observed values of the pitch-factor for the exciting reactance are plotted together with the theoretical curves. No satisfactory explanation has been offered for the considerable deviation of the two high points on the right of the figure.

Summary

All the principal pitch-factor curves for the three-phase motor are assembled in Fig. 14, and those for the two-phase motor in Fig. 15.

To sum up, the effects of a fractional pitch winding are:

a. A reduction of the several components of the leakage reactance.

b. A reduction of over-all length of the motor.

c. In some cases, a considerable gain in the convenience of winding as well as a saving of space.

d. A decrease in the exciting reactance; that is, higher densities in all parts of the magnetic circuit and a higher exciting current for the same voltage.

It will be observed that except for the reduction in endwise length over windings, the effect of fractional pitch is the same as that produced by reducing the number of active conductors, but although the latter method is in many cases the more efficient from the standpoint of operation, the former is frequently more convenient from the standpoint of the manufacturer, even when the saving in endwise length is not a controlling factor.

There are, however, cases of high-speed motors where the fractional pitch winding is more efficient from every standpoint than the full pitch winding of fewer turns.

As an example of a fractional-pitch problem, consider a three-speed, three-phase induction motor. The comparative constants for the three speeds are given in the following table:

Poles.	rev. per min.	Relative gap density	Relative core density.	Relative exciting current.	Relative reactance.	Relative safe output	Power-factor
4	1800	0.77	115	59	95	103	0.93
6	1200	100	100	100	100	100	0.90
8	900	154	115	237	75	84	0.76

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

ZIGZAG LEAKAGE OF INDUCTION MOTORS

BY R. E. HELLMUND

Various formulas have been given heretofore for the predetermination of the leakage coefficient of induction motors, but the results derived from these formulas are so divergent that the formulas themselves are rather discredited. It seems to the writer that the following study about the values of the zigzag leakage may help to clear this somewhat unsettled question.

In the study of induction motors the leakage coefficient is one of the most important factors, and therefore this value will be chiefly discussed in what follows. Unfortunately the definition of this value is very unsettled in practice. Some writers when deriving the induction motor theory introduce the leakage coefficient as a ratio of magnetic reluctances in the motor, and others introduce it as a ratio of fluxes which exists while no secondary reactance takes place. These two different definitions may be represented by the two following equations:

$$\frac{R_s}{R_p} = \tau_1 \tag{1}$$

where R_s = the reluctance of the flux being interlinked with the secondary windings, R_p = the reluctance of the flux being interlinked with the primary winding, and τ_1 = the primary leakage coefficient.

$$\frac{F_p}{F_s} = \tau_2 \tag{2}$$

where F_p = the flux being interlinked with the primary winding, F_s = the flux being interlinked with the secondary winding, and τ_2 = the primary leakage coefficient.

Two other definitions which are frequently used are as follows:

$$\frac{R_p}{R_e} = \tau_3 \qquad (3)$$

where R_p is again equal to the reluctance of the total flux interlinked with the primary winding, R_e = the reluctance of that part of the flux which is interlinked with the primary winding but not with the secondary winding, and τ_3 = the primary leakage coefficient.

$$\frac{F_e}{F_p} = \tau_4 \qquad (4)$$

where F_p = the total flux interlinked with the primary winding, F_e = that part of the flux which is interlinked with the primary winding but not with the secondary winding, and τ_4 = the primary leakage coefficient.

Since

$$F_p = F_s + F_e$$

we may easily find

$$\tau_3 = \frac{1}{1 - \tau_4}$$

Similarly, a relation between τ_1 and τ_2 may be established.

It is, therefore, always possible to find the values τ_1 and τ_2 if τ_3 and τ_4 are known, so it will be sufficient to deal in the following with the two latter values only. For instance, a three-phase motor with one slot per pole per phase in both members has been chosen. Fig. 1 shows the arrangements of the slots and windings, and the rotor in such position that the stator and rotor teeth do not coincide. It is simple to trace all the possible paths of the magnetic fluxes as shown by dotted lines. Moreover, in order to find the values of all the existing fluxes, it is simplest to treat the magnetic circuits as electric circuits. Fig. 2 gives the magnetic circuits reproduced from Fig. 1 as electric circuits. In all places where a flux passes through air a resistance has been introduced, while the practically very small reluctance of the magnetic paths in the iron has been neglected. The magnetomotive force which the primary magnetizing current impresses upon the primary teeth has been replaced by electromotive forces, E_1, E_2, and E_3. It can be easily shown that the magnetomotive forces in opposite teeth must be equal in value and in direction, and therefore that all current fluxes in directly opposite parts of the system must correspondingly be equal in value and opposite in direction. This has been taken into account in numbering the circuits and in assuming the current direction as indicated by arrows.

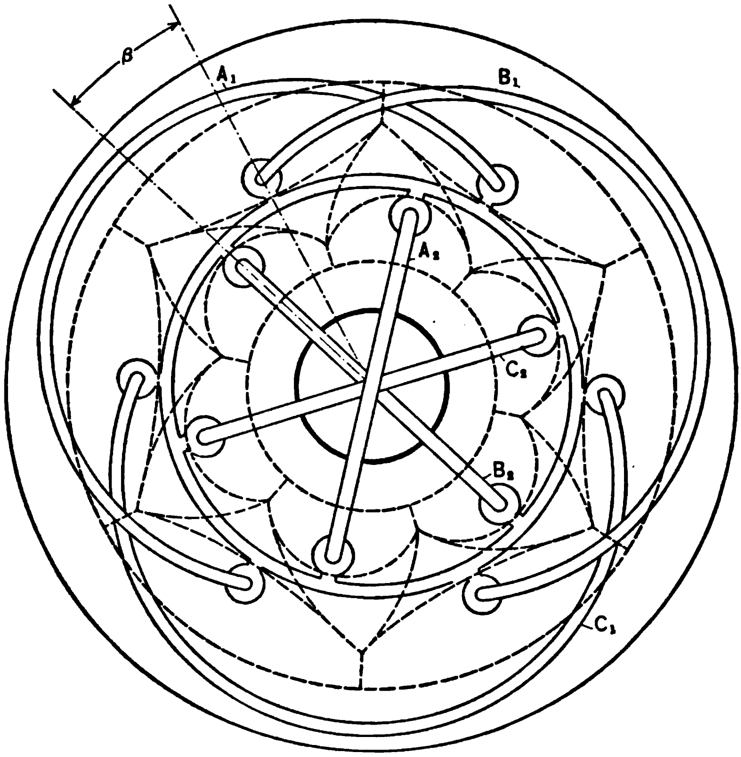


Fig. 1

It would now be possible to find all the values of the various fluxes and then to determine the value of the zigzag and slot leakage together. The zigzag leakage alone may be found simply by omitting the slot leakage fluxes in the further calculation, although thereby a small error in the values of the primary fluxes is introduced the same are of no practical importance at all, the slot leakage being mostly less than 1% of the total primary field. It is obvious from the figures that the resistances of the circuit 4, 5, and 6 are equal, and that also the resistances of the circuits 8 and 9 are equal. If, therefore, we put

$$r_4 = r_5 = r_6 = b$$
$$r_7 = r_8 = r_9 = a$$

and

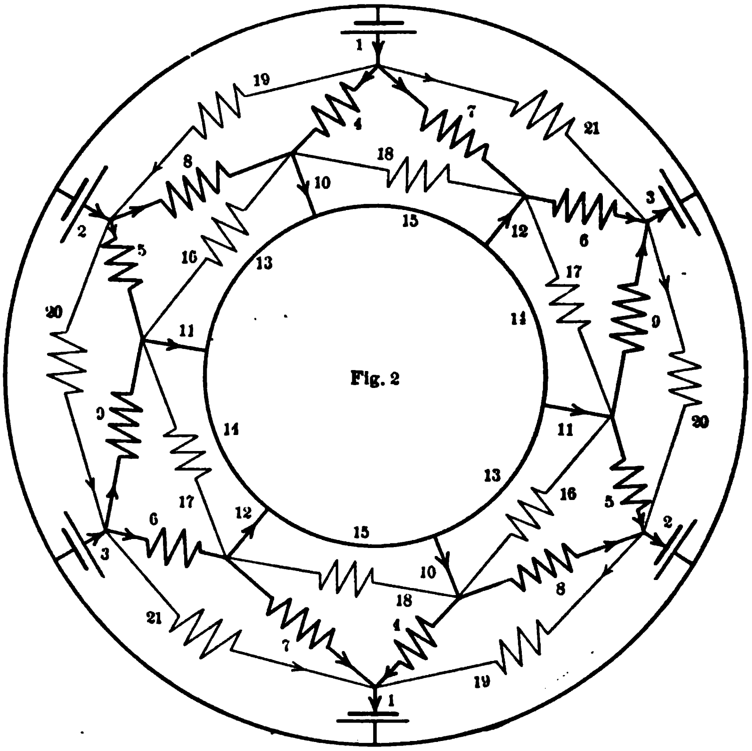


FIG. 2

we find from Fig. 2

$$E_1 - F_4 b + F_8 a - E_2 = 0$$
$$E_2 - F_5 b + F_9 a - E_3 = 0$$
$$E_3 - F_6 b + F_7 a - E_1 = 0$$

and

$$F_4 b - F_7 a = 0$$
$$F_5 b - F_8 a = 0$$
$$F_6 b - F_9 a = 0$$

From this we find

$$\left.\begin{aligned}
F_1 &= E_1\left(\frac{1}{a}+\frac{1}{b}\right)\\
F_2 &= E_2\left(\frac{1}{a}+\frac{1}{b}\right)\\
F_3 &= E_3\left(\frac{1}{a}+\frac{1}{b}\right)
\end{aligned}\right| \tag{5}$$

and

$$\left.\begin{aligned}
F_{10} &= \frac{E_1}{b}+\frac{E_2}{a}\\
F_{11} &= \frac{E_2}{b}+\frac{E_3}{a}\\
F_{12} &= \frac{E_3}{b}-\frac{E_1}{a}
\end{aligned}\right| \tag{6}$$

Now we know that the currents flowing in the primary windings are 120°, shifted against each other, and may, with open secondary circuits, be assumed to be sinusoidal.

It may be

$$\begin{aligned}
i_{b_1} &\equiv \cos(x+240)\\
i_{a_1} &\equiv \cos x\\
i_{c_1} &\equiv \cos(x+120)
\end{aligned}$$

We find, therefore, the magnetomotive forces

$$\left.\begin{aligned}
E_1 &= \cos x+\cos(x+240) = -\cos(x+120)\\
E_2 &= \cos x\\
E_3 &= \cos x+\cos(x+120) = -\cos(x+240)
\end{aligned}\right| \tag{7}$$

It follows now from 5 and 7

$$\left.\begin{aligned}
F_1 &= -\cos(x+120)\left(\frac{1}{a}+\frac{1}{b}\right)\\
F_2 &= \cos x\left(\frac{1}{a}+\frac{1}{b}\right)\\
F_3 &= -\cos(x+240)\left(\frac{1}{a}+\frac{1}{b}\right).
\end{aligned}\right| \tag{8}$$

and from 6 and 7

$$\left.\begin{aligned} F_{10} &= -\frac{\cos(x+120)}{b}+\frac{\cos x}{a} \\ F_{11} &= \frac{\cos x}{b}-\frac{\cos(x+240)}{a} \\ F_{12} &= -\frac{\cos(x+240)}{b}+\frac{\cos(x+120)}{a} \end{aligned}\right| \qquad (9)$$

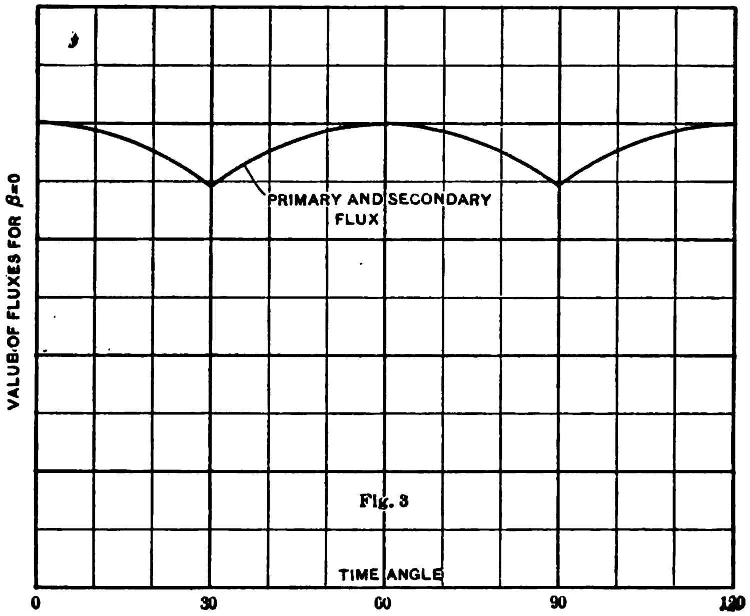


Fig. 3

It is now obvious that after the values a and b have been determined from Fig. 1 for a certain rotor position, the primary flux may be found for any time-angle, x, by simply adding arithmetically the values being found for F_1, F_2, and F_3 for this time-angle; in the same way the secondary flux may be found by adding the values of F_{10}, F_{11}, and F_{12}.

In Fig. 3 the primary and secondary flux as found in this way have been given as a function of the time for the rotor position for which the angle β, Fig. 1, is 0.

As will be seen, both fluxes change with the time,* but primary and secondary fluxes are always equal; this means that for this rotor position no zigzag leakage flux exists, and the leakage coefficient $\tau_4 = 0$.

In Fig. 4 the primary and secondary fluxes are given for a rotor position for which $\beta = 15°$; that is, for a position where the rotor slots are shifted about one-quarter tooth against the stator slots. It will be seen that both fluxes change again with the time, but their values are now different from each other. It is obvious that at any moment the difference between the primary and secondary fluxes represent the leakage flux. Fig. 5 gives the value of τ_4 as a function of the time as found from Fig. 4. The maximum value of τ_4 is for this rotor position about 0.177, and the average value may be found to be about 0.097.

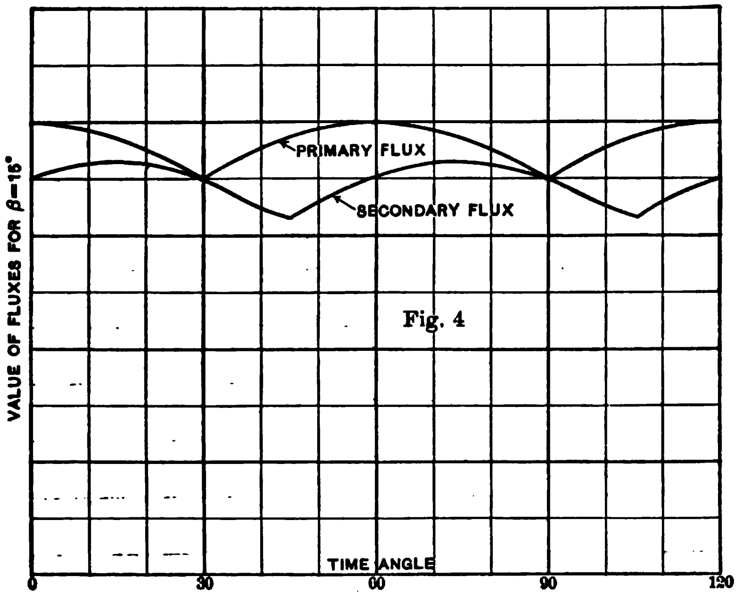


FIG. 4

Figs. 6 and 7 give the same curves as Figs. 4 and 5, but for a rotor position for which $\beta = 30°$; that is, for a position where the rotor slots are shifted about one-half tooth against the stator slots.

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* See study about the rotating field, *Electrical Review*, September 22, 1906.

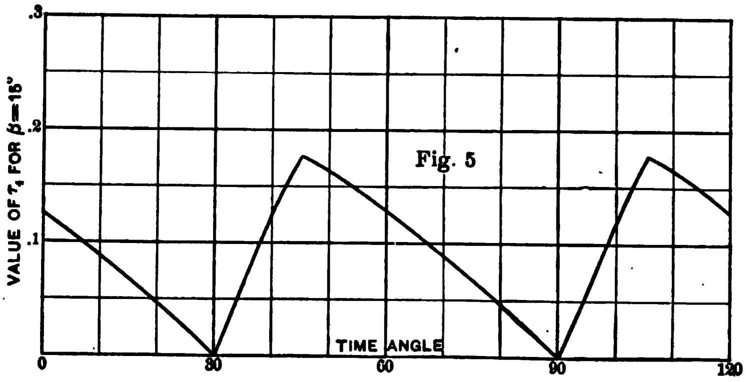

Fig. 5

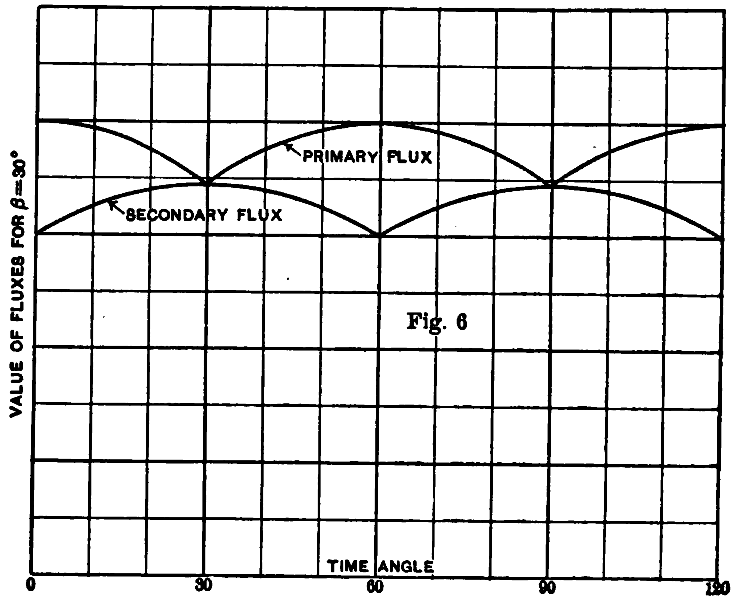

Fig. 6

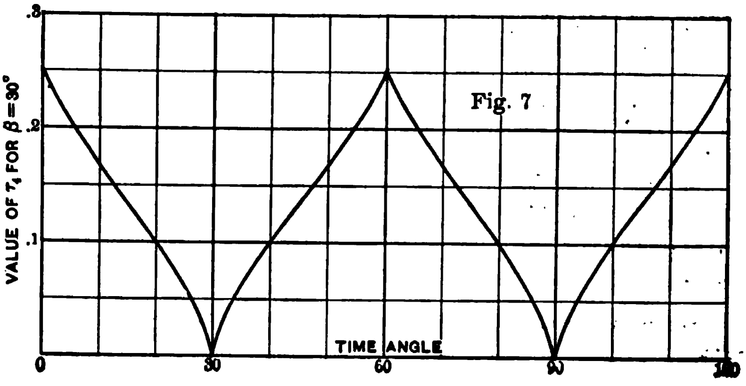

Fig. 7

In this case the maximum value of $\tau_4 = 0.25$, while the average value may be found to be about $\tau_4 = 0.134$.

It remains now to find what influence the magnetic leakage as found before has upon the value of the potentials being induced in the secondary circuits.

The potential induced in coil A_1 will be

$$e_{a1} \equiv \frac{d\,(F_1+F_2+F_3)}{d\,x}$$

or

$$e_{a1} \equiv \frac{d\,(E_1+E_2+E_3)}{d\,x} \left(\frac{1}{a}+\frac{1}{b}\right) \tag{10}$$

or

$$e_{a1} \equiv \frac{d\,(2\cos x)}{d\,x} = -\,2\sin x$$

For the potential induced in coil A_2 we find in a similar way,

$$e_{a2} \equiv \frac{1}{a}\,(-\,E_1 + E_2+E_3) + \frac{1}{b}\,(E_1+E_2+E_3)$$

or

$$e_{a2} \equiv \frac{1}{a}\,\frac{d\,[2\cos\,(x-60)]}{d\,x} + \frac{1}{b}\,\frac{d\,(2\cos x)}{d\,x}$$

$$e_{a2} \equiv -\frac{2}{a}\sin\,(x-60) - \frac{2}{b}\sin x \tag{11}$$

It is now simple to find the maximum value of the potential in coil A_1,

$$e_{a1}\ \text{max.} \equiv 2$$

and the effective potential in coil A_1

$$e_{a1}\ \text{eff.} \equiv \frac{2}{\sqrt{2}} \tag{12}$$

The maximum value of the potential in coil A_2 is obtained for

$$\frac{2}{a}\cos\,(x-60) \equiv -\frac{2}{b}\cos x \tag{13}$$

It is now possible to find for any ratio of a to b; that is, for any rotor position from 13 the value of x for which the secondary potential reaches its maximum, e_{a2} maximum. Curve A in Fig. 8 gives the relation between the rotor position and the time-angle x, for which the secondary potential reaches the maximum value. After this curve has been determined, it is pos-

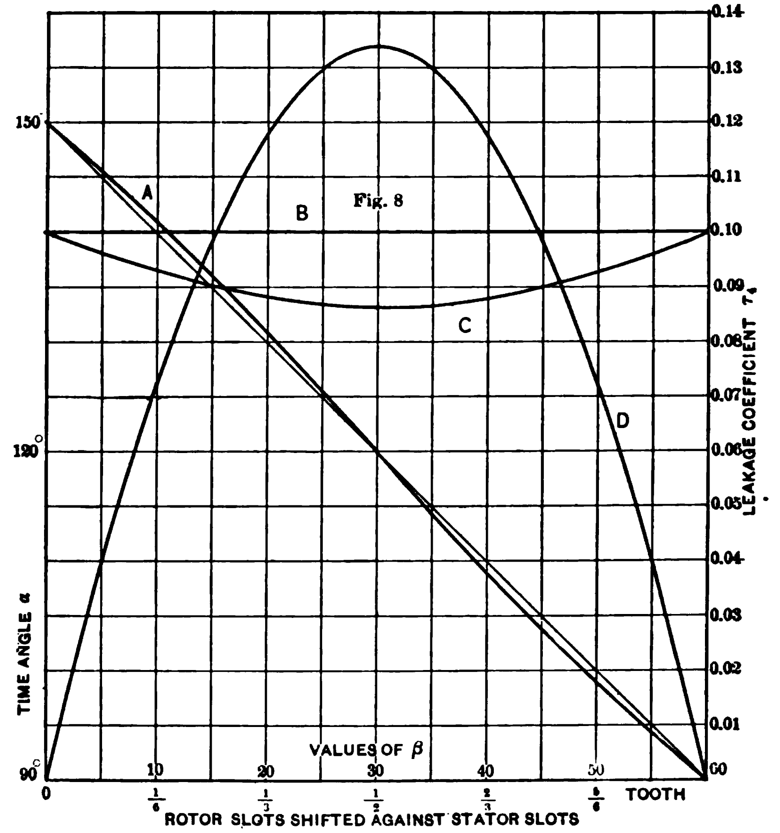

FIG. 8

sible to find from 11 the maximum and the effective potential induced in the secondary winding. Curve C gives the secondary potential as found for different rotor positions. Curve B gives the primary potential as found from 12: the same is, of course, independent of the rotor position, on the assumption that the air-gap is uniform and that the influence of the slot openings may be neglected. Curve D represents the following value:

$$y \equiv \frac{e_{a_1}\,\mathrm{eff} - e_{a_2}\,\mathrm{eff}}{e_{a_1}\,\mathrm{eff}}$$

where the value of e_{a_1} effective and e_{a_2} effective are taken from curves B and C.

A comparison of the average values for τ_4 as found from Figs. 3 to 7, with the values of y for the same rotor positions, shows that

$$\tau_4 \equiv y$$

This shows for the case under consideration the correctness of the partly customary method for determining the leakage coefficient τ_4 from tests, which consists in testing the primary and secondary potential of a motor and in assuming,

$$\tau_4 = \frac{e_{a_1}\,\mathrm{eff} - e_{a_2}\,\mathrm{eff}}{e_{a_1}\,\mathrm{eff}} = \frac{F\,e}{F\,p}$$

As the average value for τ_4 we find from curve D,

$$\tau_4 \text{ average} \equiv 0.081.$$

The fact that curve D is not a straight line shows that it is not admissible to assume the leakage coefficient equal to the average of its maximum value and its minimum value, as has been done by various authors. The mistake which would thereby be introduced in the case under consideration is quite considerable. The average of the maximum value of τ_4 and its minimum is

$$\frac{0+0.134}{2} = 0.067;$$

that is, about 20% different from the real average value 0.081.

Fig. 9 shows the rotor in its position for $\beta = 30°$. A glance on this figure shows that τ_3 according to its previously given definition is $0.333 = \frac{1}{3}$, since the total primary flux of course passes through three teeth, while the leakage flux passes through $(2\times\frac{1}{2})$ tooth only. The ratio of the resistances of the two paths is therefore

$$\tau_3 = \frac{\frac{1}{3}}{2\times\frac{1}{2}} = \frac{1}{3}$$

The value of τ_4 for the same position was 0.134, and we see therefore that τ_4 and τ_3 are two entirely different values; in the case under consideration their difference amounts to more than 100%. This shows that it is of the highest importance in any study of the induction motor to make a strict distinction between the two values.

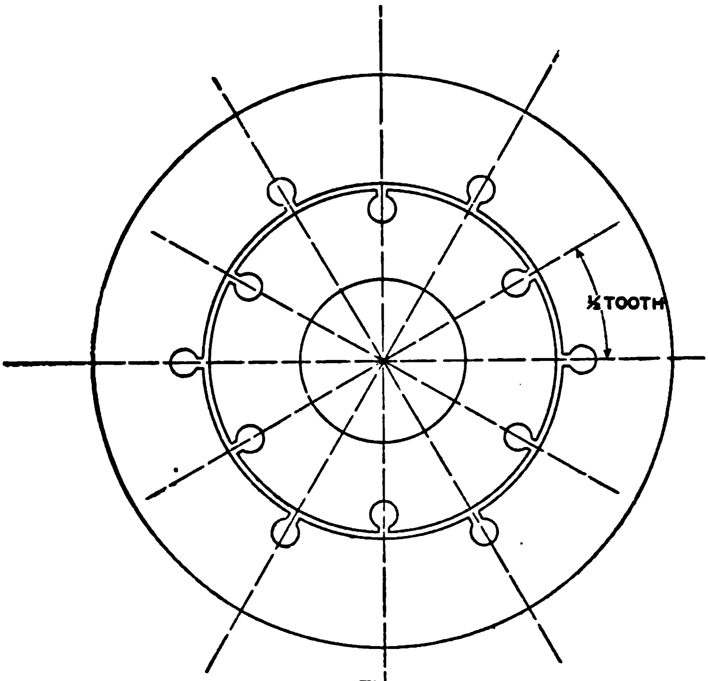

Fig. 9

The explanation of the phenomena causing the difference between τ_3 and τ_4 is comparatively simple. It is obvious that if the magnetomotive force and therefore the density over one pole face should be uniform, the values τ_3 and τ_4 would be equal. Since, however, the magnetomotive forces, and therefore the densities near the pole limits, are considerably smaller than near the center of the pole, it is obvious that the flux near the pole limits which forms that part of the flux which does not thread the secondary windings (*i.e.*, the leakage flux) must be much smaller than it would be in case of a uniformly distributed field.

It seems to the writer that in deriving the diagram of the induction motor the value τ_4 should be used, since for the field diagram the actual ratio of the various fields and not the reluctance of their paths is of interest. To introduce the value of τ_3 as leakage coefficient, as has been done by Heyland, Behn-Eschenburg, and others, is not correct unless another coefficient giving some ratio between the magnetomotive force of the main field and that of the leakage fields be introduced. The previous considerations apply, of course, to the zigzag leakage only, but it is obvious that similar facts apply to the other kinds of leakages.

The previous considerations were dealing with the leakage coefficient as determined on the assumption that no secondary reaction takes place. The coefficient τ_4 as previously determined would be the right value upon which the theories for the load conditions might be based, if the secondary reaction would be caused by sinusoidal secondary currents only for all load conditions. For the blocked rotor condition of the motor, that is, for the starting condition, this condition is fulfilled. Assuming that sinusoidal electromotive forces are impressed upon the motor we have found that all the fluxes in the motor are sinusoidal functions of the time, we also have found that the electromotive forces induced in the secondary circuits are sinusoidal. If, therefore, the secondary circuits are closed, the currents flowing will be sinusoidal and the reactions caused by secondary currents will be sinusoidal functions of the time

For all other load conditions the phenomena are not quite as simple. If the field set up by the primary windings had a sinusoidal space distribution over the poles, and if it were constant in value, and if it rotated with uniform speed, then all potentials induced in the secondary and, therefore, the currents in the secondary and the magnetic reactions, would be always sinusoidal, no matter what the speed of rotation of the rotor. This is, however, not the case. The curves given in Figs. 3, 5, and 7, for the total value of the primary field show that the latter varies in its strength.

We also may conclude from the previous considerations that the field does not rotate with uniform speed. If the field rotated with uniform speed, curve *A* of Fig. 8 would have to be a straight line. The speed of the field as a function of the time may be easily found from Fig. 8, curve *A*, and is shown by curve *A* in Fig. 10.

It also may be shown that not only the speed of the field as a whole varies, but that the speeds of the various parts of the field are different from each other, and vary with the time. If, therefore, the rotor rotates with a certain speed, the electromotive forces induced in the rotor windings are not only due to the slip, but there are also certain electromotive forces induced by the fluctuations of the strength of the primary field and by the irregularities in the speed of rotation of said field. (There is, of course, a possibility that the irregularities of the strength of the field and those of the speed of the field eliminate each other in their effect upon the secondary windings; it may be shown, however, that this is not the case.)

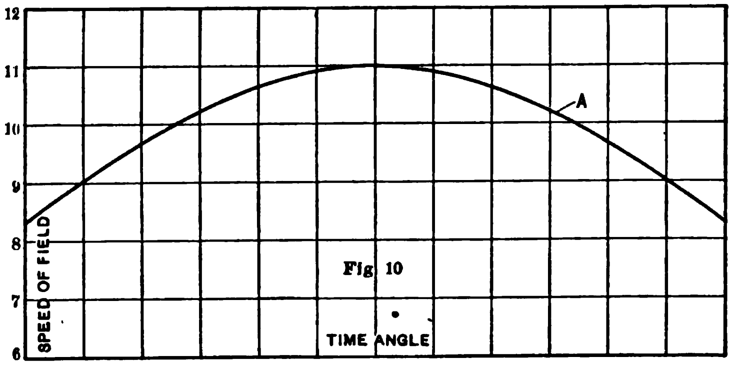

Fig. 10

It seems almost impossible to determine the exact phenomena for all load conditions. It is possible, however, to find pretty exactly what happens while the motor is running under no load. It can be shown that, while the rotor is running synchronously with a uniform speed the secondary reaction will cause the field distribution over the pole faces to have a step-form of such a shape that the area of each step is equal to the corresponding area of a sine wave. (See Fig. 11.)

The above causes of the secondary reaction have been partly discussed by other writers. A detailed and pretty complete account of them as well as a derivation of the field shape for the no load condition have been given by the writer in a study given in the *Electrical Review*, September 22, 1906.

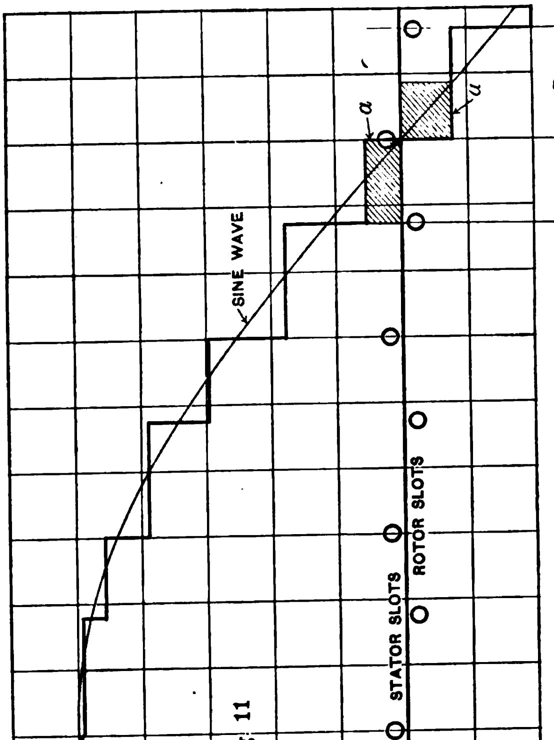

Fig. 11

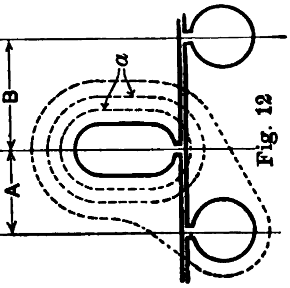

Fig. 12

The fact that the field has a distribution as outlined above gives a very simple way to determine the zigzag leakage coefficient as defined under 4, but, for the no-load condition.

If we consider the teeth near the pole limit (Fig. 12), we see that the primary zigzag leakage flux at one pole limit can never be larger than the flux a going through the smallest air-gap A

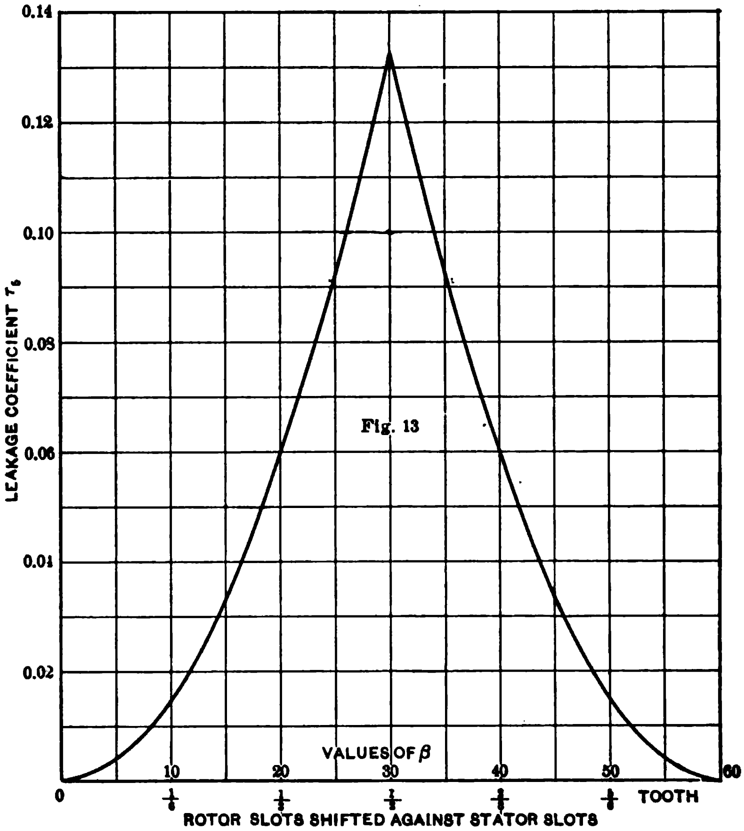

Fig. 13

to the rotor, while, except for the rotor position where $A = B$, part of the flux going through the air-gap B interlinks with the secondary conductors and only the remaining part A is leakage flux The flux through A is, however, proportional to the smallest step of the area representing the flux distribution (see Fig. 11). We may therefore define the zigzag leakage coefficient for the light running motor as follows:

$$\tau_5 = \frac{2 \times \text{area of smallest step}}{\text{Total flux area per pole}}$$

The coefficient 2 has to be introduced because each pole has two pole limits.

Now we know that the area a equals always the corresponding area of a sine wave. If the angle of the area a is β, we have

$$a = \int_0^\beta \sin x \, d x = 1 - \cos \beta$$

The total flux per pole is 2, therefore, the leakage is

$$\tau_5 = \frac{2\,(1 - \cos \beta)}{2} = 1 - \cos \beta$$

For the case under consideration the maximum leakage is obtained again for position Fig. 9, that is, for $\beta = 30°$.

Fig. 13 shows the leakage coefficient τ_5 as a function of the rotor position. A comparison of this curve with curve D of Fig. 8 shows that the leakage for the light running motor is entirely different from what it is for the stationary rotor.

The maximum value of τ_5 is 0.134; that is, the same as that of τ_4, but the average value for the various rotor positions is for τ_5 only 0.046, while that of τ_4 is 0.081.

It is simple to determine τ_5 for any number of slots per pole. If n is the number of slots per pole, the maximum leakage coefficient τ_5 is always:

$$\tau_5 \text{ maximum} = 1 - \cos \frac{\pi}{2\,n}$$

(equal number of slots for stator and rotor being assumed) and for the average value we find

$$\tau_5 \text{ av.} = \frac{2\,n}{\pi} \int_0^{\frac{\pi}{2n}} \tau_5 \, d\beta = \frac{2\,n}{\pi} \int_0^{\frac{\pi}{2n}} (1 - \cos \beta) \, d\beta$$

$$\tau_5 \text{ av.} = \frac{2\,n}{\pi} (\beta - \sin \beta) \Big|_0^{\frac{\pi}{2n}} = \underline{\underline{1 - \frac{2\,n}{\pi} \sin \frac{\pi}{2\,n}}}$$

The values as obtained from this last formula for different values of n are given in Fig. 14.

The fact that the leakage coefficient varies with the load condition makes it rather difficult to obtain an exact value for the various conditions between the no-load and blocked-rotor conditions. The writer has shown, in an article published in the *Electrical World*, that the secondary reaction of the light running motor does change not only the field distribution but also the wave shape of the no-load magnetizing current. It

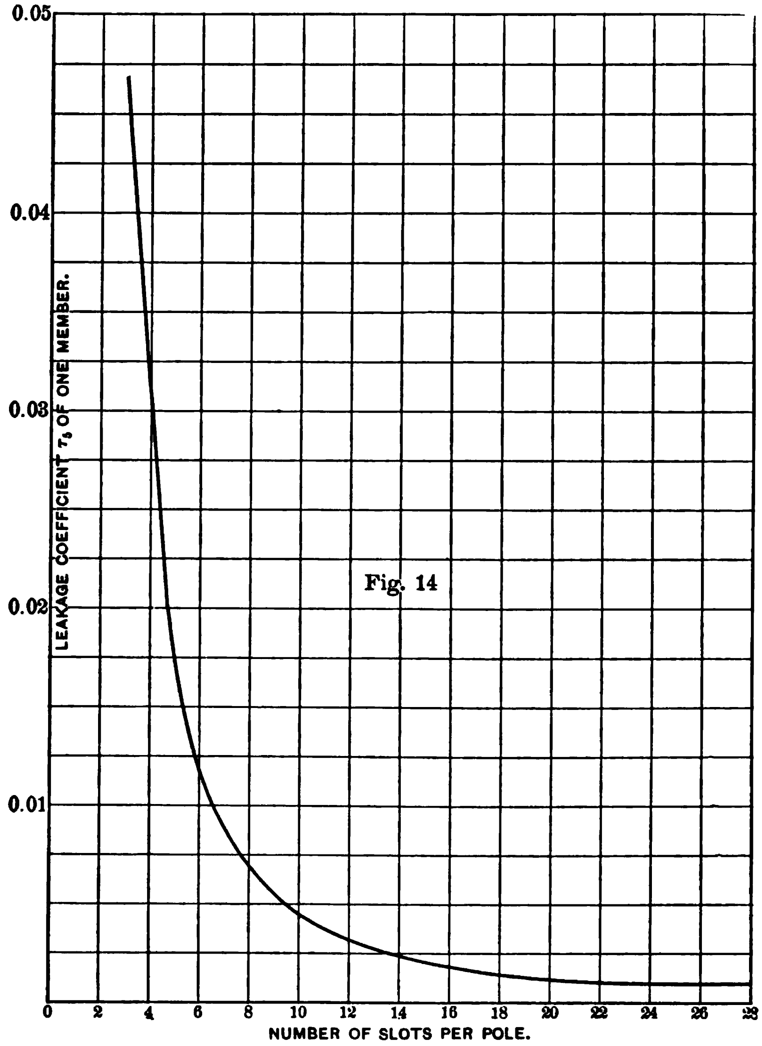

Fig. 14

remains to be investigated how the load currents combining with the magnetizing currents for the running motor are in their general character, wave shape, etc., before any final conclusions can be made. It seems reasonable, however, to assume that the right value for the leakage coefficient for the load conditions will be somewhere between τ_4 and τ_5. In fact, the writer observed quite frequently that the currents for low loads have a better power-factor than found from the diagram which is derived from the blocked-rotor condition. Of course it is necessary to be very careful in concluding from tests, since the change of the leakage coefficient, caused by the fact that the reluctance of the iron is not constant, may influence the results considerably. The writer has shown in an article in the *Electrical Review*, Jan. 29, '07, that the change of the leakage coefficient caused by the changing reluctance of the iron may amount to as much as 50% between no-load and blocked-rotor condition in commercial motors. Since these changes tend, however, to change the leakage so as to decrease it when the motor decreases in speed, the tests showing a power-factor for low loads, which is better than derived from the blocked-rotor test, seem to confirm the above theories.

It may appear that the previous considerations being of a rather theoretical nature will be of little practical value, since no final formula for the zigzag leakage for the various load conditions has been given. The more surprising it will be if the writer states that this paper is the result of an attempt to give an exact and practical formula for the calculation of the leakage coefficient. This paper should, therefore, be considered more as a preliminary work, which is merely intended to bring out certain facts which must be considered in connection with any study about the leakage coefficient.

It is obvious that in constructing a practical formula for the leakage coefficient it will be necessary on account of the rather complicated nature of the real phenomena to admit certain inexactnesses into the formula. Since this is the case it might seem advisable to use one of the existing formulas, as for instance, the one known as the Behrend formula. Although this latter formula gives for motors of standard design fairly exact values, the same seems to be to the writer objectionable for two reasons. A change of the slot dimensions will, for instance, according to this formula, change the value of the leakage considerably, while, in motors with a large number of slots per pole, a change of the slot dimensions does not affect the leakage very much. On the other hand, a change of the ratio of the pole-pitch to the width of core will, according to the formula, affect the leakage also considerably; while, in a motor with a small number of slots per pole, said ratio has little influence on the total amount of the leakage.

Since the various kinds of leakage are not dependent upon each other, a formula for the leakage should take them into consideration separately. A formula of this kind is the latest formula given by Behn-Eschenburg. This formula, however, gives, as mentioned before, the zigzag leakage coefficient as defined by formula 3 and the values for the zigzag leakage are, therefore, considerably too large. Moreover, the dimensions of the slot are not taken into consideration at all, and the so-called belt leakage discovered by Professor Adams* is also neglected. In spite of this, the latest Behn-Eschenburg formula gives also fairly exact values for the total leakage coefficient for standard motors, and the formula is fairly simple.

During several years of designing practice, the writer has become more and more convinced that the simplest formula is not at all the most practical one. In order to obtain a well-designed machine in which the best results are obtained from a certain amount of material, it is absolutely necessary for the designer to have formulas which not only give a fairly exact total result, but which also indicate in a fairly exact way the results of any change made in the design. If, for instance, the change of the slot dimensions has a noticeable influence on the performance of the motor, the designer should be able to know how much this influence amounts to. On the other hand, it seems to the writer perfectly indifferent whether the designer requires one minute or five minutes to determine the leakage coefficient of an induction motor while he is laying out a new line of machines, as long as even a small advantage may be obtained by spending five minutes instead of one. For routine design work, which, of course, should be done as quickly as possible, formulas are used very little, because most factors are usually known from previous tests.

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* The writer does not want to fail to call attention to the very valuable work about the determination of the induction motor leakage, done by Professor Adams. This paper is published in the *Transactions* of the International Congress of St. Louis.

DISCUSSION ON "FRACTIONAL PITCH WINDINGS FOR INDUCTION MOTORS", AND "ZIGZAG LEAKAGE OF INDUCTION MOTORS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907.

J. C. Lincoln: Have experiments been made to determine the relative importance of the three kinds of leakage found in induction motors?

1. The leakage across the slots.
2. The leakage across the gap, or so-called zigzag leakage.
3. Leakage in the end-connections of the stator winding.

Have experiments been made to determine the relative importance at full-load of these three sorts of leakages with reference to the main or useful flux?

Chas. P. Steinmetz: I want to call attention to one point that Professor Adams did not touch on, and that is with fractional pitch windings the extra insulation necessary plays an important factor in the design of both the motor and the alternating-current generator. That is, if we assume a Y-connected machine, three-phase, and use a fractional pitch we have increased insulation necessary on the end-windings where the opposite phases come together in the same slots. This has quite an effect on the design. I think that the vast majority of the motors we are building to-day of the induction type are built with fractional pitch windings as are also most of the alternators.

B. T. McCormick: I ask whether the claim for extra insulation is on the end-connectors or in the slots?

Chas. P. Steinmetz: The insulation is progressive; that is, if we start from the neutral point as we go out from the neutral point the extra insulation is necessary, because we have the full potential between phases instead of the potential from the winding to the neutral point.

Comfort A. Adams: Referring to the effect of fractional pitch upon the exciting current—I should like to point out that not only is the electromotive force induced in a fractional pitch winding by a given flux, less than that of a full-pitch winding, but the magnetomotive force and the flux produced by a given current with fractional pitch is less than that for full pitch. In other words, fractional pitch introduces differential action both in the electromotive force and in the magnetomotive-force generation. The two differential factors are fully treated in my paper.

It was stated by one of the speakers that if the magnetizing current increased in the same proportion as the reactance decreased, there would be no resulting gain in power-factor. That there is in some cases a very decided gain will be apparent when it is remembered that these two elements vary approximately in reciprocal relation. Take, for example, a motor in which the exciting current is 14% of the load current and the reactance electromotive force 30% of the induced electromotive force; assume that the pitch of the winding is reduced in such a way that the exciting current is increased one- and a-half times its original value, namely to 21%, then the reactance will be reduced to approximately two thirds of its original value, or about 20%, giving thus a total quadrature component of 41% in place of 44% for the full pitch winding, which means a material improvement in the power-factor, to say nothing of the increase in starting torque and break-down torque. Of course an appropriate reduction in the number of primary conductors would have approximately this same effect.

The extra insulation required by fractional-pitch windings would hardly be an item of any importance in induction motors of ordinary voltage, but might easily take on considerable proportions in high-voltage alternators.

A. S. McAllister: The problem of determining the exciting current or the " wattless volt-amperes " is rendered very simple when the solution is based on the fact that any energy that is magnetically stored in the field during any part of the cycle must be restored during the next part of the cycle, in any machine which has an alternating flux. Of course, the relation just stated does not hold in the case of the synchronous motor, where magnetic energy is initially stored in the exciting field but not given out during any part of the cycle. If, in the induction motor, we find the volume of the main magnetic path and divide it by the permeability, and find the volume of the teeth and divide that by the permeability, and find also the volume of the air gap and divide that by the permeability (which happens to be one) and multiply each of these values by the square of the flux throughout the respective paths, we can determine the value of the magnetic energy stored in each of the paths; this same magnetic energy is given out through each cycle. Therefore, the " quadrature watts " or the " wattless volt-amperes ", can be calculated just as one calculates the core-loss watts in a motor, or in any other apparatus in which the flux is alternating. This fact was mentioned during the Milwaukee meeting, at which time an equation was given for representing the actual value of the wattless volt-amperes.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907

THE VECTOR DIAGRAM OF THE COMPENSATED SINGLE-PHASE ALTERNATING-CURRENT MOTOR

BY W. I. SLICHTER

Although the compensated single-phase motor is simply a series circuit in physical connection, there are incidental reactions which have the effect of a combination of series and parallel circuits. These reactions have an effect on the efficiency and power-factor of sufficient importance to warrant a careful analysis of their character and cause.

As is well known, the motor circuits consist of an exciting field winding producing the field flux, an armature similar to that used in the usual direct-current motor, and a compensating winding wound in the faces of the poles and having its magnetic axis coincident with the axis of the armature reaction, but producing a magnetomotive force in the opposite direction. Thus, in Fig. 1 is shown the diagram of connections of a four-pole compensated series motor. *F*, *FF* is the exciting winding with coils surrounding the pole pieces, *C*, *CC* is the compensating winding from pole to pole; and *A*, *AA* is the armature circuit. The current passes through these three in series, and the main reactions of one member on the others are very simple.

But the coil in the armature undergoing commutation encloses the main exciting or torque-producing flux, and, as a result of the alternation of this flux at primary frequency, there is induced in the coil an electromotive force proportional to the primary frequency and to the magnitude of the flux. The brushes complete the circuit of this coil, and a current flows therein proportional to this electromotive force and inversely proportional to the impedance in the coil, brushes, and connections. This reproduces exactly the conditions existing in a transformer, the exciting winding *F* being the primary and the short-circuited coil *BB* being the secondary, as shown in Fig. 2.

In considering the reactions in the exciting winding, therefore, we must regard it as a complex circuit. The effect is the same as if the coil were shunted by an equivalent circuit having resistance and inductance, as at Y in Fig. 2. This equivalent circuit represents the hysteretic current, supplying the core-loss in the iron due to the alternation of the flux at primary frequency, and the current in the secondary coil *BB*.

Fig. 3 shows the relations of the various quantities in the exciting winding *F*. The resemblance to the transformer diagram will be noted. ϕ is the flux; the current which produces ϕ is $O F$, composed of $O B$ the wattless component and $O H$ the hysteretic component. $O A$ is the current in the secondary and this combines with $O F$ to form the primary or line current $O C = I_0$. $O E$, 90° ahead of the flux, is the electromotive force consumed in the primary circuit. Neglecting the impedance drop, which is very small in this case, the voltage across the terminals of the exciting winding is therefore $O E$.

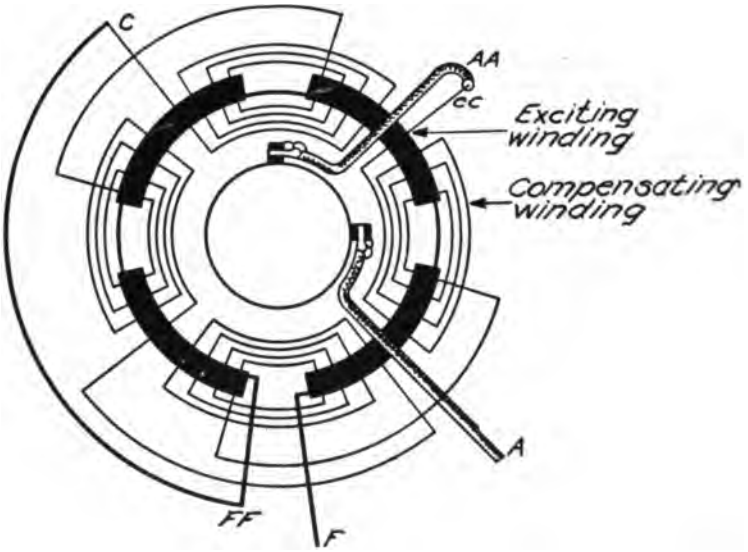


FIG. 1

In Fig. 4, we have this same diagram as a starting point for the general case. Thus, with a main current I_0, represented by $O A$, we have $I_H = A\,B$ for the energy current in the equivalent shunt circuit, and $I_M = O\,B$ the wattless component in both the primary and shunt circuits, but consisting principally of the primary magnetizing current.

The flux ϕ is in phase with $O\,B$ and proportional to this primary component of $O\,B$ (not to the main current) and the permeance of the magnetic path.

The electromotive force induced in the exciting winding is $I\,X_M = O\,E$, and is 90° ahead of ϕ. The electromotive force consumed by the leakage reactance of all the windings will be 90° ahead of I_0 and proportional to I_0. This is represented by $I\,X_L = E\,F$. The electromotive force consumed by resistance is $I\,R = F\,G$, in phase with I_0.

The counter electromotive force due to the rotation of the armature conductors in the flux must be in phase with ϕ, thus $G\,H = e_2$ (drawn parallel to $O\,B$) represents this electromotive force in phase, while its magnitude is proportional to the angular speed of the armature.

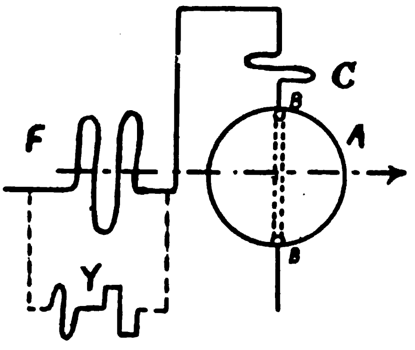


Fig. 2

The line potential E_0 is the resultant of all these components. Its magnitude determines the value of e_2, which in turn determines the speed. $O\,H$ represents the line potential, and the cosine of the angle $H\,O\,A = \gamma$ between E_0 and I_0 is the power-factor of the motor.

The product of $e_2\,I_0 \cos \alpha$ represents the output at the armature conductors. To obtain the true motor output, the armature core-loss, due to rotation, and the friction loss should be subtracted from this.

The calculation of power-factor and efficiency is made by starting with the displacement angle α whose sine is $I_H \div I_0$. Assuming the phase of I_0 as a reference point, we have the following resolution of the terminal electromotive force E_0:

Wattless	Energy
$I X_M \cos \alpha$	$I X_M \sin \alpha$
$I X_L$	$I R$
$-e_2 \sin \alpha$	$e_2 \cos \alpha$

The exact analytical expression of the reactions is as follows: Assume $e = I X_M$ the voltage across the exciting winding as reference vector or zero phase.

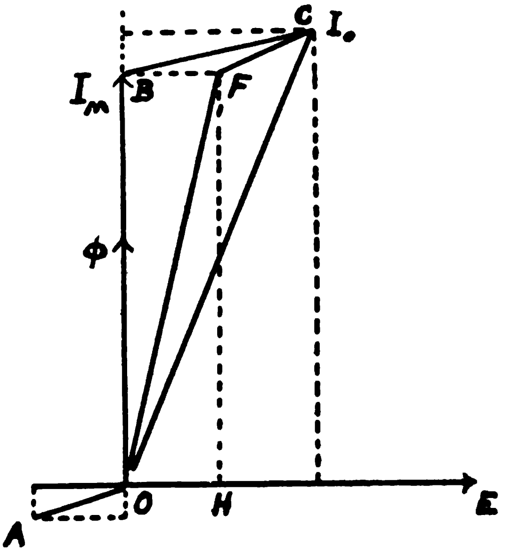


Fig. 3

Quantitatively $e = 4.44\, n N \phi\, 10^{-8}$

where: n = primary frequency.

N = number of exciting or field turns.

ϕ = flux per pole.

Admittance of exciting winding $= Y_1 = g_1 + j b_1$

Admittance of equivalent circuit $= Y_2 = g_2 + j b_2$

Admittance of combination $Y_x = Y_1 + Y_2 = g_x + j b_x$

Main line current $= I_0 = e\,(g_x + j b_x) = i_1 + j i_2$

Resistance of all circuits $= r$

Reactance (leakage) of all circuits $= x$

Impedance of motor (except exciting circuit) $= Z = r - j x$

Line voltage = E_0 is resolved into electromotive force of rotation e_2, electromotive force of excitation winding e, and the impedance voltage $I_0 Z$.

e_2 is in phase with the flux ϕ and 90° from e; therefore, if e is the base of vectors, the electromotive force of rotation is expressed in phase position by $j\, e_2$.

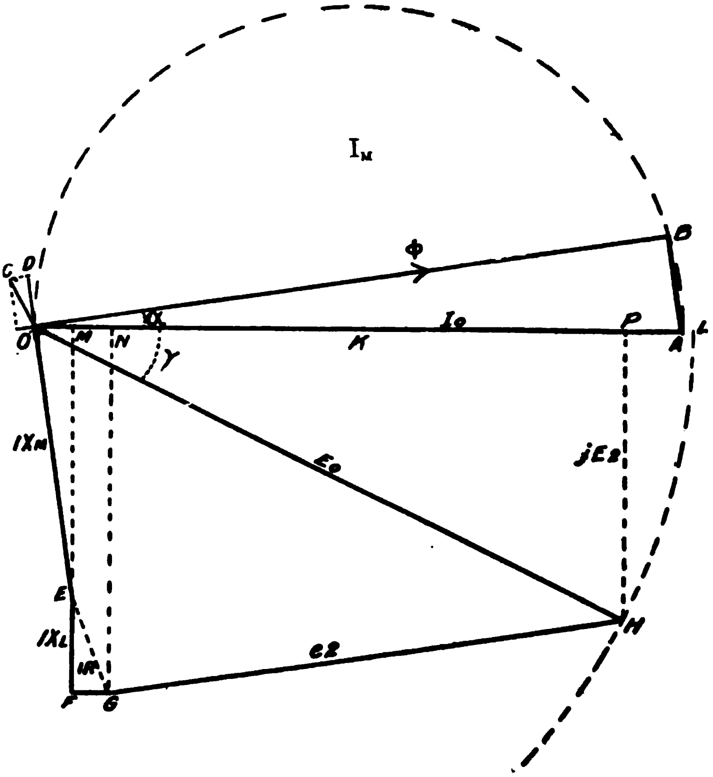


FIG. 4

Hence $E_0 = e + j\, e_2 + I_0 Z$
Substituting:

$$= e + j\, e_2 + (i_1 + j\, i_2)\,(r - j\, x)$$

$$= e + i_1 r + i_2 x + j\,(e_2 + i_2\, r - i_1\, x)$$

Reducing to absolute terms:

$$E_0^2 = (e + i_1 r + i_2 x)^2 + (e_2 + i_2\, r - i_1\, x)^2$$

Solving for e_2:

$$e_2 = \sqrt{E_0^2 - (e + i_1 r + i_2 x)^2} - (i_2 r - i_1 x)$$

The output at the armature conductors is the product of the counter electromotive force and the current in phase with it, $e_2\, i_2$.

Apparent input $= E_0\, I_0$

$$= [e + i_1 r + i_2 x + j\,(e_2 + i_2 r - i_1 x)]\,(i_1 + j\, i_2)$$

Power input is the real component of above.

$$= i_1\,(e + i_1 r + i_2 x) \ + i_2\,(e_2 + i_2 r - i_1\, x)$$

The peculiar features introduced by this equivalent shunt circuit are:

The counter electromotive force of rotation is not in phase with the main current, thus their product is not all energy.

The current in the armature I_0 is not in phase with the field flux, and the torque is not truly proportional to the current but is reduced by this displacement.

The more inductive the current in the short-circuited coil the less is this displacement, thus a resistance to limit the flow of current is not as valuable as some inductive effect.

The counter electromotive force e_2 being at an angle with the main current I_0, it is possible by increasing the speed and magnitude of e_2, or by increasing the angle α, to cause the point H to lie in $O\,L$ produced, thus making E_0 coincide with I_0, giving unity power-factor, or to cause e_2 to cross I_0, giving a leading current condition. These of course are extreme conditions resulting from a very high speed or from large losses in the equivalent shunt circuit.

The wattless component of the counter electromotive force $(-e_2 \sin \alpha)$ has a marked effect on raising the power-factor, considerably more than the mere addition of the amount of energy which causes the phenomenon.

DISCUSSION ON "THE VECTOR DIAGRAM OF THE COMPENSATED SINGLE-PHASE ALTERNATING-CURRENT MOTOR", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

V. Karapetoff: In the year 1904, I contributed to the Institute TRANSACTIONS a complete performance diagram of the series single-phase motor. The diagram is similar to the well-known circle diagram of an induction motor. Assuming the permeability of iron as constant, the reactance of the motor is constant, and there results a semi-circle as the locus of the primary current. Then by simple graphical construction it is possible to obtain input, output, speed, and efficiency. Soon after I had delivered the paper before the Pittsburg Branch of the Institute, I was fortunate enough to have in my possession complete performance curves of two single-phase motors. One was, I think, a 5-h.p. motor, the other a 25-h.p. motor, both tested very carefully. In working out backwards the diagrams of these motors, by plotting the actual locus of primary current, I found that instead of being a semicircle, as it should be theoretically, it was a different curve which for practical purposes could be assumed to be the arc of a circle, considerably flatter than the semicircle. Upon investigation, I found this was due entirely to saturation in the iron. Then I assumed empirically that for a single-phase series motor the locus of the primary current is represented by an arc of a circle, and I deduced graphically expressions for input, output, speed, etc. The saturation and the variation of permeability which it involves depend on the field current, and therefore can be determined from the short-circuit curve (locked saturation curve) of the motor.

I wish to call your attention to this fact, because in all the literature on the subject that I have happened to come across the effect of saturation has not been taken into account. Diagrams of series motors derived on the supposition of a constant permeability are good enough to demonstrate to the student the theory of the motor, but should not be used in the predetermination of actual performance.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

TRACK-CIRCUIT SIGNALING ON ELECTRIFIED ROADS.

BY L. FREDERIC HOWARD

Railroads signals may be divided into three general classes according to their functions: (*a*) Those which confer rights on trains, or restrict their rights, known as train-order signals; (*b*) Those which designate the route a train is to take, and insure the safe condition of all switches and opposing signals on such route, known as interlocking signals; (*c*) Those which are used primarily for properly spacing trains, known as block signals.

Originally the operation and control of all these classes was wholly manual. Owing to the fallibility of the human agency, however, and also on account of the greater scope of protection to be secured, means were gradually devised to take from the operator under certain conditions the power to clear signals, while permitting him at all times to restore them to, and retain them in, the stop position. In some cases the signals were taken from his control altogether and made automatic. Means were also devised to prevent the operation of any switch while a train was approaching or passing over it.

It will therefore be seen that there are three distinct types of signals according to method of control; namely, the manual or non-automatic, the controlled manual or semi-automatic, and the purely automatic. Train-order signals are of the first type, interlocking signals of the first and second types, while block signals are of all three types.

The track circuit is by far the best expedient for effecting the control of the signal operator, and the power-operated block signal. It is used largely in connection with the latter; and as a means for dispensing wholly with the human agency, and providing the safest and most practicable method of automatic control will, for some time to come, remain the essential part of the automatic signal system.

Beyond the track circuit are the various signals, switches, and other appliances, operated mechanically or by pneumatic or electric motors of various types. These are the parts used by the signal engineer in his art of increasing the capacity of a road for the safe handling of traffic over the miles of main line, and for safely accomplishing the maximum number of train movements in the least possible time, with the least cost for maintenance and operation in complicated yards and terminals.

The track circuit being the factor upon which the signal engineer primarily depends for the automatic control of his apparatus, the use of the rails on electrically operated roads as common conductors for both signal and propulsion currents has brought to the front new conditions and new apparatus in connection with the track circuit, with which it is advisable that the electrical engineer should become acquainted. In this paper I shall try to trace the development of track-circuit apparatus which has taken place in less than a decade, and give some idea of the relations existing between the track-circuit system and the propulsion system on electrified roads.

The track circuit, as it exists in its simplest form on steam roads, is shown in Fig. 1, except that the gravity cell is generally the source of electric energy. The storage-battery is rapidly coming into use for this service, however, and is shown in Fig. 1, better to illustrate the relations of the elements constituting the track circuit. These elements are: a source of electromotive force; a series resistance (comprised in the battery itself when the gravity cell is used); the rails forming the conductors, and insulated from the adjacent rails at the ends of the section, and in multiple across the rails the resistances of the relay, ballast, and ties. When the track section is occupied, there is another resistance in multiple with the foregoing; *i.e.*, that of the wheels and axles of the train.

Through the contacts of the relay are passed the circuits which control the apparatus governing admission to the section; as, for instance, the semaphore signal shown in the figure.

For convenience, the reciprocal of the resistances, or the conductances, of the ballast, ties, wheels, and axles will be used in much of what follows.

The circuit shown in Fig. 1 differs from those with which the electrical engineer ordinarily has to deal, in that it is operated by shunting, instead of disconnecting, the source of electric energy. This makes necessary the consideration of the relation of the operating shunt to the other elements of the circuit.

The " ballast conductance " (which is considered as including the conductance of the ties) is a variable, and for any given section its value depends upon the weather.

Suppose that the voltage across the terminals of the relay at which its contacts close is practically the same as that at which they open; or, as the signalman would say, that the " pickup point " is the same as the " shunting point". This supposition corresponds closely with the facts in the case of alternating-current relays, where motion may be considered as due to the reaction between currents, but is not true of the ordinary attracted armature direct-current relay where the shunting point is approximately one-half the pickup point. Suppose further that when the ballast conductance is at its highest value, as during wet weather, the track circuit is so adjusted that the relay just picks up. It is evident that when the ballast conductance has diminished, because of the moisture drying out or freezing, a conductance equal to the change in the value of the ballast conductance must be added between the rails in order to cause the relay to shunt.

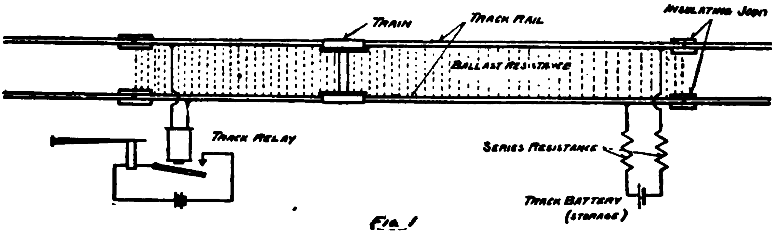
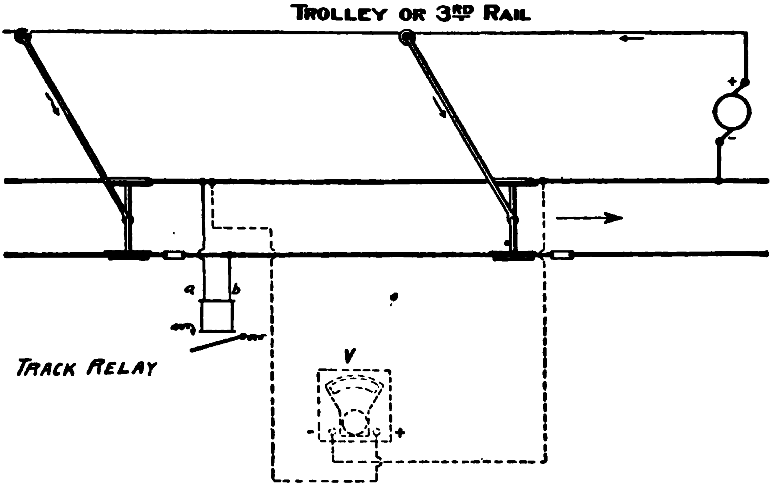


FIG. 1

If the contacts of the relay must be open when a single car is in the track section, the reciprocal of this change of conductance determines the resistance from rail to rail allowable in the wheels and axles of the single car. This, in turn, determines the length of section which can be operated, as the change in ballast conductance due to weather conditions varies directly with the length of section. In practice the limit of power available for supplying the track circuit is usually reached before the shunting limit, as the length of the section increases.

In considering the source of electrical supply for the track circuit, and its series resistance or equivalent, it should be noted that the higher the voltage of the source, the higher the value of the series resistance necessary, and consequently the greater percentage variation in voltage across the relay with a given change of conductance between rails. The higher voltage means, then, a greater factor of safety as regards any variations in the shunting point of the relay, but also subjects the relay to wider variations of voltage.*

About eight years ago the Boston Elevated Railway Company had its new elevated lines nearly ready for operation and wanted them protected by a track-circuit automatic block signal system. The motive power was to be direct current at 550 volts and with ground return. One rail at least was to be continuous; that is, not divided into sections by insulated joints. Here, then, was a new condition of affairs with one of the rails of the signal circuit traversed by a foreign current of comparatively enormous volume.



POTENTIAL ACROSS RELAY DUE TO RETURN POWER CURRENT

FIG. 2.

Fig. 2 shows at once the difficulty which the signal engineer encountered. The power generator is represented by the conventional symbol. *V* represents a voltmeter which as connected

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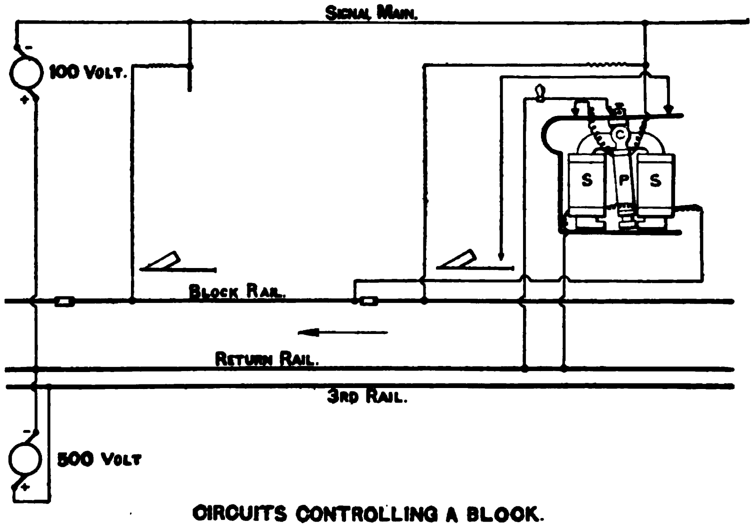
*This subject of track circuits was taken up by Mr. H. G. Brown in a paper read before the Institution of Electrical Engineers, last December.

will measure the drop of potential due to the flow of return propulsion current over the continuous rail. Now with a train at the far end of the block from the relay, the latter has the same potential across its terminals as that measured by the voltmeter, for lead *a* connects one side at the same point as the positive lead of the meter, and lead *b*, the insulated rail, the wheels and axles connect the other side to the same point as the negative lead of the meter. Whether or not an ordinary electromagnet type of relay will close its contacts under these conditions depends on whether or not the voltage at which it is adjusted to operate is greater than the drop of potential caused by the return of power current over the length of rail measured by the length of block. In the case of the Boston Elevated the maximum drop which could occur over the return rail was limited, owing to the facts that the blocks were short and the return rail was bonded at close intervals to a structure having a copper equivalent of 14,000,000 cir. mils, from which the return current was taken to three power stations suitably spaced. These conditions made it permissible to use a relay whose voltage adjustment took care of any return drop which might occur, no alternating-current signal apparatus having been developed at that time.

In addition to the armature which distinguishes the steam-road direct-current relay, the one designed to meet the conditions on the Boston Elevated had a polarized feature, which would prevent the relay from closing its contacts in case a car failed to obtain a good ground on the return rail and grounded through the relay. On account of this feature the relay had two separate and distinct sets of magnets as shown in Fig. 3. The stationary set, *SS*, is connected across the rails; the swinging set, *P*, is connected to the main leading to the negative pole of the signal generator, the positive pole of which is grounded. This generator replaced the batteries used on the steam road.

Supposing the relay to have de-energized, the sequence of operations in closing the relay contacts is as follows: the signal current coming from the positive pole of the generator, via the return rail, passes through the stationary coils to the block rail; thence through the latter via the resistance to the negative signal main. This picks up the armature which closes the left-hand contact and completes the circuit through the swinging coils. The polarity of the latter being fixed, they will swing to the right, if conditions are normal, bending the phosphor-bronze strip to which they are rigidly attached. This closes the circuit to the local control mechanism through the upper right-hand contact.

If the propulsion current from the car motors fails to obtain a ground on the return rail but flows through the stationary coils of the relay, their polarity will be reversed on account of the propulsion current flowing in the opposite direction to the signal current. This will cause the swinging coils, whose polarity remains fixed, to move to the left and open the right-hand control contact.



CIRCUITS CONTROLLING A BLOCK.
BOSTON ELEVATED RY.
FIG. 3

This Boston Elevated signal system comprises some 90 odd track circuits and 170 blades, including interlocked signals, and about 60 switches, the latter being distributed among five electropneumatic towers and two mechanical towers.

The next electric road to be equipped with signals was the North Shore Railroad near San Francisco. On this road several of the blocks were to be over 4000 ft. long, and there was to be a maximum of 8 trains of 4 motor cars each, taking about 1600 amperes per train at starting. The power station was to be in the middle. In this case there was no elevated structure of 14,000,000 cir. mils capacity to take care of the return drop of the power current, so the first alternating-current track circuit was installed.

The system used was what is termed the alternating-current single-rail return, and is shown in Fig. 4. The direct-current generator of the Boston Elevated is replaced by an alternating-current generator or transformer, stepping down from propulsion power mains to a suitable voltage for transmission of current over the two signal mains. Instead of supplying the track circuits directly from the signal mains through a resistance, a step-down transformer is used with a resistance in its secondary.

At the other end of the track section is an alternating-current relay, of the type shown in Fig. 5. It consists of a *C*-shaped laminated core carrying a winding connected across the rails. One half of each pole-piece of the core is enclosed by a copper ferule. Between the faces of the poles is a sector of aluminum rotating on a shaft at right angles to its own plane. The shifting magnetic fluxes in the pole-pieces cause the rotation of the vane according to the well-known Ferraris principle, when sufficient alternating current passes through the winding to overcome the counterweight on the aluminum sector. The shaft carries the contacts. This relay, of course, is immune to direct current so far as the operation of its contacts goes. To limit the direct current passing through it to an amount below that

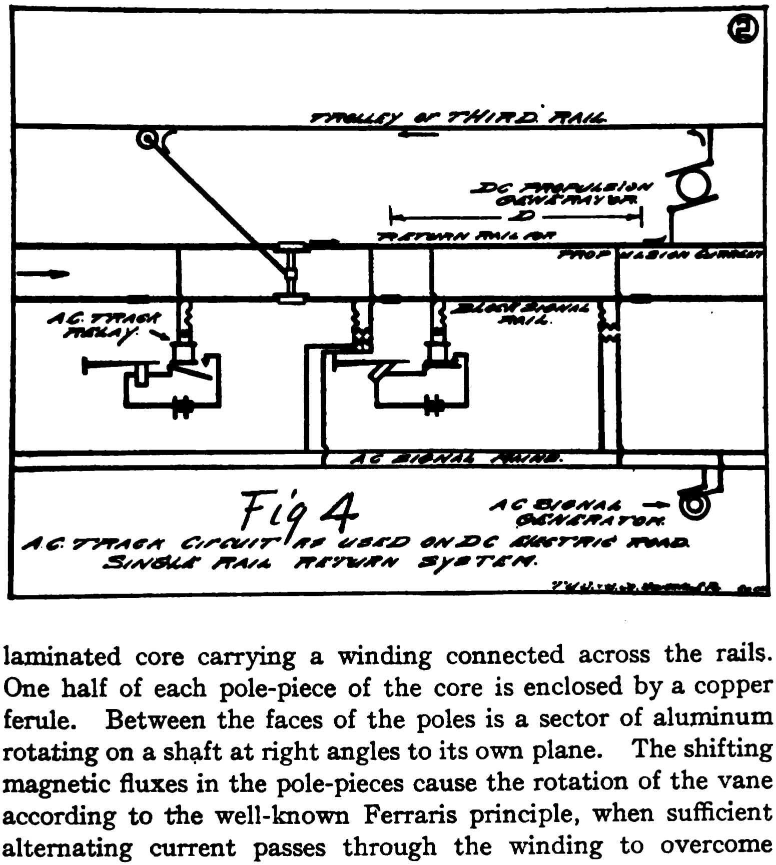


Fig 4

A.C. TRACK CIRCUIT AS USED ON DC ELECTRIC ROAD
SINGLE RAIL RETURN SYSTEM.

which would dangerously heat it, or saturate the iron, the relay is shunted by an impedance coil, and a resistance is also inserted in one end of the leads. Going back to the other end of the track section, it is seen that the resistance in the secondary leads of the transformer is assisting to prevent the flow of direct current through the secondary winding of the transformer, in addition to its other functions in connection with the adjustment of the track circuit.

The track transformer and the impedance coil across the relay terminals are furthermore made with open magnetic circuits to keep down the density of magnetization caused by the flow of direct current, due to drop of potential over the continuous rail spoken of in connection with Fig. 2.

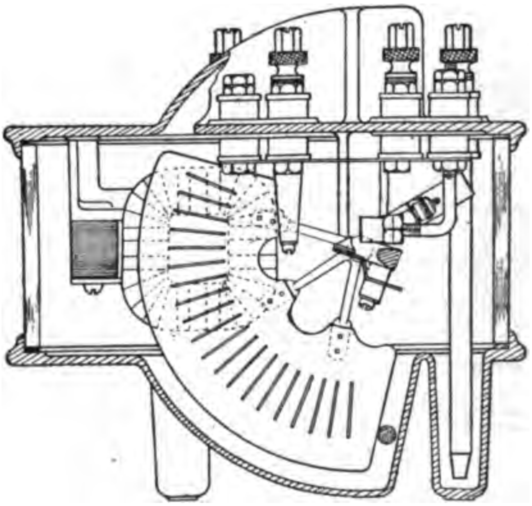


FIG. 5

On this particular installation about 10 miles of double track, and two-thirds of a mile of single track through a tunnel, were equipped with signals. The signal mains extend the length of the road and carry 60-cycle current at 2300 volts. They are supplied from the step-down transformers at the power house. One of the track sections is over a mile long.

The description of the foregoing system applies equally well to the system installed in the New York Subway, so far as the alternating-current track circuit is concerned.

The greater volume of direct current to be taken care of in the latter system was offset by the number of tracks, the steel framework of walls and roof, the close spacing of the substations, and the shorter blocks. The signal mains are supplied with 60-cycle, 500-volt current by transformers located in the sub-stations, and stepping down from the high-voltage lighting mains. In emergency, 25 cycles stepped down from the propulsion circuits is used.

The New York Subway system comprises some 500 track circuits, 700 signals, and 230 switches, and has a record of one failure of apparatus to 3,359,167 movements, with no false safety indications in more than two years. The installation of a system using practically the same kind of apparatus has recently been completed on the Philadelphia Rapid Transit Company's new subway and elevated lines.

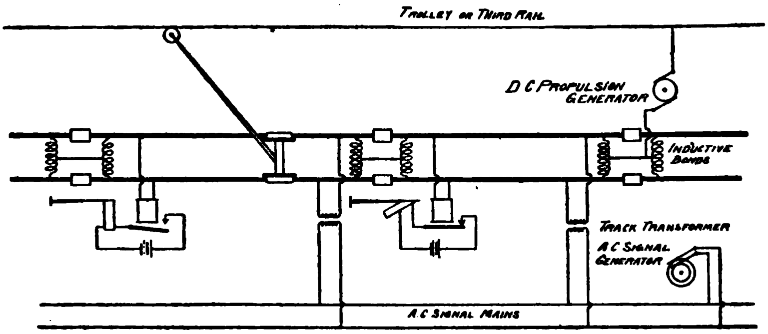


FIG 6

All the foregoing systems necessitated installing additional return conductors for the power current to compensate for the rail given up to the signal system, except where an elevated structure was available. The possibility of the use of a track circuit in which both rails should be used in common for signal and propulsion currents had been contemplated before this time. Local conditions on the Boston Elevated, the North Shore, and the New York Subway had made the single-rail system acceptable, however, and this led to deferring the development of the two-rail system shown in Fig. 6.

A path for the propulsion current around the insulating joints is provided for in the two-rail system in the form of the impedance bonds indicated in the figure. It is apparent that as the propulsion current divides so that each part passes around the iron core of the bond in opposite directions, its magnetizing effect on the core is zero, so long as the current divides evenly. On the other hand, the full impedance of the bond is offered to the signal current in preventing its passage from rail to rail.

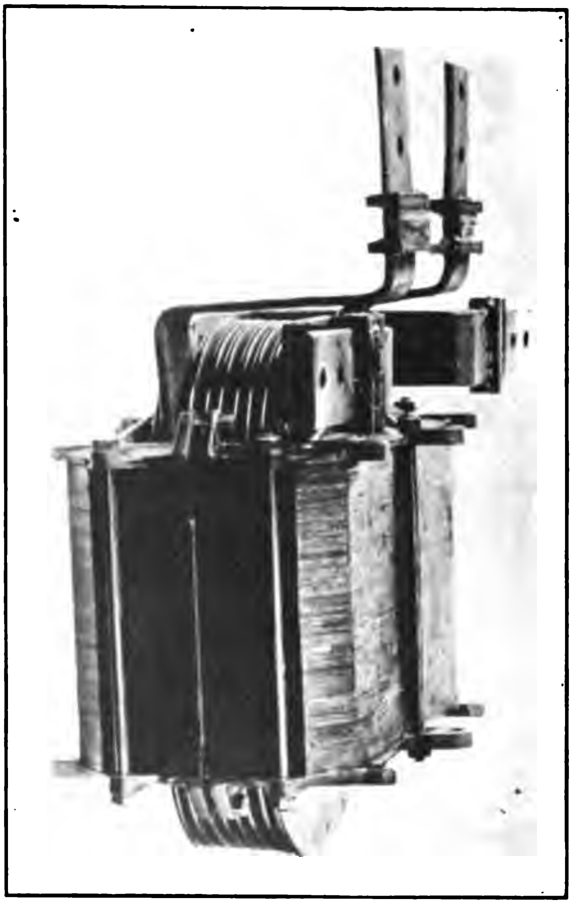


Fig. 7

Fig. 7 is a view of the bond out of its case. It consists of a shell-type core and heavy strap copper winding. The effect of unbalanced direct current is provided for, up to limits well beyond those met on properly bonded tracks, by using an open magnetic circuit and working the iron so far down on the saturation curve that the impedance of the bond actually rises with a small amount of unbalancing. These bonds may be installed between the rails of a track, as shown in Fig. 8, or just to one side.

The track transformers for this system are designed to have excessive magnetic leakage, and consequently a rapidly falling secondary characteristic, thus dispensing with the series resistance used with the battery or generator of the direct-current track circuit, or transformer of the single-rail, alternating-current track circuit

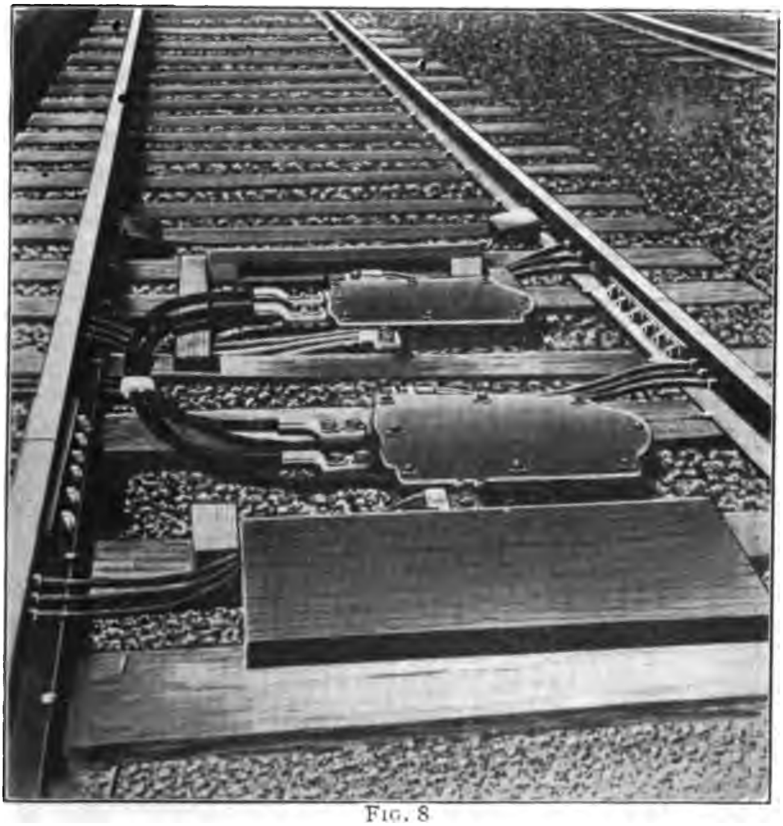


FIG. 8

Again the Boston Elevated was the scene of the installation of a new system, about 14 blocks of this type being installed during the winter of 1904–5, in the tunnel under the harbor, between Boston and East Boston.

The next installation of the double-rail return was on the electrified lines of the Long Island Railroad. The requirements here were 1100 amperes of return propulsion current per rail, and 800 amperes unbalancing. The track transformers and relays were grouped as shown in Fig. 9, instead of being placed at opposite ends of the blocks. 2200-volt mains carrying 25-cycle current supply a commercial 2200 to 55-volt transformer at each group of track transformers.

About 140 track circuits were installed and 19 miles of double-track road and 4.5 miles of four-track road were equipped with signals.

Last fall a third installation of the double-rail system was completed; namely, that on the West Jersey and Seashore Railroad. The sub-stations were to have a maximum ultimate capacity of 7000 amperes each, which, if distributed equally over the four rails, would mean 1750 amperes per rail.

The blocks were about 4000 ft. long and the innovation was introduced of placing the track transformer at the middle of the block (Fig. 10) with the relay at one end and a small step-up transformer at the other. The relay is really a motor with the armature rotating through about 45 degrees. The field winding is connected to the near end of the block, and the armature to the secondary of the small step-up transformer at the far end.

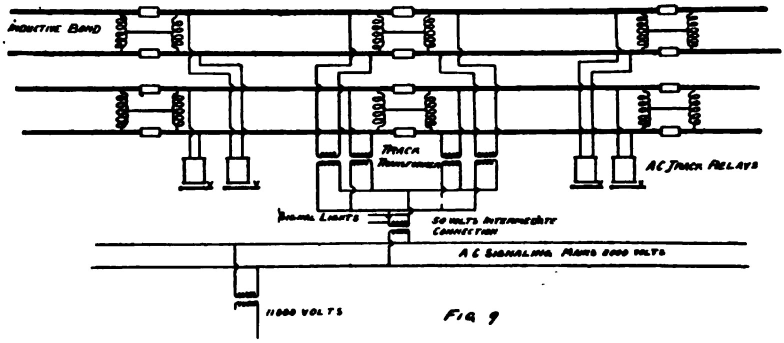


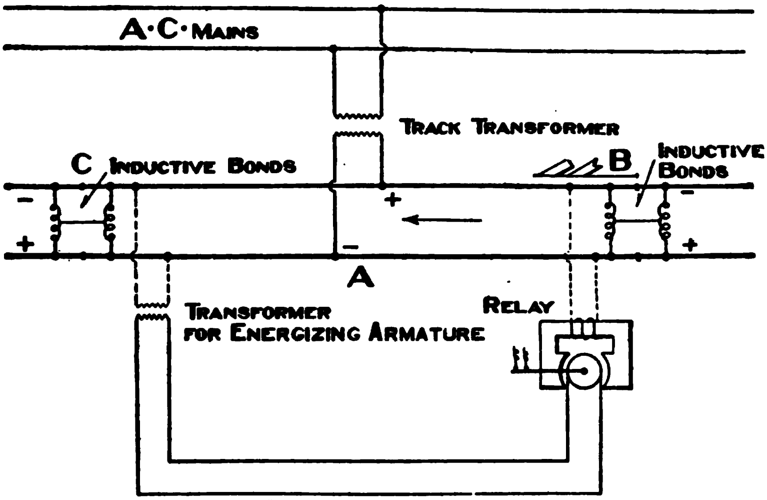
Fig 9

At each sub-station on the section equipped, a transformer between one leg of the power mains and the ground steps down to 1100 volts for the signal mains, which are carried on the poles below the power mains.

The signal system being installed in the electrified zone of the New York Central and Hudson River Railroad is also a two-rail system, using inductive bonds connected as in the systems described, but the relay is a two-phase induction motor with one phase fed from the track circuit, and the other from the signal mains, the difference in phase being obtained by the proper combination of the elements of the two circuits.

Having thus briefly described the different track circuit systems in operation on electrified roads, it is of interest to recall the discussion given in the earlier part of the paper of the simpler form in use on the steam roads, and then consider the changes made in some of the elements of the track circuit by the use of the double-rail return system. The latter system is chosen for discussion, as it constitutes the latest and most radical departure from the simpler form.

By the use of an alternating signaling current, we have an increase in the apparent resistance of the rails, due partly to skin effect and partly to magnetic induction. This increase is of course a function of the frequency.



Double Rail Return, Transformer In Middle Of Block

Fig. 10

We have also introduced an artificial apparent conductance between the rails in the inductive bonds, and they, together with the relays, introduce another inductive component.

The increase in the apparent resistance of the rails means, of course, higher voltage at the source of supply for the track circuit, and consequently more power. On account of the higher impedance of the rails and the consequently higher voltage required at the source of the supply of the track circuit, other things being equal, a given shunt applied to the rails at the relay will produce a larger percentage change of voltage across the terminals of the relay.

On the other hand, where relays with a single winding are used, and there is leakage around an insulation joint from an adjacent block, a train at a given distance beyond the relay has less shunting effect on the relay, and there is greater danger of getting a clear signal with a train in the block, than with the direct-current track circuit.

This may be seen more clearly by an inspection of Fig. 11. The insulating joint, *A*, is defective, and current from the section on the right, flowing as indicated by the arrows, will tend to make relay *R* close its contacts. The resistance of the rails between the shunt, *S*, and relay, *R*, diminishes the effectiveness of the shunt as the effective resistance of the rails increases.

This danger may be diminished in various ways, among which are adjustment of the voltage of the source of current supply to the track circuit, so that to the relay is given just enough energy to operate satisfactorily under the worst weather conditions; by arrangement of the track circuit apparatus, Fig. 9; and by the use of two element relays, Fig. 10, with the rails of adjacent blocks of opposite polarity.

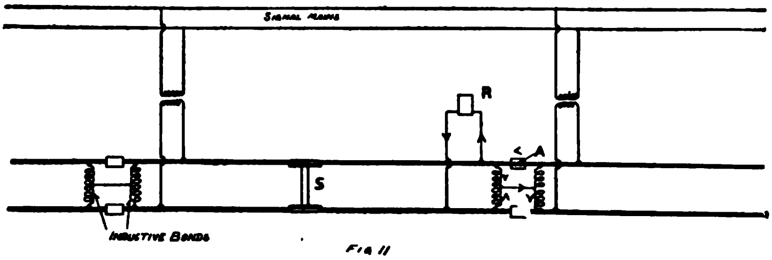


Fig 11

When two-element relays are used, they should be as free as possible from any tendency to close the contacts because of repulsion or induction motor effects, caused by normal or accidental short-circuiting. In some forms of frequency relays the effects of open circuits must also be guarded against.

The introduction of artificial apparent conductance between the rails by the use of inductive bonds also has its advantages and disadvantages. Principal among the advantages is the smaller percentage change in voltage across the relay due to changes in ballast conductance with varying weather conditions. For the same reasons the shunt produced by the train causes less percentage change in voltage across the relay.

These two effects may be taken advantage of in the design of the transformer supplying the track, by making its secondary characteristic with a steeper gradient than where the bonds are not used. The greater the apparent conductance of the bond, the steeper should be the gradient.

The principal disadvantage arising from the introduction of the apparent conductance of the bonds between rails is the extra amount of current taken and the consequent drop in voltage between the track transformer and the relay, with the resultant increase in leakage through the ballast.

It is at this point that the electrical engineer laying out the power system for a road which is to use direct-current propulsion should realize that the higher the efficiency of his return system the cheaper will be the signal system, both in first cost and operation; and when the signal engineer of the road who is making up specifications for the signal manufacturers to bid on comes to the electrical engineer for information as to how much current per rail the bonds must carry continuously, and how much unbalancing they must withstand without causing the signal to go to danger, the electrical engineer must not state an amount which would give 40% loss in the rails, and in addition state that the inductive bonds must withstand 50% unbalancing. The larger the current to be carried by the bond, the greater the first cost of the copper.

The larger the amount of unbalancing the bond must withstand, the larger must be the capacity of the track transformers, the signal mains, and the generating apparatus, and the larger the amount of power to be supplied for the track circuits.

The greater amount of signal current to be supplied to the track circuit because of greater unbalancing capacity in the bonds is due to the fact that this unbalancing capacity is obtained by widening the air-gap in the magnetic circuit of the bond. This of course increases its apparent conductance and the current demands on the track transformers.

With roads using alternating-current propulsion, this unbalancing becomes of minor importance; first, because the return propulsion current is so much smaller; secondly, because the propulsion current being alternating, the actual resistance of the rail has a small ratio to the apparent resistance, and a comparatively large difference in the actual ohmic resistance of the two rails of a track may exist without making any great change in the propulsion current values in the two rails.

The inductive bonds for roads using alternating current for propulsion can therefore be made without an air-gap. and the only effect of unbalancing is to produce a voltage across the terminals of the relay of the same frequency as the propulsion current. This voltage being small with any reasonable amount of unbalancing, it may be taken care of in the frequency relay.

This frequency relay is so constructed that the presence of a voltage across its terminals of the same frequency as that of the propulsion current will not close the relay contacts, the presence of a higher frequency signaling current being necessary to accomplish this result.

The difference in unbalancing effect on roads using direct-current propulsion from that on roads using alternating-current propulsion, together with the higher frequency signaling current, made necessary when alternating-current propulsion current is used in order to operate the frequency relay, constitutes the principal differences in the relations between the elements of the track circuit as used on the two systems; so that what has been written of the double-rail track circuit on the direct-current road applies equally well, with the exceptions noted, to the same system on the alternating-current road.

DISCUSSION ON "TRACK-CIRCUIT SIGNALING ON ELECTRIFIED ROADS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907.

Charles F. Scott: This paper is quite special in its scope and is valuable for the information it gives, but is not apt to be fruitful of general discussion. I have been interested to note during the reading of the paper, and also in my observation during the last few years of this signal development, the general course of that development and the effect of the electrification of railways on signal work. At first, on the ordinary steam road, the only electricity used in connection with the track system was the small amount employed in connection with the signals. The use of the track, however, for carrying direct current for railway motors has caused some voltages to be introduced which begin to affect the signal circuit and they have to be taken care of in ways which when they are worked out and explained seem simple and adequate, but did not seem so simple when the difficulties first arose. The introduction of single-phase alternating current and the use of the rails for conducting this current again introduces a new kind of disturbance in the signal system. It is interesting to note how the signal work has followed these various intrusions of greater currents. One rail was set aside for signal work, and later on the signal system adapted itself to the condition existing when both rails were used for propulsion current. The signal engineer follows the example of the railway engineer and gets into alternating current; if the alternating current in the railway is bad for his work he cures the evil by adopting alternating current himself. He solves the frequency question by going to a high frequency instead of a low one. This also illustrates the amount of electrical engineering which can be applied to what most of us who have not come in contact with this work at all have probably considered a very simple sort of thing, but the grade of engineering work and the knowledge and ingenuity required in devising these systems, with the remarkable reliability and excellent way in which they perform their work, is something to elicit our admiration.

There is still another source from which other currents may come and affect the signals, which I understand has been characteristic of one installation, and that is when the tracks were bonded together for the operation of the railway these track connections formed an inviting path for currents from adjacent railways which were strolling through the earth, hunting convenient paths by which to get home, and these currents got into the tracks and the signal apparatus producing some unexpected combinations of signals. This illustrates again the interference between different kinds of currents and the need of the signal engineer to be alert for their avoidance.

Henry G. Stott: I think we ought to be congratulated on the presentation of a paper of this character. It is perhaps significant of the very small general knowledge on the subject of the signaling system which we have, that so few people are ready to discuss it. I am connected with a railroad which is using the type of signaling described in Mr. Howard's paper, and I am perfectly free to admit that I know very little about it. We have a signal engineer, but his work is so specialized that it is an entire department by itself. If we all knew what signaling engineering is and the mass of details with which the signal engineer must contend and the wonderful ingenuity which he displays in arranging them, I think we would put the signal engineers at the very top of the class instead of the bottom.

In the first operation of the signaling system on the Subway in New York City considerable difficulty was encountered, due to the fact that the source of supply of the current was one which had variable electromotive force. The 60-cycle current was generated by a generator coupled to a direct-current motor which was operated from the ordinary third-rail current and subject, therefore, to very wide fluctuations of voltage. That reacted, of course, to keep the tongues of the relays on the signal system almost in continuous vibration, thereby reducing the life, and in some cases with very wide changes, resulting in failures in the signal apparatus itself. We changed that over so that the current is now supplied directly from 60-cycle turbines and the regulation on that is one per cent. Since that time the failures of signals to operate have diminished so that they practically do not exist. I forget what the record is, perhaps Mr. Howard has stated it, but I believe it is about one failure of the signal to operate in three or four million.

It seems to me that this development of the complete block system has got to come to all railroads. Until such is the case the appalling accidents which have taken place on many of our main lines during the past year will continue, because in the operation of power plants, and in the operation generally of all important apparatus, we find now that the apparatus itself has improved to such a point that the failures are not of the apparatus but of the men who operate them. A man may go along perfectly for years, doing the same thing every day, and then he fails absolutely. For example, in the power plants with which I am connected, in three years we have had only one shutdown, and that was caused the other day by the gross blunder of a man, who has done the thing perfectly hundreds of times, failing to do what he should have done. He could not explain it and no one else could explain it. The more we can eliminate the human element from our signal system the more perfect it will become.

Charles A. Perkins: It seems to me that this paper calls our attention to the desirability of extending the block system much beyond the range of signals; it is desirable, not only that the signals should be given, but also that the obeying of the signal should be beyond the option of the engineer or motorman who is operating the train. I have been in an accident caused by the engineer on a following train running by a danger signal. In the multiplication of automatic schemes for safety, such a scheme should be included in the block and signal system. I should like to hear from Mr. Stott as to how far this has been accomplished.

Henry G. Stott: On the Subway system this feature is absolutely automatic. The man cannot run past the signal. If he does the brakes are automatically set and the current is cut off. It is absolutely impossible for him to run by the signal without its being known. He may do it once, but he is not likely to repeat the offence, because he has got to get down and go under the car and reset the air-brake valves under the car before he can start the car again. This means, when he gets to the end of the line, he has to make an explanation why he ran by the block, and that means he is laid off for a week.

L. F. Howard: I shall make a few comments on the matter of the automatic stop. It is used on the Boston elevated, and I believe there are a few automatic stops on the Chicago elevated system. The matter is also being agitated on some other roads. On surface roads it is more difficult to apply, on account of weather conditions, when it is down on the ground. A number of years ago it was suggested that an arm should extend from the signal mast when the signal was at danger, this arm to be so arranged as to engage with a glass tube or stop cock on top of the engine cab. The tube or cock being connected with the train pipe of the braking system, the breaking of the glass tube or opening of the cock, in case the engineman ran by a " stop " signal, would set his brakes.

There are, however, quite a number of points in connection with the use of train stops on surface roads as yet undecided, and the present general feeling amongst the officers of such railroads is to adhere to present practice and exercise closer checks on their employees.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28. 1907.

SOME POWER TRANSMISSION ECONOMICS

BY FRANK G. BAUM

In designing power transmission systems, it is always well to bear in mind that the ultimate development of the art and of the country has not yet been reached.

In the early days of railroading, the roads and equipment were not of the present trunk-line standard. Light rails, engines and cars, and unfenced right-of-way, and unballasted roadway sufficed. To construct, at that time, up to the present standard would have meant bankruptcy. Even now the manager or engineer, who would build his branch lines of the same standard as his trunk lines, would invite a receiver to take charge of the road.

The same conditions hold true for power plants and transmission lines. The wise manager or engineer builds to meet existing conditions, looking into the future as far as he can. He can not afford to build duplicate plants and lines for every case, nor build all his lines on private rights-of-way with steel towers and other refinements and safeguards. He can not afford to build a duplicate transmission line, at an additional interest cost of $5,000 per year, when the probability of an interruption, which will cause a loss of revenue of $500 per year to a consumer, is extremely remote.

It may not be as difficult to determine the proper power station and line to build when unlimited capital and ideal power conditions exist as when there is restricted capital, limited revenue, and low-priced power at the consumer's end. Although in the latter case the amount of money to be expended may be much less than in the former, even more thought is demanded of the engineer; for, in the former case, having ample resources,

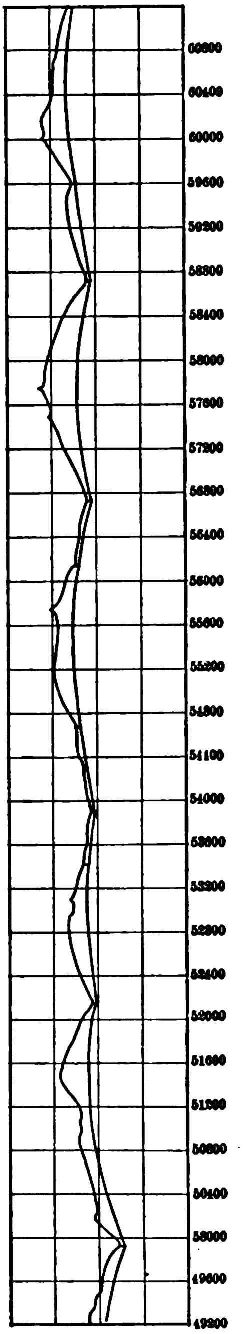


Fig. 1—Profile of Mountain Pole Line. Distances in ft

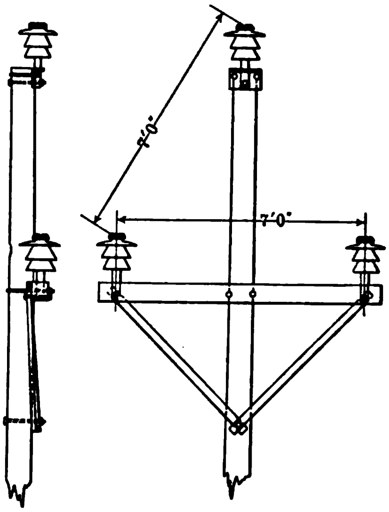


Fig. 2, Structure 1.—Spans up to 500 ft., 7-ft. triangle. Single construction. On corners, double arms and plates and one pin.

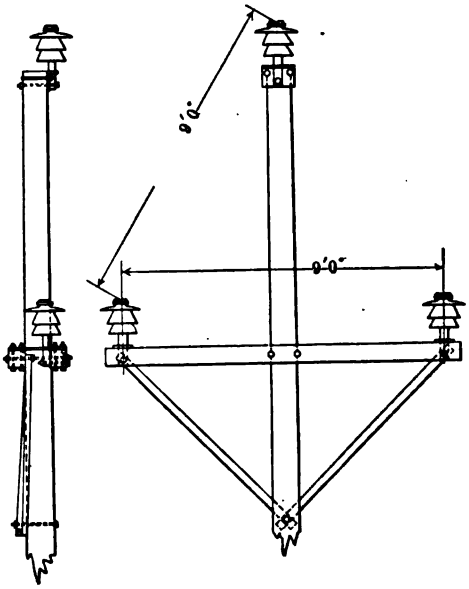


Fig. 2, Structure 2.—Spans 500 ft. to 700 ft., 9-ft. triangle. Double arms and plates, one pin. On corners, double arms and plates and two pins.

he builds as best he can, while in the latter he must be a judge of conditions and see far ahead, in order that the line which he builds may earn money and at the same time be capable of extension on some plan to meet the growing needs of the country and business.

To illustrate the necessity of doing things in inexpensive ways in the early development of an art, a business, or a country, some examples are given of the work done on the system of the California Gas and Electric Corporation. Along some of the lines where the load is small, one wire only is run to the sub-station, an inexpensive building, and one transformer, with ground return, is installed. One-phase motors are used. For larger stations, sometimes up to 500 kw., two wires are run to the sub-station and, by using ground return on the primary and open delta on the secondary, three-phase motors are operated.

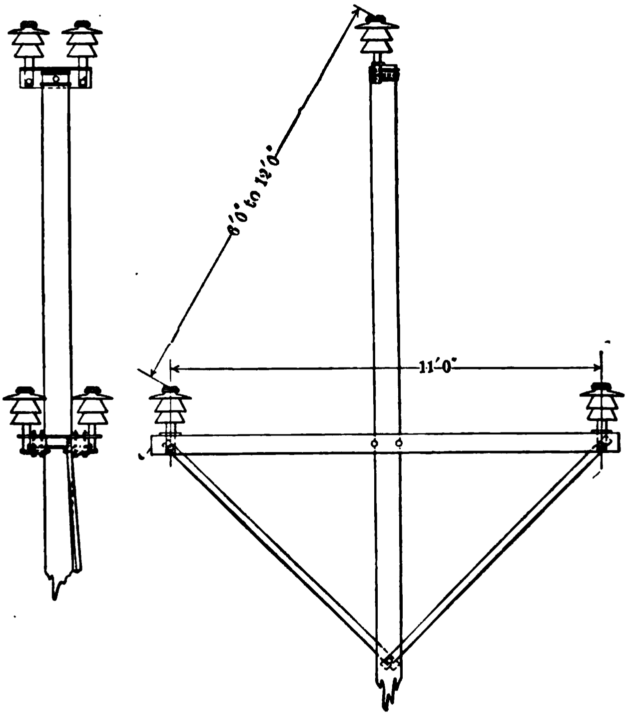


Fig. 2, Structure 3.—Spans 700 ft. to 900 ft. 11-ft. triangle. Double arms and plates and two pins. Corners special.

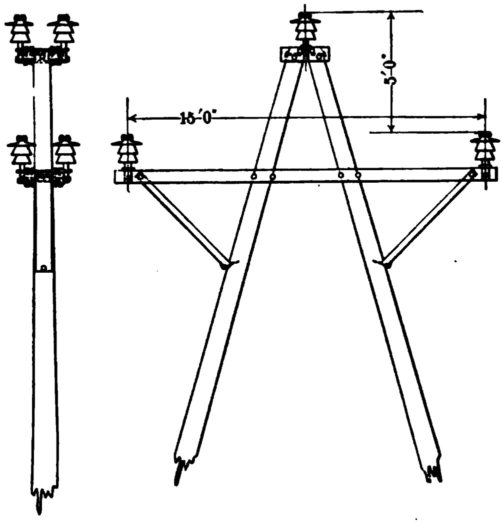


FIG. 2, Structure 4.—Spans over 900 ft. to 2000 ft. 16-ft structure. Double 6-in. by 6-in. arms, plates and two pins. Two-pole structure.

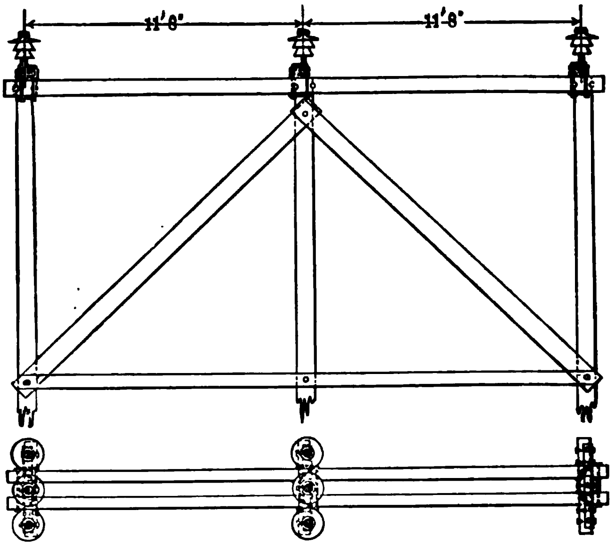


FIG. 2, Structure 5.—Spans 2000 ft. to 3000 ft. 24-ft. structure. Double 6-in. by 8-in. arms, plates, and three pins. Three-pole structure.

Loads as large as 1500 kw. have been carried to a distance of 100 miles on two transformers Y-connected on the primary, with grounded neutral, and open delta on the secondary. Neither the power consumer, nor the power-house operator has noted anything unusual.

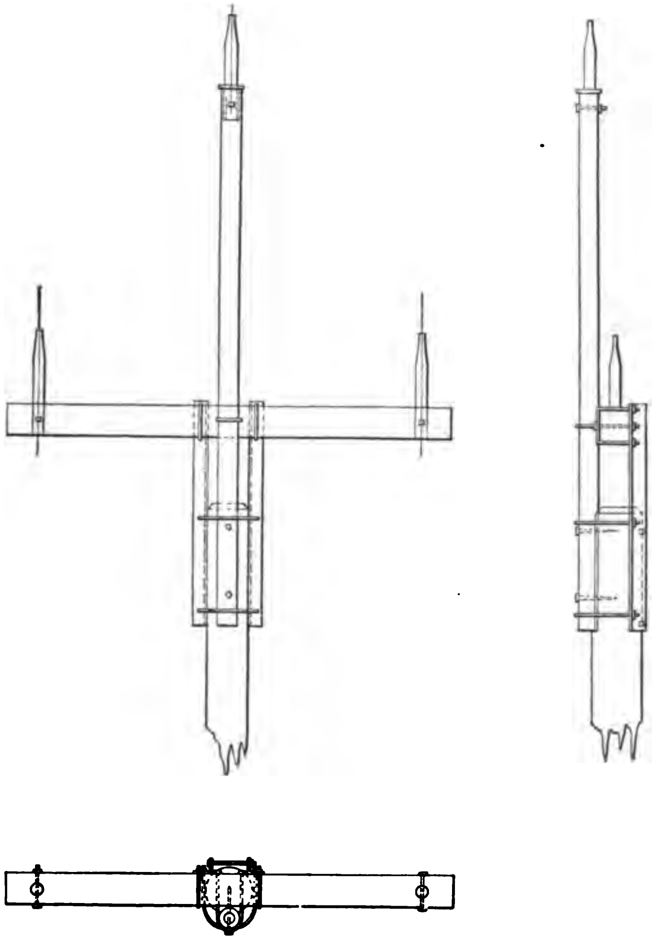


FIG. 3—Pole-top extension.

For larger sub-stations a single three-phase transmission line supplies the load, even where the length is 50 miles or more. The consumer can not afford to pay for a duplicate line when the output per year of the factory is practically unaffected by interruptions. Interruptions amounting to one hour per month would be one-seventh of one per cent. of the total time, and the power company that has an average of an hour's interruption per month is certainly giving very bad service. It is evident that the construction of a duplicate pole-line for such service is entirely unwarranted.

As to the construction of pole-lines, it has been found that in some parts of the West where cedar poles may be purchased at a low price, this class of pole-lines is still the most economical, and everyone must admit that this type of construction has proved remarkably effective. Of course under certain conditions tower lines only would be considered, but two wooden pole lines entering a city by two different routes will give greater reliability than any two-circuit tower line that can be built. The cost of a two-circuit tower line would be as great as that of two pole lines. A line using tower construction requires a private right-of-way, and in a new country it may not be possible to pay from the earnings the interest on the increased cost of the right-of-way as well as on the tower construction. The engineer, of course, always prefers the best construction, but he must consider the net revenue to be derived from an en-

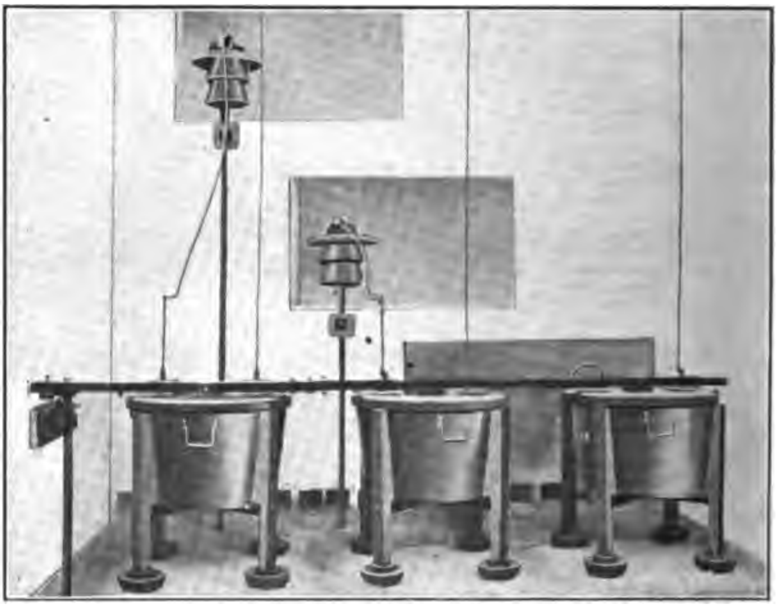


Fig. 4—Early type of oil-switch.

terprise in a given number of years. In mountain sections, the economies of line construction lie in the use of the hills for the structures and in using long spans. In some cases the amount saved in clearing, in poles, insulators, and labor will amount to 50%.

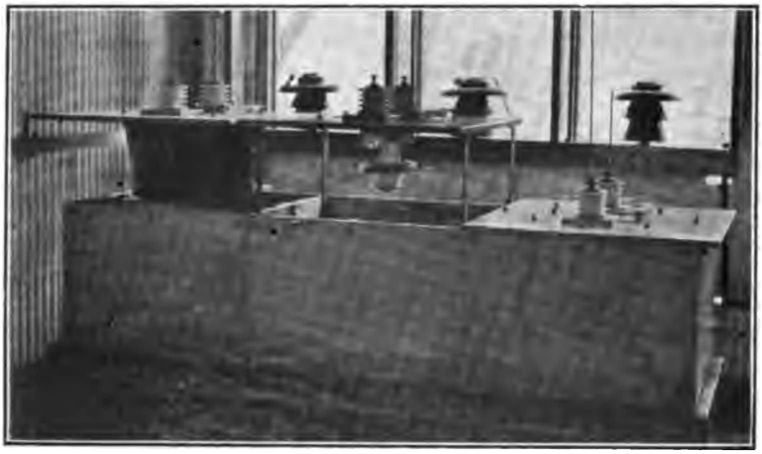


Fig. 5—Later types of oil-switches.

Fig. 1 shows a profile of a line recently constructed, the middle section of which consists of a series of spans varying in length from 700 to 2700 ft. It will be seen that by taking advantage of the hills to form the greater part of the height of the structure great economy results. A span of 3000 ft., with an allowable sag of 300 ft., would, if on the level, require towers over 300-ft. high, while, in this line on similar spans, simple wooden pole structures 30-ft. high are all that is necessary. The profile of a line of this kind is first determined, and the span-length and structures designed so that the wires clear the ground sufficiently. This gives an economical and satisfactory line

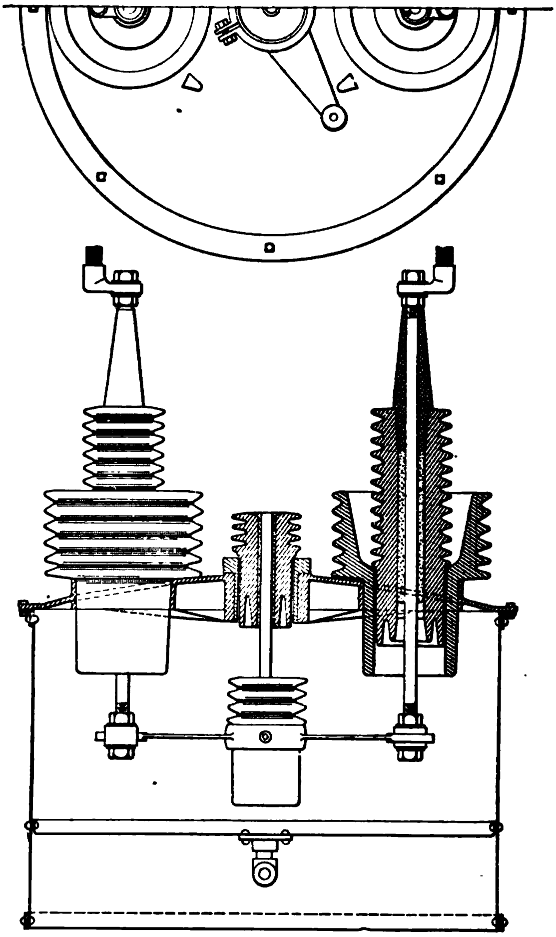


Fig. 6—Modern type of oil-switch.

On long spans the wires are spread at the structures as shown. In addition, the top or middle wire is given 10 to 40 ft. less sag (depending on the span) than any of the others. One of the outside wires is also given 5 to 20 ft. less sag than the other.

In this way there is obtained a vertical separation at the middle of the span; and 10 ft. of vertical separation is better than 20 ft. of horizontal, because the wires then can not come together even when acted upon by gusts of wind having a tendency to lift the wires. Spans greater than 2000 ft. are not installed except in certain cases where they can scarcely be avoided. Spans of 600 to 1500 ft. give the best line.

Fig. 2 shows standard types of pole structures used on some of the mountain lines recently constructed in California.

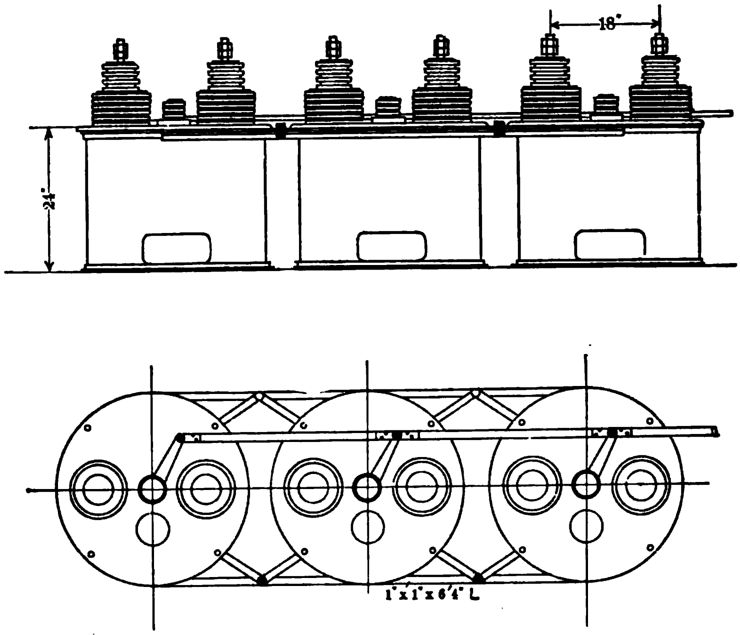


FIG. 7—Three-pole grouping of oil-switches.

Structures of this kind are sometimes also used for river crossings where the cost of steel towers is prohibitive or the time too short to install them. These are sometimes over 100 ft. high.

Referring to old lines which were constructed ten, or even five years ago, nearly all the lines were built with 40 poles to the mile, using 35-ft. poles. Now, the tendency is to use longer spans on account of the lower cost and the reduced number of insulators or weak points in the line. Some of these old lines have to be reconstructed later for a higher voltage, and, in order to obtain a reasonably good line and also to reduce the cost for insulators and future line maintenance, it is advisable in reconstructing to reduce the number of poles. To do this, the supporting points of the wires must be raised higher above the ground. In order to accomplish the result of reinsulating and reconstructing several hundred miles of line (which would have kept all the insulator factories busy for two years furnishing insulators for the old type of construction), the pole-top extension shown in Fig. 3 was used. This has proved effective. By using this pole-top extension, every other pole is taken out, with a saving of $9.00 per pole for new insulators and the additional salvage of the old poles, arms, pins, and insulators. Where sufficient height can be obtained by putting the arm below the top of the pole,

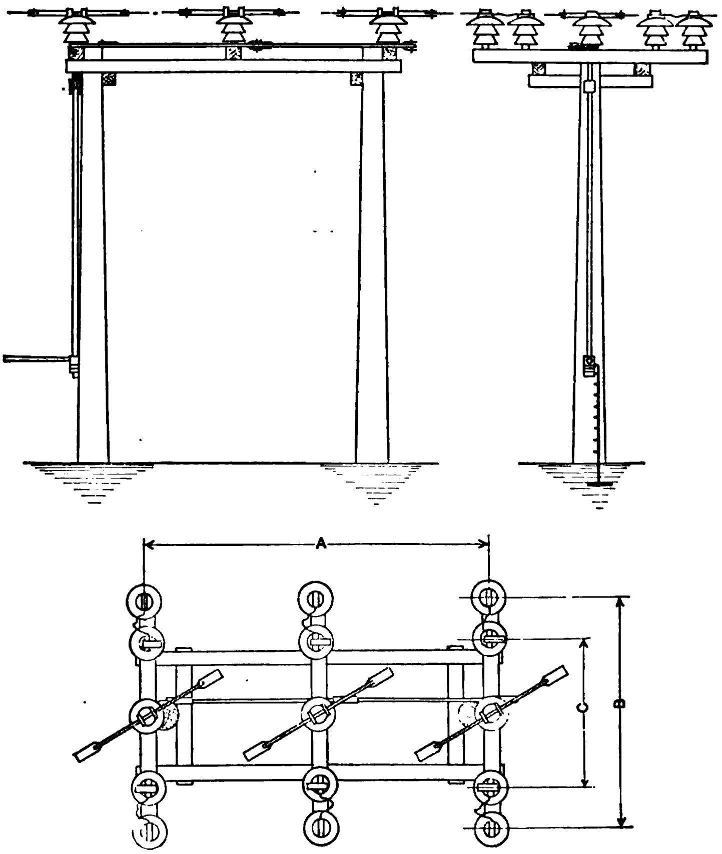


Fig. 8—Outdoor two-break air-switch.

this construction may be simplified in the fastening of the arm and pipe to the pole.

Another important adjunct of the transmission line is the switches, oil and disconnecting. It will be found that the same arguments regarding economical line construction apply to switches. Five years ago no one was sure of a high-tension switch and it would have been folly to install expensive switches of the first type that suggested itself without giving them a thorough trial during several years under operating conditions. In selecting switches and structures for high-tension lines, it is well to bear in mind that the ultimate development has not yet been reached. In solving our switch problem, this was kept in mind at all times.

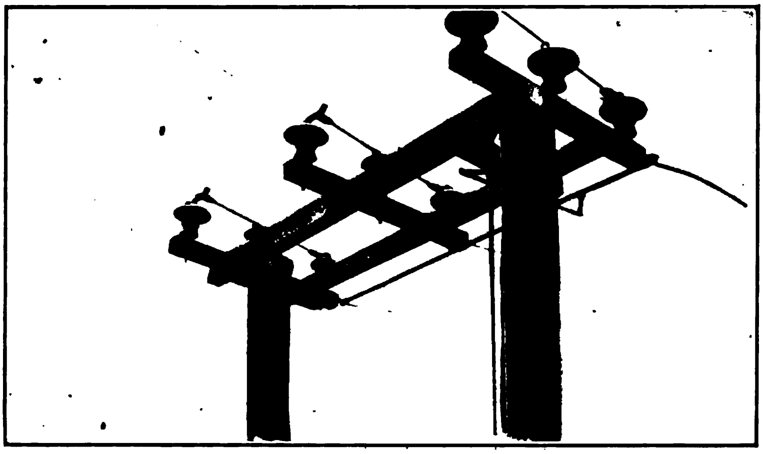


Fig. 9—Outdoor switch.

The first high-tension oil-switches were made as inexpensive and as simple as possible, and were as shown in Fig. 4. These operated so satisfactorily that we became convinced of the success of the type and soon changed to a more substantial form, as shown in Fig. 5. They are generally installed for hand-operation.

Although we have more than 100 of these switches on our lines, nearly 1000 miles at 60,000 volts all tied together, and over 50,000 kw. in generators operating on the lines at all times, the switches although cheaply constructed have given excellent results. All line switching is done on these high-tension switches, and the plants and lines are separated thereby in case of trouble. The stations are synchronized at sub-stations, which are 100 to 150 miles from any power station.

We have now adopted the type shown in Fig. 6, two-break switches for the ordinary station, and four-break in each tank for the heavy service. These switches are grouped in three-pole arrangement as shown in Fig. 7.

For small sub-stations, for line-sectionalizing switches, and for disconnecting from bus-bars, switches of the type shown in Figs. 8 to 11 are used. In handling the high-tension lines, these switches are used as much as the oil-switches.

A glance at Fig. 12 will show that our high-tension lines are also practically distributing lines, as loads are taken off at a great many points. We have more than 100 sub-stations on our lines. Such a system is, of course, much more difficult to operate than a straight away line with a power station at one end and a load at the other.

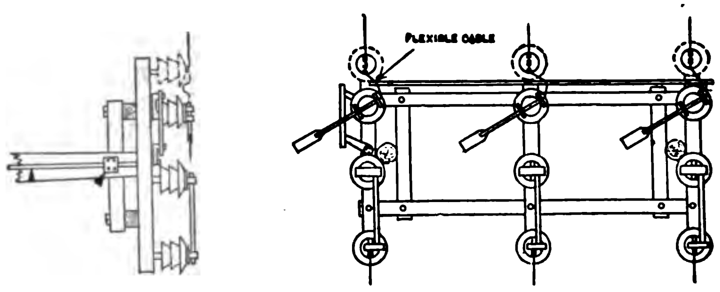


Fig. 10—Outdoor switch and fuse for small sub-stations.

On the hydraulic construction and also on the power-house and sub-station installation and construction, the engineer is required to devise something that will pay the largest net income in a given number of years. Sometimes he is called upon to make installations on the assumption that the plant is to be abandoned in a few years. Of course, the engineer will be criticized if he puts in a plant to meet present or apparent future needs and, due to some change in the industry or development of the country, the plant must be remodeled later. But it is the business of the engineer to solve his problems as he sees them.

I have given these examples of line and switch construction to show that *the best solution of a problem may be one which accomplishes the purpose satisfactorily with the least amount of money*, on account of the changes in design which become apparent as our experience is broadened and as the industry develops. That there will be further advances is certain, but, as far as high-tension work is concerned, little of the present apparatus—transformers, insulators, switches—need be thrown away; for, should the line voltage be forced up, the present apparatus may be used on the lower-voltage lines. And too, the high-tension transformer is so flexible in its operating-voltage connections that use can always be found for it. It is very probable that in time higher-voltage trunk lines will be built which will feed into the present lower-pressure (60,000 volts) lines at various points, using the present 60,000-volt lines for the primary distribution, and stepping down to about 11,000 for the regular factory distribution. An example of work of this kind is shown by our system. A great many miles of comparatively low-tension lines—10,000 to 23,000— have been changed to higher voltage, but all the old line

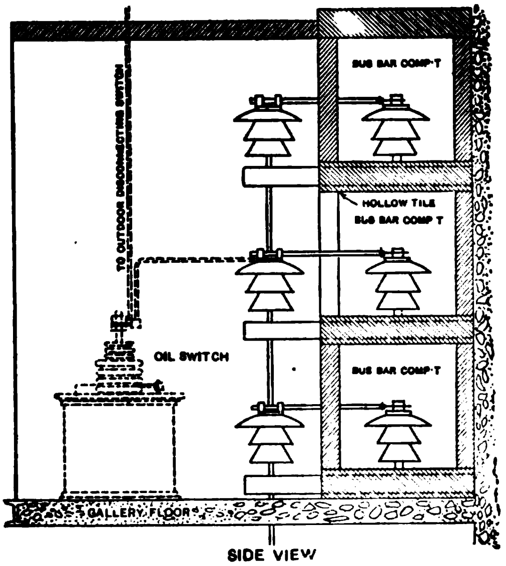


Fig. 11—Oil-switch in compartment, showing disconnecting-switches.

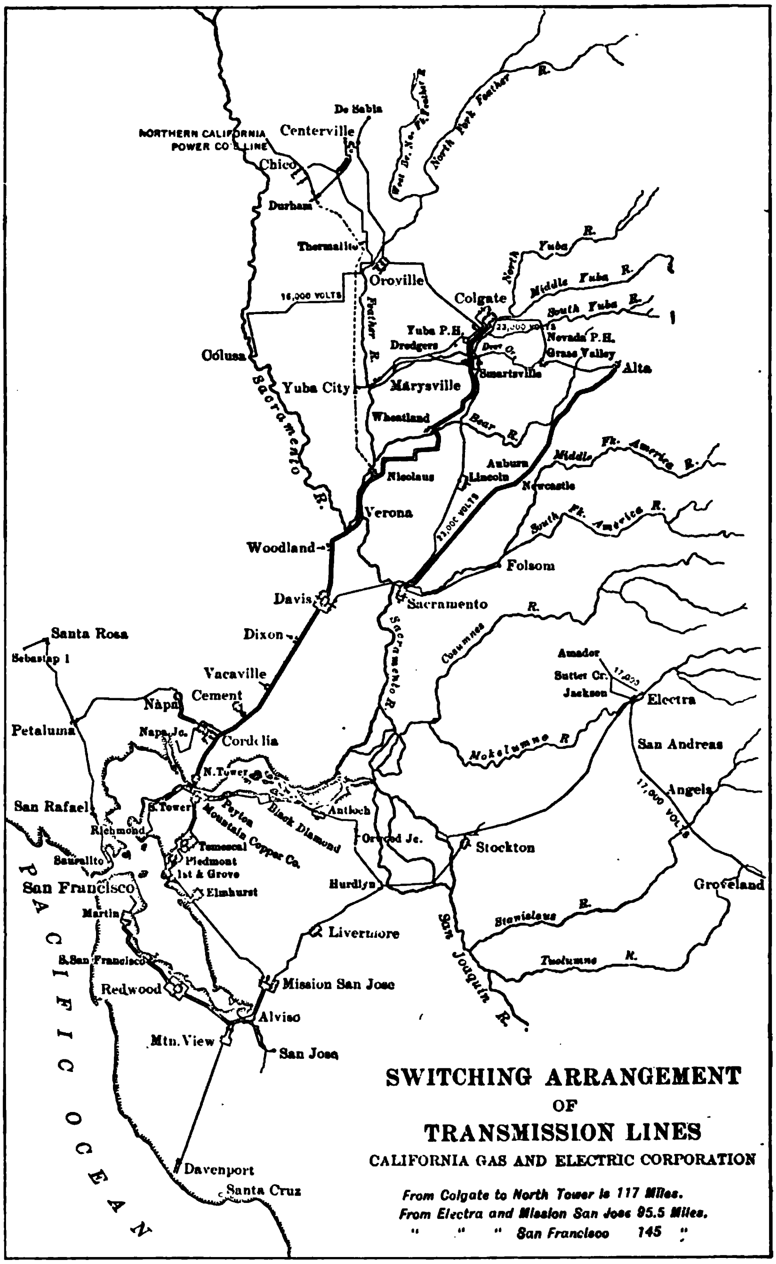


FIG 12.—All lines not otherwise marked are at 60,000 volts.

material, switches, insulators, transformers, etc., have been again utilized.

The saving in conducting capacity and the improvement in the service and the salvage have well paid for all the changes. No doubt a part of the future work of the electrical engineer will be to redesign and reconstruct the high-tension systems for the economies to be gained. The ease by which the change to the higher voltage may be made as necessity arises is encouraging alike to the transmission engineer and to the investor.

DISCUSSION ON "SOME POWER TRANSMISSION ECONOMICS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

Chas. P. Steinmetz. This paper describes a construction suitable for power transmission where the utmost reliability is not necessary, but where cheapness is needed to make the installation feasible. It is desirable in all such discussions to give some clue of what is understood by " reliable " or " satisfactory " operation. In listening to statements of satisfactory operation of transmission lines, it will be found that " satisfactory operation " is a flexible expression; for what may seem to one engineer under certain conditions as satisfactory, may to another engineer, seem very unsatisfactory. For instance, the chief engineer of a large city told me a few days ago that in his city the power has not been off the low-tension bus-bar in fifteen years. In such a case a number of shutdowns averaging one shutdown per year, of five minutes or less duration, would be unsatisfactory operation; because if it should happen there probably would immediately be a legislative committee to investigate why it happened that some thousands of citizens were caught by the failure of the power in elevators midway between the floors of office buildings. In another instance, in a transmission line supplying power to a mining district, it may be perfectly satisfactory operation if the number of shutdowns averages not more than two per month, with perhaps a total duration of an average of twenty minutes per month. That may be perfectly satisfactory in that case.

It would seem desirable, then, for an engineer who makes a statement of this kind to preface his statement with something like this: I consider as the limits of a satisfactory operation a number of shutdowns averaging not more than two per month of a total duration of not more than twenty minutes per month; or I consider as the limits of satisfactory operation a number of shutdowns averaging not more than two per year of a total duration of not more than five minutes per year, whichever may be the case. Then we really could compare the cases intelligently, while now we really cannot do so.

The thing which brought this matter to my attention is that we have had so much discussion of what is proper to do for transmission at voltages above 60,000, and we have discussed transmission lines of 100,000 volts, and more than 100,000 volts, and, too, someone has asked the question, which has remained unanswered, whether there is anywhere in this country or anywhere else any transmission system in successful satisfactory commercial operation of 60,000 volts or more. The answer to the question would entirely depend on what one calls satisfactory operation. If satisfactory operation is to be judged from the experience of the city engineer in whose system the power had not been off the bus-bars for fifteen years, I do not think there is any such system, or will be for a long time. If by satisfactory operation is meant the case of the engineer who figures the time when the power is off the circuit in per cent. of the total time, and is satisfied if it is not more than one per cent. of the total time when there is no power, then there will be quite a number of systems in successful operation.

F. B. H. Paine: I think that Mr. Steinmetz asks too much of the engineer. I was brought up in a school where the use of the word " satisfactory " was prohibited. Manufacturing companies have eliminated that word from their vocabularies and so I think it would be necessary to understand, not so much what the engineer of the transmission company thought was satisfactory, as what each one of his patrons thought was satisfactory; I have yet to find a unanimity of opinion anywhere as to what satisfactory service may be.

The great value of Mr. Baum's paper is in bringing out strongly the great difference in transmission practice of the West and the East. I have recently made an extended trip in the West in order to harmonize, if I could, the conflicting statements as to the availability of certain apparatus and methods for high-voltage transmission that are not regarded in this part of the country as permissible, yet I knew to have been in successful operation in the West. The most striking differences which Mr. Baum brings out in his paper are two: the use of the ground as a return for high voltages, and the fact not expressly stated in his paper, that no automatic apparatus is used on their system. The fact that no automatic apparatus is used permits the use of a class of switching and other line apparatus, even on a system of that magnitude, which would be utterly impracticable on a system of lesser magnitude where automatic apparatus is used. The oil-switches that are shown here are excellently constructed, but to one who is accustomed to the immense switches used for 60,000-volt service in the East they are astonishing; they only cost $200 or $300, and we are accustomed to pay $1500 to for our switches. I attribute the successful use of these cheaper well-made switches to the fact that they are non-automatic and are used only under more or less ordinary operating conditions, not emergency conditions. They are used, furthermore, on long transmission lines with comparatively small conductors and the most complex system that is imaginable. They are extremely useful devices; they ought to be available for special service in the East, but they would not do to control large transmission systems with large conductors and large generating units behind them.

The use of the ground as a conductor I have supposed to be open to serious objections. I should suppose this to be the case particularly, as in their case, where it is used for 60,000 volts, for 12,000 volts, and 2300 volts and how many other voltages I do not know, I wish that Mr. Steinmetz and Mr. Scott would speak on that phase of the subject.

There are a good many things described in the paper that indicate a construction applicable only to a country free from extremely high winds and sleet. The very ingenious pole-line construction would not be usable in such a climate as New York, and this should be fully appreciated. Mr. Baum regards two independent pole lines entering the city from different directions as being more reliable than two circuits on an individual tower line, or two circuits each on their own tower lines, presumably supplying power from the same source. The difficulty in building up one circuit out of two, two wires on one, and one on the other line is very much increased and made almost impracticable if the circuits themselves are distant from each other and if each line feeds different customers. Lines in the same vicinity are equally likely to injury from lightning whether they are adjacent or two or three miles apart.

The reason for the use of different tensions in the three wires on a pole line is not obvious, and I was not able while in the West to ascertain any satisfactory reason for the practice. Unbalanced strains on one fragile structure are mechanically very undesirable.

The reason given by those in charge of various lines was that it was found impossible to string the wires sufficiently close to the same tension, therefore in a wind storm the different periodicity of the swing of three wires would ultimately bring them together. I think a more careful inspection of the lines during construction would make it possible to string them to the same tension. On our 400 miles of line no one has ever discovered a tendency of the cables to swing together. We use a seven-foot triangle, with spans normally at 550 feet and ranging up to 1200 feet, 1200 feet being approximately the longest span we have. We find the cables swing synchronously and are sluggish in their movement when subject to sudden gusts of wind.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907

SINGLE-PHASE HIGH-TENSION POWER TRANSMISSION.

BY E. J. YOUNG.

The recent advance in Europe of the Thury direct-current system of power transmission demonstrates the fact that unless an alternating-current system approaching it in simplicity of design and economy of material is developed, it is only a question of time before the high-tension direct current will gain a hold upon this continent. Consequently, the writer proposes a high-tension single-phase system having several desirable features not in common with either the direct-current or the three-phase system.

While the present three-phase system is more flexible than the direct current, it is more complicated, and requires a considerably greater outlay for transmission material. The ordinary single-phase system is simpler than either of these two, but requires 25% more copper than the three-phase system and a proportionately greater amount than direct current. Then again, considering the strain upon the insulators as a standard of comparison, the fundamental difference between direct- and alternating-current systems gives the former an advantage that no alternating-current system can overcome.

In Fig. 1 is shown a general outline of the proposed single-phase system. Single-phase generating apparatus is supplying energy to step-up transformers—for convenience only one is indicated.

The center of the high-tension windings is permanently grounded, thereby reducing the electromotive force from line to ground to one-half that between the line wires, and in so doing placing single-phase transmission at least on a par with three phase in the matter of economy of copper. At the receiving end the step-down apparatus is similar to that at the power station, the center of all high-tension windings being grounded. At the substation there is a motor-generator set consisting of a single-phase synchronous motor and a three-phase power and lighting generator. The set is started by an ordinary single-phase series motor operated by current from an autotransformer connected across the secondaries of the step-down transformers. The exciter may be on the motor-generator shaft as in Fig. 1, or operated by a separate motor, as best suits the conditions.

An example will probably serve to illustrate the comparison between the different systems, especially those by alternating current. Therefore it is proposed to transmit 15,000 kw., 100 miles with 10% loss. The electromotive force to be 50 kilovolts from line to ground at the receiving end, and the alternating-current frequency to be 30 cycles. The following conditions for the three-phase line are assumed:

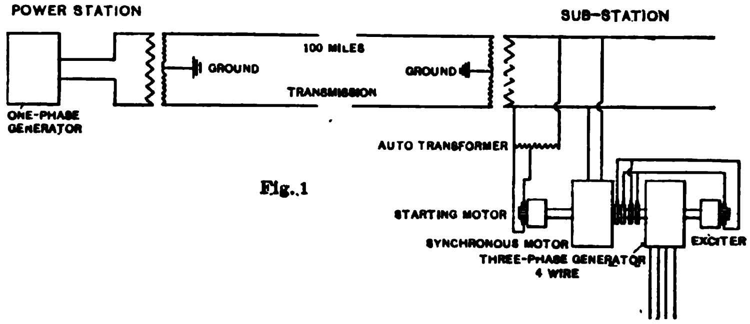


Fig. 1

Power-factor = 0.9.
Star-connected transformers with grounded neutral.
Electromotive force to ground = 50 kilovolts.
Electromotive force across line = 50 × 1.732 kilovolts.
By transmission formulas the copper section per line will be:

$$1. \qquad \text{Cir. mils} = \frac{D \times P \times K}{M \times E^2} \text{ in which}$$

D = 100 × 5280 × 1.02 ft., 2% allowed for sag in conductors, etc.
P = 15,000,000 watts.
K = 1330 for 0.9 power-factor, three phase.
M = 10% loss.
E = 50 × 1.732 kilovolts.

Consequently:

$$2.\quad \text{Cir. mils} = \frac{100 \times 5280 \times 1.02 \times 15{,}000{,}000 \times 1330}{10 \times (50{,}000 \times 1.732)^2} = 143{,}270.$$

$$\text{Weight of copper per mile of line} = \frac{143{,}270 \times 3}{62.5} = 6876 \text{ lb.}$$

As shown in Fig. 1, the center of the high-tension windings is grounded. The electromotive force of the single-phase system may therefore be double that to ground and still retain the same strain upon the insulators as in the three-phase system. One-phase conditions:

Electromotive force..........100 kilovolts.
Power-factor........0.9
Constant K........2660 for 0.9 power-factor, single phase.

Therefore:

$$3.\quad \text{Cir. mils} = \frac{100 \times 5280 \times 1.02 \times 15{,}000{,}000 \times 2660}{10 \times 100{,}000^2} = 214{,}890.$$

$$\text{Weight of copper per mile of line} = \frac{214{,}890 \times 2}{62.5} = 6876 \text{ lb.}$$

In order that the direct-current system shall be under the same conditions as the alternating current, the electromotive force to ground will be 50 ÷ 0.707 or approximately 70.7 kilovolts. This will give practically the same strain on the insulators as would 50 kilovolts alternating current. By grounding the row of generators at the power and receiving stations, as proposed on the direct-current transmission from Monthoux to Paris, France, there would be a potential of 141.4 kilovolts between line wires.

According to formula 3, with K equal to 2160 for direct-current, all other factors remaining the same, we obtain:

$$4.\quad \text{Cir. mils} = \frac{100 \times 5280 \times 1.02 \times 15{,}000{,}000 \times 2160}{10 \times 141{,}400^2} = 87{,}270.$$

$$\text{Weight of copper per mile of line} = \frac{87{,}270 \times 2}{62.5} = 2792 \text{ lb.}$$

Comparing these results, we find that as far as transmission material is concerned the direct-current system is far more economical than either the three-phase or the single-phase system.

There is practically no choice between the latter two. Therefore, any advantage the alternating-current system may have, must necessarily be in the power house and the sub-station.

Comparing now the three phase and single phase with the idea of estimating the probable saving the latter would represent in line material: on the single-phase system there would be at least 12 less insulators and pins per mile if steel towers were used, and 44 on ordinary pole construction. At $2.50 per pin and insulator, this would mean an initial saving of $30, or $110 a mile for pins and insulators alone. The cross-arms, etc. of the single-phase line would probably be longer and heavier than those of the three-phase line on account of the wires being farther apart, due to higher electromotive force, but this is more than compensated for by the poles being about 5 ft. shorter, since the upper wire is done away with. There is also the difference in cost in stringing wires—three wires on one system and only two on the other.

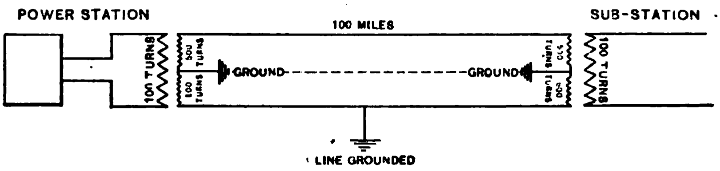


Fig. 2

One of the most important advantages of the proposed system, with reference to continuity of service in case of trouble on transmission line, is shown in Figs. 2, 3, and 4. In Fig. 2 the line is supposed to be grounded. The number of turns in the transformer windings is indicated in order to illustrate the effect of such an occurrence. With independent automatic circuit-breakers in each high-tension line at the power house and sub-stations—those at the power house operated by overload time-limit relays, and the sub-stations supplied with reverse-current relays operating with practically no time-limit—the affected line will be cleared by the short-circuit.

We have now a 50-kilovolt transmission in which the ground serves as one conductor. At the receiving end the ratio of transformation is doubled, but at the same time the electromotive force is reduced one-half. Consequently, the secondary potential will not be altered by one line being cut out of circuit on account of trouble or for repairs and inspection. In order to raise the system to approximately its original capacity, the high-tension windings, being in two sections, are connected as in Fig. 3.

Upon removing the trouble and connecting the transformers as in Figs. 1 and 2 it would appear that, by simply closing the switches upon the repaired line, normal operating conditions would be resumed. Although this last operation might result in conditions that could only be learned by experience, the illustration will show that as long as one line remains upon the insulators the service will neither be interrupted nor the transmitting power of the line very much reduced. In the event of the above trouble occurring upon the three-phase or direct-current lines, the effect is different. With three phase the entire system will be interrupted; with direct current one half the motor-generators will stop. It will therefore be seen that the necessity of a duplicate line is much less needed on one phase than on either of the other systems.

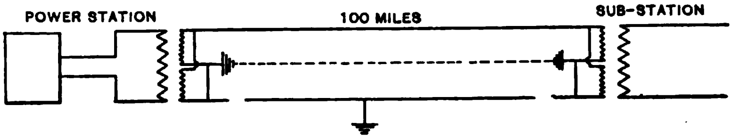


Fig. 3

Owing to the high electromotive force of the alternating-current system the space occupied by the high-tension bus-bars etc. as ordinarily installed would represent a considerable portion of the station. Consequently, a diagram of the station distribution requiring small space but giving ample insulation, the high-tension lines being under oil, is shown in Fig. 4; although applicable to three-phase or single-phase, it will obviously present less complications when used with the latter.

In Fig 4 are shown four independent transformer units placed in a single case partioned into four chambers. Each chamber contains a transformer, the switches necessary for its operation, and the interconnecting bus-bars between adjacent transformers. The lines *C* and *D* lead to low-tension generator bus-bars; *A* and *B* lead to high-tension line-switches which are controlled by overload relays; four lines, that is, *A* and *B*, being necessary in order to facilitate inspection or repairs of individual transformers while others are in operation. It will be seen that any transformer may be cut out of circuit from adjacent units by the disconnecting switches S, which, under normal operating conditions are all closed; S_1 and S_2 indicate double-pole, double-throw, remote-control switches for connecting the high-tension coils either in series across A and B, or, in the event of trouble on one line, in parallel from ground G to the unaffected line.

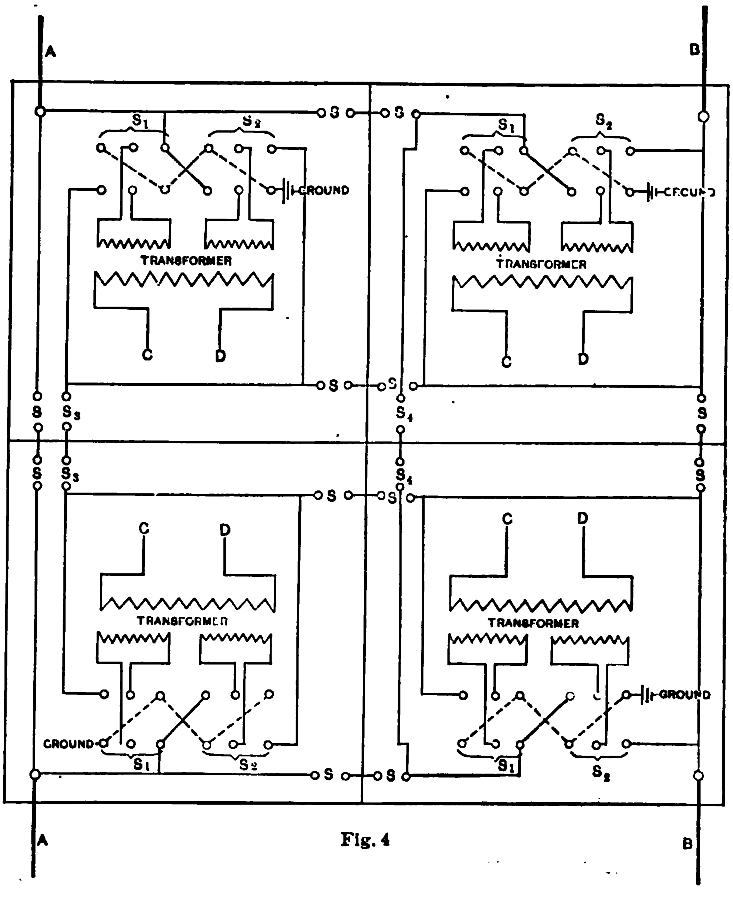


Fig. 4

The interconnecting switches S_3 and S_4 connect the bus-bars in different chambers. Under ordinary operating conditions all transformer switches S_1 and S_2 would be thrown to the right, thus putting the high-tension windings in series. In the event of line A being cut out, all switches, S_1, could be thrown to the left there by placing the two windings in multiple from B to ground G;

if line *B* is disconnected, all switches, S^1, would be to the right and S_2 to the left. Since the cooling coils have been dispensed with, the intention is to place the entire case in a pit surrounded with running water, or to have the oil withdrawn from the case and cooled externally, as is proposed in certain transmission plants.

Notwithstanding all that has been said in favor of the single-phase system it has several disadvantages. In the first place the generating apparatus costs more than three-phase, but less than direct-current apparatus. The inability of operating large induction motors is also a serious disadvantage, and would necessitate the use of motor-generators in many cases. Then again, there might be greater liability of surges in the single-phase circuit due to the larger current carried by them, but the troubles accompanying star-connected transformers, as explained by Mr. J. S. Peck, are entirely eliminated. The number of transformers upon the system, as shown in Fig. 4, will be much less with single phase, and the entire switching apparatus is not only reduced but also greatly simplified.

In the preceding suppositions the writer appreciates the fact that a number of factors which would enter into the design of a transmission system of such length and capacity have not been considered, the case taken being simply to illustrate a general theory of the proposed system. On comparatively short transmissions the disadvantages of single-phase operation and distribution would no doubt counterbalance any advantage it presents. However, where very long lines are contemplated, such as the 250-mile line in France, or electrifying railway systems in this country, single phase is not only the simplest, but unites maximum reliability of service with a minimum number of transmission wires.

DISCUSSION ON "SINGLE-PHASE HIGH-TENSION POWER TRANSMISSION", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

Chas. P. Steinmetz: In this paper Mr. Young gives a discussion of the relative economies of the different transmission systems. In bygone years considerable discussion took place on this point, and it was shown that the three-phase system requires only 75 per cent. of the copper of a single-phase system or a four-wire two-phase system, on the basis of equal maximum electrostatic stress. With the change of industrial conditions, such conclusions will have to be revised. When the matter was discussed before, then the statements were correct, because in those early days all electrical circuits were operated as isolated systems without grounded neutral; and in that case the voltage which came into consideration was the voltage from conductor to conductor, across two insulators, and in that case the three-phase system has an advantage of 25 per cent. in copper.

Now, with voltages of 60,000 or more, it is almost always the custom to ground the neutral, and in this case the maximum stress is from the conductor over a single insulator to ground, corresponding to the voltage which in the single-phase system is the voltage between the conductors divided by two, or half the line voltage. In the three-phase system the voltage between the conductors is divided by $\sqrt{3}$ or the Y, voltage; in other words, when operating with grounded neutral, all systems, single-phase, two-phase, or three-phase are exactly alike in their copper economy. They are all combinations or multiples of single-phase systems with grounded return and zero resistance in the return. All these systems, as we know, theoretically can be considered and are considered as a number of single-phase systems, each system being one of the transmission wires, returned over the ground with zero resistance in the ground. The statement that the three-phase system has an economy in copper of 25 per cent. is not correct for the high potential line with grounded neutral, for at present with grounded neutral the three-phase system does not offer any advantage in copper economy over the single-phase or four-wire two-phase system. The advantage of the polyphase system over the single-phase system is only the greater usefulness of polyphase power, since the largest part of the power is always used for synchronous motors, induction motors, synchronous converters, etc. The advantage of the three-phase system over the two-phase system is the advantage of three wires over four wires. This is what upholds the three-phase system at present.

In comparing the three-phase or single-phase system with direct-current high-tension transmission, it was pointed out in the early days that they cannot be compared as regards copper economy, on the basis of maximum voltage or effective voltage, because one stress is alternating with the average equaling zero, the other stress is unidirectional, and so all those effects of the electrical stress which are unidirectional exist to a very small extent only in the alternating-current system, while prominent in the direct-current system, and all those effects which depend on instantaneous voltage are greater in the alternating-current system. So direct-current high-tension and alternating-current high-tension cannot directly be compared on the basis of some voltage, average, effective, maximum, or whatever it may be. but require a further investigation which the future will give; and the future will indicate whether the direct-current high-potential transmission should be reintroduced to any appreciable extent. I do not believe it will.

E. H. Schwarz: It is obvious that in single-phase transmission, single-phase alternators might be used, and I would like to know, where there is a low power-factor due to a heavy overload, whether the armature reaction in a single-phase machine knocks down the voltage less than in a three-phase machine?

Chas. P. Steinmetz: The opposite is the case. In a single-phase machine the armature reaction lowers the voltage more at heavy load and low power-factor than in the polyphase machine, and not only lowers the voltage but also changes the wave shape by superimposing the triple harmonic on the main wave. The result is that a machine cannot be operated at the same output single-phase that it can be operated polyphase; that is, a certain type and size of machine when built single-phase must be rated at the lower output, probably about three-quarters of that when built as a polyphase machine.

E. H. Schwarz: In making short-circuit tests on three-phase and single-phase machines, I have noticed that it takes less field current in single than in three-phase. I thought that was due to the fact that in the three-phase alternator the maximum current in one phase would demagnetize the field at a time when the other phases should be generating a certain voltage, while in the single-phase alternator the demagnetization due to maximum current could only affect the one phase of the machine, and since the voltage would be zero at this time, the demagnetization would have no effect upon it.

Chas. P. Steinmetz: If there is a three-phase machine and it is short-circuited single-phase, it will require less excitation for the same short-circuit current as when short-circuiting the machine polyphase. But the same current in the single-phase machine corresponds to less power, since for the same power the single-phase current should be $\sqrt{3}$ times the three-phase current; while with the same current the field excitation and the regulation may be better single-phase, with the same power; that is, $\sqrt{3}$ times as much single-phase as three-phase current. The regulation single-phase must be very much poorer than three-phase; in other words, at equal output, other things being the same, the single-phase machine gives poorer regulation and also a greater heating than the three-phase machine. Inversely, to get approximately the same regulation and heating in a single-phase machine, the output has to be reduced considerably below that which the same machine would have as a polyphase machine.

C. T. Wilkinson (by letter): The feeling aroused not only in Europe but also in this country in regard to the high-tension direct-current system of transmission devised by Mr. Thury is illustrated by Mr. Young's interesting paper. As one who has observed somewhat carefully the operation of this system I beg to offer the following comments.

First, and possibly the most important consideration, is telephonic and telegraphic disturbances, due to the grounding proposed by Mr. Young. Where this one-phase system operates under normal conditions it is uncertain whether serious trouble of this character will develop. but it seems highly probable that when running under the emergency condition proposed by Mr. Young in a case of a breakdown of one line that very serious difficulty would be expected.

The connection of the two high-tension transformer windings in multiple, as shown in Fig. 3, doubles the current of the transmission line and therefore increases the losses four times while it is possible that regulation would be seriously interfered with and that considerable trouble might be experienced due to hunting or surging of the single-phase synchronous motor-generator sets at the receiving end.

In the case of a ground on the direct-current system, Mr. Young states that one-half the motor generators will stop. In this connection attention may be drawn to the method of building the Thury sets in semi-groups, each semi-group containing two armatures on the same shaft which are connected in series. the idea being that, if the station capacity is to be increased at any time, it can be done by connecting these two armatures in multiple, thus doubling the current and halving the voltage. While, of course, the switching arrangements should enable this to be done rapidly in case of breakdown, this would somewhat reduce the present remarkable simplicity of the Thury system. This method would solve the difficulty quite satisfactorily, though of course the line losses would be doubled. The semi-groups being thus connected in multiple. they would all be thrown across between the earth and the remaining line.

Perhaps, it is worth while considering the arrangement Mr. Thury has devised in case a breakdown occurs where it is not desirable to ground the whole line. In these cases he places the transmission line (as in the case of the transmission from Moutiers to Lyon) in several sections, providing what are called "earthing-cabins" at intervals in order that only the broken section of the line need be earthed.

With regard to Fig. 4, it seems at first sight as though greater simplicity ought to be obtained, since a large number of high-tension large rupture capacity switches must be employed. Further, it is not quite clear why four transformer tanks must be used; would not two separate tanks be ample with a third in reserve? Possibly Mr. Young would be kind enough to explain this matter a little more fully.

When comparing this system with the direct-current system it must be remembered that it is a comparatively easy matter to guard the latter system from lightning trouble; for in spite of the high advance made in all types of lightning arresters in recent years, trouble is occasionally experienced with alternating-current transmission.

The further troubles due to capacity and inductance need only be referred to, since it is, of course, thoroughly appreciated that their absence is an inherent advantage of the direct-current system. It might be well, however, to hold in mind that with high voltages the direct-current system allows the line wires to be somewhat closer together with resulting economy in transmission towers.

G. T. Fielding Jr. (by letter): While engineering practice sometimes drifts in the wrong direction, it seems as though there are legitimate reasons for abandonment of the original single-phase machinery and systems, passing of the quarter phase, and then gradually but surely settling down to three phase.

Engineers and station operators have not a very friendly feeling toward single-phase machinery, especially in units of appreciable capacity. The heavy vibration under load, the excessively large exciting current with inductive loads, and inferior regulation do not add in its favor. The most serious drawback to the single-phase synchronous motor is the lack of starting torque, and with units of large size difficulties in bringing up the speed and synchronizing in are anticipated.

A single-phase motor caused to drop out of step by momentary overload or any passing cause cannot of itself regain its synchronism as can a three-phase machine, but will quickly come to rest.

The cost of a single-phase machine would probably be about 20% more than a three-phase type if figured on an all around equal basis.

Though it is said that the switching would be simpler with the single-phase system, it is not evident from the writer's layout in Fig. 4. It would seem that the half transformer might be arranged to connect in series rather than in multiple in case of the failure of one line. The amount of power transmitted upon the same basis could not be doubled by making the multiple connection, and if the line insulators were based on a liberal safety-factor the series combination should reasonably be maintained until repairs are made on the damaged line.

While Mr. Young calls to attention some interesting points in making comparisons, it would seem that the disadvantages of single-phase machinery would weigh heavily upon whatever merits there may be in the transmission.

A paper presented at the 221st Meeting of the
American Institute of Electrical Engineers,
New York, Oct. 11, 1907.

THE GROUNDED NEUTRAL, WITH AND WITHOUT SERIES RESISTANCE, IN HIGH-TENSION SYSTEMS

BY PAUL M. LINCOLN

The object of this paper is to raise for discussion the question of grounding the neutral, a question that continually confronts the engineer operating an alternating-current generating, transmitting, or distributing system. The writer wishes to consider this question from the viewpoint of the operating engineer, since it is naturally he who is most interested.

The questions that would arise in the mind of the operating engineer are probably these:

1. Why should the neutral be grounded? What advantage would be gained, if any? and what disadvantages would be encountered?
2. If a ground is used, shall it be at one point of the system, or several?
3. Shall a resistance be used between the neutral and the ground? and if grounded at several points, shall a resistance be used in each place?
4. If a resistance is used, how much? and what shall be its current-carrying capacity?
5. What character of resistance is best?

Let us begin at the beginning of this list of questions and itemize, so far as possible, the advantages and disadvantages of a grounded neutral. The first part of this discussion will deal with the general question of ground versus no ground. Later in this discussion the modifications introduced into this general question by use of resistances, multiple grounds, etc., will be briefly treated.

Advantages. *a.* Electromotive force between conductor and ground remains fixed and constant.

b. Prevents abnormal static induction on neighboring circuits.

c. Provides opportunity for using the ground as a working conductor.

d. Makes possible the detection (and immediate removal if desired) of any grounded portion of the system.

e. Insures equality in the condenser current drawn from each phase.

Disadvantages. *f.* One ground disables a part or the whole of the system.

g. A proper ground is difficult to obtain.

Discussing more in detail these points of advantage and disadvantage, we find:

Advantages. *a.* In practically every transmission system the greatest danger of breakdown of insulation exists between line and ground, rather than between lines; it is therefore highly important that the voltage from line to ground be permitted to assume no abnormal or excessive value. The higher the line voltage the greater becomes the importance of this point, since the factor of safety of insulation naturally decreases with increasing line voltage. With the neutral fixed at ground potential, it is impossible to obtain, between any conductor and the ground, more than a certain definite proportion of the maximum line voltage. In a three-phase system—including as it does practically all transmitting and distributing systems—the voltage between the neutral and ground is about 58% of that between conductors. If, therefore, the neutral be connected permanently and solidly to ground, the maximum potential that can develop between the line and ground is about 58% of the voltage between the conductors. With an ungrounded system a ground on one conductor will cause full line potential to develop between the two remaining conductors and ground.

On further analysis it is doubtful if all the advantage apparent at first sight is really obtained, for it can safely be asserted that in the large majority of cases it is not the action of the steady line voltage that causes breakdowns in the insulation of transmitting or distributing systems; the voltage strain necessary to cause breaks in insulation is usually very much higher than the normal voltage applied, even in the case where a system is operating with one conductor grounded. The condition giving rise to trouble is to have superimposed upon the normal line voltage a so-called " surge " of such value that, when added to the normal strain, their resultant causes sufficient strain on the insulation to break it down. Lightning is the usual cause of surges, although they may be caused by many other things; for instance, by switching, or a partial ground, or a broken conductor, or a heavy short-circuit. Insulation being once broken down, the normal voltage is usually sufficient to maintain an abnormal flow of current through the break. With the neutral grounded, a momentary break in insulation at one point on one conductor gives rise to opportunity for a destructive arc at that point. With the neutral ungrounded, before a destructive arc can take place there must be simultaneous breaks on the insulation of two separate conductors. The use of a resistance between the ground and neutral modifies these conditions, as will be discussed in a later paragraph.

A very material advantage incident to this fixing definitely the maximum potential of conductors above ground is that it allows a much closer adjustment of lightning-arresters than would otherwise obtain; that is, the arresters can be adjusted so that a comparatively small rise above normal potential to ground will discharge across them. In an ungrounded transmission system it is not safe to adjust for a discharge potential materially less than line voltage; otherwise, in the event of one conductor becoming grounded, the constant discharge which necessarily occurs over the lightning-arresters between the two good conductors and ground will destroy the arresters within a short time.

b. An advantage incident to keeping the neutral of a transmission system at ground potential is to prevent abnormally large static induction by a transmission line on neighboring circuits. Those who have endeavored to operate a telephone line in proximity to a transmission line will realize the importance of this point. It is evident, without further explanation, that so long as the neutral of a transmission line is at ground potential its static influence on neighboring circuits is practically negligible. If, however, one of the conductors of the line is grounded, the static induction of the remaining two is usually sufficient to prevent the satisfactory use of telephone circuits strung on the same right-of-way. Grounding the neutral will prevent such a condition.

As to electromagnetic induction, it is evident that the grounded neutral can have no influence unless the ground is carrying current. In that event, electromagnetic induction on neighboring circuits is increased. This increase is due to the fact that the return circuit through the ground, instead of being in close proximity to the outgoing circuits, thereby neutralizing most of its action, is at a comparatively great distance, making the inducing loop of large area and comparatively great power.

c. In a three-phase transmission system with the neutral grounded both at the generating station and at a sub-station, it is perfectly possible to continue the transmission of power with one of the conductors out of commission. In this case, if the phases remain balanced, the ground will carry a current 1.73 times that in each of the two remaining conductors. Furthermore, it is perfectly possible to continue to transmit single-phase power with only one of the three conductors remaining. In fact some transmission plants make a practice of running but a single wire to some customers using single-phase current, and but two of their three conductors to other of their customers using polyphase currents, relying in each case on the ground to act as a return conductor for the normal operating current. Still other plants make use of the ground as a working conductor only in emergency.

It must be counted as a distinct advantage in favor of the system with a grounded neutral that it makes available at any time the use of the ground as a working conductor. This does not mean that the ungrounded system cannot make the ground available, but in the latter case special switching arrangements must be provided, while in the former its action as a working conductor is practically automatic.

The practicability of using the ground as a working conductor is also dependent upon the ground resistance. This is an element that varies largely with geological formations, soil, season, moisture, parallel return circuits, and construction of ground-plate; it is therefore difficult to make any general statement covering this matter. However, there seems to have been no difficulty in using the ground as a conductor for moderate amounts of power at pressures of 20,000 volts and above.

d and *f*. With a grounded neutral, a ground on any conductor will cause a short-circuit. This fact may be regarded as an advantage or a disadvantage, depending upon circumstances, and also upon the point of view of the operator. If it is possible by use of the grounded neutral automatically to cut out the damaged conductor, and continue service to the affected part of the system over other lines, the grounded neutral may undoubtedly be regarded as an advantage. If, however, the grounding of the neutral means an interruption of service which could be avoided with an ungrounded neutral, the grounding may be justly regarded as a disadvantage. Protection of service is of great importance to the operator, and he is willing to run very considerable risks in order to give continuous service. That certain portions of his system are temporarily overloaded, or that part of his line conductors are temporarily undergoing an abnormal insulation strain to ground, is of no particular moment, so long as service is being rendered and the abnormal condition does not give rise to further trouble. When considering questions of protection of service, the use of resistance in the ground connection is at once involved; the discussion of this phase will be treated in subsequent paragraphs.

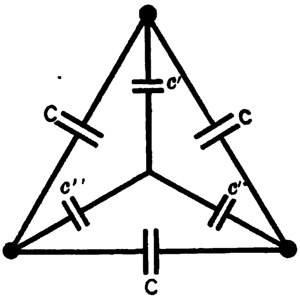


Fig. 1

e. All alternating-current transmission lines take from the generators a condenser current whose volume depends upon the size, length, and disposition of the transmitting conductors and upon the voltage and frequency supplied to them. These currents may be considered as flowing over two paths, as follows:

I. Through the condensers formed by the conductors as opposite plates, as c in Fig. 1, and

II. Through the condensers formed by considering the conductors as one plate and the ground as the other, as at c', Fig. 1.

The currents flowing through capacity c are evidently independent of any grounded neutral conditions. Those flowing through capacities c', however, depend entirely upon the potential of the neutral with respect to ground. With the neutral at ground potential, the condenser currents through c' are taken equally from each of the three conductors. Assuming an extreme case—one of the three conductors grounded—all the currents through c' are taken from two of the conductors, and further, the total kilovolt-amperes represented by these currents is double what it would be with the neutral at ground potential. A moment's investigation will show this latter point. With the grounded neutral the total kilovolt-amperes, taken through capacities c', may be assumed as proportional to $3\,c'\,E_1^2$, where E_1 is the potential between any conductor and the neutral. Grounding one conductor has the effect of short circuiting one of these condensers and throwing a potential of $E = \sqrt{3}\,E_1$ upon the other two. In the latter case the total kilovolt-amperes taken by condensers c' is $2\,c'\,E^2 = 6\,c'\,E_1^2$.

When the charging current is large compared with the generator capacity, it is probable that such an increase in its volume, as well as taking it largely from two of the three conductors, would cause a serious unbalance in voltage between phases. This seems to be a good, though not controlling, reason for maintaining the neutral at ground potential.

g. A satisfactory ground is very difficult to obtain. The antiquated idea that the ground is of zero resistance, because it is of practically infinite cross-section, has long since been recognized as an error. In case of grounding to a buried plate, most of the resistance of the ground occurs in the immediate neighborhood of the ground-plate, and the ground resistance depends upon the character and condition of the soil in the immediate neighborhood. This is to be expected on account of the fact that it is only in the immediate neighborhood of the ground-plate that the cross-section of the ground, considered as a conductor, is sufficiently restricted to give rise to any appreciable resistance. The conditions other than the character of the soil that make for a low-resistance ground are moisture and the exposure of a large surface of ground-plate: the larger the exposed surface the lower the resistance. It is this reason that makes water-supply systems good grounds.

Even where good engineering practice dictates a resistance in the neutral, the unavoidable resistance in the ground connection is not so valuable as it might be, because of its extreme variability. The difference of the seasons, as well as the drying-out action of any ground current that may flow, will cause large variations in ground resistance. However, on high-potential systems the presence of even the maximum amount of resistance that is contingent upon good construction is rarely sufficient to cause trouble.

MODIFICATIONS DUE TO USE OF RESISTANCE AND MULTIPLE GROUNDS

If an operating engineer has come to the conclusion that his neutral should be grounded, the next question is, naturally, that concerning the number of places to ground—whether it shall be at his power plant or plants only, or at other points where neutrals can be obtained. The answer to this question usually depends upon the object sought in grounding. If it is the use of the ground as a working conductor, there must naturally be grounds both at the generating and receiving points. On the other hand, if the object is to prevent an abnormal voltage rise on any conductor, due to the grounding of another, then the grounding of the neutral at one point is sufficient and in most cases preferable.

In some methods of connection the problem is still further complicated by the entire absence of an available neutral. In any three-phase system a delta connection of transformer or generator windings gives no opportunity of obtaining a neutral. A delta connection requires the use of a separate autotransformer connected across proper points of the delta, from the winding of which a tap may be brought out for the neutral connection. A three-phase star-connected generating system has of course the neutral at the star connection. If, however, a bank of transformers has both the primary and secondary connected in star, the star connection is not necessarily at the neutral point. In this case the neutral is practically free to move around anywhere within the three-phase triangle; in case of a dead short-circuit on any transformer, the voltage on that particular one disappears and the two remaining transformers assume the whole potential of the line, being then virtually connected in *V*. If, therefore, the star connection of a star-to-star group of transformers be connected to ground, it does not follow that the neutral is grounded; if one side is connected in delta and the other in star, then the star connection can be treated as a fixed point at the center of the three-phase triangle. In a star-to-star group proper conditions can be assured only by connecting the star point on either side to a fixed neutral; such for instance as the connection of the star of the transformers to the star point of the generating system. The star point of the generating system being fixed at neutral, this also fixes the transformers.

The question as to how many points of a system shall be grounded is naturally influenced by the above considerations. The final answer, however, must be dictated by considerations which depend upon the reason leading to making any ground connection.

Probably the most important question in connection with this whole matter of grounding the neutral is that as to the use of resistance between the neutral and ground and the amount of resistance that is best. In considering this question the following analysis is pertinent. In any polyphase system, so long as each conductor has the same capacity and ground, the same insulation from ground, and a balanced load, the neutral will remain at ground potential, whether it is connected to ground or not. In other words, so long as conditions on the transmitting or distributing system remain normal there is no occasion for grounding the neutral, as nothing will be accomplished thereby. The object sought in grounding the neutral is to take care, not of normal conditions, but abnormal ones. It is the first thought of the operating engineer to maintain his service, and he therefore installs automatic circuit-breakers and other devices to protect his system in case of an abnormal condition arising. The abnormal conditions that may arise are: 1, short-circuits; 2, open circuits; and 3, grounds.

1. *Short-circuits.* By short-circuits is meant accidental connection in any manner between conductors of opposite polarity. It is evident that under this condition the behavior of automatic devices is in no way influenced by grounding the neutral, so that the consideration of this contingency is not pertinent to this paper.

2. *Open circuits.* In a three-phase line, with the neutral grounded at both generating and receiving stations, the ground will, under normal conditions, carry no current, even though the ground be of zero resistance. If, however, one of the conductors should break, the ground immediately begins to carry current. If induction or synchronous motors are being used at the receiving end, the three-phase relation will be approximately maintained, the degree of approximation depending upon the ground resistance and upon the relative motor load to non-motor load. If the neutral is grounded at one point only, an open

circuit in one conductor would have an effect no different from that which would take place if the neutral were not grounded, except that the distribution of charging current between conductors will be somewhat disturbed and more or less of this current would pass through the ground connection.

3. *Grounds.* A ground is the most frequent abnormal condition that is encountered, and also is the one most affected by grounding the neutral. With the neutral connected direct to ground, another ground on any conductor means a short-circuit; the action of automatic circuit-breakers will then take place accordingly. The amount of current that will flow through such a short-circuit can be limited by inserting resistance, and practically the only object of resistance is to cause such a limitation of current.

The flow of excessive currents, such as would take place were there no resistance, is detrimental for several reasons. It throws an unnecessarily great strain upon the circuit-breakers which are called upon to interrupt the current. The large current flow which takes place may cause a phase distortion and drop of voltage which may, in turn, be sufficient to cause synchronous apparatus on the line to drop out of step. Almost invariably an arc takes place at the point of grounding of conductors, and an excessive current will cause excessive destruction at this point. A dead short-circuit on any system causes a heavy shock due to the tremendous currents, and a consequent tendency to distort the windings of any synchronous apparatus connected to the system.

All of these objections can be overcome to a greater or less degree by resistance in the neutral. Increased neutral resistance, however, while it limits the current flow through a grounded conductor and overcomes the above objections, can do so only by allowing an increase in the potential of the two good conductors above ground while the current flows. If the object in grounding is to prevent such an abnormal rise, the inserting of resistance tends to defeat that purpose. The choice of the proper resistance becomes a question of compromise between the disadvantages of going to either extreme. There seem to be good reasons for adopting a ground resistance which would lie between the following limits: on the one hand, large enough to prevent a severe shock to the system; or the voltage on the affected phase dropping to a point where the synchronous apparatus will drop out of step. This consideration would dictate a resistance that will not allow more than, say, three times full-load current at the most to flow through the armatures of the generators supplying the circuits. On the other hand, the resistance must be small enough to permit sufficient current to flow to trip the heaviest circuit-breaker on the system.

In all alternating-current circuits there is present a condition equivalent to a neutral grounded through a certain amount of resistance, in that static capacity exists between any conductor and ground. The longer the line and the higher the voltage and frequency, the lower the resistance in the equivalent circuit having a resistance in grounding connection. The effect of a grounded neutral, either with or without resistance, is, in case a conductor becomes grounded, to pass a current of greater or less volume through the affected conductor and into the ground. The effect of the static capacity of conductors to ground is exactly the same, the difference being that no current passes into the ground at the generating station, and that the phase relation of the current through the capacity to the electromotive force producing it are not the same in both cases. The static capacity of an overhead conductor to ground is, with ordinary line construction, from 30 to 50 per cent. greater than that between conductors. Assuming a fault that makes the affected conductor of the same potential as the ground, the affected conductor would take roughly 50 per cent. more charging current than the unaffected ones. It may be noted also that the total kilovolt-amperes of charging current in all conductors would be increased about 33 per cent. Where the normal charging current amounts to a considerable percentage of the total generating capacity, as it would in long, high-voltage, high-frequency lines, it will be seen that the condenser effect has the same action as a moderately-low ground resistance.

If a ground resistance be used, the question of its current-carrying capacity is an important one. Since current is drawn through the ground resistance only during emergencies, its capacity should be chosen to meet the maximum that any emergency can throw upon it. Usually the time during which current will flow is limited to the time required to trip a circuit-breaker, probably not more than a few seconds at most. The quantity of current that will flow as a maximum is also fixed as that which is required to trip out the most heavily set circuit-breaker. The question of current carrying capacity is therefore one which depends upon the character and setting of the safety devices used.

As to the character of resistance, permanency is the most essential. Considerable latitude is allowable in the amount of resistance, but that latitude does allow variations of many hundred per cent., such as past experience has shown is apt to take place with graphite mixtures or similar structures. A metallic resistance is satisfactory but has the objection of being expensive and bulky when the voltages involved are high. This problem has not yet been satisfactorily solved, but it seems probable that where high resistances are demanded—200 ohms or more—some form of non-metallic resistance will be found of sufficiently permanent character to be satisfactory.

In the preceding matter the writer has endeavored to present some of the considerations to be taken into account when this question of grounding the neutral arises. There are so many variables connected with this matter that it is impossible to draw any conclusion that is general in its nature. The proper action to be taken depends upon the specific conditions surrounding each individual case.

A paper presented at the 221st meeting of the American Institute of Electrical Engineers, New York, October 11, 1907.

THE GROUNDED NEUTRAL

BY F. G. CLARK

During the consideration of the design of one high-tension installation, the question of grounding the neutral was investigated, and resulted in a decision to ground the neutral points of the generators through a limiting resistance. It was my privilege to contribute to that design and to recommend that this resistance be omitted. The reasons for grounding, the reasons for and against the resistance, and facts relatively to operation covering a period of over two years may therefore be of interest in connection with this discussion.

The installation comprises a power station centrally located for the ultimate conditions prescribed, but unfavorably to the preliminary electrification of a steam railroad requiring seven sub-stations, and undergound and overhead transmission of three-phase current at 11,000 volts and 25 cycles. Fig. 1 will give an idea of the present and ultimate conditions. The future circuits from the power station will be underground cables. There are now five 250,000-cir. mil three-phase circuits leading from the station undergound to No. 1 cable house. From there the feeders are aerial to sub-station No. 3. This will be seen to be the distributing point for the present installation. Two aerial circuits lead to sub-station No. 5. At cable-house No. 2 the circuits are submarine, and again at cable-house No. 3 submarine cables are used from the north end of the draw to the sub-station.

The feeders leading east and west from sub-station No. 3 are underground. Three circuits lead to sub-station No. 2, and from there two circuits lead to sub-station No. 1. Three circuits lead to sub-station No. 4 and are overhead from cable-house

No. 4. From No. 4 sub-station one circuit leads direct to sub-station No. 6 and another to portable station No. 1, and from there to No. 6. At portable station No. 1 a three-phase No. 2 conductor branch leads to sub-station No. 7. One circuit leads from sub-station No. 4 to portable station No. 2, and from there a single-phase No. 1 conductor circuit leads to transformer station No. 1. A typical location of this system and length of feeders is shown in Fig. 2.

The protective features are low-equivalent lightning-arresters, inverse time-element relays on circuit-breakers, a peculiar method of operating exciters, and the grounded neutral. A voltage regulator has lately been installed and has a bearing on the situation.

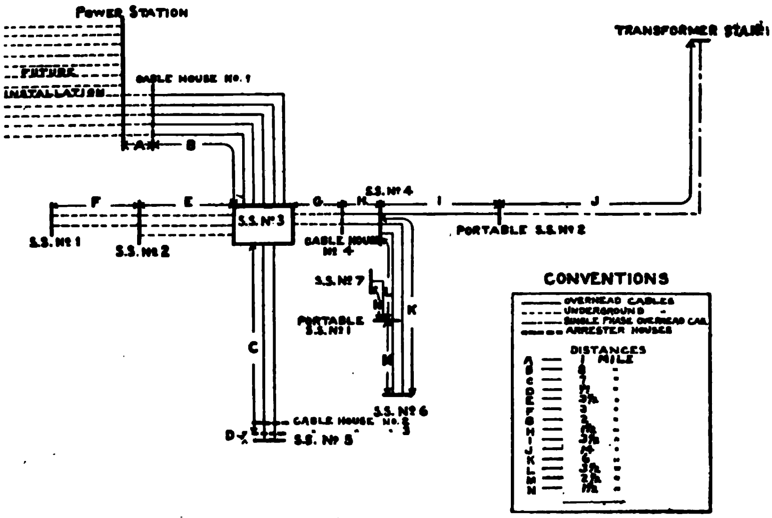


Fig. 1

The lightning-arresters are used in connection with choke-coils at the ends of all overhead feeders. They tend to protect the undergound feeders, the station apparatus, and, to a certain extent, the aerial transmission lines from the effects of lightning and from static strains due to switching, grounds, or short-circuits. The arresters are set to discharge at 8500 volts. The pressure between the ground and two conductors of the 11,000-volt, three-phase system, with one conductor grounded, is 11,000 volts when the neutral is not grounded; it is 6380 volts when the neutral is dead grounded; it is between 6380 volts and 11,000 volts with resistance in the neutral conductor. The locations of the lightning-arresters are shown in Fig. 2.

The inverse time-element relays afford protection against overloads, and are used in connection with the oil circuit-breakers on all feeders. The speed in opening the circuit-breaker varies with the increase of current in the circuit controlled.

The relays at the power station ends of the feeders are set to allow a maximum of current to flow for a period of five seconds before they actuate the control circuits to open the circuit-breakers. This is just above the amount of current allowed as a maximum per feeder. The relays at the nearest sub-station are set to open the circuit-breakers on feeders to more remote sub-stations in four seconds for the same current. The relays in the sub-station next in progression are set for three seconds with the same current, and so on. The relays are connected with series transformers, one on each leg of the circuit controlled, to open the circuit in the event of one leg grounding.

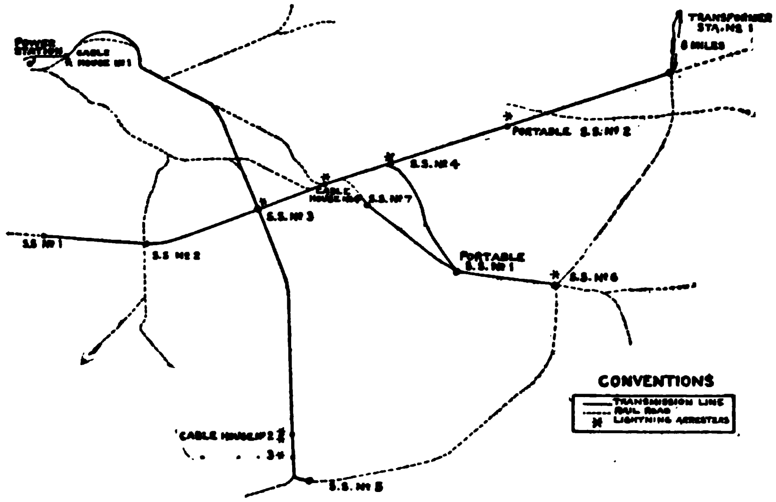


FIG. 2

The excitation of the generators depends upon induction motor-generators, with no steam exciter or battery reinforcement, although both are available for starting up in case of an interruption. The induction motors are supplied from the main generators through transformers and have about 2.5% slip. The output of the exciters depends upon the power-factor, which decreases with the voltage. The excitation automatically ceases whenever the bus-bar voltage goes below 5,000.

A voltage regulator tends automatically to increase or decrease the generator excitation as its voltage lowers or rises. The effect of this is to increase the intensity of the accidental overload and therefore hasten the automatic interruption. This is a radical change from the usual practice of holding up the exciter voltage under all conditions. It means a few more power station interruptions, but less damage when short-circuits occur, and less time lost in sub-stations.

The foregoing explanation of the protective features of this installation may appear to be irrelevant to a discussion of the grounded neutral, though it has a bearing which should not be overlooked. The neutral point of each generator is led to a bus-bar through a fourth pole of the generator circuit-breaker. The neutral bus-bar is connected to one end of a cast grid resistance suitably insulated. The other end of the resistance is connected to a ground-plate located in earth kept moist with salt water. There is 6.7 ohms resistance, or sufficient to allow 1000 amperes in the neutral circuit in the event of a ground. A current of 1000 amperes will raise the temperature of the resistance approximately 1000° fahr. in one minute. An ammeter on the switchboard indicates the amount of current in the neutral connection. A pilot lamp lights whenever 50 amperes or more flows through the resistance. This lamp remains lighted until an auxiliary circuit is opened, and has been instrumental in determining the number of short-circuits that were also grounds.

The grounded neutral affords protection against rises in potential and high-frequency oscillations due to grounds. An accidental ground will establish a power circuit supposedly sufficient in all cases automatically to open the circuit-breaker. Were the neutral not grounded, the accidental ground would allow the charging current to be discharged through it, tending to burn the insulation and cause a short-circuit in the case of an underground cable, or burn off the conductor in the case of an aerial line. The electrostatic charge would also tend to cause oscillations in the case of underground cables and possible breakdowns at various points of the system. This has occurred during the operation of several high-tension systems.

Grounding the neutral has the disadvantage of increasing the number of short-circuits, and consequently the interruptions of service. These short-circuits are dangerous to power-station apparatus, as they may cause breakdowns involving greater expense and loss of service than the possible resonance troubles.

There are conditions peculiar to each installation which have a bearing on this question, and these conditions determine the necessity of a resistance in the neutral circuit, the amount of resistance to be used, and whether more than one generator should be grounded.

In systems where synchronous converters have low synchronizing power, the voltage drop due to grounds will cause the converters to drop out, and a limiting resistance must be placed in the grounded neutral. In other systems the generator coils are insufficiently braced, and resistance in the neutral is a preventive for generator breakdowns. In stations where the generators are driven by slow-speed reciprocating engines the neutral points cannot be connected to a common bus-bar on account of cross-currents. A resistance would be required for each generator or that one generator be run with its neutral grounded.

A consideration of these facts led to a decision to use a resistance of 6.7 ohms in the power station of the installation described. It was anticipated that this resistance would allow sufficient current to flow through any ground which might occur to clear the system of that ground, and that grounds on two legs or short-circuits would be cleared by the inverse time-element relays, or, if very close to the power station, by an interruption of service due to the " killing " of excitation. The events of operation indicate that the neutral ground is essential and that the other protective features perform their functions suitably.

Conditions obtain, however, which mitigate against the proper operation of this protective feature. One instance will serve to illustrate this point. A wire-rigged sloop which had been anchored near the cable-house No. 2 draw (Fig. 1) drifted out of the channel until a stay-line connected with one leg of the transmission circuit, causing a ground. The ground held for about three minutes, when the boat shifted and another part of the rigging connected with a second leg, causing a short-circuit which opened the circuit-breaker. The current in the ground circuit was approximately 400 amperes, which was not sufficient to open any of the circuit-breakers between the ground and the power station. It was enough, however, to burn off an anchor chain and several of the wire stays on the boat, and to raise the temperature of the neutral resistance to that of a bright-red heat.

When the ground occurred, the neutral point rose from 0 to about 2700 volts, and the two ungrounded legs were approximately 9000 volts to ground. The electrostatic condition very nearly approached that which would obtain in an ungrounded system. The lightning-arresters being set at 8500 volts, began to discharge, and oscillations were a possibility.

The inductive drop and the resistance of the ground, added to the set resistance of 6.7 ohms, were sufficient to limit the current to 400 amperes. With the 6.7-ohm resistance out, the current would have been above 650 amperes, or sufficient to have opened the nearest controlling circuit-breaker in less than one second. The inductive drop was about 1000 volts and the resistance through the ground sufficient to divert the current to the numerous telephone lines as paths of least resistance. The fact that telephone troubles are not coincident with grounds of short duration would seem to indicate that induction is not an important factor in this particular case. There have been no indications of trouble in telephone or telegraph lines due to induced potential.

Some action must be taken to prevent this ground current from causing trouble. The grounded neutral is a preventer of electrostatic troubles and therefore shoud be retained. The resistance is a positive detriment to receiving the full benefit of this effect. It should, therefore, be omitted whenever the local conditions will permit. In the case described this can be done without perceptibly increasing the hazard to apparatus. This would enable the relays to clear any of the grounds that have occurred within five seconds.

A transmission line may be so long that its total drop and the resistance of the ground will produce a condition analagous to that described. Such a case would require special treatment, as, for example, providing a low-resistance neutral conductor leading to a point safely within the area normally protected by the neutral ground at the station, and equipping the feeders to points beyond, so that they may be opened by a relay. The relay could be actuated by a small current flowing in this extension of the neutral, and in phase with current flowing in one leg of the feeder. Such a condition does not obtain on the system described and we can therefore be reasonably assured that in removing the neutral resistance we will have removed the cause of trouble incident to the grounded neutral.

During two years' operation there have been over 70 short-circuits. About 25 of these have caused sub-station interruptions, and 6 have been close enough to cause power-station interruptions. About one-half of these short-circuits showed a ground connnection. There have been 10 grounds, of which the neutral ground cleared 8. One held for four minutes and one for three minutes, both developing into two-wire short-circuits.

It is quite probable that in a system operating with underground cables only, there would be no outside disturbances in connection with sustained grounds. The lead sheaths which are generally bonded together in manholes would provide the path of least resistance for the ground circuit. The ultimate installation will require undergound cables, and except for the greater power effects, and greater charging current, will alter the present situation but little.

A paper presented at the 221st Meeting of the American Institute of Electrical Engineers, New York. October 11, 1907.

EXPERIENCE WITH A GROUNDED NEUTRAL ON THE HIGH-TENSION SYSTEM OF THE INTERBOROUGH RAPID TRANSIT COMPANY

BY GEORGE I. RHODES

The chief circumstance which led to the grounding of the neutral of the Interborough Rapid Transit Company's high-tension system was the serious nature of cable burn-outs. As a rule the detectors gave indication of a ground on one leg of the system from five to thirty minutes before the circuit-breaker opened, but on account of the large number of feeders connected it was practically impossible to isolate the damaged feeder before the short-circuit occurred. In a total of twelve operating burn-outs, the grounded cable was located but twice in time to prevent trouble.

During the period between the first grounding of the cable and the final short-circuit, the system was operating under abnormal potential conditions, the two ungrounded phases operating at full delta potential of 11,000 volts above the ground. Undoubtedly the potential between phases was raised to a certain extent by the increased charging current due to unbalanced potential conditions. The presence of abnormal potentials during this period of ground was evidenced by static discharges in the power and sub-stations that could hardly be accounted for by the operation of two legs at 11,000 volts above the ground potential.

The charging current which flowed to ground through the fault before the short-circuit between phases was large enough seriously to injure the insulation of all three conductors, so that when the burn-out occurred it was so severe that the oil-switches usually opened with considerable violence. Surges were started which at times caused other burn-outs to follow, in one instance causing a very disastrous shutdown.* The cable itself was always considerably burned, all three legs being grounded and usually burned off. At times the conductors were blown apart several inches. With the faults in this condition, it was quite impossible to locate them by the bridge method, and it was necessary to open a great many manholes before locating the trouble.

In view of the fact that one phase of a cable almost invariably grounded some time before short circuiting, it was decided to ground the neutral through a resistance of proper magnitude to allow sufficient current to flow to remove the grounded feeder without affecting the system in any other way. It is obvious that with only two feeders to a sub-station, a ground on one of them will open the circuit-breakers of both, and that the certainty of continuous operation of the sub-station increases with the number of feeders.

The scheme of grounding the neutral as originally proposed was as follows: the neutral point of each generator was connected to a common or neutral bus-bar through a disconnecting switch and a current transformer. The transformer operated a relay on the main switch of the generator. The neutral bus-bar was grounded through a resistance of about six ohms in each power station, making about three ohms' resistance between the neutral of the combined system and ground. In case of a ground, the maximum possible current was 1000 amperes per rheostat, all of which was generated by the grounded generator. The relays on the feeder-switches were set to operate instantaneously at 300 amperes, and the generator relays at about 900 amperes after five seconds. Under these conditions it was to be expected that a ground on a cable would instantly remove it from service before any other disturbance could result.

The neutral rheostats were of the iron grid type having a resistance of about six ohms and a reactance at 25 cycles of about 0.3 ohms. They were made up in sixteen series sections, each insulated from the others and from the ground by porcelain insulators. Each section was made up of six series groups of cast-iron grids connected two parallel and twelve series per group. Each grid was made up of ten bars 0.25 in. by 0.75 in.

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*See paper on "High Power Surges in Electric Distribution Systems of Great Magnitude," by C. P. Steinmetz, Transactions A. I. E. E., 1905, also discussion on same.

by 6 in., and two bars 0.25 in. by 0.75 in. by 4 in. A number of extra grids were used to adjust the resistance to the required value. The rheostat will carry 1000 amperes for two minutes, a capacity far in excess of anything that would be required in service.

With the scheme as above outlined, very serious trouble was encountered from the triple-frequency cross-currents in the neutral connections. These neutral currents fluctuated very rapidly from nothing to one-half full-load current per generator. Upon synchronizing there was a very large rush of current in the neutral, so large in fact that with four generators running it was very difficult to synchronize a fifth with its neutral grounded.* These cross-currents had such serious effects on the operation of the system that the scheme of grounding the neutral was delayed for a time to allow making some experiments.

Fig 1.—Neutral rheostat.

An oscillographic study of the neutral currents was made

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* "Experience with a Grounded Neutral on a High Tension Plant," C. W. Ricker, *Electric Journal*, September, 1906.

and has been described fully.* The records (Figs. 2 and 3) proved without a doubt that the currents were caused by irregularities in the angular velocity of the prime movers and unequal excitations of the generators. It was found that the insertion of resistance in the neutral connections of the generators would reduce the currents to a safe value. This, however, was undesirable on account of the variable resistance in the ground circuit, depending on the number of generators in operation. Furthermore, resistances of sufficient magnitude and capacity would have occupied too much space to be used in these power stations.

It was finally decided that full protection could be obtained by connecting but one live generator at a time to the neutral bus-bar in each power station. The transformers in the neutral connections were also disconnected from the relays on the main generator switch. Even with but one generator grounded in each power station, the interchange of current through the neutral rheostats, and the tie-line between the stations, is at times large enough to make it undesirable to open the neutral disconnecting-switch of a live generator.

FIG. 2.—Combined effect of excitation and fluctuation of angular velocity. Curve 1, Potential between phases. Curve 2, Neutral current.

The Interborough Rapid Transit Company's system was operated for about three and one-half years without a grounded neutral, in which time about 150 miles of cable was operated for three years and 330 miles for one-half year. Since grounding the neutral, the system has been in operation for two years with about 330 miles of cable.

Previously to grounding the neutral, there were twelve distinct operating burn-outs, and since then there have been sixteen. It appears from this fact, that grounding the neutral has had no material effect on the number of burn-outs. This is as was expected.

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* "Neutral Currents of a Three-Phase Grounded System," *Electric Journal*, July, 1907.

Of the twelve burn-outs occurring previously to the grounding of the system, four shut down the power station; one other shut down two sub-stations; and four more shut down one sub-station. Of the other three which did not shut down the sub-station, two were isolated in time to prevent a short-circuit. In all of these cases, there were five or six cables to a sub-station. During most this period only the Seventy-fourth Street power station was in operation, so that there were no tie-line troubles.

Of the sixteen burn-outs that have occurred since grounding the neutral, not one has caused a shutdown of either power station; eight have shut down the sub-station fed by the cable, two have caused one other feeder to open, and six have caused no disturbance other than the opening of the switches of the feeder in trouble. In three of the cases in which the sub-station was shut down, the tie-line between the power stations opened, but without disturbing the operation of either. Of the eight burn-outs which shut down the sub-station, three were stations having three feeders each, one having four feeders, two having five feeders, and two having six feeders. Of the other eight burn-outs which did not shut down the sub-station, two were sub-stations having three feeders each, two having four feeders, two having five feeders, one having six feeders, and one having seven feeders.

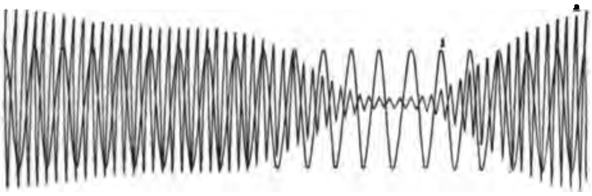

FIG. 3.—Effect of fluctuation of angular velocity. Curve 1, Potential between phases. Curve 2, Neutral current

Previously to the grounding of the neutral, the switches operated with explosive violence on the short circuiting of a cable, at times throwing oil and burning the contacts. Under present operating conditions, however, the switches always open very quietly, so quietly in most cases that it was necessary to install a tell-tale to indicate when there had been abnormal current through the neutral rheostats.

Before grounding the system, in all burn-outs the cable was so badly injured that it was impossible to make any bridge test, and it was necessary to open a great many manholes before locating the trouble. Of the sixteen burn-outs that have occurred since the grounding of the neutral, fourteen of them were in such condition that the fault could easily be located by the Murray loop method. In most of these cases but one leg was grounded. In the two cases where all three legs were grounded, making the bridge test impossible, the burn-out was the result of very severe mechanical injury. Locations of the fault are always made to within a duct length, even on the longest cables of more than 45,000 ft. The saving in time effected by this accurate predetermination of the trouble by the bridge method is an important factor in the time necessary to restore a sub-station to normal conditions of operation.

It is probable that something would be gained by increasing the resistance between the neutral and ground. When the scheme was first contemplated, it was planned to ground the neutral through six ohms, there being at that time but one power station. Now with two stations in parallel the effective grounding is through but three ohms, making the possible ground current twice that originally planned for. There is no doubt but that with the resistance as first decided upon there would have been fewer sub-station shutdowns.

From the above data, it is seen that grounding the neutral of this system through a series resistance has been quite successful. It has greatly reduced the disturbance from cable burn-outs and the time necessary to restore an injured cable to service.

DISCUSSION ON "THE GROUNDED NEUTRAL," AT NEW YORK, OCTOBER 11, 1907

Peter Junkersfeld: In November, 1900, the Commonwealth Electric Company of Chicago in one portion of its territory put into commercial service the first extensive system of four-wire, three-phase distribution at 4000–2300 volts. This 60-cycle system was soon installed in all the company's outlying and suburban territory, and has since grown to such an extent that the total length of three-phase or equivalent line of feeders to-day aggregates 525 miles, of which 55 miles is underground, the remainder overhead. The neutral of this 60-cycle system has always been connected solidly to ground.

In May, 1902, the Chicago Edison Company raised the voltage of its three-phase, 25-cycle transmission system from 4500 to 9000 volts, and put into service its first star-wound generator delivering 9000 volts directly to the bus-bars without step-up transformers. This system now aggregates 270 miles of three-conductor cable and is practically all underground, only nine miles being overhead. The neutral of this 25-cycle system has been connected to ground from the beginning. During the last year a part of this system has, however, been connected to ground through resistances. The remainder of the system during the last year and all of the system during the previous four years has been connected solidly to ground.

In June, 1907, the Chicago Edison Company put into commercial service its first 25-cycle underground line operating at 20,000 volts. The transformers were connected in delta at the receiving end and in star at the sending end. The neutral at the latter is connected solidly to ground.

The two companies mentioned above have recently been consolidated into the Commonwealth Edison Company, which thus operates a total of about 800 miles of three-phase overhead and underground lines at pressures of 4,000, 9,000, and 20,000 volts in the various zones and for different purposes, but on all of which the neutral either with or without a resistance is connected to ground. The experience in operating high-tension systems with the neutral grounded has, therefore, been considerable, and the engineering policy on this matter has been definite for several years. The experience, however, in grounding the neutral through a resistance is still somewhat limited. The various steps in this experience and development, and some of the reasons, with the conditions now existing, may be of interest in this discussion.

The 4,000—2,300-volt, four-wire, three-phase system of distribution in the outlying and suburban sections permits standard 2080 to 115–230-volt line transformers, thus giving a single-phase, three-wire lighting and small power service at 115–230 volts. It was felt that such a system of distribution would be unstable and would permit annoying and serious voltage fluctuations if the neutral of the primary system were not grounded. After considerable discussion the neutral was finally grounded, under the writer's direction, just before the first four-wire, three-phase circuit or feeder was put into service.

Among those who at that time (November, 1900) argued most strongly against the grounding of the neutral but who later, after making some experiments, became one of the most ardent advocates, was Mr. George N. Eastman, who, early in 1901, had occasion to make certain tests which led to a series of very careful investigations at a time when accurate information on this subject was very meagre. Some of the results of these investigations were presented by him in a paper before the Boston convention of the National Electric Light Association in May, 1904. These investigations, with the first few years of actual experience, practically fixed the engineering practice on this particular matter in the two Chicago central station companies, who have, since 1900, continued to develop their three-phase transmission systems with the neutral grounded.

We have no direct comparative experience with an ungrounded system under exactly similar conditions. The results from this grounded system have, however, been very satisfactory. There have been practically no underground cable burn-outs on this 60-cycle system, and comparatively little trouble on pot-heads or on the other overhead construction. The total number of transformer burn-outs from all causes, including lightning, overloading, and defects in the apparatus, during the last two years, has been about 1.4%, and 1.2% of the total number of line transformers in service. The percentage expressed in kilowatt capacity connected has thus far been even less. Similar, four-wire, three-phase systems with grounded neutral have during the last few years been installed in so many cities of the country that this practice has become quite well known. The grounding of the neutral on three-phase systems for general distribution has also become very common, at least in parts of Europe.

The 9,000-volt, 25-cycle transmission system in Chicago is used exclusively for transmission to sub-stations, not for general distribution. With the exception of a few induction motor driven exciters, all equipment consists of synchronous converters or synchronous motor-generators.

The present total continuous capacity of the two principal and two subsidiary generating stations is about 110,000 kw. The neutral of the 25-cycle, 9,000-volt system is, however, grounded directly only in the Harrison street and the Fisk street stations. The latter at present contains ten turbo-generator units, the first four of which were originally rated at 5,000 kw. and the last six at 9,000 kw. each, with the usual overload guarantee. The transmission lines from the two stations are operated normally as "radial" systems; that is, outgoing lines are independent of each other and are not tied together at the sub-station ends.

The neutral of this system was connected solidly to ground in May, 1902, when the first 9,000-volt generators were started at the Harrison street station. Since the Fisk street station was put in service, the transmission system has at times been operated all in multiple; at the other times, sectionalized. In the latter case each part or section of the system had a grounded neutral so as to avoid having two non-synchronous sections without a grounded neutral on each. At present, and during a large part of the last year, the entire 25-cycle system has been operated in two approximately equal sections, designated "System A" and "System B." Previously to this time the Fisk street station contained but four turbo-generator units, to which have since been added six units of a larger type with slightly different characteristics. Partly for this reason, and partly for the reason that with the rapidly increasing generating capacity it might be well to limit, in case of accidents, the possible flow of current to ground, there was installed a 0.5-ohm resistance between the neutral of each of the four new generators and ground. The four older generators are left with the neutral grounded solidly on each. Normally, the two sets of generators are operated on separate sections of the system, one of which was thus operated with, and the other without, a resistance in the neutral.

During the previous four years, or since May, 1902, the neutral had always been grounded solidly, and with satisfactory results. In case of a cable breakdown between conductors and ground, each cable was usually disconnected from the bus-bars by the overhead relays and oil-switch before the remaining two conductors became involved, thus permitting a quick and accurate location test by the Murray loop method. As the generating capacity of the system increased, and as it became necessary to have heavier overload and longer time-limit setting of relays on outgoing lines, the destructive effects of cable breakdowns have apparently been somewhat greater, although this may be due in part to the very heavy setting of relays. This indicated the desirability of limiting in some manner the current flow in case of accidents to decrease the destructive effects. It was also desirable to secure some comparative data on this matter of resistance or no resistance.

Four possibilities naturally presented themselves: 1, the design of generators with a lower short-circuit current; 2, grounding the neutral on only one of the groups of generators running in parallel, leaving the neutral open on the remainder so as to limit the flow of current to ground to the short-circuit current of the one generator; 3, the introduction of one large resistance between the neutral bus-bar from a group of generators and ground; 4, the introduction of a separate resistance between the neutral of each generator and ground. Partly for reasons previously stated, the latter method was adopted.

Both of the first two methods mean holding the neutral where it belongs, while both of the last two methods will cause displacement of the neutral with attendant rises in potential, as has been pointed out in Mr. Lincoln's paper.

In four cases of trouble, each affecting from 10 to 30% of the total service at the time, during the two years before the installation of resistances, and during the one year since, the effects might or might not have been modified if the neutral had been grounded with instead of without a resistance. In all the other cases of trouble during this period, and in most of the cases during the three years previously, the use of a resistance in the neutral would probably not have effected any improvement. In most instances the overload relays on feeder oil-switches were set at 100% overload for six seconds, although in some cases they were set at 100% for three seconds. The generator switches are all non-automatic and are opened only by the switchboard operator.

During the last five and one-half years, even after eliminating all cases of trouble which have no bearing on this subject of the grounded neutral, in addition to the four serious cases above mentioned, there have been quite a number of minor cases which have a strong bearing on the matter of the grounded neutral. Especially is this true of cable troubles which, during the last three years, have averaged only two cases per one hundred miles per year. This includes all troubles on 9,000-volt cables from known or unknown causes, except those due to external injury to the lead sheaths.

Notwithstanding these results, we have started some investigations with the oscillograph, and have also installed for purposes of observation some spark-gaps at different points on the system, all with special reference to securing more accurate information for guidance in the development of the 20,000-volt underground system into suburban districts. These investigations have not yet progressed sufficiently to afford much definite information. There are some indications that in the Fisk street station the spark gap when set for 100% above normal, discharges occasionally when the oil-switch on the distance sub-station end of the line is opened. This instantaneous rise of potential occurs even with the neutral grounded, and may be due to the stored energy of the line. We have thus far not been able to find rises of potential coincident with any other switching or other operation.

Our investigation and experience with one system for five years, and another system for seven years, leads us to believe, that between operating with the neutral grounded or not grounded, under our conditions the grounding of the neutral is the better policy. As to whether or not any additional benefits would be secured by grounding the neutral through a resistance, we feel that our experience is still too limited.

Philip Torchio: The papers presented by Mr.. Rhodes and Mr. Clark give the experience of two moderately high voltage systems operated with grounded neutral. I shall contribute to their discussion the experience of the New York Edison Company's system which is also operated at moderately high voltage, but without grounded neutral. This comparison is not offered in a spirit of criticism of the admirable work described by Mr. Rhodes and Mr. Clark, but as an expression of opinion of those who have not yet found enough evidence of either the desirability or the necessity of grounding the neutral of 6600-volt, high-tension systems operated underground.

The Edison system operates at 6600 volts, three-phase, 25 cycles. The cables are mostly paper insulated, with $\frac{10}{32}$ in. insulation between conductors and $\frac{10}{32}$ in. between each conductor and ground. The feeders are operated on the radial system, not connected in multiple at the sub-stations. The system was started in 1898 with about three miles of high-tension cable, and grew steadily from year to year to the present system of about 200 miles. During the nine years' operation we have had 66 cable troubles of all kinds; of these, 32 developed during operation, and 34 were found either by the periodic insulation test or by inspection of the routes.

Table I gives a summary of all kinds of troubles divided into three classifications. In the first column are the operating troubles proper, cable troubles manifested during operation of the system; in the second column are cable troubles manifested when the cables were out of service, by periodic or special insulation test; the third column shows defective cable troubles found by visual inspection by the line inspectors. It must be noticed that the Edison Company's high-tension cables are distributed over all the city, where a lot of underground work has been done, causing a lot of interference and damage to the cable line. The table shows that there have been, in nine years, 32 operating cable troubles, 14 of which were due to mechanical injury. The majority of the troubles in the rest of the cases were in splices due to defective installation, etc.

If we eliminate the 14 troubles due to mechanical injury, and make allowance for the great amount of interference attendant to the subway conditions under which the New York Edison Company operates, we see that the number of troubles per mile of cable per year compares favorably with Mr. Rhodes' figures for the Interborough system. As to the extent of trouble caused by the cable burn-outs, in no case was the cable subway damage more than nominally.

We have been fortunate up to now in not having a severe blowing up of the subway cables, as mentioned by Mr. Rhodes. In one instance only the cable short-circuit was so severe as to overtax one of the old circuit-breakers—not of standard make—which caused a shutdown of the generating station. The short-circuit was caused by the driving of a pick into one high-tension

TABLE I

Classification of All High-Tension Cable Faults for the Period Between November 14, 1898, and October 8, 1907, Inclusive

Manifested by opening of circuit-breakers during operation	Manifested by low insulation test	Reported by line inspectors
1. In splice	1. In splice	1. Injured in manhole by arc cable burn-out
2. Nail driven into cable (extraneous injury)	2. In splice	2. Nail into cable
3. In sharp bend in manhole	3. In splice	3. Damaged in manhole by alternating-current lighting cables burn-out
4. In damaged sleeve (extraneous injury, cause unknown)	4. In cable (steam exhaust)	4. In cable (extraneous injury)
5. In bend in small manhole	5. Moisture in old rubber splice	5. Damaged by outside parties doing subway work
6. Wet end of cable (extraneous injury due to water leak)	6. Moisture in old rubber splice	6. Damaged by outside parties doing subway work
7. In splice	7. Moisture in old rubber cable (extraneous injury)	7. Damaged by outside parties doing subway work
8. In bend (extraneous injury)	8. Nail driven into top conductor (extraneous injury)	8. Burn-out Fortieth street manhole, injury from adjacent cables
9. In bend—defective	9. In cable (steam leak)	9. Armor damaged by adjacent burning cables
10. In cable (possibly extraneous)	10. In splice (steam leak)	10. Armor damaged by adjacent alternating current burning cables
11. In splice	11. In defective splice	11. Armor damaged by adjacent burning cables
12. Drill forced through tile duct into cable (extraneous injury)	12. In cable (steam leak)	12. Armor damaged by adjacent burning cables
13. In splice (extraneous injury)	13. At splice end	13. In cable, damaged by adjacent burning cables
14. In splice (extraneous injury due to water leak)	14. At splice	14. Splice damaged by adjacent burning cables
15. In cable		15. Punctured splice probably due to surges
16. In splice		16. Damaged by outside parties doing subway work
17. In cable		17. Damaged by adjacent burning cables
18. In splice		18. Damaged by outside parties doing subway work
19. In cable (extraneous injury)		19. Damaged by outside parties doing subway work
20. Crowbar driven into cable (extraneous injury)		20. Damaged while doing excavation work
21. Puncture in straight section of cable (connected with station trouble)		

Manifested by opening of circuit-breakers during operation	Manifested by low insulation test	Reported by line inspectors
22. Ground detector acted in conjunction. Drill forced through tile duct into cable (extraneous injury)		
23. Ground detector acted in conjunction. Moisture in straight cable due to extraneous injury		
24. Ground detector acted in conjunction. Moisture in straight cable due to extraneous injury)		
25. Defective splice		
26. In easy bend in cable—connected with station trouble		
27. Defective splice		
28. Burns and mechanical injury to cable		
29. Damaged by adjacent burning low-tension cables		
30. Ground detector acted in conjunction. Defective cable in duct		
31. Defective splice connected with operating trouble		
32. Ground detector acted in conjunction. In straight cable—connected with station trouble		
14 Mechanical injury 8 At or in splice 4 In bends in manholes 6 In cables	5 Mechanical injury 9 At or in splice	19 Mechanical injury 1 At or in splice
32 Total	14 Total	20 Total

RECAPITULATION

38 Mechanical injuries
18 At or in splices
4 In bends
6 In cables

66 Grand total.

cable in proximity to the generating station. In other cases the relays and oil-switches cleared the short-circuited cable without affecting appreciably the bus-bar voltage.

Mainly on account of the large storage-batteries on the low-tension system, the effects of cable troubles have been considerably minimized. For the last three years all the cable troubles lowered the distributing voltage an average of 5% for 45% of the total system load with a total elapsed time of reduced pressure of 2.5 minutes. I omit other data corroborative of the general good results of the operation of this system and its freedom from violent disturbances due to cable burn-outs. Furthermore, in every instance when we had a burn-out or disturbance of any kind, we fully investigated all attendant circumstances and tried to figure out how the results might have been modified by having the neutral grounded. In no case of cable burn-outs did we find that the results might have been sensibly improved by the presence of the grounded neutral. On the other hand, station and sub-station troubles, which are usually minor but considerably more numerous than cable troubles, would in some cases have been made very serious by the presence of the grounded neutral. In the papers presented by Messrs. Rhodes and Clark no mention is made of these troubles inside the stations. But I think that they have an important bearing on the subject, and in most of the plants would weigh very heavily against the adoption of a grounded neutral without resistance, or with low resistance allowing ground currents considerably in excess of the condenser capacity current of the system.

Aside from these practical experiences, there is the theoretical side of the matter, which has been very ably treated by several prominent engineers in this country and abroad.* But unfortunately we know very little of the direct bearing of the theories applied to the operation of the underground systems now under consideration. And in this connection I want to make clear that none of the experiences with grounded neutral given here to-night claims that the grounded neutral. *per se*, will prevent violent surges on the system when under the provocation of a heavy two-wire short-circuit; that is, the grounded neutral has been made to assist in making the operation of certain mechanical relays and switches reasonably more positive than they would otherwise be. If for any reason a heavy two-wire short-circuit takes place, the presence of the grounded neutral is ineffective to change the results from those that would take place if the neutral were not grounded. Furthermore, by grounding the neutral without resistance, a dead short-circuit occurs on a cable every time the insulation resistance of the cable is reduced enough to let an appreciable amount of current pass to ground, while without a grounded neutral the operator might have time to disconnect the defective cable from the system before the ground had developed into a short-circuit. Now, the elapsed time between the beginning of the deterioration of the insulation around one conductor and its final dead grounding is usually very long. It may be several minutes, or hours, or days.

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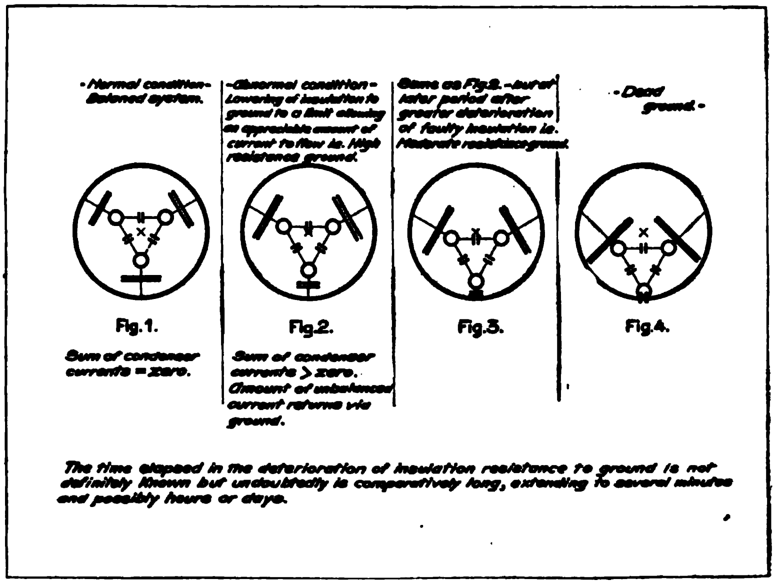
* Steinmetz, American Institute Electrical Engineers, 1901; Kennelly, Electrical World and Engineer, 1901; J. D. Nies, Electrical World and Engineer, 1902; Thomas, American Institute Electrical Engineers, 1902; G. N. Eastman, Western Electrician, 1903; G. H. Eastman, Electrical Congress, 1904; David, Societe Int. des Electriciens, 1904; Blondel, Societe Int. des Electriciens, 1905; Brylinski, Societe Int. des Electriciens, 1905; Steinmetz, American Institute Electrical Engineers, 1905; Thomas, American Institute Electrical Engineers, 1905; Patchell, Institution of Electrical Engineers, 1905–1906.

The speaker and Mr. T. W. Varley have taken advantage of this fact and have developed a device now being applied to the New York Edison system by which it is expected to obtain all the advantages of selecting and disconnecting the defective cable considerably before the condition of a dead ground is reached. The device can be operated on a system with or without grounded neutral. The device takes advantage of the unbalance of condenser capacity current on the cable system when the insulation of any conductor begins to deteriorate.

In Mr. Lincoln's paper there is shown very clearly the condition of an electrostatically balanced system, when there is no faulty insulation to ground; a similar diagram in Fig. 1, Plate 1, shows approximately the amount of capacity current between conductors, and the condenser current between each conductor and ground. The sum of these condenser currents under normal conditions is zero. If the insulation resistance to ground begins to get lower, and an appreciably small amount of current flows between one conductor and ground, there will be an electrostatic disturbance that will cause the different amounts of condenser current to vary proportionately to the discharge from the conductor to ground as shown in Fig. 2. It should be noted that the sum of the condenser currents is greater than zero, and the amount of unbalanced current would now have to find another path to the bus-bars, and that path is through earth.



- Normal condition - Balanced system.

-Abnormal condition - Lowering of insulation to ground to a limit allowing an appreciable amount of current to flow i.e. High resistance ground.

Same as Fig.2. - but at later period after greater deterioration of faulty insulation i.e. Moderate resistance ground.

- Dead ground -

Fig.1.

Sum of condenser currents = zero.

Fig.2.

Sum of condenser currents > zero. Amount of unbalanced current returns via ground.

Fig.3.

Fig.4.

The time elapsed in the deterioration of insulation resistance to ground is not definitely known but undoubtedly is comparatively long, extending to several minutes and possibly hours or days.

PLATE I

Fig. 3 shows the same condition as Fig. 2, but the resistance to ground is still lower, almost a short-circuit of conductor to ground. Fig. 4 shows the condition of a dead ground, as when all the capacity current of one conductor is discharged to ground.

Referring to Plate II, the device consists of a current transformer applied to the lead sheath of each feeder. The secondary of the transformer is connected by means of a condenser to a relay, which is intended to operate either the circuit-breaker or a signal similar to a telephone drop relay of standard make, as desired. This plate shows how the transformers are applied.

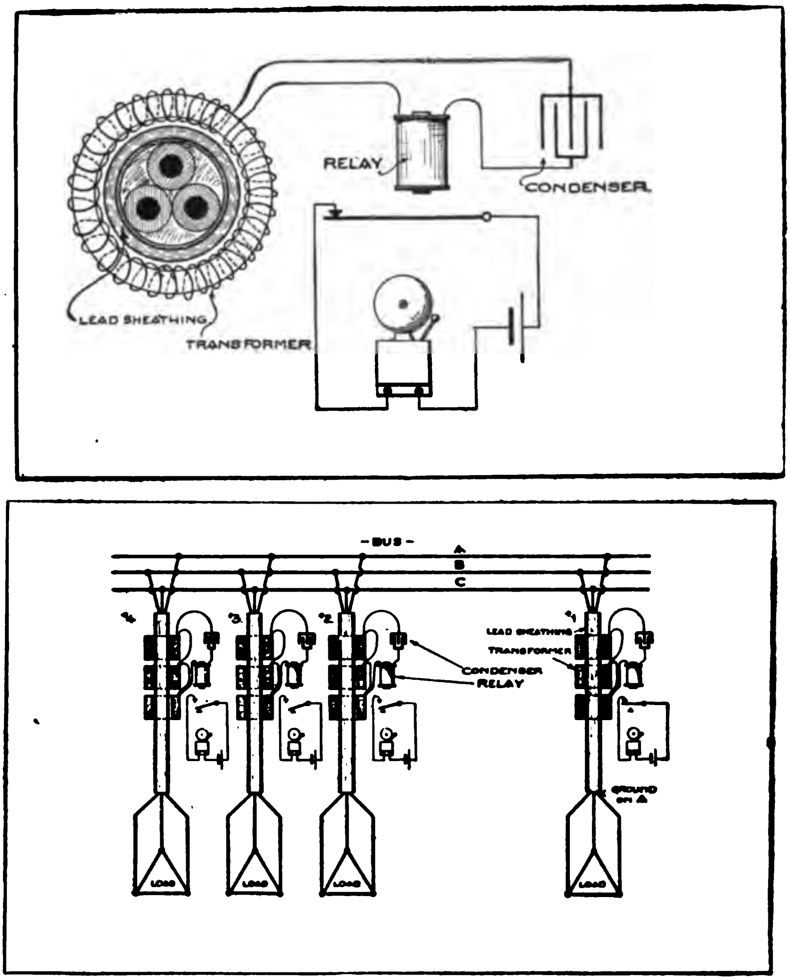
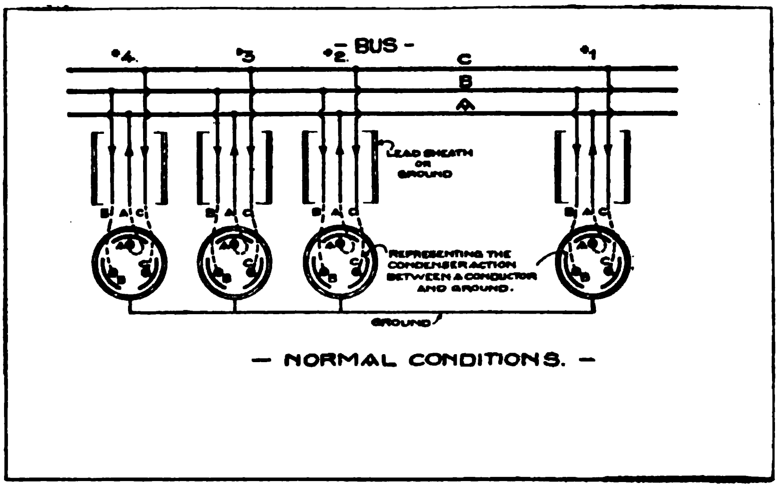


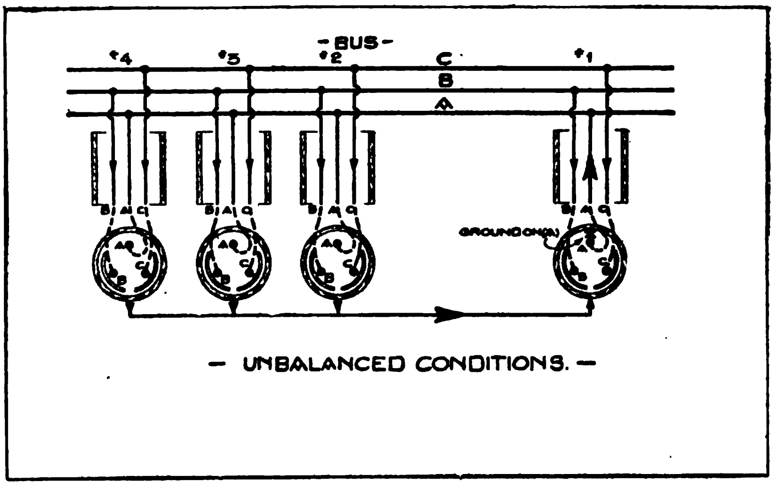
PLATE II

On each feeder we are putting on three of these transformers; they are about 6 in. long, and cover about 18 or 20 in. of the cable.

In Plate III are indicated a set of three-phase bus-bars and four high-tension feeders. The feeders can be extended to any number. The circles indicate diagrammatically the cable, and the segments of circles inside indicate the capacity current to ground of each conductor; and they are made equal, which indicates that the capacity currents in each cable are balanced and no current flows through the earth. The conditions of un-



— NORMAL CONDITIONS. —



— UNBALANCED CONDITIONS. —

Plate III

balanced capacity current as illustrated in Plate I, Figs. 2, 3, and 4 are covered by the arrangement of the devices shown in Plate III. When there is a dead ground, the condenser current of that wire disappears and the condenser current of the other two wires has grown to twice the size. The return for these unbalanced currents is shown by the arrows via earth to the faulty insulation and the grounded conductor of the defective feeder which takes the unbalanced current of all the other feeders on the system. By applying the relay in proximity to the bus-bars we detect the sum of the unbalancing of all the feeders By this means we expect to detect trouble long in advance of the short-circuiting of the feeder which is going to be in trouble, and give plenty of time to the operator to disconnect it from the system. This relay can be operated as well on an ungrounded system as on a grounded system and even with the grounded system I think it will be a valuable auxiliary, especially if the grounded neutral is made through a high resistance limiting the ground current to a few amperes (in the order of the condenser capacity current of the system to ground) sufficient to discharge the cumulative electrostatic charges, and also hold the ground current as soon as the insulation at any point of the system lowers sufficiently to allow an appreciable flow of current.

N. J. Neall: I have chosen for my part of the subject a few comments on the effect of grounding the neutral with or without resistance, from the lightning protective apparatus standpoint. An analysis of the papers presented to-night shows that one deals with comparatively low-voltage underground service; the other intimates the needs of a high-voltage overhead system. We are not much concerned about the lightning protection for an underground system, for certainly no arrester or arrester scheme between the conductors and the ground will be of great benefit, perhaps of no benefit at all, in the line of the disturbances that have been described to-night. Endeavors have been made to protect across phases; perhaps that is the remaining and only form of protection required for underground service. Lightning protection for high-voltage overhead systems has as much bearing on the selection of a grounded neutral as any other one element of operation. Moreover, the mere benefit of grounding is not the sole consideration in selecting the type of apparatus or the method of operation. For example. in an underground system there are a number of conductors in multiple, so that the elimination of one conductor does not cut out the entire service.

The situation can be looked at from the standpoint of design or manufacture and also the standpoint of operation. Manufacturers I think, follow rather than lead in the adoption of high-voltage protective apparatus; so that as the contemplated voltages for commercial service get higher, it is very doubtful whether one can obtain arresters as quickly as one can get apparatus suitable for this service. Now, to ground the neutral would throw the arrester ratings into a group which has been already only partly developed. Moreover, the question of insulators for these high voltages is also an important element in the selection of the method of connection. Neither a grounded neutral nor an ungrounded neutral will save the puncturing of insulators by high-voltage strains induced by lightning. I do not refer to direct strokes, but to those concentrated charges that are known to exist on transmission lines and do not seem to be able to pass more than a few hundred feet at most from the point of application. It has been thought in times past that these charges jumped over the insulators, but it often happens that they cause punctures. Now, if a line be grounded, with resistance or without, and the charge just described takes place—discharging over the insulator—a short-circuit follows which might be of sufficient strength to shatter the insulator. If it be an ungrounded system, it might be merely a static discharge of the local condenser current, so to speak, which will not have heat enough and will be so attenuated that it will not cause anything further than a temporary disturbance of that particular part of the line.

A grounded neutral, moreover, does not help lightning-arrester operation. Theoretically, it throws more of a strain on the arrester at the time of operation than if the line were not grounded. The arrester, as Mr. Lincoln has said, can be insulated for a lower voltage and closer adjustment to the normal voltage of the line, but it is a grave question whether that is not offset by the fact that the arrester helps to form at the time it operates a partial short circuit on the system, provided the resistances do not give way under the strains, which is most doubtful.

Another element of line operation that is not helped very much by grounding is the telephone plant. One of the most serious conditions in long-distance transmission at the time of any disturbance is the interruption of telephone service within the transmission system itself.

If a resistance must be used—and there seems to be in certain cases good reason why this has been selected—it seems an easier matter to select a resistance suitable for low voltage than one suitable for high voltage. Those of us who have studied the resistance for lightning protective apparatus know that a resistance of small size, of small cost, of large current-carrying capacity, and current-choking capacity, is a very hard thing to get. The same problem in only a modified way exists in the high-tension system with the grounded neutral. I do not believe it is possible to predict any positive method of operation, but I should say, judging from the progress of the art, that if the apparatus can be made sufficiently insulated to be connected in delta, and lightning-arresters can be found that will operate nicely at that voltage, and proper provision is made for the sectionalizing of the line or cross-sectionalizing of the line if it happens to be a parallel circuit, that a minimum of interruption of service can be obtained. If in addition to this the progress of the art of lightning protection will indicate relief from a great deal of these induced disturbances that I have spoken of, and if the promise of electrolytic lightning-arresters can be fulfilled, a great deal that I have just said about lightning protection will be very happily modified.

John B. Taylor: The grounded nuetral with or without resistance must be regarded as a protective device, and for this reason the trend of discussion seems to be similar to discussions on lightning-arresters and choke-coils. Apparatus or devices which become operative only in emergency conditions cannot be subjected to tests that will absolutely determine their value for the emergency condition, hence the reported results of successful operation from plants where the neutral is grounded and also where it is not grounded.

Mr. Lincoln speaks of obtaining a neutral connection from " an auto-transformer connected to proper points of the delta." I have had occasion to make up stable artificial neutral points where no neutral is available on any of the apparatus, but my arrangements could not be described in his terms and I ask Mr. Lincoln to show us a diagram of the arrangement he has in mind.

In discussing the proper value of resistance in the neutral lead, Mr. Lincoln states that this resistance must be such as to pass sufficient current to trip the heaviest circuit-breaker. This requirement appears proper for feeder distribution systems which have already been referred to as " radial feeders," but these should be considered as a special rather than a general case. The general case where it will be found desirable to make use of resistance in the neutral, is a system mainly of underground cables, supplying a number of sub-stations, having two or more cables which are parallel on the sub-station bus-bars as well as on the main station bus-bars. A consideration of this interconnection of cables will readily show that the current flowing to ground at the cable fault will divide according to the resistance of the various branches, part flowing from the main station over the faulty cable which has to be cut out, the rest flowing by way of healthy cables, sub-station bus-bars, and faulty cable from the sub-station end. In general, then, the limited current must be at least twice that at which the circuit-breakers are set, and in addition to this there must be a liberal allowance for combined effects of conductor resistance, resistance at the fault itself, resistance of earth return, and drop in voltage at the generator. This requirement makes it difficult to make an entirely satisfactory application of the neutral resistance to systems that have heavy feeders and at the same time fluctuating load, so that only limited generator capacity may be at times in service, especially in the small hours of the night.

From the record of cable breaks, in Mr. Rhodes' paper, I have figured out the number of breaks per mile of cable per year. I think it a matter of interest that Mr. Junkersfeld's figures on cable breaks, on a 9000-volt system in Chicago, for 100 miles of cable per year, are very nearly the same. From Mr. Rhodes' figures the number of cases of burn-outs per mile of cable per year are slightly greater since the neutral was grounded. While the purpose of the ground in this plant is to secure selective operation of switches, yet I should look for a reduced number of burn-outs. With the resistance, grounds are more quickly removed, with consequent reduction in time of increased voltage strain on the whole system. Possibly the records do not cover a sufficiently long time to eliminate the element of chance; it is also possible that the increased number of faults since the resistance was installed are due to trouble in the joint, etc., incidental to the installation of a number of miles of new cable.

Mr. Clark's experience with neutral resistance is certainly interesting and I hope that he can give us some more data on the following points. What is the resistance of the plate ground? Why have they not availed themselves, in addition to the plate, of the extensive system of water pipes, etc., which is generally available in the neighborhood of any large generating plant? We have very little data on resistance of circuits with different earth terminals, and if Mr. Clark can advise how much the neutral resistance (given as 6.7 ohms) is increased by the earth resistance at the plate, we shall be indebted to him. I also hope that Mr. Clark will tell us the material of the neutral resistance, as cast-iron heated up to 1000° fahr. will practically double its resistance with corresponding reduction in current allowed to pass.

The assumption that the resistance will pass 1000 amperes, apparently makes no allowance for resistance in the rest of the circuit. Obviously, if conditions were such as to permit the flow of 400 amperes—and this is insufficient to trip the circuit-breakers—the neutral resistance could not be expected to accomplish much under these adjustments. I will ask Mr. Clark to tell us what the circuit-breakers are set at? and whether or not parallel feeders are interconnected at sub-station bus-bars?

I am also interested to know how Mr. Clark distinguishes alternating current shunted into telephone lines from alternating current with the same frequency induced in telephone lines. It is of course quite possible to have this current in telephone lines due either to fall of potential between two points in the earth, or due to induction, and I hope Mr. Clark will give a little more data on the local conditions showing that the alternating currents are due to conduction rather than induction.

Carl Schwartz: On account of the many variables connected with grounding the neutral of a three-phase generating and distribution system, a careful study of the individual conditions should govern a decision as to:

1 Whether the neutral should be grounded or not.

2 Whether directly or through resistance, and

3 If resistance be used, its amount and proper connection.

In the system referred to in the following discussion, the neutral is grounded through resistance, but partly owing to the fact that the system has been in operation for a comparatively short time, not very extensive experience has been gained. The only statement which perhaps can be made is that so far no trouble has occurred to reason against the arrangement adopted, nor have objectionable features appeared. There are two power stations, ultimately to contain six units of 5000 kilowatts, 11,000 volts, three-phase, 25 cycles each, and eight sub-stations, one power station with 20,000-kw. capacity, and three sub-stations in operation at the present time.

The neutral ground connections are arranged as follows:

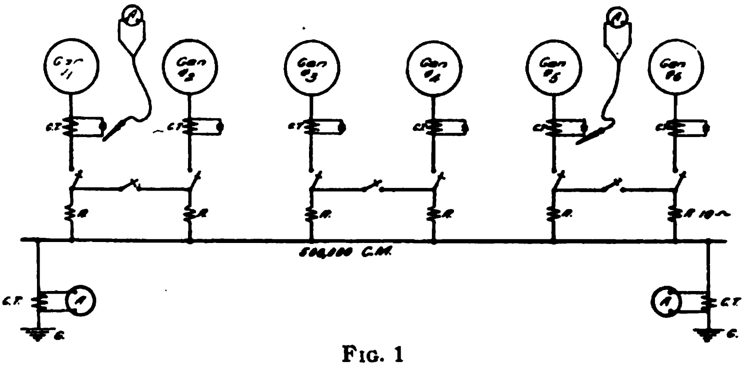


Fig. 1

Fig. 1. A bus-bar of ground potential, 500,000 cir. mils, grounded at both ends, runs through the station. To this are connected the neutrals of the individual machines through separate resistances. Disconnecting knife-switches between machines and resistances allow their separation as may be required.

The ground plates are of copper, about 20 square feet, and buried deep enough to be always under salt water. Current transformers are inserted in each neutral, and also in the ground connection. The secondary leads of the neutral current transformers are brought to the main operating switchboard and ammeters can be inserted in the circuits by means of plugs. For the neutral ground connections, however, the two ammeters are located on a record board in the office of the load dispatcher.

The former instruments are of little importance, while the latter indicate any ground or abnormal condition in the system and are used as "trouble indicators." The neutrals of two adjacent generators can be connected together by a tie-switch which is ordinarily kept open, and closed only in case one machine alone is running in a station, as one resistance alone would not allow sufficient current to flow to trip the feeder-switch relays.

The resistances are constructed of cast-iron grids, set in iron frames on porcelain insulators, and enclosed in fireproof brick compartments, with proper ventilation. The resistance of each of them is about 19 ohms, so that with a difference of potential between phases and ground of 6300 volts, about 330 amperes can flow through each resistance. From two to four resistances are to be used in parallel at one time.

There appear to be a few points in favor of the arrangement outlined, as follows:

1. It will be noted that two resistances, equal to about 38 ohms, are always in series between two machines, and experience confirms that practically no cross-current flows between the machines at the time of synchronizing or otherwise. A heavy, 75-cycle, cross-current flows if the neutrals are tied together directly, unless the field current can be adjusted to avoid this condition.

As Mr. Rhodes points out on the third page of his paper, these cross-currents may have a very serious effect on the operation of the station and interfere more or less with synchronizing of the machines. For instance, with a load of 1800 kilowatts on each of two generators, 90 and 160 amperes field current respectively, a cross-current of 130 amperes was observed. With 120 amperes field current on both machines, and 2100 and 600 kilowatts load, respectively, the cross-current was 65 amperes. In both cases the neutrals were tied together solid.

The difference in load in these particular instances was not very large, but the figures indicate the conditions to be expected with a greater difference or with improper field adjustment. This cross-current disappeared entirely with the resistance of 38 ohms inserted.

2. The main bus-bar has ground potential like all resistances and apparatus connected thereto and not in use. This would not always be the case were resistance inserted between the main bus-bar and ground.

3. The arrangement allows the testing of either ground connection; one of these can be opened any time for this purpose.

4. As not all the resistances are required for normal operation, the others serve as a reserve in case of a burn-out.

5. The amount of resistance to be inserted into the neutral ground connection can be sufficiently varied to suit different operating conditions, at the discretion of the operating superintendent.

C. W. Stone: With an ungrounded system a short-circuit is expected to open the feeder-switch. If the neutral of that system were grounded without a resistance, it would contribute to the chance of a short-circuit, because one phase to ground means an equivalent to a short-circuit and a consequent shock to the apparatus. It seems advisable, therefore, to put in a resistance to cut down the amount of current existing at this time, and for this reason I have always contended that the resistance should be inserted in the neutral.

In one of the papers it is stated that it seems inadvisable to put in a resistance for each unit, resulting in a variable resistance according to the number of units in service. This is true. But it seems to me that a larger current flowing through the circuit is not serious if there are more machines in circuit, and the relative effect on the system is no greater than if with the single resistance and only one machine.

Mr. Lincoln mentions the different points for grounding a system. I think it a bad plan to ground at more than one place. I know of one case where a lighting system was operated with the ground, not only in the main station, but in different sub-stations; and when a car started up in an outlying district the fluctuation in the lights was serious, due to the flow of direct current on this grounded connection, the neutral being a better ground return than the rails.

If the neutral be grounded on a high-tension system, and an automatic switch be used, three current-transformers will be necessary instead of two—and current-transformers are not the best things to use in a high-tension system.

Mr. Lincoln leaves wide latitude in the selection of the type of resistance. I think that care should be taken in selecting the type of resistance. I note in both of the other papers that iron grids have been used for the neutral resistance. I think this is objectionable, because there is no doubt but that there is a certain amount of reactance with the iron grid. Reactance in series with the condenser action of the cables is not good, as we all know. It therefore seems best to use some resistance with practically no reactance. In the case cited by Mr. Junkersfeld, they carefully avoided the iron grids and put in german-silver ribbon.

F. B. H. Paine: There are places where it is desirable to use a high resistance in the neutral in order to limit the current to a certain small amount, regardless of the amount of energy being sent out, or the number of generators in service. There is no difficulty in operating the main switch with this limited neutral current if a current transformer is placed in the neutral and connected through a relay to operate the main switch with the predetermined current in the neutral.

There is one case where it is desirable that the sub-station neutral at the end of the line be connected to ground through a resistance as well as that of the power station; that is, where this sub-station is connected to the source of power through fuses or other automatic apparatus which may open one leg of the circuit and leave the other legs connected, thus permitting the electromotive force of the unconnected wire to soar according to the static capacity of the line, transformer, connections etc. and resulting in injury to the sub-station transformer.

Chas. F. Scott: One point has received but little consideration, and that is the automatic circuit-opening devices. Relays and circuit-breakers have been mentioned, but their importance and their bearing upon the question now under discussion have not been fully brought out. One of the purposes of grounding the neutral is to facilitate the cutting out of a defective circuit. The presence of a permanent ground and the amount of resistance which may be inserted in it for limiting the current when one of the circuit wires becomes grounded are, therefore, very intimately related to the automatic opening devices. These devices are of various kinds. There must first of all be a discriminating, selective instrument which can recognize the conditions under which the circuit should be opened. Such an instrument may act upon overload or upon reverse current and it may incorporate certain time-elements. This device transmits its indication, usually through a relay, to the circuit-breaker. The circuit-breaker should be one which will act instantly and smoothly, cutting out the damaged circuit so quickly that the operation of the other circuits will not be appreciably affected. The action must be practically instantaneous in order to prevent a drop in potential on the system in general, which would affect the running of synchronous apparatus. The opening devices must, therefore, provide for action not only in case of a ground on one wire but also when there is a short-circuit between two of the wires. The whole matter of automatic circuit-opening devices is, therefore, very intimately connected with the grounding of the neutral. This indicates some of the various ramifications of the general problem of grounding the neutral in an operating system.

The discussion this evening confirms an opinion that I expressed some time ago with regard to experience with grounded neutrals. I said that so far as I had been able to determine, the managers of those plants which operate without a ground abhor grounds of all kinds and would not think of purposely grounding any point on the system. On the other hand, others who have operated with a grounded neutral place great reliance for safety and reliability upon the fact that the neutral is grounded, and would not think of operating in any other way.

Paul M. Lincoln: Answering Mr. Taylor's question as to the method of obtaining a neutral in the delta connected system, there is no particular difficulty about this matter. In the absence of a blackboard, if Mr. Taylor will imagine an equilateral triangle as a three-phase system, a conductor at each corner, then the neutral of that system will be at the centre of that triangle. Now, draw a line through the centre and let it intersect the side where it will, and call that line which you have drawn through the centre an auto-transformer, with a number of turns proportional to the length between the centre and the points where it intersects the side, that will be the proper connection for an auto-transformer to obtain a neutral. For instance, if one end of the auto-transformer be connected to the middle of one side of an equilateral triangle, and the other end to the opposite corner, so to speak, then the neutral will occur at a tap in the auto-transformer winding such that there is one turn in the section between the tap and the middle of our equilateral triangle to two on the opposite side.

Another point which Mr. Taylor mentioned is that in cases of multiple-connected feeders, a short-circuit occurring at a point near the farther end of these feeders, the ground currents will divide nearly equally between them.

The point is well taken, but is not at variance with the statement in my paper that, " the resistance must be small enough to permit sufficient current to flow to trip the heaviest circuit-breaker on the system ".

Mr. Stone has raised the question as to relative advantages of a resistance in the neutral of each generator as against one resistance for all. So far as the action upon the windings of the generator is concerned, the former is the logical method of operating, because the resistance in neutral of each generator will limit the current which can flow through that particular generator to the point that the resistance is adjusted for. However, that is not the only point to take into consideration when fixing the neutral resistance. Of more importance than the destructive effects on the windings is the damage which will occur at the point of breakdown. Where the current is large, the damage at the point of breakdown is bound to be large, and I believe that limiting the damage at the point of breakdown is one of the great functions of resistance in the grounded neutral. Limitation of damage at the point of breakdown requires a fixed resistance rather than a resistance dependent on the number of generators in circuit.

George I. Rhodes: The object of the neutral resistance is to minimize the effect of a ground and still remove the damaged feeder. With a single rheostat, the possible disturbance to the generating system will be a maximum with one machine running, and a minimum with all generators on the line. With a separate rheostat for each generator, the relative disturbance will be the same at all loads. In either case, the effect will be the same with a single machine on the line, hence a constant resistance will give the better results when more than one generator is running.

In an underground system such as that of the Interborough Rapid Transit Company, a ground on a cable is invariably followed by a short-circuit when the neutral is insulated. I do not see any way in which grounding the neutral can increase the number of short-circuits. In most of our burn-outs since grounding the neutral, the switches have opened very easily without evidence of heavy currents.

The inductance of cast-iron grids is very small. Our 6-ohm rheostat has a reactance of about 0.3 ohms at 25 cycles. In view of the large inductance of the generators and transformers on the system, this small increase can have very little influence on resonance effects.

Chas. P. Steinmetz: In the early days of designing high-potential long-distance transmissions, engineers were very careful thoroughly to insulate every part of the system from ground. In later years grounding the neutral was tried, and the results were so satisfactory that the practice found extended acceptance and many engineers since that time have recommended grounding the three-phase neutral. While I do not believe in promiscuous grounding, I recognize that in many cases a great advantage results from grounding the neutral of a three-phase system. It seems to me that the conditions in this respect are about as follows:

1. *The neutral of the three-phase system should not be grounded where grounding is not necessary.* Grounding the neutral introduces the liability of a number of troubles and disadvantages, for any ground on a conductor of a system with the neutral grounded is a short-circuit, and shuts down the system or a part of the system. Theoretically it is true that with one conductor grounded and cut off by some automatic device the three-phase system can be operated with two lines and the grounded neutral as the third. This is called the "inverted three-phase system". But this practice is not always feasible or safe; and just in those cases where grounding is especially desirable to maintain the electrostatic balance of the system, this inverted three-phase system, which is electrostatically unbalanced, would very likely be inoperative—it might lead to high-frequency oscillations and other serious disturbances.

There is an essential difference in this respect between Western long-distance transmission lines and Eastern underground cable systems. Many things that are feasible and safe on a long-distance transmission line would prove disastrous in an underground cable circuit. Where the resistance of the circuit is large, so large that the effect of the resistance is comparable with that of the capacity, as is usually the case in a long-distance transmission line, it frequently is feasible to operate safely with an unbalanced electrostatic condition. It is also feasible to dead ground the neutral, the currents being limited, and oscillations, high-frequency disturbances are damped by the dead resistance. In an underground cable system the problem of keeping down the temperature of the cable, with its poor heat-radiating capacity, limits the resistance of the cable to such values that the resistance effect is practically negligible compared with the capacity effect. In such a case, the damping effect of the circuit resistance is small, the volume of current passing over an oscillating arc is large and correspondingly dangerous, and frequently the operation of the system when electrostatically unbalanced is not feasible, or at least unsafe. The experience with such low-resistance cable systems is then quite different from that with high-resistance long-distance transmission lines.

Another difficulty liable to result from grounding the neutral is ground currents, which may reach serious values, flowing over the neutral, especially where several neutrals are grounded, the current flowing between generator neutral and generator neutral, or between transformer neutral and transformer neutral; or, which is usually the most vicious case, between generator neutral and transformer neutral, in the latter case overheating the transformer by excess current even at no load.

Another trouble is that grounding the neutral superimposes upon the pressure difference between ground and line an additional electromotive force, usually of treble frequency, generated in the generators or the transformers. This changes the wave shape of the potential difference between the ground and line, produces a sharp peak, and raises the potential difference of the conductors against the ground by sometimes as much as 40 per cent. and more beyond their normal values. These higher frequency voltages may lead to serious surges or high-voltage oscillations, due to the building up of the voltage by the capacity of the circuit between line and ground being in series with the inductance of transformers or generators in the circuit of these treble-frequency electromotive forces.

Furthermore, telephone disturbances are liable to result from grounding the neutral, electrodynamic induction due to the currents flowing over the ground, or electrostatic induction due to this treble-frequency electromotive force appearing between line and ground. I have known a number of instances where the ground had to be taken off the generator neutral because of telephone interference.

2. *The neutral should be grounded if the system cannot be operated safely when electrostatically unbalanced.* The three-phase system with grounded neutral is electrostatically balanced; that is, all three conductors have equal potential differences against ground. The three-phase system without grounded neutral, in normal condition of operation, is also electrostatically balanced, and the three conductors have equal potential differences against the ground, and the electrostatic relations are the same as in the grounded system. If, however, a ground appears on one of the phases in the ungrounded system, then electrostatic unbalancing occurs and the other two line conductors rise to full potential difference against ground. In this case the grounded system shuts down.

There are two kinds of electrostatic unbalancing by grounding one conductor: first, by a continuous ground or dead ground; secondly, by an intermittent or oscillatory ground, as an arcing ground or spark discharge. The electrostatic unbalancing due to the continuous or permanent ground on one phase leads to a higher potential difference between the other two phases and the ground. This may be serious in a system of very high potential, as 100,000 volts. As a rule it would not be serious, but should be well within the margin of insulation safety of an ordinary medium or high-voltage system. The effect of this unbalancing is that lightning-arresters discharge when set close to the normal voltage, so as to afford efficient protection, because during ground they are receiving 73 per cent. more voltage, the full delta voltage instead of the Y voltage. In an ungrounded system, then, the precaution must be taken to arrange a number of additional spark-gaps so that they are automatically thrown into the lightning-arrester circuit, to raise the discharge voltage up to the voltage which in this case exists between line and ground. This can easily be taken care of automatically, as by a fuse shunting these auxiliary spark-gaps, the fuse opening when at the higher voltage the arrester begins to discharge continuously.

There is also to be considered the electrostatic induction from the unbalanced high-potential circuit to lower potential circuits, related to them by step-up or step-down transformers, which may give very serious potential differences; for instance, between the low-potential generator circuit and ground, thus leading to a breakdown in the generator system, or in a primary distribution system, at 2200 volts, fed by the high-potential line. Protective devices are therefore required on these low-potential systems; but aside from this the continuous ground seems to be of minor importance, different from the intermittent or oscillatory ground. The latter leads to serious high-potential, high-frequency disturbances, which may cause rapid destruction. I believe that these are the main causes of the breakdowns in ungrounded underground cable systems where the operation has not been quite successful. Here again is seen the great difference between the high-resistance, long-distance transmission line in which the oscillating discharge over an arcing ground is of very limited volume, due to the high resistance of the line, and the condition in an underground cable system of negligible resistance, where the volume of this high-frequency oscillation is such as to lead to rapid destruction.

In an overhead line this oscillation may finally lead to a permanent ground, while in a cable system it would lead to a short-circuit between the phases. Those arguments against using isolated systems, because such an oscillating arc would lead to a short-circuit between phases, apply only to the underground cable system and not to the overhead line. Where, therefore, such an oscillating ground leads to dangerous results in a high-potential system, it is advisable to ground the neutral.

3. *Wherever it is not necessary to have more than one ground*

on the system, it is desirable to ground the neutral at one place only. Several grounds are necessary where the circuit extends over so long a distance that the inductance between the ends of the circuit is too large for the ground on one end to safeguard the electrostatic balance against a high-frequency disturbance at the other end of the circuit. In this case both ends of the transmission line must be grounded. Otherwise multiple grounding is undesirable, since it introduces the danger of currents passing over the ground through the neutral, thus leading to electrodynamic induction, as on telephone circuits, to overloading and heating of apparatus by ground currents, and other troubles. Since no apparatus is in circuit at all times, with one ground only some method of switching the ground, or the use of a grounding bus-bar, is necessary to insure one ground being on the system. If it is desired to use the ground as an emergency return circuit, naturally grounds on both ends of the lines are needed, but I do not believe this practice is to be recommended, except for very low power in rather less important lines.

4. *Whenever it is not safe to ground without resistance, resistance should be used in the ground circuit.* Grounding without resistance becomes unsafe in a system of large power, for there would be a severe shock on a system with a grounded neutral if one phase grounds, resulting in a short-circuit. Furthermore, there is the possibility of an electromotive force of treble frequency appearing between the ground and the line, which with a dead-grounded neutral is liable to give rise to serious surges in the system between lines and ground, which are overcome by a resistance in the ground circuit. Therefore, to guard against surges between lines and ground, resistance is desirable in the ground circuit; occasionally it is absolutely necessary. In this case a single resistance is sufficient to dampen and so make harmless an oscillation between lines and ground.

To limit the cross-currents between the grounds of different generators, or generators and transformers, a number of resistances are necessary, one in each generator or transformer neutral. The resistance should be as high as possible so as to produce but little disturbance or shock on the system, and rapidly to damp any oscillation that may arise from a grounded neutral. The resistance should be low enough to act as a ground; that is, to insure a flow of current large enough to open the heaviest circuit-breaker, and thus cut off the damaged part of the system.

Obviously, the resistance should be non-inductive and should be permanent; that is, should withstand excessive overloads, because the current which flows over the resistance in normal operation is insignificant compared with the current which flows in the case of an emergency as a ground on one line. I believe this fairly excludes the use of wire-wound resistances as liable to be inductive, and it also excludes the use of such mixtures of clay and graphite as have been mentioned, which are very inconstant in their resistance when exposed to high temperatures and excessive overloads. The requirements, however, seem to point especially to that class of resistances which decrease in resistance with increase of current, the pyro-electrolytes, because such materials would permit the use of a rather high resistance between ground and neutral, thus passing very little current at normal operation; while in case of a short-circuit by a ground on one line, they rise in temperature and decrease in resistance rapidly and then pass a current amply large to open the circuit-breaker and cut out the disabled feeder. That would also give the advantage of introducing a time-limit into the operation of the resistance.

5. I desire to draw attention to a general principle based on human nature, though it has some exceptions. Where the trend of the times is very strong in one direction; for instance, in favor of using induction motors instead of synchronous motors, or vice versa, or grounded neutrals instead of ungrounded neutrals; wherever a case occurs in which it is doubtful whether one should do one thing or the other, it is usually safe to decide against the favored practice, for the reason that no one can remain entirely unbiased in his judgment if the general trend of sentiment is in a certain direction. Where one therefore thinks the advantages about equal, in most cases he unintentionally favors that side which is the fad of the time, and the impartisan argument therefore would be more in favor of the other side.

Frank G. Baum (by letter): The advantages of the grounded star connection over delta for high-voltage transmission (from 60,000 upwards) are as follows:

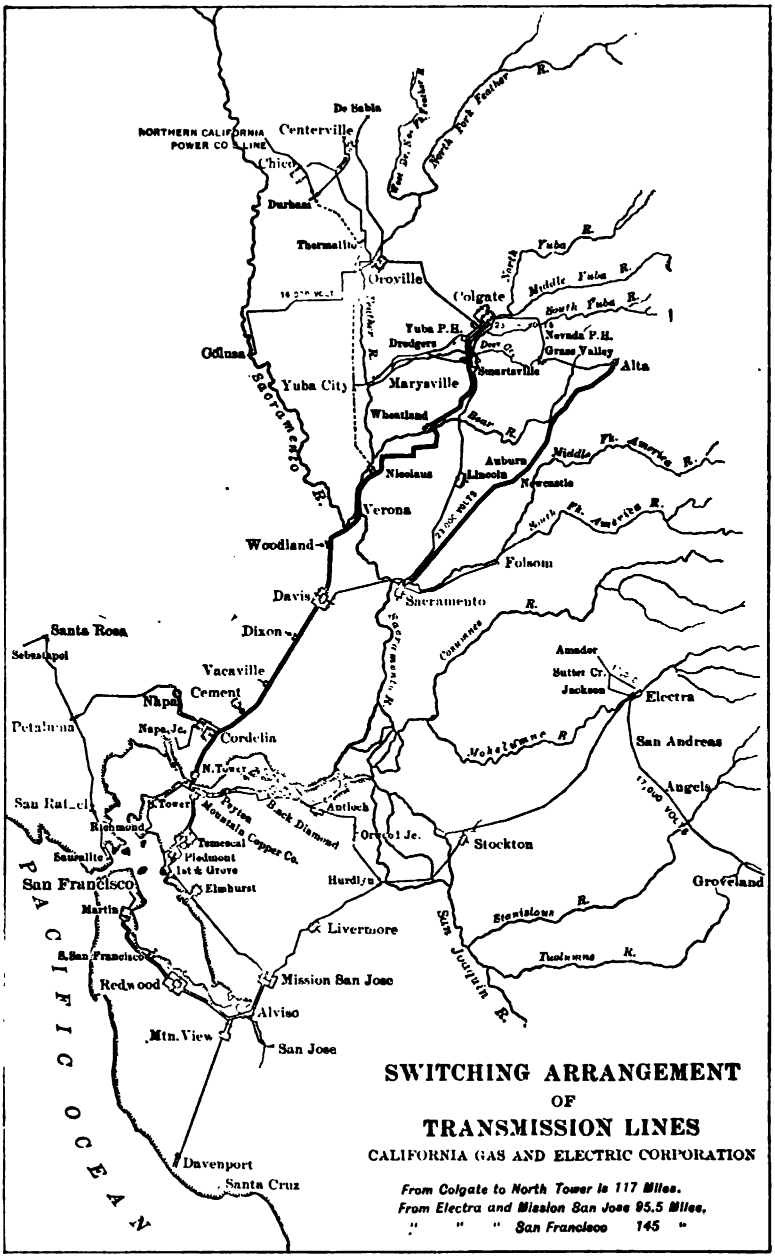
1. The transformer potential is reduced in the ratio of $\frac{1}{1.732} = \frac{0.58}{1}$, and for very high potentials the transformers may be designed for reinforced insulation on one end of the transformer only, making them safer and cheaper.

2. The maximum potential on all insulators, switches, etc., is 42.2% lower than with delta connection under normal or abnormal conditions.

3. The station wiring is simpler.

4. Small consumers may be supplied with one or two transformers.

A number of years' experience with several large transmission systems operating at voltages from 10,000 to 75,000, both delta and star, demonstrate that where the systems are properly installed there is no more difficulty in operating one than the other. Most of the troubles of the early transmission systems came from lack of insulation; with improvement in insulation



SWITCHING ARRANGEMENT
OF
TRANSMISSION LINES
CALIFORNIA GAS AND ELECTRIC CORPORATION

From Colgate to North Tower is 117 Miles.
From Electra and Mission San Jose 95.5 Miles.
" " " San Francisco 145 "

FIG. 1—All lines not otherwise marked are at 60,000 volts.

there disappeared nearly all the troubles variously ascribed to "static charges", "lightning", "ground currents", "telephone and telegraphic interference", etc.

Fig. 1 indicates the area covered by the California Gas & Electric Corporation. On this system there are now operating about 75,000 kilowatts in water-power units, and about 30,000 kilowatts in engine units. The generators are star and delta connected, about equally divided. The star-connected generators are not grounded.

Most of the lines are star-connected for 60,000 volts, but other lines are operated delta-connected from the same generators. There are about 1000 miles of circuit at 60,000 volts; 250 miles at 10,000 to 40,000, and 125 miles from 4000 to 10,000 volts. The distributing lines are star or delta, as desired. There are over 100 sub-stations connected to the lines, a great many of them without operators.

The entire system is operated in parallel as a unit, and all the 60,000-volt lines are in parallel. The lines, transformers, etc., are switched in and out of service under any condition of load or short-circuit, and are handled in every respect in switching as though they were 2300-volt lines.

For very high voltage systems I see no reason for adopting anything but a star connection.

O. S. Lyford, Jr. (by letter): This is a subject which has as many sides as there are people interested in it. The grounded neutral is a sort of antitoxin administered, not to prevent initial distemper, but to keep it from spreading. The danger is that the remedy may prove more serious than the disease, or that the handicap to the general elasticity of the system may be greater than the immunity obtained.

When the neutral ground is adopted, its group of evils is accepted as the lesser of two. There is greater flexibility and greater convenience in the use of apparatus if the system is ungrounded. I refer particularly to the use of transformers in delta and the ability to operate with only two of the three. This advantage has led to the use of delta-connected transformers in the great majority of transmission systems, and this grouping of transformers prohibits the use of a neutral ground except by adding more transformers from which a neutral connection may be brought out.

As has been stated, the grounding of the neutral does not decrease the normal working strains or reduce the number of initial disturbances; furthermore, it does not prevent the first surges which may follow an insulation failure. When used, it is generally in the hope that it will minimize the abnormal voltage between line and ground and insure prompt action of the automatic circuit-breakers which will cut off the defective circuit before the damage is extended or the system as a whole shut down.

There are many cases where even the subsequent troubles may not be prevented by a grounded neutral. Last year a case in point was reported which affords an illustration with a ludicrous side. A high-voltage line in Montana, having a pole spacing of 200 feet, lost a pole. As a result the wire crossing a cattle ranch hung about four feet from the ground. A steer came along to investigate, put his head over the wire and " got it in the neck " literally. Steer No. 2 came along, took a smell of No. 1 and fell dead. Steer No. 3 smelled of No. 2 with corresponding effect. Nos. 4, 5, etc., did likewise until there were half a dozen or more lying dead in a row.

A grounded neutral would not have reduced the amount of fresh beef materially, for even if the circuit-breakers had opened after each smell the operator would have had no alternative but to close the breaker again, making everything ready for the next. With a long line extending across the country the principal problem is not how quickly can one cut off a defective line, but how quickly can the defect be removed and to what extent can one operate until the defect is removed.

We had one case where one wire of a 15,000-volt three-phase transmission line operating a number of converter sub-stations broke and one end laid on the ground all day without causing any interruption of the service until the next morning when attempt was made to start up the system and it was discovered that only one phase was operative. This would not have been possible with a grounded neutral. We had another case, on the system to which Mr. Clark refers in his paper, where the object of the grounded neutral was defeated in a very fortunate way. The poles of the 11,000-volt trunk line of this system are of steel and are carefully grounded. The cross-arms, however, are of wood. In this case lightning struck the line, shattered some of the insulators and at least one of the wires was left lying on the cross-arm. The current was put back on this circuit and operation continued for some hours until repairs could be made conveniently.

All of this does not prove that the grounded neutral should not be used, but that it is by no means a cure-all; many times it is a positive detriment.

Referring to Mr. Lincoln's list of advantages and disadvantages, there is not much weight to advantages *a*, *b*, and *c*. Although a slight reduction in first cost of equipment may be effected by using weaker insulation, this insulation must be sufficient to resist lightning strains which are greater than any due to a ground on one leg. Static induction in neighboring circuits is seldom a serious matter and can usually be taken care of in some other way. The regular use of the ground as a conductor is a practice that can be adopted in only a certain few instances.

Advantage *d* is the main one, and on the other hand the principal disadvantage, although referred to later in Mr. Lincoln's paper, is not mentioned in the list; namely, the increased damage which may result to the generating apparatus and in some instances to the transmission system

Referring now to the use of a resistance in the ground connection of the system; this is really a compromise. With a neutral dead-grounded, any insulation failure in or near the power house means a practically dead short-circuit on the generators. Such a shock to the system is a serious matter which must be avoided as far as possible. It is inevitable with a short-circuit between phases, but there are few such short-circuits compared with the number of grounds, and one hesitates to adopt a measure which makes these grounds equivalent to short-circuits. The seriousness of these shocks develops, even if the short-circuit is of very short duration. Even fuse-testing in the immediate vicinity of the power station has caused displacement of the generator armature coils. Turbo-generators of high potential are peculiarly vulnerable in this particular.

In the case referred to by Mr. Clark, the neutral ground was adopted principally because of the unusual arrangement of overhead and underground circuits with many possible combinations which may tend to resonance. The object desired was to cut off a defective circuit before such a result should follow. The resistance was placed in the neutral circuit to minimize the shock to the system. This system is laid out with the expectation that there will eventually be 38,000 kw. of generating capacity in the present station, (or possibly double this amount), another power station operating in parallel with this, and a greatly extended underground and overhead transmission system.

As the ultimate conditions are approached, the advantage of limiting the current in the neutral circuit will increase. As matters now stand, the combination of equipment is such that we might expect very satisfactory results with either an ungrounded system, a dead-grounded neutral or a neutral grounded through resistance. There would undoubtedly have been fewer short-circuits, if there had been no neutral ground; on the other hand the character of the protective devices as a whole is such that very few of the interruptions have materially affected the service. As Mr. Clark points out, out of the 70-odd disturbances two would have been handled better with a dead grounded neutral. Neither of these two were very serious, however, and they do not in themselves prove that a change to one of the other combinations is preferable. Damage to the power station equipment by the surges which might occur without a neutral ground or by the shocks which might occur with a dead grounded neutral would result much more seriously.

It is an interesting fact that three of the most important systems, one of which was started without a neutral ground, and two of which were started with neutral dead-grounded, have for different reasons subsequently adopted a neutral ground through a resistance or resistances.

For the general case, it may be said that the ungrounded system is preferable, the exception being where there are special conditions which make an interruption of service on a particular circuit of less importance than the consequences if the defective circuit is not immediately cut off. If the system is a large one and conditions necessitate a neutral ground, present experience indicates that there should be a resistance in the neutral circuit.

George I. Rhodes (by letter): There were one or two questions asked during the discussion which I did not care to answer without looking further into the facts.

Mr. Torchio remarked that no mention whatever was made of troubles inside the power and sub-stations which were increased by, or the result of, the grounded neutral. The reason for the apparent omission is that there have been absolutely no station troubles which would not have occurred with equally bad results had the neutral of the system been insulated.

The only possible station troubles that can be increased or affected in any way by the presence of the grounded neutral are grounds on the station bus-bars, wiring, or transformers. Let us consider the effect of a ground on the power station bus-bar under the conditions of operation described in the writer's paper. If but a single generator is in operation, the station will be shut down. If more than one is on the line, that machine whose neutral is grounded will be removed from service, the remaining generators carrying the load. Even with but two generators in operation the remaining machine can easily carry the 100% overload for the short time necessary to get another machine into service. After changing over to the auxiliary bus-bar, the neutral of one machine can again be grounded and condition of normal operation resumed without interruption of service.

With a ground on the sub-station bus-bar, the sub-station will be shut down if the total current required to operate the relays is less than the maximum possible current to ground. If the relays require more current than this, the sub-station will continue in operation, but the generator whose neutral is grounded may be shut down. If a ground occurs on the sub-station bus-bar when the neutral is insulated, it will be impossible to remove this ground without first shutting down the sub-station on account of the large current flowing to ground (about 160 amperes).

It is to be seen, then, that with the neutral grounded, grounds in the power and sub-stations may seriously affect the continuity of service only when a single generator is running.

Mr. Taylor called attention to the fact that since the neutral of the system has been grounded, the burn-outs per year per mile of cable have been more frequent than before. He suggested that perhaps this was due to the large amount of new cable installed. This is undoubtedly true to a certain extent, but it must be remembered that the amount of new cable in the original installation was almost as great. He also suggested that the time was so short that the element of chance was not removed. I fully agree with this.

However, I have made a further study of the burn-outs occurring before and after the grounding of the neutral. In the original paper the writer gave a number of distinct operating burn-outs—12 before grounding and 16 after. Of these, there are known to be due directly to severe external mechanical injury, one before grounding, and seven since. Eliminating the latter, there are left 11 burn-outs before the grounding, and 9 after, which were due to internal causes. The writer believes that these burn-outs alone should be used in determining whether or not grounding the neutral has increased the number. Previous to grounding there were operated approximately 620 year-miles of cable, and since then there have been 660 year-miles. This gives the burn-outs per year per mile of cable due to internal causes 0.018 before, and 0.014 since the grounding. It thus appears that the grounded neutral has actually reduced the number of burn-outs that are not traceable directly to mechanical injury.

A paper presented at the 222d Meeting of the American Institute of Electrical Engineers, New York, November 8, 1907.

COMPARATIVE PERFORMANCE OF STEAM AND ELECTRIC LOCOMOTIVES

BY ALBERT H. ARMSTRONG

So many excellent papers bearing upon the subject of steam road electrification have recently been presented to the engineering public that the writer hesitates to add to their number. In the hope, however, of offering a somewhat clearer insight into the fundamental reasons underlying the electrification movement, this paper is written from the standpoint of a technical comparison of the performance of steam and electric locomotives.

Among the many electrification projects now in course of construction, nearly all were inspired by such motives as cleanliness, smokelessness, convenience, etc., but few indeed have been considered strictly from the standpoint of direct financial benefits to be obtained. The improvements in and around New York City terminals, the various tunnel projects such as the early Baltimore and Ohio installation, and later the Sarnia, Detroit River, and Cascade Tunnel projects—all are examples of steam road electrification in which there were distinct reasons for displacing steam as a motive power, but there are other sections of our steam lines where these same reasons do not apply with equal force, and benefits of a more far-reaching nature must be made evident before such electrifications can be considered as necessary or desirable. It is concerning these other sections of steam lines demanding other reasons for electrification that this paper is written, and the best means to be employed in getting a thorough grasp on the subject seems to lie in an investigation into the comparative inherent qualities of steam and electric locomotives.

Before considering the electric locomotive, much the simpler of the two, it is advisable to determine the general characteristics and limitations of the steam locomotive viewed from the standpoint of the electrical engineer, in order that the scope of the problem may be thoroughly understood and the lines of contrast be sharply drawn

This preliminary study of the steam locomotive is made necessary by the fact that railroad practice to-day is essentially *steam* railroad practice and is hedged about by practices and methods of operation demanded by the use of the steam locomotive as a type of motive power. Viewed in the light of greatest benefits to be secured, the coming of the electric locomotive is not due to petty economies affected in coal consumption and cost of locomotive repairs; indeed, with coal as a common source of power, little gain in efficiency is secured through burning the same grade of fuel under stationary boilers over the excellent results obtained with the highly perfected modern compound locomotive. As will be discussed later, there exist certain fundamental relations between the cost of producing a horse power at the drivers of a steam locomotive burning its fuel on the structure, and a horse power at the drivers of an electric locomotive deriving its energy from a distant stationary power house via a distribution system. The use of water power, or of a cheaper grade of fuel than can be burned on a steam locomotive, will in many cases afford a means of reducing the fuel cost well below the present cost of high-grade coal required for successful locomotive operation; but in general the fuel item reduction does not in itself offer a sufficient saving to pay an adequate return on the large investment required for electrification.

It is necessary, therefore, to look for more far-reaching benefits, and, not considering the reasons governing the introduction of the electric locomotives at terminals and in tunnels, we find in a comparison of the characteristics of the steam and electric locomotives a contrast so marked that it shows not only the superiority of the electric locomotive for general railway conditions but it also suggests changes of a fundamental nature in present methods of operation now necessary with steam locomotives. And these benefits to be secured occur not only in the operation of passenger trains, but are felt to an even greater degree in the haulage of the heaviest freight trains, a field supposedly the exclusive domain of the steam locomotive.

The steam locomotive has two component parts, the boiler and the engine, both of which have their own individual characteristics; and the relation between the two is generally determined by the character of the service for which the locomotive is desired.

The steam locomotive boiler is universally of the fire-tube type, though experiments with water-tube boilers point to certain possibilities in this direction. Owing to the restrictions of width and length available, the locomotive boiler must of necessity be worked to its limits in order to generate the greatest amount of steam possible. It is not the purpose of this paper, nor is it necessary, to go into a detailed discussion of the proper relation between grate area and heating surface, fire-box construction, length of tubes, diameter, etc., all constituting improvements in locomotive design directed to the better evaporation of water per pound of coal burned and the greater capacity of a boiler built within the space allowed. It suffices to use values of water evaporation, coal consumption and general boiler performance as obtained in experimental tests, and modify these " best performance " values by the knowledge of conditions obtaining in practical service.

The locomotive engine is distinct from the locomotive boiler, and when supplied with unlimited steam at constant pressure it has its own characteristics and maximum output both in tractive effort and horse power. Engines are of two general types, simple and compound, the latter being introduced in order to affect a saving in the large steam consumption inherent to non-condensing engine operation. The success of the compound locomotive is very much a matter of discussion among railroad men, but it seems to have found a permanent foothold upon easy-grade lines although its use is still open to serious question upon the heavy mountain-grade divisions. In general, the electric locomotive must compete with the compound steam locomotive on level divisions and the simple engine on heavy grade divisions, although the Mallet compound has lately been introduced with some success in this latter class of work.

The general shape of the steam locomotive characteristic is given in Fig. 1, which shows the relation between the speed and tractive effort of a simple consolidation locomotive designed for heavy freight service. Owing to clearances it is seldom that a locomotive can work at more than 90 per cent. of the theoretical full stroke, and hence the maximum tractive effort at starting with lever in the corner will not be much greater than 88 per cent. of the theoretical tractive effort available with gauge pressure in the cylinders. An inspection of Fig. 1 shows that the steam locomotive is limited as to maximum tractive effort by its engine design, and limited as to the speed at which this tractive effort is available by the capacity of the boiler to supply steam. Thus, assuming that the locomotive will give 88 per cent. of its theoretical tractive effort when starting, it is capable of providing but 80 per cent. tractive effort at a speed of 10.6 miles per hour (with the constants of the particular locomotive chosen for illustration) at which the boiler is giving its full output. Hence higher speeds can only be reached with a lesser cut off and a consequent reduction in mean effective pressure and tractive effort. Locomotive engines are generally designed to give their maximum tractive effort at 90 per cent. theoretical cut-off at a point corresponding to a coefficient of adhesion of approximately 22 per cent. of the weight upon the drivers; that is, at about slipping point of steam locomotives with good rail

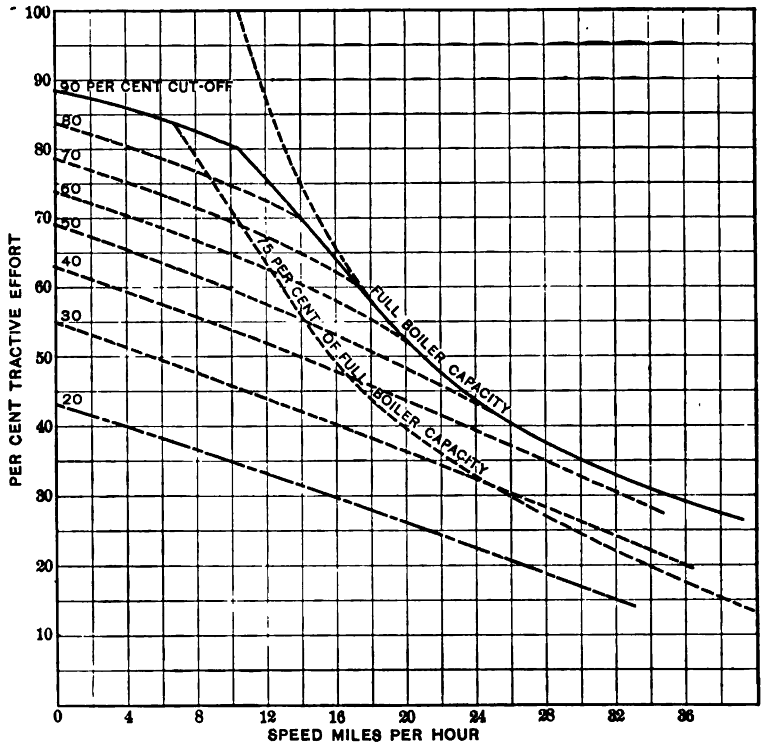


Fig. 1.—Typical steam locomotive characteristic (simple)

conditions. It is immediately evident therefore, that the tonnage rating of the locomotive on ruling grade must be so proportioned that the maximum tractive effort called for will be less than the available tractive effort of the locomotive in order to provide a small percentage, say 10 or 15 per cent., for possible starting under maximum grade and load conditions. In other words, as the steam locomotive is designed so that the maximum tractive effort is delivered at a point not greater than 22 per cent. of the weight upon the drivers, it is not possible to take advantage of possible abnormally good rail conditions (either natural or made abnormal by the use of sand) as the engine itself will fail to deliver any excess tractive effort thus made available with increased coefficient of adhesion.

On the other hand, the tractive effort of the electric locomotive is limited only by the adhesion between driving wheels and rail, and aside from some 15 per cent. greater adhesion possible with the uniform tractive effort provided by the electric locomotive, it is possible with this type of motive power to take momentary advantage of abnormally good rail conditions or to derive full benefit from the use of sand; indeed, tests have been taken with electric locomotives showing as high as 35 per cent. coefficient of adhesion between driving wheels and rail. This point is emphasized as with the greater tractive effort of the electric locomotive it becomes possible to give them a higher tonnage rating for the same weight upon the drivers than would be possible with steam locomotives operating over the same track profile.

There is a marked difference in the speed characteristics of the steam and electric locomotive, and indeed there is also a marked difference in the speed characteristics of different types of electric locomotives. Although this paper is not intended to enter into any discussion of the relative merits of different types of electric locomotives, there is so striking a difference in the several speed characteristics, each of which possess special advantages for certain operating conditions, that Fig. 2 has been prepared contrasting the characteristics of the steam locomotive and the direct-current gearless, alternating-current single-phase geared, and alternating-current three-phase geared electric locomotives. As all types of motive power share in common the fact of a certain critical speed beyond which full tractive effort cannot be maintained, the curves in Fig. 2 have been prepared on the basis of showing the relation between percentage of maximum tractive effort available at speeds higher than the critical speed, ordinates being tractive effort and abscissas percentage of critical speed to running speed.

A more familiar presentation is given in Fig. 3, showing a concrete case of a 22 by 30 steam locomotive of the simple type equipped with 57-inch drivers, contrasted with both an alternating-current geared and a direct-current gearless electric locomotive designed for the same tractive effort both maximum and running, but for a higher speed. The contrast of these different speed characteristics brings out sharply the small speed variation with different tractive efforts delivered by the electric locomotives, this small variation being even more marked in the case of the direct-current gearless than in the case of the alternating-current geared motor working at a lower iron saturation and thus affording a more sloping speed characteristic.

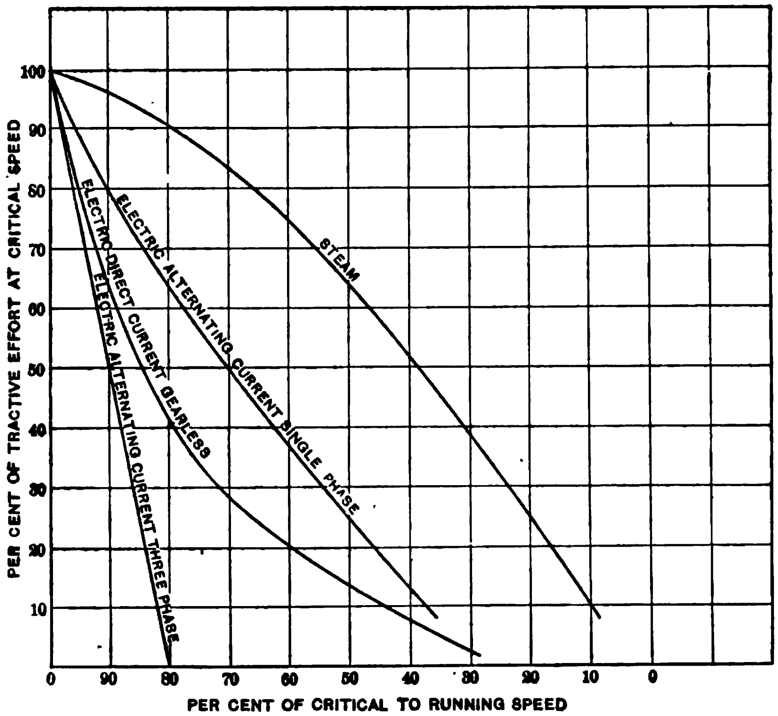


FIG. 2.—Typical characteristics of steam and electric locomotives.

The steam locomotive chosen is typical of those in general use upon our mountain-grade divisions, the tonnage rating in operation of this particular locomotive being such as to call for a tractive effort of 25,600 pounds on *average* grade and 33,200 pounds on the maximum ruling grade occurring on a certain engine division, thus leaving a margin of 6,300 pounds above the demands of

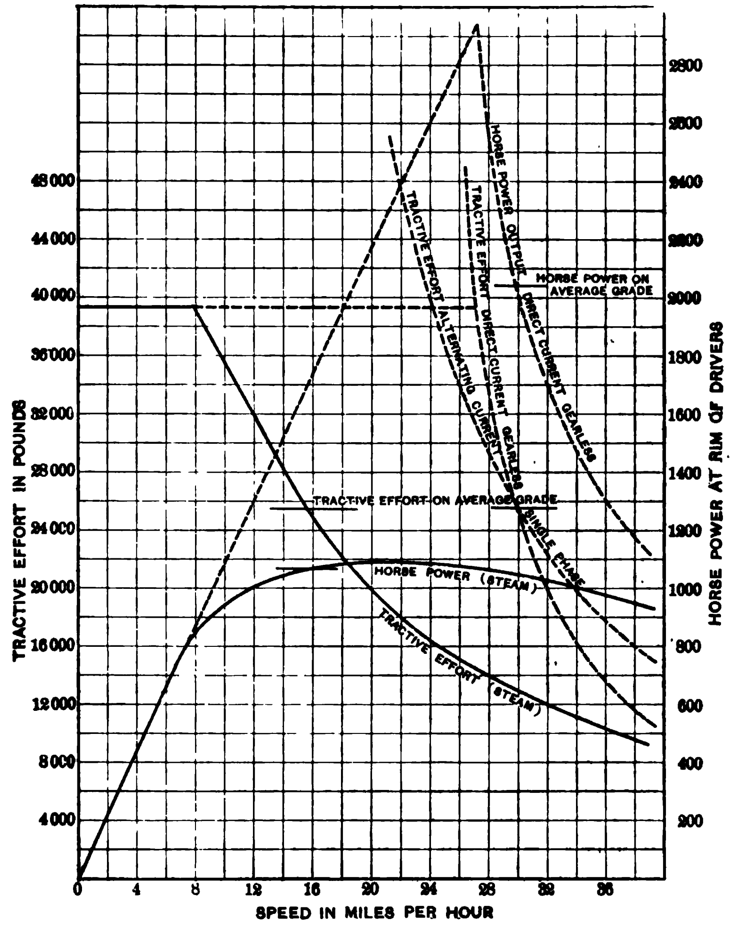


FIG. 3.—Steam and electric locomotive characteristics.

maximum tonnage on maximum ruling grade for starting the train from rest.

The maximum speed available at the different tractive efforts is a matter of boiler capacity, condition of boiler, quality of coal, and efficiency of fireman. The first of these factors, the boiler capacity, can be controlled by properly proportioning the design of the boiler to engine capacity, but there are three other factors which the locomotive manufacturer cannot control and two of these factors constitute sufficient cause to warrant a considerable reduction in the *theoretical rated capacity* of the boiler. Thus, referring to Fig. 1, such a locomotive in prime condition carefully fired with the best coal (approximating 14,000 B.t.u.'s) should be able to deliver full tractive effort at 10.6 miles per hour, but in practice it has been found that the average condition of boilers and the average firing provided by the none too conscientious or diligent fireman, cuts the *sustained* boiler output down to not much greater than 75 per cent. of its output under what must be considered exceptionally or momentary conditions, By sustained " output " is meant the output required while ascending the continuous up grades met with on our western mountain divisions, Though full boiler capacity may be attained for short periods, the average performance of all the locomotives on the division on the average up grade will show a marked reduction in capacity from the results obtained in a stationary test or single experimental test runs.

The locomotive characteristic in Fig. 3, has been prepared on the basis of 75 per cent. of the possible boiler capacity in the following manner:

GENERAL CONSTANTS OF SIMPLE CONSOLIDATION LOCOMOTIVE

Diameter of cylinders	22 in.
Length of stroke	30 "
Diameter of drivers	57 "
Heating surface	3397 sq. ft.
Total weight of locomotive	103.5 tons
Weight on drivers	93 "
Weight of tender	61.5 "
Total weight locomotive and tender	165 "

This particular locomotive has been chosen for illustration as it is the type in daily use on the mountain division of one of the largest Western roads.

Under the above conditions, the theoretical tractive effort is 49,500 pounds, of which 39,600 pounds is available at 90 per cent. cut-off. The contents of each cylinder is approximately 6.6 cu. ft. and with four cylinders of steam per revolution and with steam weighing 0.41 pounds per cu. ft. at 170 pounds cylinder pressure, each revolution requires 10.85 pounds steam. With 3397 sq. ft. of heating surface there is a possibility of evaporating six pounds of water per pound of coal when burning two pounds of coal per sq. ft. of heating surface, thus giving an available supply of 40,700 pounds of steam per hour when working boilers in prime condition at the full output resulting from perfect firing with good quality of coal. In practice, however, the available steam for sustained output would not be greater than 75 per cent. or 30,500 pounds per hour, thus giving full tractive effort at 46.8 revolutions of the drivers corresponding to 7.93 miles per hour on a 57-inch driver. The "critical speed" of the locomotive is therefore 7.93 miles per hour when working at 75 per cent. of full attainable boiler capacity, and the coal consumed under such circumstances will be 4,360 pounds per hour, corresponding to 1.28 pounds of coal burned per sq. ft. of heating surface, at which rate we would expect an evaporation of approximately seven pounds of water per pound of coal.

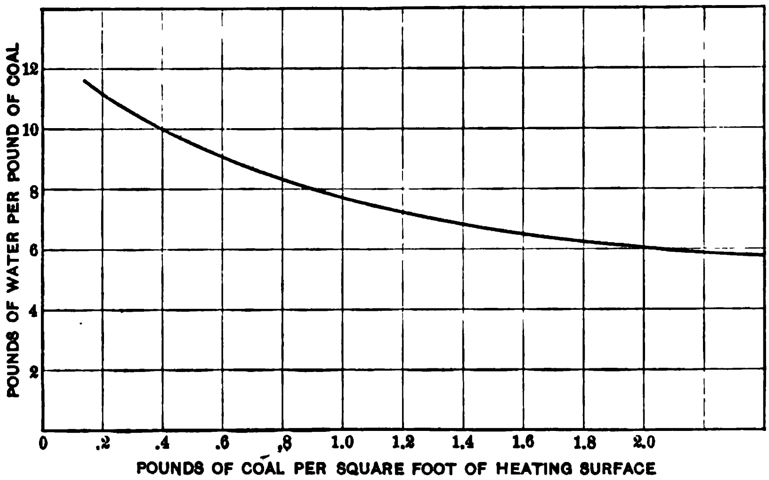


Fig 4.—Rate of evaporation

What might be termed the "performance capacity" of a steam locomotive may be worked out from the speed and tractive effort characteristics given in Fig. 3, using as a basis the 1000 ton-miles trailing load moved per hour on a level or any gradient selected. The prevalence of 2.2 per cent. ruling grade on many of our Western roads perhaps justifies the selection of that figure for demonstration purposes; and the coal consumed, crew wages, and maintenance charges, may all be worked out from the basis of continuous operation per 1000 ton-miles trailing load on 2.2 per cent. grade, these results being shown in Fig. 5.

Certain assumptions are necessary and are as follows:

Cost of coal		$3.00 per 2000 lb.
Engineer	wages per hour	$0.50
Fireman	" " "	0.35
Conductór	" " "	0.40
Three brakemen	" " "	0.90
Total crew		2.15

Average mileage per locomotive per year, 36,500.

Total maintenance including round house charges, $5,000.00.

Maintenance per locomotive mile actually run, 13.7 cents.

General locomotive constants are the same as previously given.

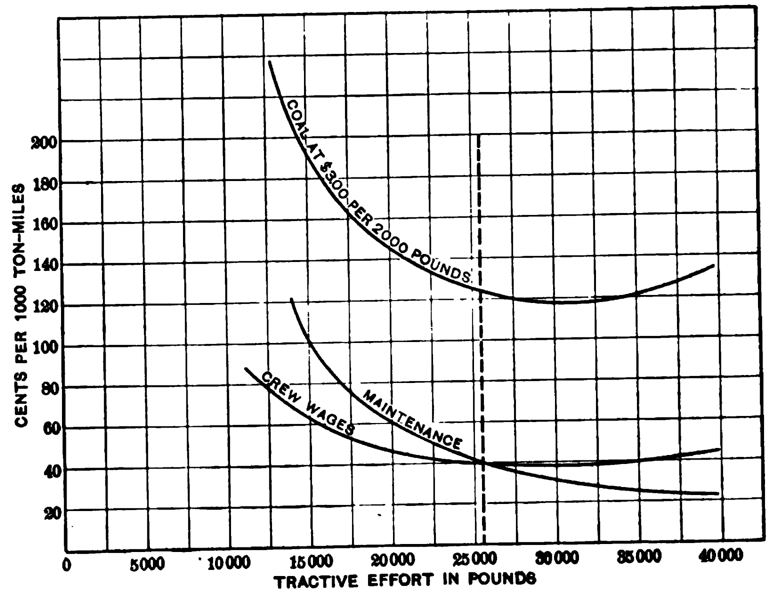


Fig. 5.—Performance capacity steam locomotive (simple) grade 2.2% (up)

Having broadly outlined the performance characteristics of the simple consolidation engine frequently met with in heavy grade operation, it becomes necessary so to proportion the constants of the electric locomotive, assumed to replace it, so as to gain the greatest benefit from the different inherent characteristics of the latter type of motive power.

Referring to Fig. 2, it is evident that with the small speed variation of the electric locomotive, and due to the fact that its motive power is separate from its unlimited source of power generation, it is possible to consider radical changes in the method of moving freight, more especially on mountain-grade divisions.

It has become a partly accepted fact that the electric locomotive characteristic should be so proportioned as to enable it to operate trains at a high rate of speed on level track and at a much slower speed on grades, in fact conforming with present steam practice in this respect. The writer would again point out that steam railroading to-day is in reality steam locomotive practice in that the speed possibilities of different track divisions are restricted to a large extent by the limitations of the steam locomotive. In other words, the only reason why it is common practice to run at very low speeds on mountain-grade divisions instead of continuing the high speeds in vogue on more level portions, is because a steam locomotive cannot be built powerful enough to supply the heavy tractive effort required at any higher speeds than those now in vogue.

Railway economies teach us that the lowest cost per 1000 ton-miles is obtained when operating the greatest train weight at the highest speeds, and Mr. J. J. Hill's well known saying to the effect that " Expenses are per train-mile and receipts per ton-mile ", is only partly true, as the time consumed in hauling the train one mile enters as a most vital factor.

Considered broadly, the one expense in train operation that is fundamental is the cost of fuel, this factor being influenced only by the economy of the fuel-burning plant. Other expenses, such as locomotive maintenance, crew wages, etc., are affected entirely by the method of operation, and no radical departure from present methods is to be looked for until the coming of a type of motive power which offers possibilities not equally enjoyed by the steam locomotive.

This point is further illustrated by reference to the operating sheet of one of our greatest Western roads using the simple consolidation locomotive previously described.

SPEED RELATIONS. ROAD " A " MOUNTAIN DIVISION

	UP GRADE	DOWN GRADE
Schedule speed................	7.35 miles per hr.	12.5 miles per hr.
Average speed while running....	12.1 " " "	20.0 " " "
Number stops per mile.........	0.177 " " "	0.149 " " "

The average schedule speed of a number of trains, including all layovers due to the despatcher or failure of motive power, as obtaining on another mountain division of a different road, showed values as low as 6.7 miles per hour up grade. In general it may be stated that the freight movement over mountain divisions is effected at very low schedule speeds, and the cause is evident from an inspection of the steam locomotive characteristic. Except for the fact that curves are usually of shorter radius on heavy grades than on levels, there is no reason for the slower speed of trains, provided a type of motive power is available that is capable of supplying great draw-bar pulls at high speeds. It is just this characteristic which the electric locomotive possesses to an almost unlimited extent, and such locomotives can be built which are even more powerful and operate at higher speed than can be utilized at present.

For example, the simple consolidation locomotive considered is capable of sustaining a tractive effort of 25,600 lb. at a maximum speed of 15.4 miles per hour, and weighs 165 tons with tender, while a single New York Central electric locomotive of the 6000 type is capable of delivering the same tractive effort at approximately 37 miles per hour, and the weight is only 100 tons. The Central locomotive is of course designed for moderate speed passenger service and could not be run continuously at such a large output, but it is cited only as an example of a well-known electric locomotive having an enormous horse power capacity, although in this respect it is but the forerunner of other electric locomotives having still greater outputs. Owing to the fact that such units may be run in groups of two or more and still be perfectly under the control of a single operator, the advantage of very large single units is somewhat modified, and the introduction of the electric locomotive may also introduce new ideas as to the size and construction of single hauling units.

The electric locomotive may be equipped with motors of several different types each having characteristics best qualifying it for certain classes of work. Fig. 6 and Fig. 7 illustrate the usual speed, torque, and efficiency curves of two typical motors, the direct-current gearless and the alternating-current single-phase geared type. The type of motor to be adopted is a matter requiring full local knowledge of the conditions obtaining in each individual instance before a proper selection can be made. All three of the available motors—direct current; alternating current single-phase; and alternating current three-phase, possess the one needed characteristic of great output per pound and hence the arguments advanced for the substitution of the electric for the steam locomotive are general in character and do not apply strictly to locomotives equipped with any one type of motor to the exclusion of all others. As the direct-current gearless motor can be built in the largest sizes, is the best understood, and is in successful operation upon a very important division of one of the largest steam roads, it is here chosen as the equipment of a typical electric locomotive.

The large output, 840 h.p. for one hour and 400 h.p. continuous, shown in Fig. 6, illustrates what can be accomplished with this type of motor. The output of the complete locomotive is dependent upon the number of motors permitted with the construction adopted. Thus, such a four-motor equipment is capable of delivering a tractive effort of 56,800 lb. at a speed of 23 miles per hour approximate (depending upon the voltage) while the efficiency of conversion at this output would be 87 per cent., rising to a maximum of 93 per cent. at higher speeds and lower tractive effort. Another form of construction, say one similar to that employed in the largest Mallet compound. would permit the use of two four-axle articulated trucks, providing an equipment of eight motors and an output of 113,600 lb, at a speed of 23 miles per hour.

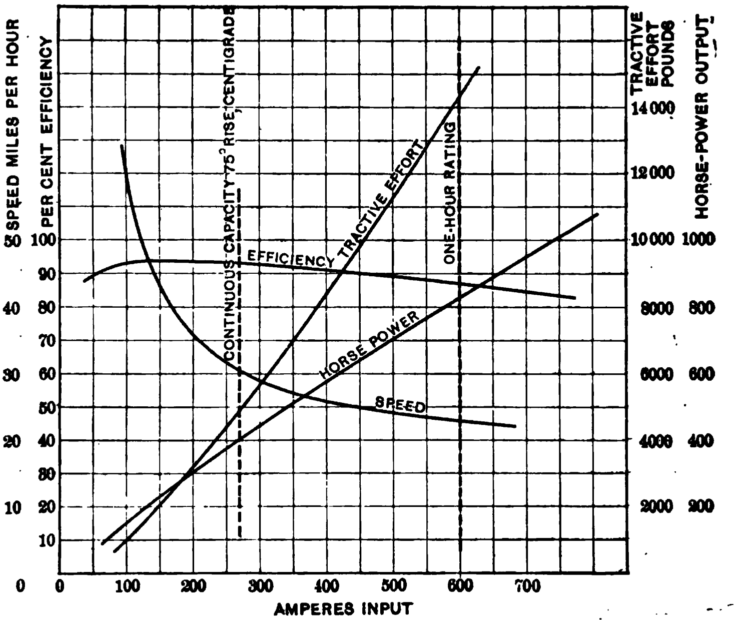


Fig. 6.—Direct-current gearless motor characteristics, 1200 volts

The same motors could readily be rewound to give the same tractive effort at *considerably increased speeds* if desired, without materially increasing the internal losses of conversion. Bearing fully in mind the fact that a single operator has this enormous energy under perfect control, and that such a locomotive could do the work of two or more Mallet compounds and several locomotives of the simple consolidation type, and it becomes evident that in the electric locomotive there are tremendous possibilities of improving present methods of railway operation as now conducted with the steam locomotive. Carrying the thought a step further and appreciating that several such electric locomotive units may be operated in a group forming a combined unit, it becomes evident that in the electric locomotive we have a type of motive power capable of furnishing any output in tractive effort and speed that present or future operating conditions may demand.

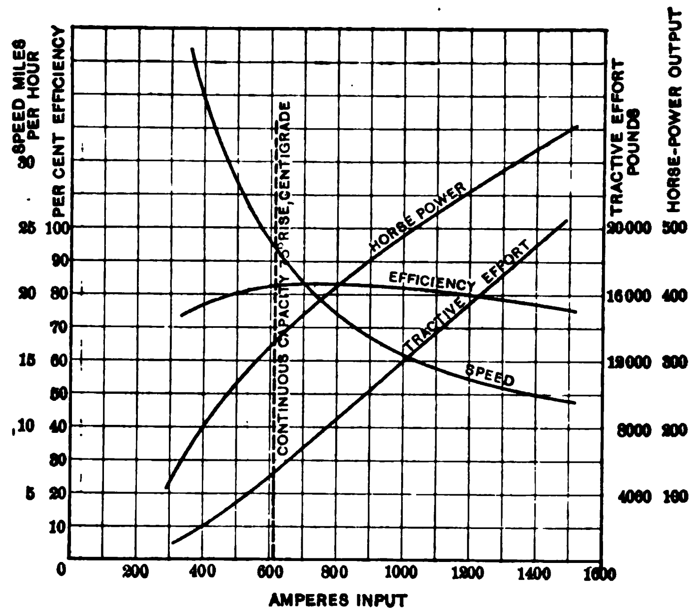


Fig. 7.—Alternating-current single-phase motor characteristics, 25 cycles, 375 volts

Returning to the direct comparison of the simple consolidation and electric locomotive, Fig. 3, was plotted on the basis of a speed of 30 miles per hour for the electric and 15.4 miles per hour for the steam locomotive, giving in each instance a tractive effort of 25,600 lb. at the rim of the drivers. Though the electric locomotive could very readily be designed to give the same tractive effort at a higher speed, 30 miles per hour was assumed as the highest speed permissible due to the alignment of the track on heavy grades.

To plot a performance capacity curve for the electric locomotive, certain further assumptions are necessary.

Type of equipment, direct-current gearless motors.

Weight of total locomotive		125 tons
" on drivers		100 "
Engineer	wages per hour	$0.50
Conductor	" " "	0.40
Three brakemen	" " "	0.90
Total wages of crew		1.80

Efficiency of transmission rail to bus-bar, 70 per cent.
Maintenance of locomotive, 5 cents per mile run.

The train crew is so divided as to permit the location of a brakeman in the engineer's operating cab.

The cost of electrical power must in this instance be most arbitrarily assumed, owing to the widely different cost of coal, possibility of water power, etc., obtaining in different localities. As the cost of coal for steam locomotives will also vary greatly as to price and quality, it has been assumed at $3.00 per 2000 pounds, and a cost for electric power of one-half cent per kilowatt-hour is based upon using the same price and quality of coal. As it is further assumed that an entire engine division of say 150 miles is to be electrified, it gives promise of a 24-hour load-factor of 50 per cent. and this figure has been taken. Approximating the first cost of installation of the generating station at $100.00 per kilowatt, and allowing ten per cent. per year for interest and other fixed charges, the cost of power is brought up to possibly $0.0075 per kilowatt-hour at the station bus-bar. Other conditions obtaining will in a given instance modify the figures arrived at, but for purposes of demonstration $0.0075 is a conservative estimate, and such a figure is needed to compare the cost of power with the fuel item in steam-locomotive performance.

The effect of increased speed on cost of operation is clearly shown by comparing the performance capacity curves of the steam and electric locomotives, Figs. 5 and 9.

It will be observed that the reduction in the operating expenses is effected in the two items of crew wages and maintenance of locomotives, and that the cost of fuel remains practically unchanged. This is as it should be, as the cost of fuel in the case of steam locomotives or power with electric locomotives is the only fundamentally necessary expense in train movement. Overcoming train friction and raising a train up grade against gravity represents useful work performed, and this work is accomplished at an expenditure of approximately four pounds of coal per horse power-hour at the drivers with simple engines and 2.66 pounds of coal per horse power-hour at the drivers with electric locomotives, including all intervening losses between rail and generating station bus-bar. The speed at which this work is performed, therefore, does not affect the cost of fuel or power, it being assumed that the motive power for the various speeds is so proportioned as to operate at the point of greatest economy.

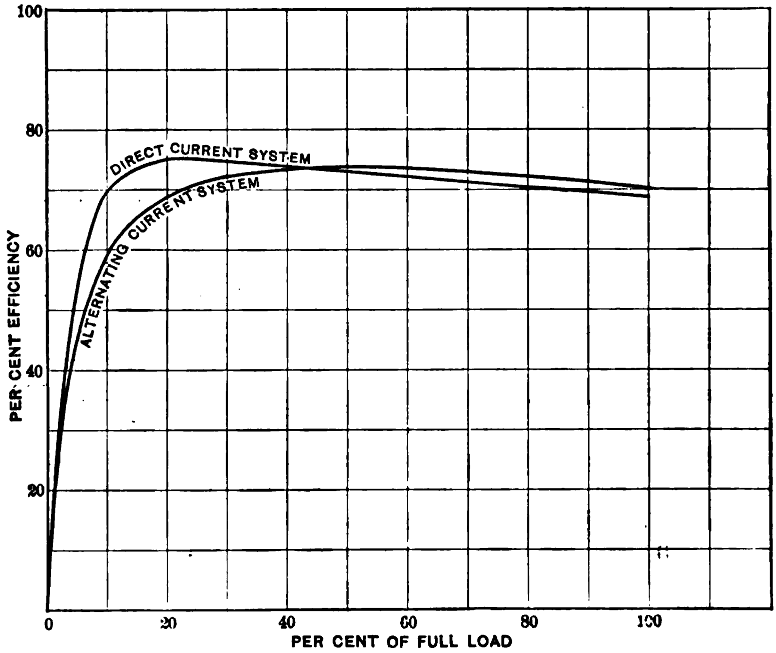


Fig. 8.—Efficiency of distribution generator to rail

Thus with coal at $3.00 per 2000 pounds in each case, the steam locomotive can generate a horse power at the drivers at an expenditure of $0.006 as against $0.0039 for fuel alone with the electric. The two figures are not directly comparable, as to the cost of fuel for steam locomotive operation must be added the extra cost of hauling, which on grade divisions may constitute a large percentage of its original cost; and the waste incident to handling and storing in many bunkers along the tracks. In addition, there is a considerable quantity of coal burned under the boilers of steam locomotives standing idle or coasting down grades, which will be shown later, may equal ten per cent. of the total consumption in main line freight movement and much more in the case of helpers and switching engines. If, therefore, coal be delivered at the engine division terminal at $3.00 per ton, the actual cost on the tender will be considerably in excess of this figure, and due allowance must also be made for the coal wasted, burned or otherwise, and not producing useful brake horse power-hours at the rim of the drivers.

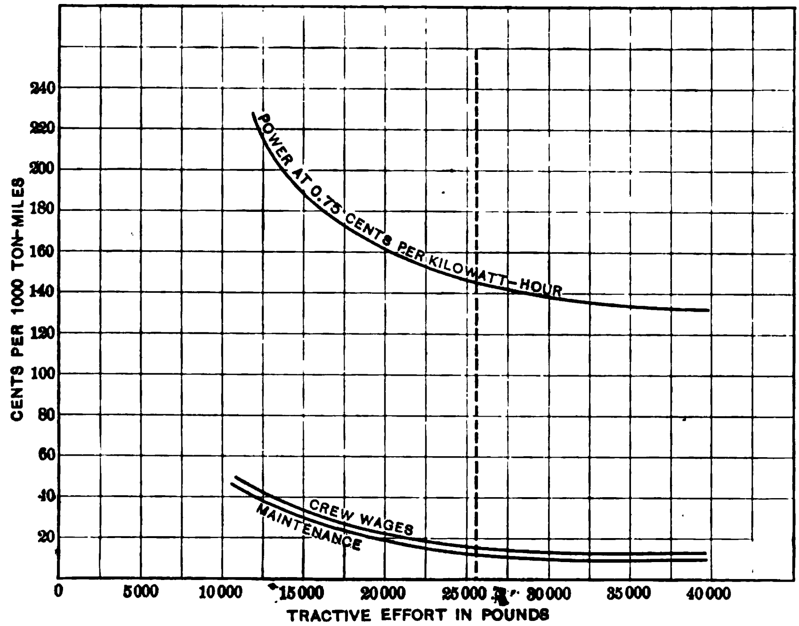


FIG. 9.—Performance capacity electric locomotive (Direct-current gearless) grade 2.2% (up)

In the electric system also, besides the allowance made in distribution losses in arriving at 2.66 pounds coal burned per horse power-hour at the rim of the drivers, there will be an additional charge for labor and fixed expenses incident to power-house operation and first cost. The electric system, however, is not restricted to the use of high-grade fuel and coal of an inferior quality, and much lower cost, such as lignite, can be utilized, besides the large opportunities for cheap power presented by the water powers generally available on mountain divisions.

The saving or deficit in the power item with electric as contrasted with the fuel item of steam locomotive operation must, therefore, be largely determined by the local factors entering into the case. A common cost of $3.00 per 2000 pounds for coal is taken in this discussion; it is rather favorable than otherwise to steam locomotive operation, as coal can be dropped into the bin of a power house located at a division terminal at less expense than it can be hauled up a severe long grade and distributed in several pockets along the route.

It is evident that the cost of fuel or power, being fundamental, constitutes a fixed item in the total cost of operation while the other two items, crew wages and maintenance expenses, will be determined solely by the method of operation and the excellence of motive power used. We have become so accustomed to consider that fuel, crew wages, and engine maintenance each constitute approximately ten per cent. of the total cost of operating a railway that we rather lose sight of the fact that two of these items are a theoretically needless expense and subject to considerable modification in practice with the adoption of another type of motive power possessing characteristics which will permit making radical changes in operating methods.

While the figures shown in Figs. 5 and 9 indicate a certain relation among the three items of fuel, crew, and maintenance expense, this is not the true relation obtaining in practical operation for the reason that the values given in the curves assume continuous operation up grade under the conditions outlined. Unfortunately, train crews must be paid full value per mile whether the mile be up grade or down, and with steam locomotives there is also a considerable loss in fuel resulting from engines standing or running light which must be also taken into account; hence it becomes necessary to modify the figures arrived at, and for this purpose certain references must be made to current railroad practice on mountain-grade divisions in order to arrive at the proper tonnage relations, schedule speeds, etc., obtaining in up-grade and down-grade operation.

Previous figures have been given showing that the schedule speed on several mountain divisions is approximately 50 per cent. of the average running speed and this figure is assumed in the following statement of cost of operating 1000 ton-miles with steam locomotives, averaging the cost of up- and down-grade running. Owing to the higher schedule speed of electrically operated trains, resulting in fewer meeting points with the same tonnage handled, and due to the absence of forced stops to take on fuel and water, etc., it is assumed that with electric motive power the schedule speed may be 60 per cent. of the running speed.

With the electric locomotive standing, or coasting down grade, there is no demand whatever made upon the generating station, and hence the only expense carried through these periods is that for train crew and a certain amount for maintenance. On the other hand, with the steam locomotive there is a considerable amount of fuel burned and water wasted when standing at sidings and when coasting. In the case of mountain railroading with its frequent and prolonged delays, this waste may reach considerable proportions.

The following results of a carefully conducted series of tests will illustrate this point. Two test locomotives and trains were operated over a mountain division under regular service conditions—steam and fuel consumption, duration of delays, etc., being carefully noted. The total work expended up grade was 5700 horse power-hours at the rim of the drivers including allowance for 1.54 per cent. average grade and seven pounds per ton track and curve friction. The total water evaporated on the trip divided by the total horse power-hours gave a steam consumption of 36 pounds per brake horse power-hour at the rim of the drivers. Indicator cards taken upon the engine in question at all cut-offs up to 90 per cent. showed that the greatest steam consumption did not exceed 32 pounds per indicated horse power-hour, or 35.5 pounds per brake horse power-hour, allowing ten per cent. internal engine friction. Values as low as 23 pounds of steam per indicated horse power-hour or 25.5 pounds per brake horse power-hour were recorded for the average cut-off of 40 to 50 per cent. used throughout the run. A third and fourth series of tests conducted up the same grade gave similar results, except that the values were slightly higher than those quoted, showing that there was a considerable loss of water unaccounted for by indicator cards and useful work performed.

Operating down grade, it was necessary to accomplish 1110 horse power-hours on account of the somewhat broken profile, and again the water consumption showed on two trips 57.7 pounds of steam per brake horse power-hour, and on two subsequent trips 66.5 pounds, values entirely unaccountable on the basis of useful work performed.

During all tests the usual service delays occurred, and as the traffic on the road in question was very much congested, these delays constituted a considerable proportion of the total elapsed time. In fact during the runs up grade the trains were in motion but 66 per cent. of the total elapsed time, and down grade the trains were in motion from 52 per cent. down to 40 per cent. of the total elapsed time. As these delays were frequent and undetermined, it was necessary to maintain full steam pressure while waiting for the momentarily expected release from the block, hence the waste of fuel and water was considerable. Averaging this waste at 400 pounds per hour, at which low rate of consumption the water evaporation would approximate ten pounds of water per pound of coal burned, or 4000 pounds of water evaporated per hour, and reducing the total water consumption measured by the waste losses thus obtained, the steam consumption in eight different tests up and down grade ranged 34.7 pounds, 32.4 pounds, 28.1 pounds and 25.3 pounds, etc., water per brake horse power-hour. These values are fairly commensurate with results of indicator cards taken, and, with the type of engine used and under the operating conditions obtaining, an allowance of 400 pounds of coal stand-by losses per idle locomotive-hour seemed not too great a value to allow, and this figure has been taken in subsequent calculations.

Locomotive performance capacity curves may therefore be plotted which will show approximately the true relation between the several items of fuel, crew wages, and motive power maintenance, by adhering to the following assumptions:

Ratio schedule to running speed up-grade steam locomotive,	50 per cent.
" " " " " electric "	60 per cent.
Schedule speed down-grade steam	15 miles per hour.
" " " " electric	18 miles per hour.
Cost of coal	$3.00 per 2000 lb.
" " electric power	0.0075 per kw-hr.
Efficiency of distribution	70 per cent.
Crew wages per hour steam	$2.15
" " " " electric	$1.80
Maintenance locomotive steam	$0.137 per mile.
" " electric	$0.05 per mile.
Fuel waste per idle hour steam	400 lb.

An inspection of the performance curves shows that in practical operation the fuel expense approaches more nearly to the value of the other items considered, instead of being greatly in excess of them as indicated in the theoretical performance curves, Figs. 5 and 9, showing up-grade operation only. For operation on lesser grades than 2.2 per cent., all items are reduced and the total and subdivided comparative costs are given in the following table and in Fig. 11.

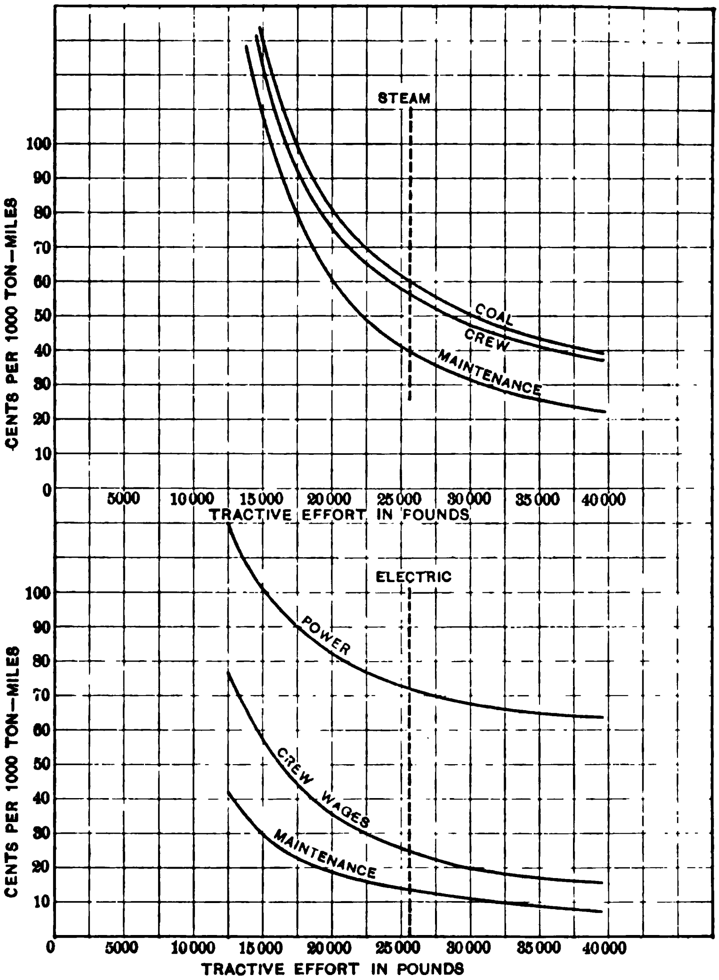


FIG. 10.—Tractive effort in pounds. Service capacity steam and electric locomotives average of up and down 2.2% grade

COMPARATIVE OPERATING EXPENSES PER 1000 TON-MILES STEAM (SIMPLE) AND ELECTRIC LOCOMOTIVES

AVERAGE OF UP- AND DOWN-GRADE OPERATION

Steam Locomotives

Grade	½%	1%	1½%	2%
Coal	15 cents.	25.5 cents	38 cents.	53 cents.
Crew	13.5 "	24 "	36 "	50 "
Maintenance	10.5 "	17.8 "	26 "	36 "
Total	39 "	67.3 "	100 "	139 "

Electric Locomotives

Grade	½%	1%	1½%	2%
Power	20 cents	35.5 cents	50.5 cents	66 cents.
Crew	7.2 "	12.2 "	18 "	24 "
Maintenance	3.6 "	6.2 "	9.0 "	11.9 "
Total	30.8 "	53.9 "	77.5 "	101.9 "

Saving effected by electric operation

Grade	½%	1%	1½%	2%
	8.2 cents	13.4 cents	22.5 cents	37.1 cents

A study of the above table is most instructive, as it shows that while the percentage saving with electric operation is approximately the same whatever the ruling grade, yet the actual money saving is much greater on the heaviest grades. As about the same investment must be made in each case for distribution system including third-rail or overhead trolley, sub-stations, etc., the inference must be drawn that heavy-grade divisions present a more attractive field for electrification than level sections when considered from the purely economic standpoint. There are other items of saving and other reasons for electrification which may be more or less controlling in individual cases, but it seems possible to make the broad statement that the mountain-grade division offers a particularly attractive field for the electric locomotive, and its introduction should be the means of affecting such economies in both freight and passenger transportation as to pay a satisfactory return upon the investment required.

So far, the matter has been viewed from the standpoint of comparative operating expenses for a given tonnage moved. There is another argument for electrification which may in certain instances be of a much more controlling nature. Most of our mountain roads are single track and transcontinental tonnage has so increased as seriously to congest these mountain divisions. The heavy trains of the plains, weighing 2000 to 3000 tons, must be split up into units of about 1000 tons in order that the present steam engines, operating double and even triple, may haul them over the heaviest grades. The slow speed obtainable makes the number of trains on a mountain division large, the meeting points frequent, and hence, however good the despatching system employed, there will of necessity be a considerable amount of lost time introduced. Add to this the failures of motive power being worked to its limit, and there is reason for the claim that the tonnage capacity of the division will be greatly increased by the introduction of electrically hauled trains.

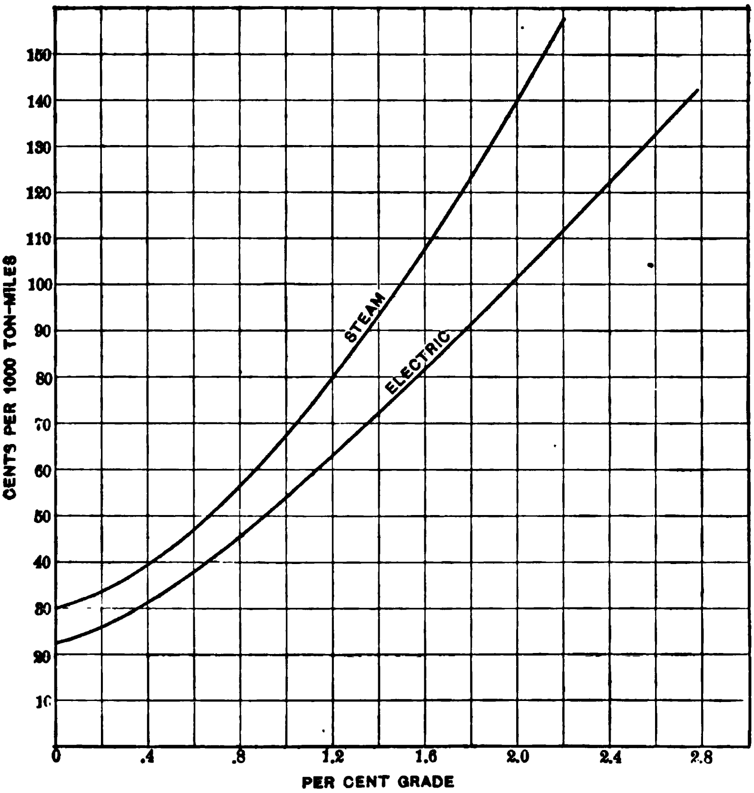


FIG. 11.—Service capacity of steam and electric locomotives average both directions and any gradient

Lest the writer be accused of unfairness in selecting the simple engine for comparison, it is proper to touch upon the economies effected with the use of the compound locomotive and also by the introduction of such coal-saving devices as superheaters and feed-water heaters.

Reference to Fig. 13, shows a saving in water consumption per horse power of approximately 20 per cent. with the compound locomotive, but in spite of this generally accepted saving the simple locomotive still rules the mountain division after repeated trials of the compound. Not being an ardent supporter of either type of locomotive, the writer leaves the battle of the simple and compound to their enthusiasts, commenting only upon the fact that, except in the case of the Mallet compound, the arguments for the compound are based upon fuel economy only.

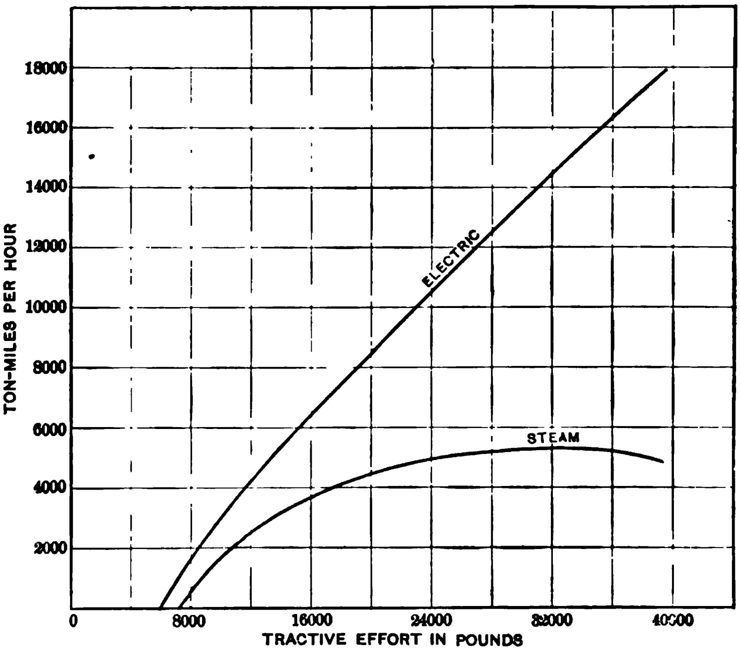


Fig. 12.—Hourly tonnage capacity of steam and electric locomotives up 2.2% gradient

The latest Mallet compound, weighing 413,000 pounds, is the largest steam locomotive yet built, and is of particular interest owing to the enormous boiler which such a construction permits. With a total heating surface of 5300 sq. ft. we should expect an evaporation of 63,600 pounds of water for a short period and possibly 48,000 pounds water continuously. With a possible evaporation of six pounds of water per pound of coal, this would necessitate the burning of 8,000 pounds of coal per hour, requiring the best efforts of two firemen if maintained for several hours. Assuming a steam consumption of 22 pounds per brake horse power-hour, such a locomotive should give a sustained output of 2180 horse power at the rim of the drivers, and this with a weight with tender of approximately 300 tons, or three times the weight of an electric locomotive of the New York Central 6000 type giving the same horse-power output.

The two locomotives are, of course, designed for entirely dissimilar classes of work; but it is not unfair to compare them on a horse-power basis as it is the huge boiler of the Mallet that is remarkable, and upon this basis the selling price of the two machines is approximately the same.

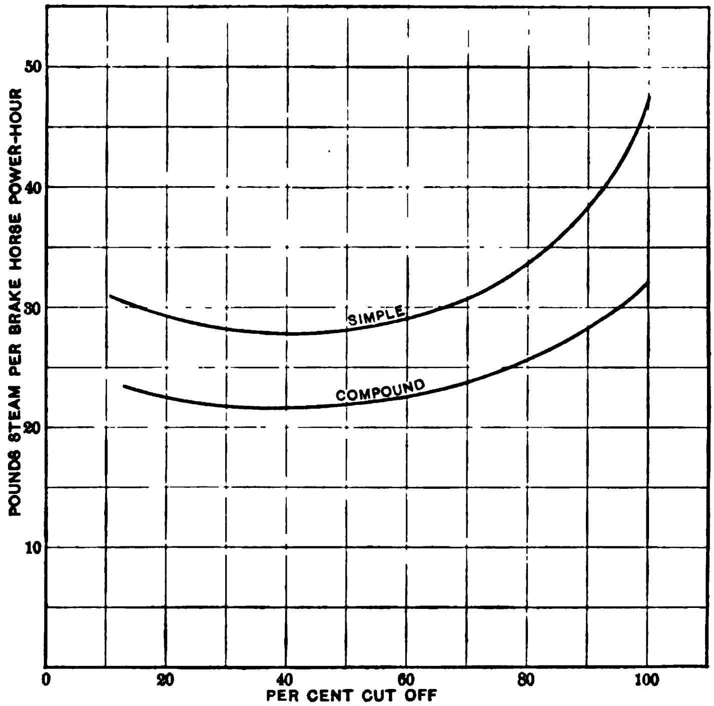


Fig. 13.—Steam consumption simple and compound

The comparative cost of electric and steam locomotives is generally considered as very favorable to the steam units, but reversing the usual methods and comparing the cost of the electric with that of the steam locomotive or locomotives required to replace it, may reverse the relations. The electric locomotive requires no more than casual inspection, can be side-tracked indefinitely and still be ready for instant operation at full capacity, can run 24 hours without a stop, if necessary, and all these advantages and others offers a guarantee for a much greater annual mileage than is possible with its steam competitor. Then, too, compare the cost of a group of steam locomotives (no single unit could be designed to give the output) capable of delivering even 4000 h.p. continuously with a single electric unit of this output, and the difference in cost is not great. It may be stated broadly that for a given gross annual ton-mileage moved, the cost of steam locomotives may be even greater than the cost of the electric units replacing them.

The term " horse power " is perhaps not fully appreciated by the steam railway fraternity. When the statement is made that a certain electric locomotive is rated at so many horse power output, it does not leave the impression it should. The horse power output of a locomotive is a direct measure of its capacity to do work, and while the tractive effort available governs the tonnage of the trailing load, it is the product of the tractive effort times the speed at which it is available, or in other words, the horse power output, that measures the hourly tonnage capacity of the locomotive upon which the crew expenses of the entire train depends. Hence the great claim for recognition of the electric locomotive lies in its great horse power output, that is, its ability to carry full tractive effort or to slip its wheels at speeds two or three times greater than can be done with any steam locomotive yet built.

Superheating promises something in fuel economy as does the introduction of feed-water heaters. Such improvements, together with the adoption of the four-cylinder locomotive, either compound or simple, must necessarily call for more expense to maintain and less reliability in operation. In fact, superheating in stationary boiler plants has given much trouble, and excessive superheating has not been a complete success even when used with turbines, with which superheating has given the best results. Judged from stationary engine practice, it seems fair to assume that the amount of superheat in locomotive practice must be moderate and result in small benefits to be secured.

The feed-water heater is also a coal-saving device and should prove to be worth its added complication as soon as it is commercially developed.

As against the reduction in fuel expenses promised by the use

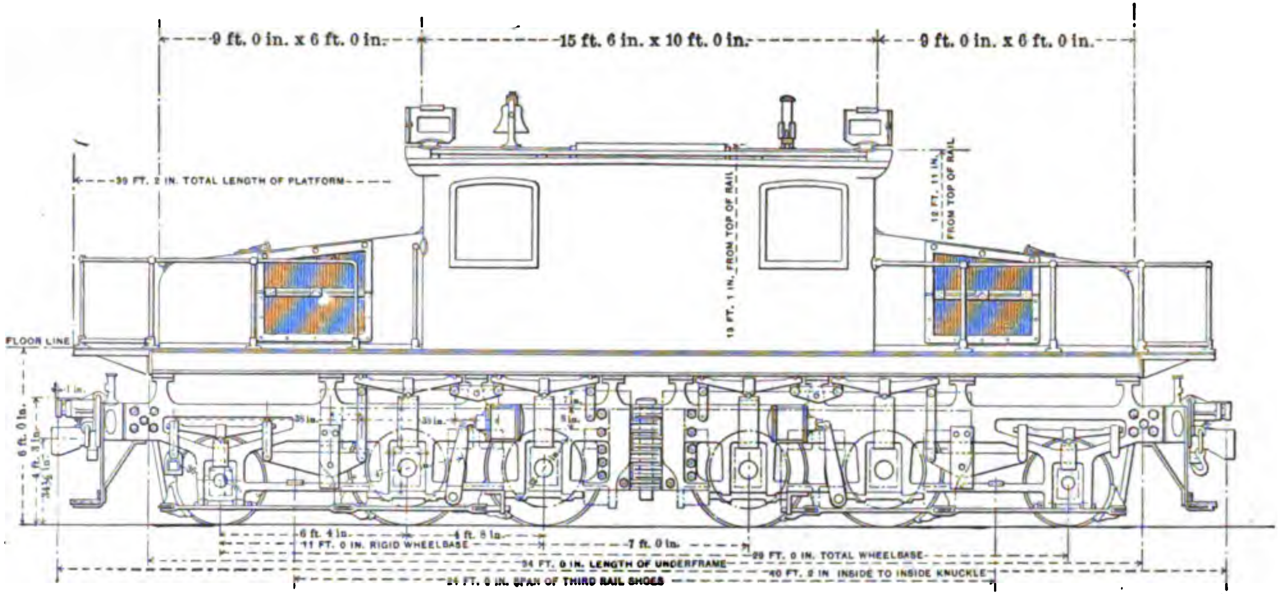


Fig. 14.—Typical electric freight locomotive 2-4-4-2 type

of the compound locomotive fitted with superheaters and feed-water heaters, the electrical engineer has up his sleeve the great possibilities offered by regeneration of power while electrically braking on mountain-grade divisions. The amount of power saved by this means may in certain installations amount to as great a percentage of the total as is the saving affected in coal expenditure with steam locomotive by compounding and providing superheaters and feed-water heaters. Such an electrical saving is of course restricted to heavy-grade divisions, but the feasibility of electric braking by regeneration is unquestioned. Indeed with three-phase induction motors regeneration is automatic, the motors being perfectly reversible and returning energy when operating down grade with no change whatever in their connections. Other types of motors may be adapted for regeneration with slight modifications in the control system.

The chief advantage of regeneration lies in the assurance it offers of greater safety in operating on heavy grades. The present method of braking, by friction between wheel and shoe, results in overheated parts, breakages resulting therefrom and consequent danger of derailment. The descent of a long heavy mountain grade is accompanied by the shoes and wheel rims becoming heated to a dull red, while the introduction of the electric locomotive offers an opportunity of holding the train in whole or in part by means of the same motors used to haul it up grade, and thus eliminating one of the greatest sources of danger in mountain railroading.

All of our railway managements have felt the need of establishing a so-called express freight service comprising a light train operating at much higher speed than is the case with the bulk of the freight movement. It is well known that the cost per 1000 ton-miles for moving express freight is very much higher than in the case of low-speed freight. An inspection of Fig. 3, illustrates the reason for this. The steam locomotive is essentially a slow-speed unit when delivering its full tractive effort; that is, a tractive effort equal to 22 per cent. of the weight upon the drivers, and high speed is only obtained at the sacrifice of tractive effort. Hence a high-speed freight train is of necessity a lighter train than could be handled over the same profile by a given locomotive, and the crew and maintenance expense is therefore large. That such a class of service is nevertheless profitable or at least necessary is evidenced by the continuance of the practice and the proposed introduction of elec-

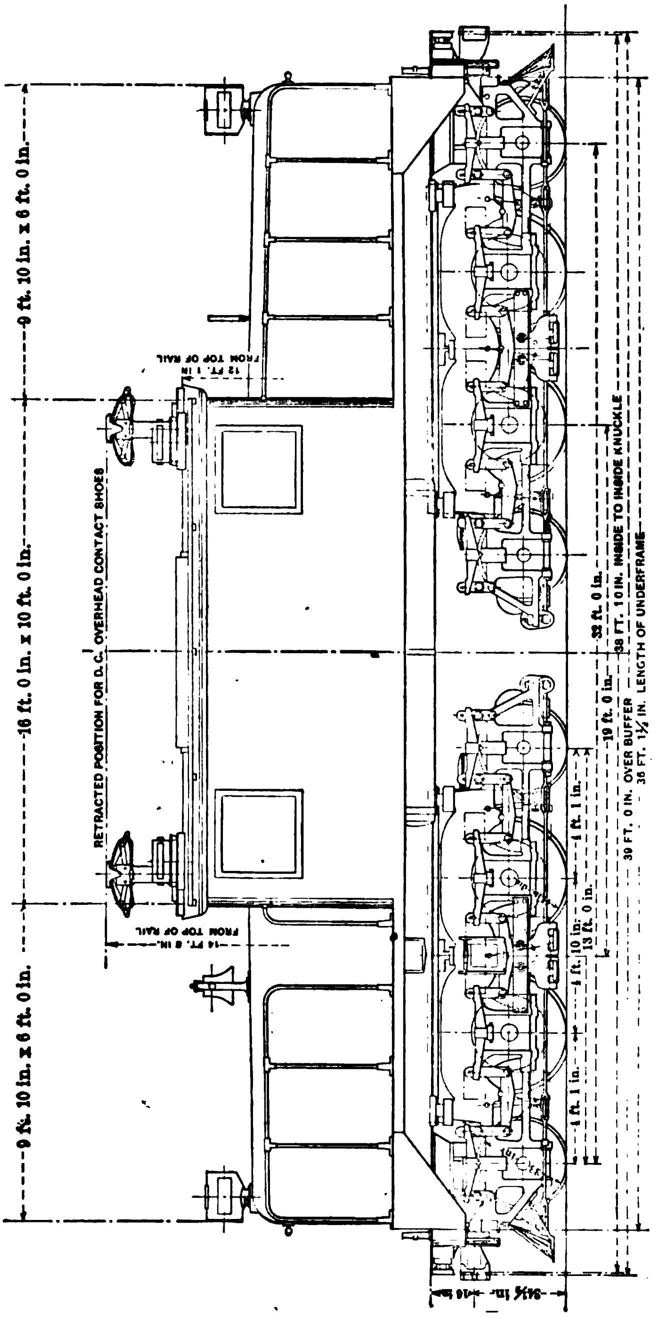


FIG. 15.—Typical high-speed passenger electric locomotive

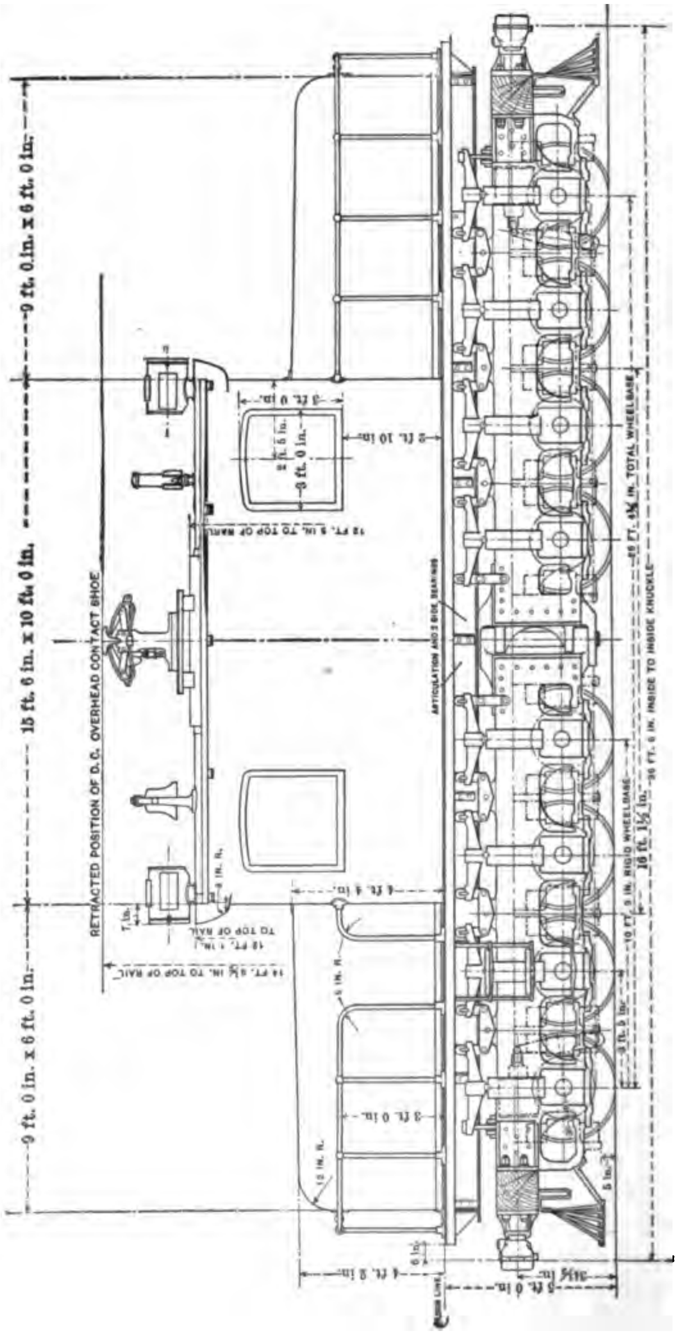


FIG. 16.—Typical electric locomotive heavy freight 0-8-8-0 type

tric locomotives, in effect, makes all trains fast freights, gaining the benefits of such a service without incurring the penalty of increased operating expenses inherent to steam operation.

In this paper the writer has attempted to outline some of the fundamental reasons for the electrification of steam roads; the figures submitted are used for illustrative purposes only and are not intended as being directly applicable to any concrete case. Many of the points touched upon, such as steam locomotive improvements, compound versus th simple, and the comparative advantages of different types of electric locomotives, etc., could all be treated in separate papers by themselves, so replete with interest are the different points raised. Rather than befog the main question at issue, which is the electrification of steam roads, detailed proof of many statements made has not been attempted, as the introduction of such proof would unnecessarily extend a paper already too long. Nor does the writer believe that the time is ripe for the electrification of steam roads at large; indeed, the electrical enthusiasts would be hard put to it if called upon to show reason for the electrification of many branch steam lines carrying a small tonnage at infrequent intervals. There are, however, certain divisions of our steam railways which, either on account of their broken profile or heavy traffic, offer an opportunity to introduce a superior type of motive power which will effect such economies in operation as to provide adequate return on the investment required for the electrification. There are still other divisions where a much desired increase in the track-tonnage capacity can only be effected by double tracking so long as the steam locomotive is adhered to as the type of motive power used. Double tracking a mountain-grade division is often a matter of enormous expense, and electrification of the single track may relieve the present traffic congestion at a moderate cost.

On mountain-grade divisions the subject of regeneration with electric locomotives should receive very careful consideration, not so much on account of the saving in power which it may effect, but rather on account of the greater safety of operation which it guarantees by eliminating the serious defects of holding trains on heavy grades by wheel and shoe friction. Finally, there are the many incidental advantages to be gained with electrification which cannot be predicted with any accuracy, as they result from changes in operating methods sure to follow the introduction of a type of motive power not subject to the service limitations of the steam locomotive. No attempt has been made even to approximate the saving effected in engine supplies, roundhouse expenses, elimination of water supply with its often attendent expensive purifying outfit, and the many items incident to steam locomotive operation. These items are incidental and seldom assume an importance sufficiently great to class them as fundamental, though the difficulty of procuring good water, even with purifying plants, may approach very closely to being a controlling factor in certain cases.

The freight-car shortage problem itself is a very serious one at certain times of the year on some roads, and as the total freight-car mileage can be increased with the higher speeds provided with electric locomotives, it should result in the saving of a considerable expense now incurred for rental of foreign cars, or even increase the gross receipts by the movement of tonnage which more available cars would make possible.

The subject of the electrification of steam roads is, therefore, a very broad one, and while this paper has been devoted largely to a discussion of operating expenses as affected by the different characteristics of the two types of locomotives, it has been done to illustrate the advantages resulting from increased locomotive capacity. The keynote of electrification is *capacity;* by approaching the problem from this standpoint only can full benefits be obtained.

DISCUSSION ON "COMPARATIVE PERFORMANCE OF STEAM AND ELECTRIC LOCOMOTIVES", AT NEW YORK, NOVEMBER 8, 1907.

William J. Wilgus: Instead of apologizing for adding to the number of papers on the electrification of steam railroads, the author should feel entitled to congratulations for calling attention to many of the advantages of the electric locomotive that have heretofore escaped analysis. In my judgment the cause is injured rather than benefited by arguments for the wholesale application of electricity to steam railroads, and it is pleasing to note the increasing tendency in our technical societies to sane discussions that will really enlighten the railroad officer anxious to be in the van of progress.

Unquestionably, electricity in heavy traction work has come to stay. As the author states, until now the reasons that have lead to the principal changes of motive power are entirely apart from questions of economy in operation. Conservative advocates of heavy electric traction, while urging its self-evident advantages in the abolition of the products of combustion in tunnels and cities, the increasing of terminal capacities, and opportunities for growth of traffic, have refrained from dwelling too strongly on saving money. They have been contented with the belief that more money could be made. The burden of additional interest charges, taxes, maintenance and depreciation attendant upon the substitution of electricity for the old form of motive power has very properly caused the careful engineer to pause in admitting even to himself that in addition to increased capacity to handle traffic, there might be a net saving in cost of operation. This cautiousness has sprung from the absence, until recently, of any actual data on the cost of heavy electric traction operation.

The pioneer electrical installation in heavy trunk-line service, on the New York Central & Hudson River Railroad, has now been in complete and successful operation since July 1, 1907, the gradual change from steam power having commenced in December, 1906. The working side by side of both kinds of motive power has given unsurpassed opportunities for the observation of their comparative capacity and efficiency. The results are even more gratifying than were expected; and substantiate many of the author's claims of superior capacity of electric equipment, although the conditions differ widely from those that he has assumed.

At this point it may be well to venture a word of caution on the subject of costs. Comparisons are worthless unless all elements of expense that will affect the results, are included. For instance, the cost of current delivered at the contact shoes should include not only costs of operation and maintenance, interest, depreciation, taxes and insurance on the power station, but likewise on the entire distributing system. If this is properly done, the real cost of current, as finally delivered at the electric equipment, will be found very largely to exceed the usual assumptions. The author's cost of current seems to me to be considerably too low.

On the other hand, the cost of maintenance and care of equipment should embrace not only wages and supplies, but also interest, taxes, insurance, maintenance and depreciation on the structures and real estate required to house and repair the equipment. Steam locomotives require extensive engine-houses, coal and water stations, ash-pits and appurtenances, often on very expensive lands, whereas electric equipment needs the simplest form of inspection sheds occupying limited areas of land. Also steam locomotives require extensive and complicated heavy-repair shops, usually at far distant points, that necessitate costly dead mileage and lengthy idle periods, while electric equipment because of its simplicity can be much more quickly repaired in nearby shops and returned to service. Many of these features have been mentioned by the author, but possibly their importance can be emphasized by giving some concrete examples from actual practice on the New York Central.

Because of less cost of maintenance of electrical equipment, and less idle time in shops, the greater cost of interest charges and depreciation is not only neutralized, but a net saving in repairs and fixed charges over steam equipment is effected of 19 per cent.

Electric locomotive inspection and light repairs, as compared with coaling, watering, drawing fires, repairs, etc., of steam locomotives show a saving in time in favor of the former of over 4 hours per day, equal to 18 per cent.

The electric locomotive, while busy, is a much more nimble and efficient machine than the steam locomotive, showing an increase in daily ton-mileage of 25 per cent.

While not so important in freight service, the question of locomotive weight is a large factor in a comparison of the relative economy of handling passenger traffic by steam and electricity. For instance, in switching service at the Grand Central terminal, 65 per cent. of the total steam ton-mileage is due to locomotive or " dead " weight, while the electric locomotive percentage is but 54 per cent., a saving for the latter of 11 per cent.

In the regular schedule service, the steam locomotive shows 51 per cent. dead ton-mileage as against 35 per cent. for the electric equipment, a saving for the latter of 16 per cent. When we realize that this saving of " dead " ton-mileage has a direct proportionate effect on the cost of fuel and current, and an indirect effect on wages and fixed charges, its importance is manifest.

The author calls attention to the speed advantage of electric over steam locomotives in mountain-grade operation. This is strikingly apparent in the New York Central installation, where the increase in coal consumption for car ton-mileage in high-speed service as compared with slow-speed service, is shown to be 165 per cent., whereas under exactly the same conditions the increased consumption of current for electrical equipment is but 18 per cent., a difference in favor of electrical operation of 147 per cent.

The net result of all of the economical advantages of electric operation, over steam, *for the conditions existing on the New York Central,* after including all elements of cost of additional plant, shows a saving in summer months of from 12 per cent. to 27 per cent., depending on the character of service. A larger saving may be expected under winter conditions.

In addition to this saving, the nuisances and dangers from smoke and gas in the Park Avenue tunnel have been eliminated, and the capacity of the Grand Central terminal has been increased about one-third. Later when the New Haven Company effects its change of power, complete electrical operation in the tunnel will permit the use of shorter blocks, and correspondingly increase the capacity of the four-track main-line entrance to the terminal.

I feel sure that the author will be pleased to know of this actual demonstration of the correctness of many of his views, and that the members of the Institute, regardless of their advocacy of rival systems of electrification, will take pride in the successful inauguration of this pioneer trunk-line installation, on such a large and complicated scale.

It might be well to add to the author's keynote *capacity,* the equally important one of *efficiency,* as the two combined, applied to the problem under consideration, will demonstrate whether or not the adoption of electricity is justifiable from the standpoint of economics.

Cary T. Hutchinson: I think that Mr. Armstrong gives the clearest statement of the capacity of steam and electric locomotives that I have seen. I agree with Mr. Armstrong that no project of electrification of trunk lines has up to the present been undertaken from an economical point of view. The matter has so far been determined by special considerations, such as the terminal problem in New York City, or the mountain-grade problem, or something similar. I doubt whether there are sufficient data on hand to permit the making of an accurate estimate of the total annual cost of electrical operation of any steam road; all data on the subject that I have seen are subject to criticism from one point of view or another.

Mr. Armstrong considers especially two points; the relative capacity of steam and electric locomotives as machines, and the relative cost of operating the two. I think, however, that he does not emphasize strongly enough one feature of the capacity of electric locomotives, that is the capacity in *continuous service.*

Regardless of the type of motive power, the design of a locomotive is limited to a certain weight on each driving axle, the maximum being about 50,000 pounds; the coefficient of adhesion, as Mr. Armstrong states, in steam locomotive practice is taken at about 22 per cent. Each driving axle will then be able to deliver a tractive effort of 11,000 pounds, and a draw-bar-pull of, say, 9,000 pounds. A steam locomotive can exert this draw-bar pull continuously, up to a certain speed determined by the capacity of its boiler, which for the sake of illustration may be taken at eight miles per hour, so that in freight service each driving axle will give a continuous duty of 9,000 pounds. Owing to the limitations of space, no electric locomotive can be built to deliver continuously a draw-bar pull of 9,000 pounds per driving axle; probably 5,000 pounds is the maximum that can be obtained; that is to say, an electric locomotive cannot work *continuously* at a coefficient of adhesion greater than about 12 per cent. Therefore, for continuous service at low speeds a steam locomotive, for the same weight on drivers, can pull from 60 to 100 per cent. greater load than an electric locomotive.

The electric locomotive can, however, deliver this draw-bar pull at any speed that it is practicable to use, the limitation being fixed by the equipment and the track, and not by the locomotive. The draw-bar pull of the steam locomotive falls off from the critical speed of, say, eight miles per hour, as is well brought out by Mr. Armstrong in the paper, whereas an electric locomotive, designed for the purpose, will give its continuous drawbar pull at any practicable speed; hence, at a certain higher speed the two locomotives will pull equal loads continuously, at say about 16 miles per hour. At all higher speeds the electric locomotive will have the advantage.

The size of an electric motor is determined principally by the torque that it must exert and not by the speed at which it must exert this torque; hence a locomotive designed for 10 miles per hour and a draw-bar pull of say 5,000 pounds per axle, can, by changes in the windings, which will not change the size or weight of the motors, exert a draw-bar pull of 5,000 pounds at 40 miles per hour, or any other practicable speed. This is the great advantage of electric as compared with steam locomotives.

Another way of looking at the matter is that electric locomotives are designed for the *average* work to be done, steam locomotives for the *maximum* work, since an electric locomotive designed for the average work will under all conditions easily be able to handle the maximum work. The use of the electric locomotive then makes it unnecessary to consider the ruling grade as a limiting feature to the capacity of the locomotive, whereas it must always be the limiting feature to the capacity of a steam locomotive. An illustration may make this clearer.

The six-axle Mallet compound locomotive used by one of the railways will pull, on the mountain division, having a grade of 2.2 per cent., an average of about 800 tons at a speed of 8.5 miles per hour, delivering therefore about 1,200 horse power at the driving wheel. The locomotive weighs 250 tons with tender; the output is equal to 4.8 horse power per ton total weight. An electric locomotive weighing 100 tons, all on the drivers, will haul the same load up the same grade at 15 miles per hour and will develop approximately 1,800 horse power, equal to 18 horse power per ton. In other words, the power developed per ton on drivers in the electric locomotive is four times as great as in the steam locomotive.

Moreover, an electric locomotive could easily be designed to exert the same draw-bar pull at a speed of 20 to 25 miles per hour, and have no greater weight, than for 15 miles per hour. This Mallet locomotive will pull a load of only 530 tons up the grade at a speed of 15 miles per hour, using Mr. Armstrong's curves as a basis. The comparison on a basis of 15 miles per hour is then:

MALLET.	
Engine and tender	250 tons
Train	330 tons
Total	580 tons
ELECTRIC	
Engine	100 tons
Train	800 tons
Total	900 tons

or the useful load at this speed is 2.4 times as great. This is merely another way of saying that steam service is incapable of handling heavy loads at high speeds.

The great advantage of the electric locomotive is, therefore, in the much higher speed possible. There is no inherent reason why a freight train should run at a lower speed than a passenger train; they do run at lower speeds simply because locomotives can not be built to haul them at the higher speeds, but the electric locomotive will probably change this and the speed of the freight service will be increased very greatly.

Another point should be noted in the above comparison. The steam locomotive weighs 150 tons more than the electric locomotive; assuming a duty of 100 miles per day, there are 15,000 ton-miles daily dead haul, which at the rate of 2 mills per ton mile amounts to about $30 per day, or say $10,000 per year. This is a clear saving in favor of electric locomotives. It can also be viewed as permitting an increase of 150 tons in the possible train load, and from this point of view the net earnings of an electric locomotive would be greater than that of a steam locomotive by the 150 tons extra load.

Something has been said by Mr. Armstrong about three-phase locomotives. I have recently decided to use the three-phase locomotives for the Cascade Mountain grade of the Great

Northern Railway, and among the reasons leading to this decision was the fact that the locomotive would have a fixed speed and could not be operated at a greater speed on the down grade. This equipment is for the freight service of the road only, at a place where much trouble has been caused by trains running away on the down grades.

Another reason leading to this decision was the recuperation on the down grade; this is valuable, not so much in the saving of energy, for in this case the additional energy, being supplied from a water power plant, would cost nothing, as in lessening considerably the capacity of power house required for any particular service. Two tons going down the grade will pull one ton up the grade; it is therefore necessary only to supply power for the tonnage up grade in excess of the down grade tonnage; with a system of train dispatching having this in view, a material saving can be made.

W. S. Murray: Law or economy brings electrification of railroads. It is peculiarly interesting, too, to note how economy hugs up to law, if law has been the cause. After law has had its turn, then comes the turn of the engineer. Such conditions may be levied by the law as to make impossible the operation of a certain piece of railroad mileage as economically by electricity as by steam. It is the duty of the electrical engineer to choose such a system consistent with safety and the guarantee of continuity of service, which will increase to a minimum amount the original operating expense. When economy dictates the electrification, again it is the duty of the electrical engineer to elect a system consistent with safety and continuity of service, which will decrease to a maximum extent the original operating expense.

The closing sentence of Mr. Armstrong's paper is:

> The keynote of electrification is capacity; by approaching the problem from this standpoint only can full benefits be obtained.

I am in full agreement with Mr. Armstrong on this score, except I feel that while he has furnished the horse, there has been no mention of the carriage and what the carriage contains; in short, I should have said the keynote of electrification is "ton-miles", then capacity to handle it. The track capacity of a railroad is tremendously enhanced by electrification, but ton-miles must be on hand to make necessary the increased locomotive capacity.

I cannot escape a decided exception to Mr. Armstrong's reference, " Petty economies effected in coal consumption and cost of locomotive repairs". Examining the principal heads under operating expense, we find "maintenance of way and structures", "maintenance of equipment", "conducting transportation" and "general expenses". There is little choice in this list that electrification can detach upon which to practise its economies other than fuel and locomotive repairs. Of course the inference concerning the general increase of track capacity and operating facility, together with the fact that electrified lines offer more inducement for traffic in general, is not lost, but I cannot withhold figures that have come within my personal observation and keeping, which have a value keenly *important* rather than " petty " and, indeed, point directly to and are a demonstration of the keynote to electrification; namely, ton-miles.

In a previous contribution to the Institute's TRANSACTIONS in connection with the Stillwell-Putnam paper on the substitution of the electric motor for the steam locomotive, I presented figures that were worked out in a faithful effort by all concerned in it to secure what could be absolutely relied upon as the resistance of the main line of the New York, New Haven & Hartford Railroad Company between New Haven and Woodlawn. I shall briefly say in regard to this work, that after days of careful indication of steam locomotives on east- and west-bound runs with trains of varying weight for express and local-express service, the resistance for these several conditions was obtained, and the real relations between the ton-mile, the pounds of coal per ton-mile, and the horse-power-hours per ton-mile, were established in figures, upon which has been based the power house capacity necessary to operate the electric trains of the New Haven road. This effort was made to secure the actual service conditions rather than to depend on hypothetical resistance curves, the opinions on which are conspicuous for their wideness of variation.

Generating, transmission line, and railway equipment efficiencies are too well known not to be able, having determined the rim horse power required for propelling trains, to figure back to the power house the amount of the kilowatt capacity required to operate a predetermined schedule of trains. We cannot afford to quarrel with the machine efficiency of the steam locomotive. It is the equal of the machine efficiency of the electric motor morning, noon, and night. We shall take issue, however, on the efficiency which lies behind the two engines, viz: the generation of steam in the boiler of the locomotive versus its generation at the power station with its attendant transmission and conversion into electricity for application to the motors driving the locomotive.

The following table shows the saving of fuel which will be effected on the New York division when all freight and passenger trains, now operated by steam, receive their draw-bar pull by the electric method of traction.

	Ton-miles per annum	Tons of coal steam traction	Tons of coal electric traction	Cost of coal steam traction	Cost of coal electric traction	Saving of electric over steam traction
Express..............	592,240,000	57,447	29,870	$183,830	$89,620	$94,210
Local-express.........	348,000,000	58,300	28,600	186,560	85,800	100,760
Freight...............	2,223,000,000	187,844	139,010	563,530	417,030	146,500
	3,163,240,000					$341,470

In connection with the work done in the field to secure the data as compiled in the table just read, a diagrammatic tabulation of the observations considered pertinent to the test was made,

SHOWING {
Average cut-off variation
Boiler pressure variation
Water consumption
Indicated horse power
Grade profile.

Ten locomotives were included in this test, and eighteen days of consecutive observation of performance were utilized.

Briefly, this diagram indicates that in express work 2055 indicated horse-power-hours are developed in the evaporation of 57,594 pounds of water, giving an average, therefore, of 28 pounds of water per indicated horse-power-hour; and on local trains this figure is slightly increased, the evaporation being 42,987 pounds of water for 1435 horse-power-hours, making the rate, 30 pounds of water per indicated horse-power-hour. I mention these figures, as we are all familiar with the turbine guarantees of 20 pounds of water, including auxiliaries, per kilowatt-hour at the switchboard which, reduced to a horse power basis, would be 15 pounds of water as measured at the switchboard. Remembering the ratio of 7 to 10 in the evaporation of locomotive vs. stationary boilers per pound of coal, it is not a stretch of conscience to concede that twice the draw-bar pull can be developed by the electric method of traction for coal burned under the boilers of stationary plants vs. coal burned in the fire-boxes of locomotives.

In that contribution, I also submitted figures bearing on the cost of repairs and maintenance of 20 steam, freight, and passenger locomotives; these have been kept most carefully over a period of one year and show 8.1 cents per locomotive-mile for freight engines and 5.6 cents per locomotive-mile for passenger engines. The engine mileage of the New York division of the New Haven road amounts to about 4,836,992 miles. This mileage is divided for passenger and freight service into 2,993,328 and 1,843,664 miles, respectively. These figures were based on week ending October 25, 1907, and it is to be noted that it will, therefore, be below the average, on account of the summer months bringing the heaviest traffic. This means an operating cost of $316,962.00 per annum, for the maintenance and repairing of engines.

The average figures that I have been able to secure on electric engine repairs per locomotive-mile are about 2 cents. Increasing this figure 25 per cent. for safety and assuming the same number of electric engines replacing steam locomotives, (as a matter of fact there would be less electric engines required on account of the greater mileage per diem derived from electric locomotives) the total would be $120,924.00 per annum, showing a saving over steam locomotives of $196,038.00. Therefore, the net saving on fuel and locomotive repairs in favor of electrification gives a round sum of $562,470.00 per annum. This, upon a capital basis with money at 5 per cent represents $11,249,400.00, a rather effective credit on the expense necessary to invest.

Messrs. Stillwell and Putnam's exhaustive and comprehensive analysis of the statistics of railroads for 1904, compiled by the Interstate Commerce Commission, and proof sheets of the report of the Commission for the year 1905, give the undeniable records of railroads of this country; and the averages for over five years, as shown in the paper read by them before this Institute, show fairly and honestly, where and where not economies may be effected. Of the four principal headings of operating expense as mentioned before, two of them, viz.: "maintenance of way and structures" and "general expenses" may be equated. Of the remaining two, viz.: the "maintenance of equipment" and the "conducting of transportation," the first of these indicates that operation could be effected by electricity at an expense of about 63 per cent. of that of steam; and of the 37 per cent. saved, 75 per cent. of this is on account of the economies in the repairs of electric vs. steam locomotives. Our steam experience, to date, enables me to confirm these figures of Messrs. Stillwell and Putnam.

Concerning the second item, viz: the conducting of transportation, which is generally the largest item in the operating expense of any railroad, it is to be noted that the estimated cost of operation by electricity is 79 per cent. of that of steam; and it is safe to consider that of the 21 per cent. saved, 90 per cent. of this is on account of fuel and round-house expenses. These figures are confirmed by the practical investigation which I have been conducting in an effort to secure the relative operating costs of the New York Division by electricity vs. steam.

Mr. Armstrong's paper is full of a most interesting line of initiative, and is particularly attractive to me on account of the broad scope in which he has handled this subject. The matter of fuel and locomotive repairs, has been one of such interest to me that I must ask the indulgence of the Institute in having dwelt with such length on these two details, from a paper which has covered so much other ground.

I may say that I almost regret to see the disappearance of the steam locomotive from the electric zone of the New York, New Haven & Hartford Railroad, as contrasts in operation are never better seen than when they are almost inseparately attached to each other.

In closing, I would refer to two details in operation, which unquestionably increase the capacity of a given trackage for trains operated by electricity, viz: yard switching, and turning of engines at terminals. I believe it is safe to say that our experience, to date, has demonstrated that in the first instance double the amount can be accomplished in the same time; and in the latter, electric engines are ready to make their reverse train movement in 25 per cent. of the time required by steam locomotives, assuming that the water-tanks, ash-dumps and turntables, are within the yard limits of the terminal.

Wm. McClellan: We shall not be able to state positively what basis there is for electrification on the score of reduction in operating charges until we have a complete engine stage equipped electrically, with no steam locomotive shops, no steam repairs, no unnecessary buildings, but everything equipped to handle electrical equipment only, in the most economical manner. For this reason I think that the speaker of the evening has taken the proper view, when he bases his whole argument on capacity. He believes that heavy grades will prove the most fruitful field in which to start, and we must agree with him very heartily. It cannot be gainsaid that he has proved his case so far as this point is concerned in this paper. It should not be forgotten that all electrification to date has included a very great change in operating conditions and frequency of train service. As a result, electrification has been charged with many expenses which properly belong to amplification of the service and not to electrification proper. To get a just comparison in such cases it would be better to estimate what it would cost to give the increased service, both in quantity and quality, by steam locomotives, and compare this with the estimate required to do the same work by electric locomotives. In most cases I believe it would present the case for electrification in a much more favorable light than the way it is usually done.

I must also agree with the author that the electrification problem is not a substitution problem. It involves taking the traffic problem of the railroad and solving it along wholly different lines, from wholly different points of view. An electric locomotive is not something that is designed to replace a steam locomotive taken off rails. It has different capabilities,different possibilities, and these must be considered as influencing the whole traffic problem. The very greatest stress should be laid on this point in discussing the matter with our steam locomotive friends.

C. L. de Muralt: My belief is that, when one or two of the large railroads have been electrified, we shall find economies in operation to have slipped in, with or without intention. But the largest electrification work in the near future will likely be done for the reason that very much more traffic can be handled over existing tracks with electric locomotives than with steam locomotives. My office has recently had occasion to work out a problem where a road with something like eighty miles of double track was actually nearing the end of its ability to handle traffic with steam locomotives. The question came up of adding new tracks to increase its capacity. In this case, there would have been two additional tracks which would have cost something like $15,000,000. On the other hand, a complete electric equipment for the old tracks, comprising power stations, distributing system, and locomotives, will cost only about $3,000,000. The handling of the present amount of traffic by electricity will save in operating expenses something like $200,000 out of $800,000 and with the electric equipment pushed a little harder, there will be a chance to increase traffic forty to fifty per cent. over what the tracks will stand under steam. Here, therefore, is a case where electricity should be used and electric equipment installed just as soon as the $3,000,000 can be raised.

Mr. Armstrong has not only reaffirmed that increase in capacity is the keynote, he has also shown us what he understands by capacity and what we should all understand by that term. It is a pity that so many engineers, who have to draw comparisons between electric and steam locomotives, are not quite clear on this point, and that comparisons have been made which are really quite a little misleading. It is not so much the tractive effort or the draw-bar pull which a locomotive can give, but the speed at which that draw-bar pull can be developed, which is important. And that is what Mr. Armstrong so nicely points out, when he defines as capacity, not merely draw-bar pull, but the product of draw-bar pull times speed. From this viewpoint Dr. Hutchinson's statement will look different. If I understand him correctly, he believes that steam locomotives could give about 9000 lb. draw-bar pull per axle, while no electric locomotive could be built to do the same. Personally, I am absolutely convinced that electric locomotives can do better than that. But, even if an electric locomotive could give only 4000 or 5000 lb. draw-bar pull per axle, but can carry that 4000 or 5000 lb. up to three or four times the speed at which the steam locomotive can develop 9000 lb. draw-bar pull, cannot the electric locomotive handle more traffic? In other words, is not its actual capacity much larger than that of the steam locomotive? As an illustration I have in mind a high-speed steam locomotive of the New York Central Atlantic type, which weighs about 160 tons, and develops a tractive effort at 45 miles per hour of about 13,000 lb., while the New York Central continuous-current locomotive weighs about 95 tons, and will carry at the same speed of 45 miles an hour a tractive effort of about 14,000 lb. In the one case about 80 lb. per ton, and in the other about 150. A European type of three-phase electric locomotive weighs about 70 tons and will carry at 45 miles an hour about 23,000 lb. of tractive effort, which is a still better showing. In short, I believe the question raised by Mr. Armstrong, and the solution offered by him, both show clearly what we are likely to come to: those lines will probably first be electrified which, with steam as motive power, are now at the limit of their traffic capacity. Electricity will show that for a comparatively small expenditure of money we can increase the traffic of such lines considerably, and I think we may look to an early use of electric locomotives for such purposes. That type of electric locomotive will in the end prove to be the most useful, which in a given unit weight is able to concentrate the greatest amount of tractive power.

W. N. Smith: There is very little to add to what may be called the statistical feature of Mr. Armstrong's paper. He has had exceptional opportunity to go into such parts of the relative costs as are covered by the scope of his paper. But the problem is so complicated that the part of it which has here been covered in some detail does not cover the whole question. I agree fully with those who have remarked that the items which he has called petty or incidental are of considerable importance. They depend, of course, on the conditions of the particular road which the engineer may be called upon to investigate. A mountain road, or a road with a continuous long pull of 20 or 30 miles up-grade, is a different condition from a broken profile, or a level profile, such as the road from which Mr. Murray has given some figures. It is a very interesting proposition to consider the total resistance to be overcome in drawing a train over a line, and it is a relatively easy matter to consider it from that standpoint when the road is almost absolutely level; but when a large amount of drifting comes into play, with long down-grades, or with a broken profile, the problem becomes somewhat more complicated. It is very true that the whole question focuses upon capacity; but there are several different ways of looking at capacity, and one of the aspects that has not to my knowledge been given very much consideration in most of the communications on the subject, is the *capacity for train movement* of any given piece of single-track railroad. This is really a deep question. It is one that railroad operating men are daily in contact with, and it is to them that any question of capacity must appeal first. They are the men whom, first of all, you have to convince that you can increase the capacity of a piece of track, and while the possibilities of double track, as to increase, are considerable, the possibilities of single track are considerably less, particularly if the profile is undulating and operating conditions generally are difficult. It is quite conceivable that it would be found impracticable to get as many trains over a given piece of single track as would be required to make it a financial object to electrify that particular section. In such a case, of course, electrification would be reduced to an absurdity.

I mention this simply as a possibility. I have not had opportunity to examine a particular instance of this type carefully enough to define where it would begin to be an absurdity, but I know that such a consideration is apt to be present, and cannot be left out of the calculation. The operating man's standpoint is of the greatest importance, and it is one, I fear, to which many electrical engineers have not hitherto given sufficient consideration. The general trunk line electrification work of the future, however, must be considered from that standpoint.

I suppose that considerably more than 75 per cent. of the mileage of the railroads of the United States is single track, and the cost of increasing the capacity of these roads by double tracking them, in order to enable a much greater number of trains to be run over the road in both directions, would stagger the imagination if it were estimated. Electrification is in some respects a simpler proposition to estimate on, in so far as cost is concerned, but there is no use trying to figure out how to run more trains over a piece of road than the road will accommodate. The questions of block signaling, turn-outs, and train-dispatching must enter into the problem first of all.

The capacity of the steam locomotive has been mentioned as being in some instances greater than could possibly be obtained continuously from an electric locomotive, but it occurs to me that this will depend to some extent on the conditions under which the steam locomotive is to operate. We know that up-grades of 30 miles or longer actually exist where a steam locomotive working at full power has to stop for water on the way up; of course it can go right along again at its maximum capacity after it has filled its tender, but when it has worked up to the point where all its water is exhausted, the locomotive must stop to have the supply replenished; and to that extent there must be some qualification to statements regarding the uniformly high capacity of a steam locomotive.

The question of load-factor has not been touched upon in the discussion of the cost of power. I will not undertake to discuss it, except to state that it seems to me rather an important matter to consider in making an estimate of what the cost of power will be in predicting the economic performance of an electrified section. Of course it goes without saying if the section is congested the load-factor will be high, but if the trains are few it will not be high and the cost per kilowatt will run up.

The weight of the tender has been mentioned, and any one who will examine the general data of the heaviest steam locomotives now being turned out will perhaps be somewhat surprised at the enormous weight of the tender, a dead weight, which, though a part of the motive power, cannot produce any tractive effort.

It is probable that a comparison with the consolidation type of steam locomotive will show a greater economy for electric power than will a comparison with the Mallet type of locomotive, which is said to be very successful in mountain work.

The various items of cost, even those called " petty", which enter into locomotive operation and maintenance, whether steam or electrical, are so variable that differences of a comparatively small number of cents per locomotive mile in a few items may make a large difference in the showing that the final tabulation will produce, and may throw the balance one way or the other, and every possible item of expense must be taken into consideration in making a comparison that will pass as valid when presented to the practical railroad operating man.

Chas. P. Steinmetz: The leading conclusion of Mr. Armstrong's paper seems to be that the advantage resulting from electrification is to be found in the increased capacity; that is, the ability of the road with the same trackage to handle a greater amount of traffic. This, however, means that the change from steam power to electric power is not a mere substitution of the electric locomotive for the steam locomotive, but a readjustment of the ways of operation; that is, an increase of the speed of operation of freight service by taking advantage of the feature of the electric locomotive to be able to carry its draw-bar pull up to a higher speed. We usually find, when introducing a more advanced way of doing a thing, that we have not a mere substitution, but to get the greatest benefit from the change, the method of operation must be rearranged. Nearly a century ago when the stage coach was replaced by the steam engine, the first attempts to attach the steam engine to the stage coach and pull it over the country roads came to naught, and steam propulsion became successful only by putting the locomotive on the railway track. A characteristic of the steam locomotive is that it is essentially a constant power motor. It gives approximately the same power whether running at high or low speed. The draw-bar pull, therefore, does not tell the whole story, but the limit is the steaming capacity of the boiler, and the faster you move the oftener you fill the cylinders, and since you cannot for a long time exceed the ability of the boiler to produce steam, you have to cut off earlier, and so get less draw-bar pull. Not so in the electric motor; in this the limitation essentially consists in the constant loss of power. The limit of the electric locomotive is that it must lose only so much power in the motor, in the general average, as to be within safe heating limits. Since efficiency rapidly increases with the speed, it means you can get more power out of it at higher speeds, up to a certain limit, and therefore the electric locomotive is best at higher speeds than the steam locomotive, and we have to take advantage of this feature if we desire to show the best results. It, therefore, as you see, does not mean a mere substitution, but also means a readjustment especially of the most important part of the railway service, the freight traffic, for higher speed. Higher speeds necessarily mean increased capacity of the system, even without any increased draw-bar pull, even with less draw-bar pull, and in this feature I believe lies the main advantage of electric traction; but it makes it necessary to readjust the method of operation to the changed condition of railroad motive power, to get the best results of the electric locomotive. You may merely substitute, but you get better results by not merely substituting, but also by increasing the speed to operate at the most economical speed of the electric locomotive, and this in general is higher than the most economical speed of the steam locomotive.

A. H. Armstrong: In working up the comparison of the performance of the steam and electric locomotive I was impressed with the fact that the greatest benefit to be secured seemed to lie in the electrification of mountain-grade divisions. That is, the greatest necessity for electrification as well as the greatest return for the money invested are met with on heavy grades, and I am, therefore, very much pleased to find that the economy figures given by Mr. Wilgus as obtained in actual service on the New York Central check up in some degree the final results I have arrived at by calculation. Also that the calculated figures by Mr. Murray for another section of a level road, New York, New Haven & Hartford Railroad, indicate a comfortable return upon the capital required for electrifying the New York division of that road. With these figures for level operation it would seem as if my general conclusions for the electric operation of mountain-grade divisions were very conservatively arrived at.

In regard to the remarks of Dr. Hutchinson, that a total draw-bar pull or tractive effort of 9000 pounds could not be continuously sustained by an electric locomotive, I have only to point out two or three facts of operation which may perhaps have been overlooked by him in making the statement. With 50,000 pounds per axle and a tractive effort of 20 per cent., which is conservative for average conditons of track, 10,000 pounds of tractive effort is available. In practice, however, it is not possible to work any locomotive at this tractive effort continuously irrespective of its type of motive power, owing to the broken character of all profiles, as even on mountain-grade sections crossing a continental divide the grades are not uniform, but the average grade is seldom more than 60 per cent. of the maximum or ruling grade. For example, the greatest extent of continuous grade in this country is on the Sacramento Division of the Southern Pacific system, which has a 1.54 per cent. average grade for 83 miles with a ruling grade of 2.2 per cent. In other words, during the rise of 7000 feet in 83 miles the average grade is 70 per cent. of the ruling grade. A locomotive operating over this division will be called upon to sustain, say, 60 per cent. of its maximum tractive effort, thus leaving a margin of 10 per cent. over the demands of the ruling grade in order to start up the train on maximum load and grade conditions. Under these conditions the electric locomotive would not in any way suffer in comparison with the steam locomotive, as the heating of the motive power would not in any way prohibit the delivery of 6000 pounds per axle at any speed that may be safe in operation. Furthermore, it is necessary to take into account the very serious delays occurring on single-track roads where the traffic may be heavy; so that all operating conditions considered, I see no reason why it should not be possible to keep the temperature rise of the electric motive power well within safe limits in practice.

In choosing the word "petty" I seem to have been particularly fortunate in irritating Mr. Murray into giving some very valuable data pertaining to tests made by him on the

New York, New Haven & Hartford tracks with steam locomotives. Mr. Murray's figures are going to prove very interesting reading when we have a chance to go into them in detail at greater leisure, but I am surprised to see that such a low steam consumption (28 to 30 pounds per i.h.p. hour) was arrived at in actual tests. This steam consumption could be looked for by indicator, but it seems rather low if it includes all the stand-by losses of the locomotive not in actual operation.

In dealing with steam locomotive statistics I have found it necessary to divide the determination of coal and water consumption into two parts. First, that required for the actual hauling of the train; secondly, that lost while coasting or standing still. For instance, I show in the paper that on a certain road there are some 400 pounds of coal and 4000 pounds of steam used per hour while locomotives are idle at terminals, turn-outs, or coasting down grades, while the performance of this simple consolidation engine when actually hauling a train corresponded to a steam consumption of 28 to 30 pounds per boiler horse-power-hour with an evaporation of approximately six pounds of water per pound of coal. The Mallet Compound requires more coal than this chargeable to stand-by losses, and further requires the admission of steam in order to coast down grade at a speed much higher than 10 or 12 miles an hour. All of these losses in steam locomotive operation amount up to a grand total that in many cases will show a considerable excess cost over the cost of electric power for hauling the same tonnage with electric locomotives. Hence my feeling that the figures submitted by Mr. Murray are somewhat low for the total coal and water consumption of the locomotive for twenty-four hours in regular service.

I must adhere to my position taken in the paper that economy of operation as regards coal consumption does not constitute any sufficient cause for electrification in the great majority of cases, and I think we cannot bring out this fact too strongly. It is not sufficient to show the management of steam roads that they can get a return of 10 per cent. or even 20 per cent. upon $10,000,000 or more required for electrification, as they are not looking for investments of this character. Careful consideration, however, will be given to any report showing means of increasing gross receipts or that will offer a reliable substitute for the double tracking that may be necessary to provide for a rapidly increasing tonnage. I must adhere, therefore, to the idea that the main reason for electrification of roads other than terminals, tunnels, etc., is embodied in the increased capacity of the electric locomotive, providing increased tonnage capacity of the tracks, decreased running time, etc.—all of which guarantee an increase in gross receipts and a possible saving in expenditure for additional tracks, reducing ruling grade, etc. That this electrification will be accompanied with a gratifying reduction in operating expenses is a still further argument for replacing the steam locomotive, but it is not of sufficient importance in itself in the majority of cases, to encourage electrification.

I note the doubt expressed by Mr. Smith as to the saving effected in the electrification of single track roads, and would state that it is on just such roads as these where the greatest saving can be effected both in cost of electrification and in operating expense. A large volume of traffic is carried over a single-track road under the greatest difficulty and at considerable expense. This applies especially to trains hauled by steam locomotives which are capable of only six or seven miles per hour schedule speed up severe grades, and add considerably to the number of signal stops by reason of their limited radius of action with their coal and water supply. For instance, a steam locomotive working at an average of 75 per cent. of its full boiler capacity on a mountain grade cannot cover more than 15 to 20 miles without taking on more water, in this respect very much resembling the electric automobile forced to return frequently to its charging station for the material for a fresh start. It is entirely safe to say, therefore, that the total tonnage capacity of a single track will be very much increased with the adoption of the electric locomotive, and the cost of such electrification in some cases may be considerably less than the capital required to double track or duplicate the single track already installed. In other words, where a mountain-grade division has reached the maximum tonnage capacity possible with single track, and it becomes a question of double tracking with steam locomotives, a careful analysis of the conditions may show that electrification of the present single track may be accomplished with a lesser expenditure and be followed with a greater return upon the money invested.

I agree with Dr. Steinmetz in the views expressed by him and would draw the attention of the members to the entire revolution in methods of handling short-haul passenger traffic by the introduction of the electric motor. I believe also that the introduction of the electric locomotive will bring about fundamental changes in the method of handling freight traffic by reason of the many inherent advantages enjoyed by the electric locomotive and not shared by its steam competitor.

W. S. Murray (by letter): In answer to Mr. Armstrong's question as to whether the coal measurement was made for the full 24-hour day, including the hours during which the engine was not doing revenue work, such as time spent in the round-house, over ash-pits, cleaning fires, etc., I would say that this was the case; the idea not being simply to get the rate of coal per horse-power-hour while the engine was making its revenue runs, but to secure the real commercial rate or day consumption, which governs the bill the railroad company pays.

A paper presented at a meeting of the Ithaca Section of the American Institute of Electrical Engineers, Ithaca, N. Y., Dec. 6, 1907.

PRACTICAL ASPECTS OF STEAM RAILROAD ELECTRIFICATION

BY W. N. SMITH

In view of the extended treatment which has already been accorded to this subject on the floor of the Institute, and elsewhere by distinguished engineers during recent years, it is difficult and in fact hardly necessary to add anything to the electrotechnical side of the subject. So many are the electrical schemes proposed for the accomplishment of the various ends that it now seems desirable to examine the subject from standpoints other than electrical, in order to facilitate intelligent consideration of the problem as a whole.

The trend of some of the papers that have recently been presented, and the discussions that have accompanied them, convey the impression that electric railway engineers are ready to apply any one of several well developed systems of electrical propulsion to any railroad, and attempt to make it pay. Although much has been published, most of it is of so general a nature that it is only partly convincing; and while it doubtless stirs up professional enthusiasm and tends to keep up active emulation in devising attractive schemes and systems, the railroad man with a particular problem to solve is almost as much in the dark as ever as to the practical value of the new motive power for his particular conditions.

Although at first sight there would seem to be as many different types of problem as there are railroads to be electrified, the writer believes that some general classification is possible; and while it might be further specialized by paying especial attention to topographical and transportation features, which may be distinctly peculiar to each individual case, the writer thinks that railroads in general could be classified as follows:

1. Suburban lines or sections.
2. Tunnel and terminal sections.
3. Heavy trunk lines with low grades, dense traffic, and more than two tracks.
4. Double-track trunk lines with grades under one per cent.
5. Single-track trunk lines with grades under one per cent.
6. Mountain railroads with single or double track, with long grades steeper than one per cent.
7. Single-track branch lines or feeders.

It would seem that a large proportion of the railroad mileage of the country could be included in some one of the above classes, and there are individual railroad companies which have mileage under all of them.

The question of density of traffic is often brought up in discussions of steam railroad electrification, and it is generally admitted that the problem deals with the economic effect of increasing the train movement; but the physical features involved in the study of train movement are so difficult to define in general terms, and the number of concrete cases is so infinitely great, that very little information has been gathered or classified that will enable general rules to be made for determining where, so far as train movements are concerned, it becomes economical to abandon steam in favor of electric motive power. It seems to the writer that this very complicated subject must be approached by degrees, and upon the basis of concrete illustration drawn from examples of conditions as classified under the above suggested headings. Such a treatment of the problem in general would make it more attractive to those charged with the practical management of railroads—the men to whom general curve sheets, which appeal to theoretical electrical considerations, are apt to be meaningless unless accompanied by voluminous explanation. As generalities, solutions by curve sheets are usually of very limited application.

The fact has recently been emphasized that hitherto steam railroad electrification has been carried out only in very special problems, coming mostly under the headings: (1) Suburban, (2) Terminal, and (3) Heavy trunk lines, in the above classification, but only for relatively short sections. Considerable attention is now being given to problems of the class under (6) Mountain-grade division, and one such project is actually under way in this country.

The electrification of a portion of the Erie Railroad Company's Rochester Division, could properly be classed as that of a feeder or branch line under (7), but even that, as at present constituted, is only a partial electrification, as only passenger traffic of the suburban or interurban type is handled electrically at the present time, steam power still being used for through passenger and for all freight service. The West Jersey and Sea Shore electrification should also be put in this class, though an enormous summer excursion business is its principal justification.

Furthermore, the writer believes that in discussing a problem of such tremendous proportions, the matter of the particular electric system to be employed should not necessarily be placed foremost, but that practical railroad operating conditions must be regarded as of paramount importance. It is, of course, impossible to cover the whole field in a paper as short as this is intended to be, but it is certainly in order to get a larger perspective upon the activities of the railroad as a whole, rather than to keep our attention focused upon the purely electrical part of it.

The fields of activity concerned in the electrification of a steam road may be subdivided into two broad divisions.

1. The electrification project, as it calls for the services of the manufacturer and the engineer.

2. Railroad operation, which in this connection may be considered as threefold:

a. Financial or economic,

b. Railroad construction or standardization, and

c. Transportation or operative.

Reviewing these divisions, the electric railway industry occupies a peculiar position as compared with the general trade in railway appliances.

A practical monopoly of electric propulsion apparatus is divided among a very few large companies. This is somewhat similar to the general situation as regards steel rails, and steam locomotives, both of which commodities are produced by a relatively small number of manufacturers. Until recently the steel-rail situation was kept very close to a uniform standard in quality of product, as well as in price, but there having been a strong protest by the railroads against the defects that have been developed in quality, this feature is now undergoing revision by the steel companies. With respect to locomotives, however, more liberty of action is preserved by the railroad companies. The requirements of the motive-power departments of different railroads are so diverse as to afford little opportunity for wholesale standardization, which is a matter that is left entirely in the hands of the railroad customers rather than with the manufacturers. There are certain tendencies toward standardization on a large scale, such as that made possible by the associated Southern Pacific, Union Pacific, and allied lines east and west of the Mississippi, for the sake of securing economy in maintenance and operation; but such attempts as have been made toward standardization on the part of the locomotive manufacturers seem to have pertained more to certain interchangeable parts of the locomotives, than to types which have usually been developed by the needs of individual roads. With electrical motive power apparatus, however, the art is relatively much newer, and the number of trained specialists is fewer, and mostly concentrated at the manufacturers' shops so that the opportunity afforded the manufacturers to inspire and direct the formation of their customers' ideas on electric propulsion has not been neglected. It has had a great effect upon the development of the industry.

This does not mean that the manufacturing engineers' judgment may not be excellent concerning questions pertaining solely to the design of the apparatus intended to meet particular conditions. It can hardly be expected, however, that manufacturing engineers can always look upon their apparatus in any other light than that of a special commercial product, the responsibility for whose performance comes home to themselves in particular, they are therefore prone to consider the various conditions of construction and operation from the standpoint of the effect of railroad conditions upon their apparatus as more important than the sum total of effects of the apparatus upon the railroad problem as a whole.

In general, standardization of any railroad equipment on the part of manufacturers is more usual in commodities which the railroad companies cannot or do not ordinarily manufacture themselves in their own shops. Railroad companies have been compelled to leave to steel mills the work of making the rails, but they have frequently made a practice of building locomotives in their own shops. Their necessary repair-shop facilities place them in a position to furnish for their own locomotives and cars whatever equipment a locomotive manufacturer or car builder may decline to furnish. It is quite possible that some years hence railroads will devise their own systems, and build their own electric motors and locomotives. There is even now a tendency in this direction by the large trolley railway companies who make many of their own electrical repair parts. The Standardization Committee of the American Street and Interurban Railway Association has made an excellent beginning along the same general lines as have been followed in years past by the Master Mechanics' and Master Car Builders' Associations of the steam railroads; and in the course of time it will undoubtedly come to pass that advances in standardization will emanate not so much from manufacturers' engineers as from the railroad companies' own electrical engineers, who will be held directly responsible for the results.

By the time that twenty or thirty roads have electrified their lines, wholly or in part, the attitude of their operating and maintenance engineering forces may become an important factor in the situation; and the commercial rivalry now shown in devising and perpetuating electric systems will then be diverted from its present tendencies, toward the more natural function of competing to furnish apparatus as specified by the railroads.

The consulting engineer's standpoint at the present time is that of an interpreter between the manufacturer and the railroad. He has to translate the limitations of the electrical apparatus in terms easily understood by railroad officials, who generally do not pretend to be electrical experts; and he must be sufficiently familiar with railroad standards and practice to insist that the electrical manufacturer shows due regard for the general fitness of his apparatus to railroad purposes, both in design and reliability. He is frequently charged with a very grave responsibility in aiding the railroads to decide some very fundamental and perplexing question arising from the relationship between the old art and the new. Although he may write new and complete specifications for all the parts of manufactured apparatus involved, he is generally not called upon to design it in detail, as that function is still practically monopolized by the manufacturing companies, though subject in some degree to the consulting engineer's control. He has not only to act as mediator between the railroads and the manufacturing companies, but he must also secure coöperation between the various departments of the railroad itself which are intimately concerned with the work he is doing; that is to say, the construction, maintenance, mechanical, and transportation departments—all of which, in many instances, have to be consulted with reference to a single detail. The pioneer engineering work of steam railroad electrification up to the present time, has largely been done on the initiative and with the aid of consulting engineers, whose usefulness to the railroad in the above described capacities has been very notably demonstrated.

The standpoint of the railroad management as above suggested comes under three general heads; the financial or economic, the constructive and maintenance, and transportation.

The control of a railroad being in the hands of those who represent the investors, the financial aspect of any improvement is the first to receive consideration. The financier looks upon the problem of railroad motive power as only one of a large number to be solved from the standpoint of the maximum possible return for every dollar invested, whether it be for the purpose of reducing the cost of conducting the existing business, or of largely increasing that business. A project for the electrification of a railroad is usually attractive, because of the increased amount of traffic it becomes possible to handle in proportion to the expense of handling it. This is usually directly accomplished by increasing the speed of revenue train-movement over a given piece of track, and by reducing the amount of non-revenue train-movement.

Such questions are, of course, most pressing where conditions of traffic congestion are most severe; and for that reason most of the heavy railroad electrification has hitherto been worked out in and near New York City, where the maximum movement of passenger trains is required in the minimum amount of area available for terminal facilities. The electrification, first of the Baltimore & Ohio tunnel, then the Long Island Railroad, the New York Central Railroad, the New Haven Railroad, and the Pennsylvania Railroad's New York terminal now under construction, was called into being, first of all by public necessity, and secondly by the desire of each railroad company to place itself in a position where it could handle at its terminal the maximum traffic that its lines and territory could develop, steam motive power having for one reason or another reached its limit. These installations are distinctly special in character and can hardly be taken as representative of the general railroad electrification problem, although the general principle of increasing net earnings by increasing capacity is of universal application. In much of the work referred to about New York City, the prospect of immediate returns upon the investment had to be considered as of secondary importance. But in proportion to the total mileage of the country which may ultimately prove fit for electrification, territory of such a character is relatively small in extent. Tunnels and terminals like those mentioned have been electrified simply because of the physical impossibility of meeting the business and public necessities in any other way.

The more general cases, however, are not likely to be regarded by the financier in quite the same light, although it is believed that they can be more convincingly solved on their financial merits alone than is possible in the case of expensive metropolitan terminals. Each case that is brought up for solution must, through careful detailed estimates, justify itself on its own merits, as affording facilities for making transportation more profitable.

When the railroad man is looking at a transportation problem from the constructive and maintenance standpoint, he has in mind the crystallized experience of some 70 years of steam railroad practice that has resulted in the development of railroad equipment along certain lines, which, generally speaking, are rather conservatively maintained. It may be well to recall the fact that the steam locomotive of the present day is in its essentials practically the same machine that was developed by George Stephenson; that is, it comprises a horizontal multitubular boiler with a fire-box at the rear and smoke-stack at the front, and the wheels are propelled by a direct-coupled, high-pressure engine, which increases the rate of combustion of the fuel by discharging its exhaust into the smoke-stack. Similarly, the passenger car has been developed from the old omnibus. A departure from some previously recognized form is often found good, but there is nevertheless considerable resistance to change. In justice to steam railroad men, however, perhaps it should be said that opposition to new forms is not likely to be so great because of radical difference in themselves, as because of the great cost of keeping on hand a line of repair parts entirely different from those which their present historic equipment obliges them to carry in stock. This, of course, pertains more especially to rolling stock and track material. Most railroads have worked up a line of standard parts of equipment, and the Master Mechanics' and Car Builders' Associations have coöperated extensively to promote the use of these standards upon all the railroads, and there will naturally be considerable opposition to any disturbance of such standards. Although the electrical equipment will necessitate, for its own maintenance, the addition of a considerable quantity of repair stock, it should not without good reason be permitted to change any previously existing standard that it is desirable to keep. On the other hand, there may be some very fundamental reasons for changing existing standards in order better to accommodate certain electrical features. An instance of this upon a certain railroad was the adoption of a new shape of splice-bar, specially rolled, to accommodate a heavy rail-bond underneath it, upon a section where some new track was to be laid; while the objection of another railroad to increasing the diameter of a motor-car wheel on account of the additional size of tire that would have to be carried in stock eventually resulted in the retention of an electric motor originally adopted for a lighter car. At first the motor had been thought too small for the increased duty which was to be imposed upon it, but was found to be adequate when fitted with suitable means for increasing its capacity, thus satisfying the desire of the railroad for the maintaining of standards in its equipment and at lower cost.

The question of clearances has often been most perplexing, particularly as regards the location of either third-rail or overhead trolley construction. The stationary features pertaining to the right of way, and the dimensions of moving equipment. must not be allowed to interfere with each other. The third-rail sometimes conflicts with bridge-gussets on the one hand, or with hopper-bottom coal-cars on the other. The use of third-rail also makes more necessary the elimination of highway grade-crossings, and requires careful attention to the protection of the public at station platforms. Low overhead bridges conflict seriously with trolley construction, particularly when high voltage is desired.

High-tension trolley construction introduces, among other problems, the purely mechanical one of providing suitable warning signs or ticklers for trainmen on the tops of freight cars; these must not only be light enough not to injure brakemen, nor damage the trolley mechanism on moving equipment, but must also be heavy enough to withstand the blows they receive from the trolley without being broken or rendered useless.

Either type of construction may require special and often expensive arrangements at drawbridges. The civil authorities in cities sometimes arbitrarily insist upon placing high-tension lines underground, which is always expensive. Telegraph and telephone lines have to be protected from mechanical and electrical interference. These are a few of the characteristic problems that arise with each electrification scheme, but solutions of them do not appear on the mathematical curve sheets with which professional papers are sometimes illustrated.

Looking again at cars and locomotives, the steam railroad man will commonly take his standard coach as the point of departure, and suggest at the outset that it be equipped electrically practically as it stands. Here it is entirely in order to remark that the main object of electrification is to facilitate traffic. The car bodies themselves should be built with that end in view, in order to get the full benefit of the superior type of power. The object to be attained affects the dimensions of the vestibules, doors, and seats, as well as the length of the car, and even the form of roof of the car may be altered from standard types without detriment to passengers, if external conditions make it desirable. Suburban service is the type of service that admits of the greatest modifications in this respect; and that car is likely to be the most popular with the patrons of the road which is so built as to enable freer ingress and egress of passengers, a matter which should not be lost sight of where there is competition between different lines to be taken into account. It is no little tax upon the engineer's ingenuity to get the best results in a new development, and still conform to the general lines of conventional car designs, some features of which have been based upon rules and practices primarily imposed for the greater safety of the traveling public.

Coming now to locomotive design, perhaps the most fundamental advantage which an electric locomotive has over its steam predecessor is greater mechanical simplicity, particularly as regards translation of the tractive effort from the motor to the wheel-rim. The absence of reciprocating parts is advantageous to a high-speed electric locomotive for passenger service, because of the lessened vibration of the locomotive itself, and the greater diminished wear and tear on the track. In the case of a slow-speed electric freight locomotive, the uniformity of tractive effort in hauling heavy train loads is a very desirable feature, particularly at starting. The tendency towards simplification and elimination of reciprocating parts has caused the concentration of great weight at a less height above the rail than is usual for a steam locomotive of equivalent power; and this lowering of the center of gravity is not without its effect in running conditions at high speed, particularly upon a curved track. Steam locomotive men regard a high center of gravity as advantageous rather than detrimental, because its longer leverage from the top of the rail, which is the fulcrum, eases the side-thrust against the rails, due to whatever centrifugal force or lateral vibration there may be. So confident are steam engineers that this is a cardinal point of superiority that they express a desire to see electric locomotives so built that the essential difference between a steam and electric locomotive will consist in the replacement of the boiler upon the locomotive frame by an electric motor, in order to keep the center of gravity at something like its present height. If electric locomotive designers in this country keep as clear of the use of side-rods in the future as they have in the past, there does not seem to be much chance for increasing the distance of the center of gravity from the track to the height it frequently reaches with a steam locomotive; but in Europe some of the latest and most successful electric locomotive designs show a tendency to set the motors above the driving wheels, two motors being used to drive three axles through side-rods. The mechanical excellence of workmanship of these locomotives has been attested by some of the foremost electrical engineers of this country who have seen them. Whether or not the tendency of this design will persist, will depend upon how applicable this method of coupling proves to be to the loads and speeds met with in this country.

The latest developments in American locomotive practice as exemplified by machines actually in commerical operation or under test show three types: first, that of which the driving-wheel base is rigid, as in the case of the New York Central and the St. Clair tunnel locomotive units, the former having pony wheels, the latter none; secondly, the articulated or bogie-truck type, with two large driving trucks pivoted to the locomotive body, each truck carrying a large motor on each axle; and a third type, now being tested by the Pennsylvania Railroad, which is built upon a locomotive frame of standard type, borne at the rear upon the outside journals of two large driving axles, each carrying a 500-h.p. motor, the forward end of the frame being carried upon a four-wheeled bogie truck generally similar to that commonly used with the American or Atlantic type of steam locomotive. This particular sample is designed primarily for single-phase traction, and a transformer is carried over the bogie truck but not at a relatively great height above the rails. The superstructure of each of these locomotives is a steel-plate cab or enclosure housing the engineman and the control apparatus, but in no way approaching the weight of the boiler mounted upon the frame of the steam locomotive. The third type above described has appealed to steam locomotive men as conforming more nearly to their preconceived ideas of locomotive construction, but it remains to be seen whether American designers will work out any method that will result in further lifting the center of gravity along the lines followed by the latest European practice.

Railroad electrification invariably raises questions of safety to the traveling public. Both the third-rail and the trolley are frequently described in the daily press as " deadly ". The fact that on a third-rail system a bad short-circuit can take place without blowing the station circuit-breakers, which have to be set for heavy overloads, sometimes results in serious blockades. When the damage is done it is usually expensive, and takes time to repair. In the case of a high-tension trolley system only a small leak is sufficient to cause a short-circuit, and the amount of actual damage done thereby is trifling. Such troubles as may be developed by short-circuits are generally not of long duration; whatever wires or cables are burned in two are burned quickly, and clear themselves promptly. With a high-tension system there is no possibility of confusion between an overload and a short-circuit.

Another feature of the question of safety involved is the dependence of a large number of electrical transportation units upon one power station as opposed, in the case of steam transportation, to an equivalent number of entirely independent units. It is perfectly possible for a disabled electric train to ground or short-circuit the line in its own vicinity in a manner that will prevent other trains from approaching. This is not the case with steam locomotive trains, as the terrible record of steam train collisions bears witness. Generally speaking, the combination of electric propulsion with the block-signal system for protecting trains has not been developed, though in the early days of the art the matter was occasionally brought forward as additional argument in behalf of electrification. The paramount desire to keep all traffic in motion has militated against the idea of permitting the disabled train or line-section to hamper in any way the movement of other trains on other sections. It is evident that there are possibilities along this line, particularly in the case of high-tension systems, that can justly receive further consideration, because with the smaller currents flowing in high-tension systems, control of them at a distance is relatively easier than in the case of the heavier currents in low-tension systems.

We now come to a phase of the question which in the writer's opinion is probably the most complicated and least understood of all; namely, the standpoint of the railroad operator or transportation superintendent, and his organization, upon whom the railroad depends for maintaining its earning power. It hardly need be said that the transportation man has it in his power either to make or mar the earning capacity of a railroad, and no matter what facilities for increasing transportation capacity are furnished by the management, the duty of making them pay dividends devolves upon the operating department. The business of a railroad being primarily transportation, and transportation being the special function of the operating department, we here come in contact with the highly trained specialist, upon whom falls the burden of getting the traffic over the road whether it be level or hilly, straight or crooked, single or double track.

It is conceded by all, that the great thing to be desired in a railroad of given proportions is capacity for train-movement. The capacity of a double-track road is stated to be in general, about four times that of a single-track road, general conditions as to grade and location being equal; but as more than seventy-per cent. of the railroad mileage of the country is single track, the most universal problem of increasing track capacity by electrification will apply to single-track rather than to double-track lines. This, of course, excepts terminal and suburban conditions, but includes the majority of mountain railroad conditions where double-tracking is sometimes a physical impossibility.

On the greater proportion of single-track railroad mileage, trains are handled by the telegraphic train-order system under the control of train dispatchers. On some railroads, however, block-signal systems are installed to facilitate the movement of trains, as much time is thereby saved by each train in getting the right to pass from one block to the next. According to a report by the Interstate Commerce Commission, published about March 1, 1907, the total number of miles of railroad lines which had any block-signal system at all was 143,615, of which 48,743 miles was actually equipped and operated by some form of block-signal system. Of this 48,743 miles, 6,826 were operated by the automatic system and 41,916 by one of the several forms of non-automatic system. Of the mileage controlled by the automatic system, 2,032, or somewhat under one-third, was single track. Of the lines controlled by non-automatic signals, 33,585 miles were single-track lines, making a total of 35,617 miles of single-track railroad in the United States controlled by some form of block signal. The total mileage of single-track lines in the United States is estimated at about 200,000, so that about 17.5 per cent of the total single-track mileage is controlled by block signals at the present time. Inasmuch as the operation and maintenance of a block-signal system is undoubtedly cheaper per mile of road than the total annual cost that would be incurred by electrifying, it would appear that the first step in increasing the capacity of a road is to establish a suitable block-signal system. Thus from a practical standpoint the mileage of track where electrification could profitably be considered under present conditions would be greaty reduced; but when the increased capacity created in any instance by a block system has been fully utilized, a further increase is still possible by the use of electric motive power.

Engineers familiar with the interurban trolley development of the past ten years are aware that most lines of this type dispatch their trains very largely by the telephone system. Generally speaking this method works very well, though on the more highly developed systems it is combined with some of the features that have been standardized by the rules of the American Railway Association, and adopted by practically all the steam railroads. It must be remembered, however, that conditions on trolley roads are somewhat different from those on steam roads. The vast majority of the trains are light passenger trains of one car each, stops are of shorter duration, and the speed of all trains is more nearly uniform. The distance between turnouts is less. The penalty of a wreck due to misunderstanding or miscarriage of orders is, generally speaking, much less with the average interurban trolley road than with the average steam railroad; and trolley railroad operators are correspondingly more willing to run the risks incidental to dispensing with the system of transmission of train orders, which experience has shown to be necessary on steam railroads. The meeting points are generally much nearer together, and a block system of any kind would cost relatively more to maintain and operate in proportion to the business done than is the case with steam railroads. At least there seems to be some such motive preventing the universal adoption of signal systems by trolley roads. In any event, it is not at all convincing to a steam railroad man to point out to him the apparent ease with which trains at frequent headway in opposite directions are handled with single-track trolley roads, as a reason why the same course should be adopted by steam railroads in order to increase the rapidity of train movements. Although it is undoubtedly true that the telephone is used extensively as an adjunct to standard methods of dispatching steam-railroad trains, railroad managers generally do not seem disposed to supersede the method developed by the use of the telegraph, except in the relatively small amount of mileage protected by automatic block signals.

Whether the telegraphic train-order system or one of the other systems of block signals be used, the rules governing the operation of trains on steam railroads are very rigid. The telegraphic train orders, emanating from the train dispatchers' office, must be signed by the recipient and the signature telegraphed back to the dispatcher, who then replies " complete " to the various operators to whom he has sent the message as fast as their replies come in. An order restricting the rights of a superior train is more rigidly safeguarded in this respect than an order increasing the rights of an inferior train; and a superior train must receive and reply to its orders before any can be given to the inferior train. Much time may be and often is thus consumed, which may restrict considerably the capacity of a line to handle traffic. Another rigid type of rule is that requiring an inferior train to clear the time of a superior train at a meeting or passing point by not less than five minutes. This holds whether a train-order system or a block-signal system be used. This five minutes' clearance is frequently, for special reasons, increased to ten minutes and often to twenty minutes, thus placing the inferior trains at a still greater disadvantage. Instances of this kind occur when some especially fast express train is operated, where, to insure the greatest possible degree of safety, twenty minutes clearance is provided. The fastest high-speed " flyers " of the present day are thus protected, to the greater safety of the passengers, but to the disadvantage of freight trains. Two such flyers, one in each direction over a road per day, will thus cut down the current of slower traffic over the whole road to the extent of at least forty minutes per day, and frequently more. If an inferior train cannot make an intended siding in time to allow for the required clearance it is obliged to wait on a nearer siding and lose the time required for the superior train to cover the distance between the two sidings, plus any extra time which the superior train may have been delayed. One such delay is more than likely to lead to another, and so the delays pile up into hours during the run intended to be made in ten or twelve hours. If traffic is dense, and sidings far apart, such delays become very serious, and besides the delay to freight, and disappointment and inconvenience to shippers and per diem charges on cars, there is added the overtime due to the employes, which increases the operating expenses. It seems to the writer that conditions of this character are not taken into sufficient account as having a bearing on the subject of electrification for increase of track capacity; and something more than the ability to accelerate rapidly and maintain higher speeds must be given consideration in estimating the increase in the net schedule speed of train movement that at first sight may seem directly to result from the substitution of electricity for steam.

One item peculiar to steam operation which causes delays is the stopping for water. The frequency for such stops will depend both upon the weight of the train, and the grade of the road. Stopping for water sometimes adds to the delays from other causes that have previously held up a train; but for any particular problem the effects of stops for water should be considered separately from stops for other purposes. Where combined with a stop for some other purpose, no marked gain is effected by eliminating the necessity for taking water, unless perhaps three or four engines were to take water in succession.

A case was recently cited of a single-track road in a mountainous country where double tracking would be a very expensive proposition, this road having a heavy traffic in both directions, loaded ore cars coming down and empties going up. It was found in operation that the easiest way to get the traffic over the road was to make every siding a meeting point, that is to say, the road was practically full of trains. The only way of increasing traffic on such a line other than by double-tracking would be to increase the speed of all trains in the same proportion. This might seem feasible enough by electric motive power, but then arises the question whether the increase in speed that could be thus obtained would be sufficient to enable an increase in the daily traffic that would pay a dividend on the total cost of electrification. This would be an excellent instance of a concrete case in which other things than motive power costs alone, of steam and electricity, would have to be considered. In a case of this kind, the capacity of a single-track road would be limited by the speed of the slowest train.

The task of working out the results in such a case is necessarily complicated and would require nothing less than a close study of all the conditions on the ground. The fact that it is impossible to generalize upon the capacity of single-track roads for train movement, renders it equally impossible to generalize upon the applicability of electric motive power thereto in comparison with steam. It is necessary to pick out a concrete case and estimate all the features in detail, just as it is in order to properly gauge the economic value of any other engineering enterprise. It is obviously unscientific to advocate wholesale electrification as a means of increasing capacity, when the capacity can be increased more cheaply, as it sometimes can, by the introduction of a block-signal system, or when the capacity of a piece of road even when equipped with a block-signal system, could not be increased in practical operation to a point that would enable enough more ton-miles per day to be run off at a lower cost per ton-mile, to show a saving in total annual cost.

The writer is a firm believer in the value of electric motive power as a means of increasing a railroad's earning capacity, but begs to suggest that in the future more professional papers be devoted toward giving concrete illustrations in a manner that will carry some conviction to the minds of the progressive and highly trained specialists in transportation, who are doubtless willing to be convinced if the subject can be dealt with in a manner that appeals to their practical experience in the operation of trains.

A paper presented at the 223rd Meeting of the American Institute of Electrical Engineers, New York, December 13, 1907.

THE RATIO OF HEATING SURFACE TO GRATE SURFACE AS A FACTOR IN POWER PLANT DESIGN

BY WALTER S. FINLAY, JR.

Power plant design, in its modern development, is controlled solely by the specific application of general laws modified and moulded to suit special requirements. To attempt the construction of a comprehensive ruling from the results of a particular line of investigation in some particular plant, and then to advise the general use of such ruling as conducive to economical operation, would cause confusion, possibly resulting in a wholesale rejection of the good with the bad. However, the value of specific results and their publication lie in the opening up of a line of technical thought, or in adding information to some subject, from which specific deductions or particular application may be made.

The results obtained in the investigation, which was primarily the foundation of this paper, should be looked upon merely as specific, but whose bearing upon the general subject by means of a general development, may be of value, particularly in certain new phases of plant design.

As a fundamental and almost initial point of attack in the comprehensive subject of steam power-plant design, the ratio,

$$\frac{\text{heating surface}}{\text{grate surface}}$$

has been a value fixed from the beginning of results of commercial usage, and the expression of the same in empyrical formulas or figures suited to the requirements of this or that designer, builder, or manufacturer.

A summation of practice from early engineering times to values developed by the most modern idea, gives a great range to this ratio; namely, from the extreme value as advised by Dalton in 1839 of ten to one, to modern values up to seventy to one used, not only in locomotive, but even in power-plant practice. Of course the primary object in view has been the adaptation of values to produce the maximum useful effect. but the question now arises as to whether or not " maximum useful effect " is not being interpreted as maximum economical efficiency with reference to fuel only, as a primary consideration, and with an undue subordination of total plant costs. By total plant costs are meant, of course, the combined fixed charges resulting from interest on plant investment, depreciation, taxes, etc., and operation and maintenance charges.

Properly to investigate the subject in its particular applications would require an extremely tedious and complicated study of innumerable individual requirements; but for a general survey assumptions based upon commonly accepted values will suffice to direct the attention to the point involved.

Assuming a plant first cost of $125.00 per kilowatt; the equipment, including turbo-generators, boilers equipped with stokers, with, say, sixty to one ratio, the following relative costs may be assumed:

Total cost per kilowatt	$125.00	100 %
Building " "	43.75	35 %
Boilers " "	6.875	5.5 %
Grates " "	1.75	1.4 %
Piping " "	5.625	4.5 %
Coal-handling apparatus per kilowatt	2.30	1.84%
Balance of equipment	64.70	

The value of the building as assumed might be considered low, particularly in the case of a turbine plant; the boiler cost is, possibly, average; grates high—a stoker valuation; the piping value is about average.

Assuming as a fair value for determining fixed charges: interest on investment, 5%; depreciation, 6%; taxes and insurance, 1%, then the total fixed-charge rate would equal 12%.

Upon bases of load-factor and charges, a curve has been drawn showing the relative value of the fixed charges over a range of factor variation from approximately 3% to 100%, in the case of the plant as assumed. (Curve A, Fig. 1.)

To determine total charges, the variation of maintenance and operation charges, relative to load-factor, must also be considered. It is rather difficult to assume this curve, as conditions in this respect vary rather widely. However, Curve C, Fig. 1, has been drawn through points located by comparative results obtained in actual cases of operation. The shape of the curve will practically be constant for any figure which may be assumed, and its relation to the general results will be such that the value of the principle involved will be unaffected.

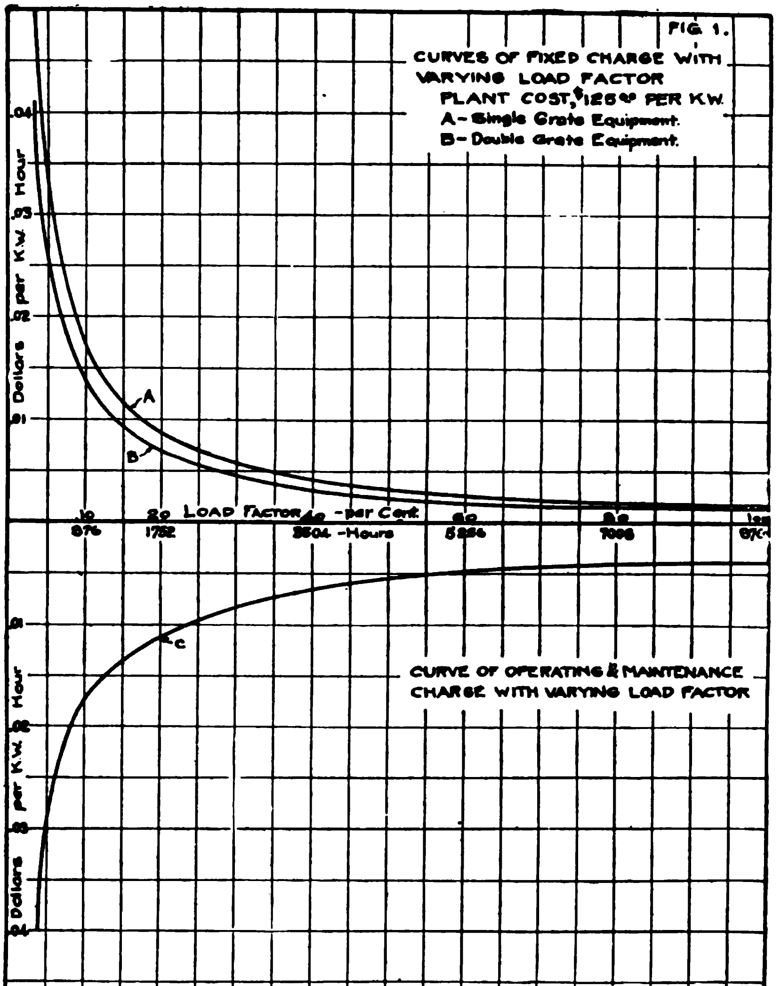


FIG. 1

The sum of the ordinates between the two curves gives total charges per kilowatt-hour.

In a reconsideration of the plant design as affecting first cost, the natural method of procedure is to consider separately each item involved.

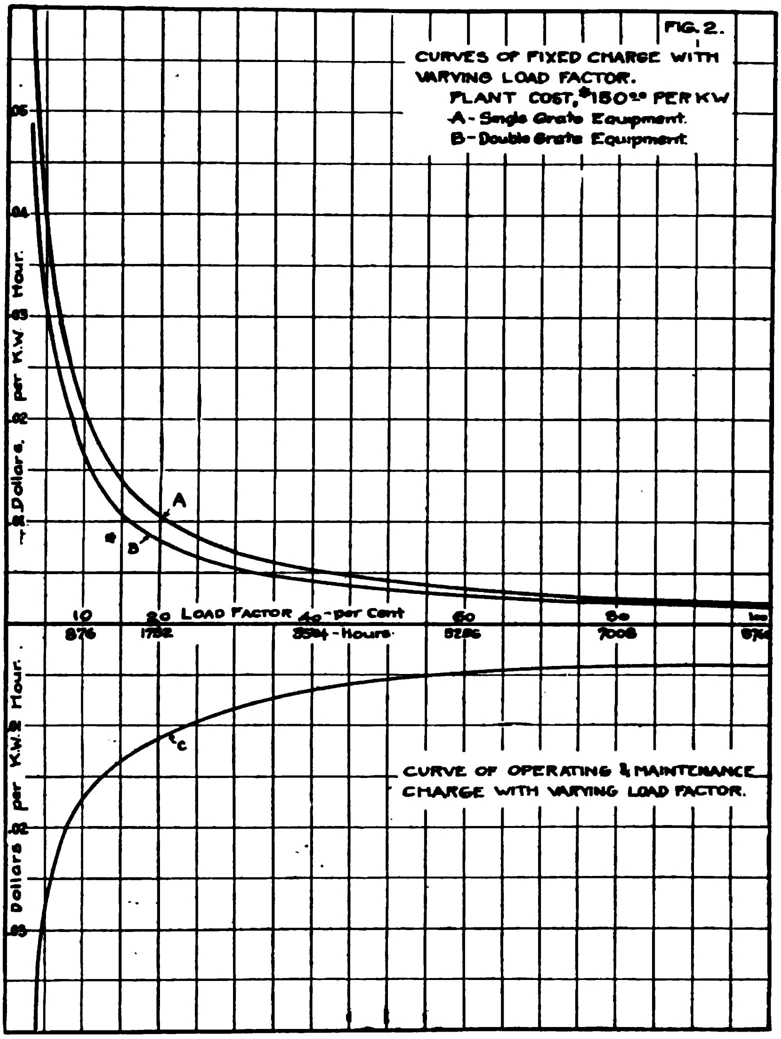


Fig. 2

1. *Building*. In turbo-generator plant design, it is a generally accepted rule that total plant dimensions are controlled by boiler-room dimensions; that, for instance, a diminution in

the actual size of the boiler room may be accompanied by a proportional diminution in the size of the turbine-room, the output remaining the same. The methods of accomplishing such results are perhaps various, change in size of units, difference in type, closer grouping of units, etc.

2. *Boilers.* The consideration of this feature is naturally interlinked with the subject of "*Grates*" and the two would better be discussed together.

Rules of boiler-practice have been derived chiefly, if not entirely, by experiment and investigation; and only those rules validated by general acceptance can be quoted as bases for argument. Such a law is the following one:

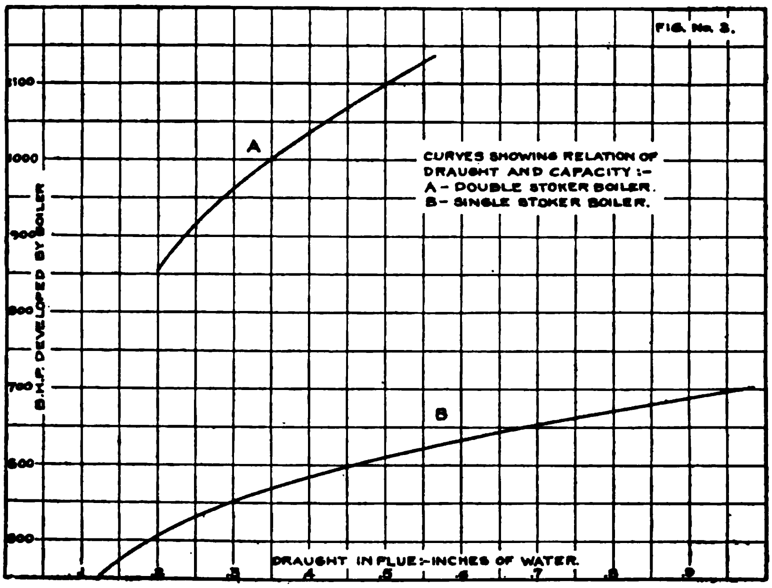


FIG. 3

All other conditions remaining constant, capacity developed is, with slight modifications, in direct ratio to the area of the active grate surface. An increase in capacity—heating surface remaining constant—caused by an increase in grate area, is accompanied by a loss in economical evaporation, due to the increased temperature of the escaping gases.

This loss in economy is the fundamental factor which must necessarily be the object of a careful study, involving the complete investigation of the heat interchanges taking place in a boiler. The research work of such men as Newton, Péclet, Joule, and Rankine, together with recent investigation, has not, as yet, produced sufficiently definite and authoritative results, which may be used as bases of rational calculation in this regard. Under normal conditions of present boiler-practice, estimates of loss vary from practically zero to as much as 15% fuel economy for an increase of 100% in boiler capacity.

Lately, however, the opinion has been advanced that considerable increase in capacity can, without great sacrifice in economy, be obtained by proportional increase in grate area. This idea is based upon the possibility that combustion and

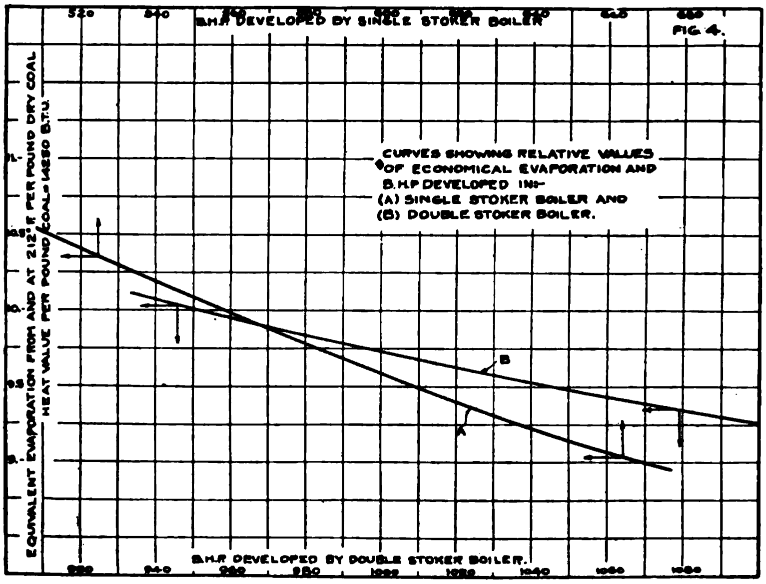


FIG. 4

heat distribution and transfer could be much improved under the new conditions, when in increasing the grate area careful attention is given to details of design most conducive to these features. Other conditions being favorable, and with a belief in the correctness of this theory, a change was made in the design of eighteen of the boiler furnaces in the Fifty-ninth street plant of the Interborough Rapid Transit Company. See Fig. 7. Such a design gave the possibility of operating within the range of the original single-stoker boiler together with the higher range of the double stoker.

The second stoker installed; that is, the one beneath the mud-drum as shown in Fig. 7, has an area of 80% of that of the original stoker. Certain features in the construction of the plant prevented installation of a larger size. A detailed description of points in the design are unnecessary, save to call attention to the fact that the lower stoker is constructed practically within a so-called " Dutch oven " and whatever is conducive to good combustion is provided for therein. The curve shown on Fig. 8 is given as corroborating this fact. Operation of these stokers has shown that such is practically done with but little more complication than existed in the single type.

Tests to determine the comparative economical operation of the double and single stokers show results as given graphically in Figs. 3, 4, 5, and 6. The curves in Figs. 3 and 4 are self-explanatory. Fig. 5 shows a curve plotted upon the values as determined by curves in Fig. 4, this curve being indicative of the fact that operation with the double type was as economical in fuel values, as the single type increased in boiler capacity approximately seventy-one per cent. In the curves in Fig. 6 is shown the fact that the economical loss for an increase in rating of 80%, as proportioned to the increase in grate area, varied between two and three per cent.

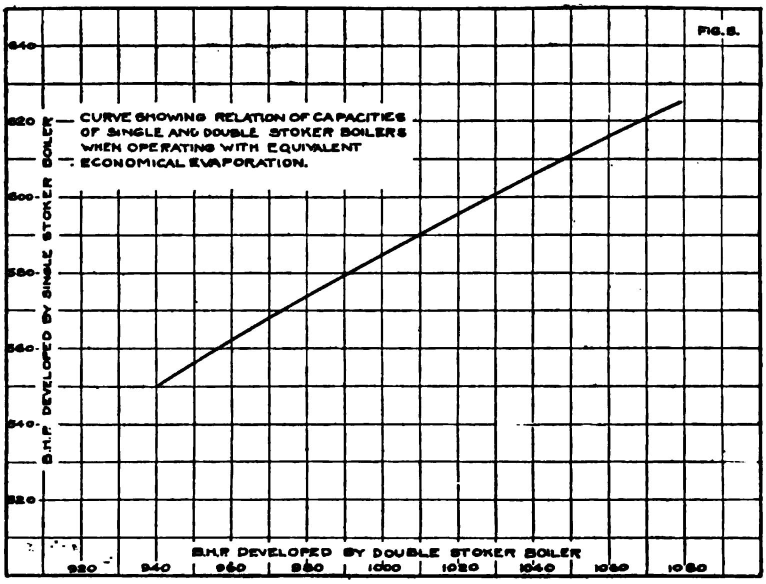


FIG. 5

To summarize the results of these tests: it has been made evident that in this particular case double-stoker operation covers the entire range of single-stoker operation and adds an increase of capacity proportionate to its larger grate surface with but slight loss in economy, and that the increase of 71% in capacity is accomplished with no loss in economy.

With these results as a basis, let it be assumed that boiler capacity is increased in ratio to increase in grate surface with but little loss of economy. This view might be further strengthened when consideration is taken of the possibilities of economizer practice, the increase in saving, by proper design, being high in ratio to extra cost involved.

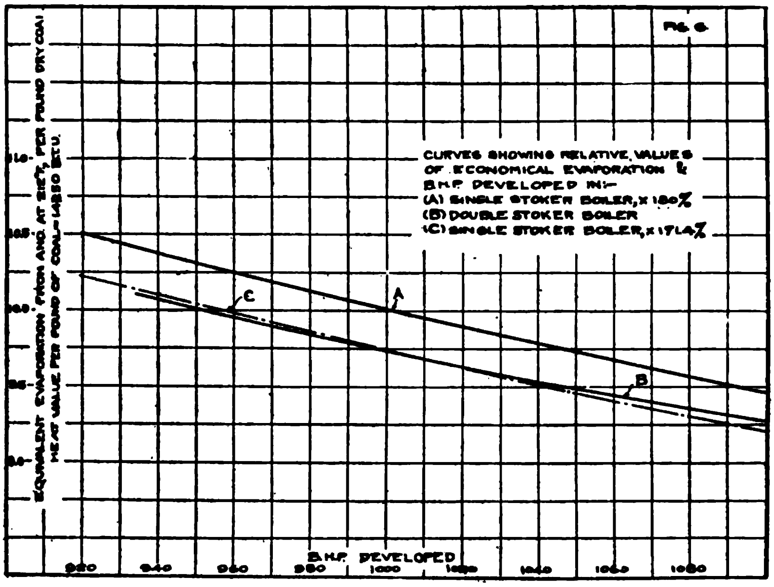


FIG. 6

To return to the consideration of the items under the power plant whose first cost has been assumed to be $125.00 per kilowatt, the next point is:

Piping. In the case involved, the cost of steam piping between boilers and manifolds, plus boiler-feed piping, plus boiler blow-down piping, has alone been considered. With any change in number of boilers, capacity remaining the same, the cost of piping will vary in the same ratio times a factor due to change in size of pipe.

Coal-handling apparatus. Fixed plant capacity would seem to demand fixed cost of coal-handling apparatus, but the pro-

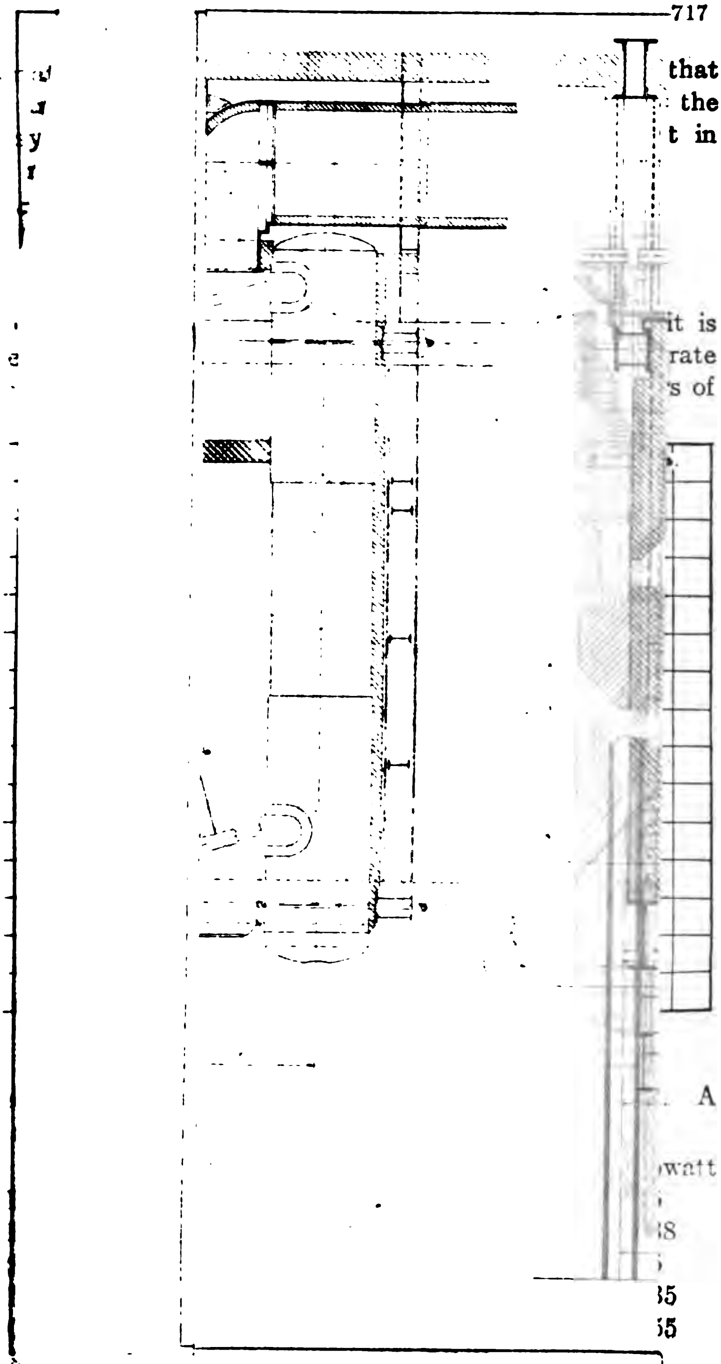


Fig. 7

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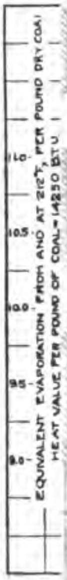

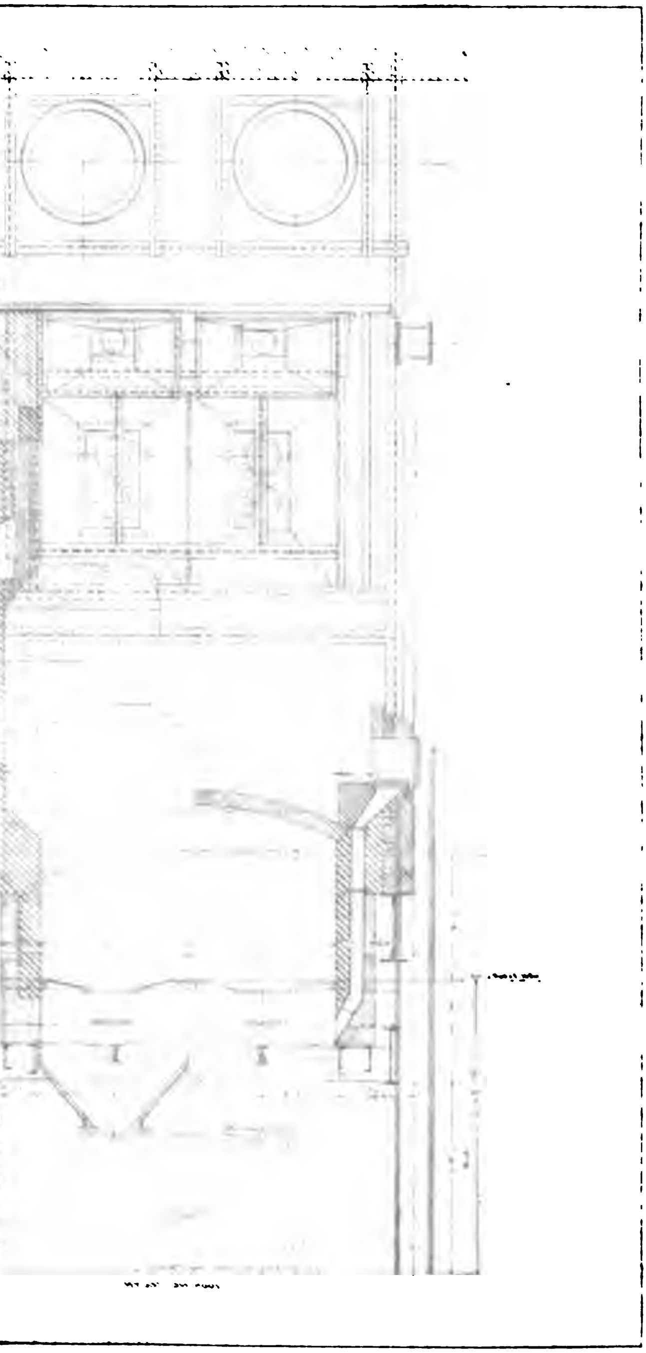

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portionate value of the conveying apparatus is so large that when any change is made affecting the length of carry the total system cost will be raised or lowered, although not in direct ratio to such change.

Effect of change of ratio:

$$\frac{\text{heating surface}}{\text{grate surface}}$$

Suppose that in a reconsideration of the plant design, it is decided to cut in half the ratio of heating surface to grate surface by the use of double grates or stokers under boilers of the same rating. Plant output is to remain the same. A tabulation of the costs as revised would be as follows:

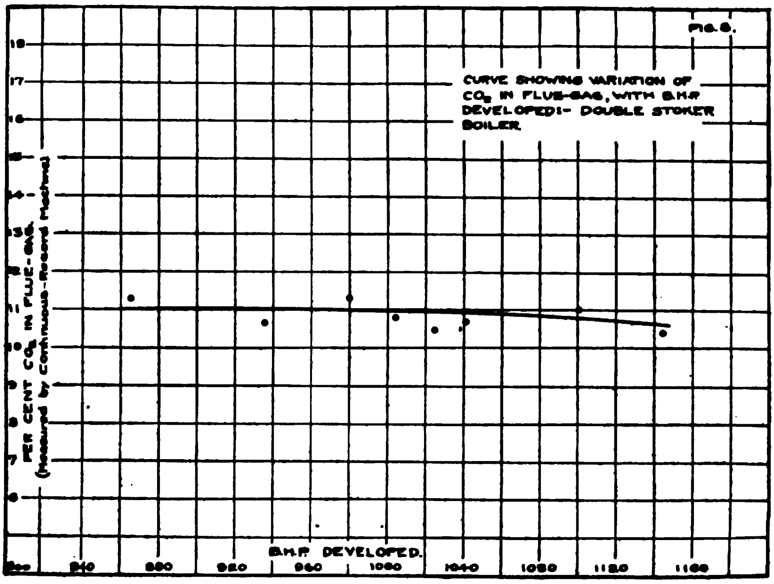

FIG. 8

	Per kilowatt
Building (reduced 40%)	$26.25
Boilers (reduced 50%)	3.438
Stokers (remain same)	1.75
Piping (reduced 40%)	3.735
Coal-handling apparatus (reduced 15%)	1.955
Balance (remains same)	64.70
	$101.828

A curve (B Fig, 1) is plotted upon this new basis.

Summation: Plant first cost and fixed charges, each reduced 19.6%.

The next consideration is that of the effect of such changes upon plant maintenance and operation charges. Properly to discuss this, the following tabulation based upon the figures given by Mr. H. G. Stott in his paper on " Power Plant Economics " will furnish a means of comparison:

Maintenance:	Single grate	Double grate
Engine room mechanical	0.64%	0.64%
Boiler room	5.40 - (16%) =	4.54
Coal- and ash-handling apparatus	0.68	0.68
Electrical apparatus	1.41	1.41
Operation.		
Coal- and ash-handling labor	2.65	2.65
Removal of ashes	1.18	1.18
Dock rental	0.93	0.93
Boiler-room labor	8.38 - (18.5%) =	6.83
Boiler-room oil, waste, etc	0.21	0.21
Coal	71.94 + (3%) =	74.10
Water	0.90	0.90
Engine-room mechanical labor	1.70	1.70
Lubrication	0.44	0.44
Waste, etc	0.38	0.38
Electrical labor	3.16	3.16
Total	100.00%	99.75%

The saving in boiler room maintenance and operation may be accounted for in the following itemized statement of boiler-room charges:

Maintenance.	Cost	
	Single grate	Double grate
Boilers	29.5%	14.75%
Economizers	2.78	2.78
Furnaces	17.29	17.29
Stokers and stoker engines	40.68	40.68
Boiler feed-pumps	5.42	5.42
Boiler feed-piping	2.20	1.10
Boiler blow-off piping	0.44	0.44
Water supply piping	1.52	1.52
Total	100.00%	83.98%
Operation.		
Water-tenders	20.82	10.41
Stoker operators	38.09	38.09
Assistant stoker operators	15.49	15.49
Stoker oilers	2.54	2.54

Economizer oilers and cleaners	5.84	2.92
Boiler feed-pump men	5.08	5.08
Boiler cleaners	10.41	5.21
Miscellaneous labor	1.73	1.73
Total	100.00%	81.47%

Thus with changes as noted, the decrease in maintenance and operation would be 0.25%, the curve for same practically coinciding with Curve C, Fig. 1.

A second set of curves based upon a plant cost of $150.00 per kilowatt is shown in Fig. 2.

Plant cost per kilowatt	$150.00	100%
Building	60.00	40
Boilers	8.25	5.5
Stokers	2.25	1.5
Piping	6.75	4.5
Coal-handling apparatus	2.63	1.75
Balance	70.12	

Same plant double stoker.

Building	(reduced 40%)	$36.00
Boilers	(reduced 50%)	4.13
Stokers	(remain same)	2.25
Piping	(reduced 40%)	4.05
Coal-handling apparatus	(reduced 15%)	2.24
Balance		70.12
Total		118.79

showing a reduction in first cost and fixed charges of 20.8%.

Summary. In the case of the $125.00 plant, the following savings might be effected by use of double grate:

First cost, 19.6% saving.

Total plant charges varying from a saving of 5.64% at 100% load-factor to 7.54% at 50% factor and to 9.65% at 4.16% factor (365 hours per year).

In the case of the $150.00 plant,

First cost, 20.8% saving.

Total plant charges vary from about 7.06% saving at 100% load-factor, to 9.26% at 50% factor to 11.51 at 4.16% factor.

Thus summarized, the remarkable effect that the grate area and heating surface ratio, when furnace design is carefully considered, may have upon plant first cost and total annual costs, should certainly place this particular feature well up in the list of subjects for careful investigation, and make it a point of primary and fundamental consideration in advanced design.

DISCUSSION ON "THE RATIO OF HEATING SURFACE TO GRATE SURFACE AS A FACTOR IN POWER PLANT DESIGN", AT NEW YORK. DECEMBER 13, 1907.

Chas. E. Lucke: Comparing the two curves of Fig. 4 it would appear that for an equivalent evaporation of 9.25 lb. of water per pound of coal, the ratio of boiler horse powers with double and single stokers is as 1100 is to 638 or about 1.72; with 9.5 equivalent evaporation the ratio is as 1046 is to 609. or about 1.72, with an equivalent evaporation of 9.75 the ratio is as 996 is to 582, or about 1.71. It thus appears that when operating this boiler at capacities 1.71 times as great with double stoker as for single, the equivalent evaporation, and, therefore, the boiler efficiency, is in nowise altered. At the same time referring to the curve for single-stoker operation there is reported for 512 h.p. an evaporation of 10.50 lb., which fell to 9 lb. on an increase of boiler horse-power to 670. In this case, therefore, an increase of boiler horse-power from 510 to 670, a ratio of capacities of 1.31, the efficiency or equivalent evaporation decreased in the ratio of 10.5 to 9; or the efficiency for the higher capacity is to the efficiency for the lower capacity as 9 is to 10.5, or, approximately, 0.86. An increase of boiler capacity in a given boiler is to be obtained by burning more coal primarily. From the preceding it would appear that burning more coal under this boiler with a single stoker gave a continuous drop in efficiency; also from the other curve an increase in the burning of coal on two stokers gave a decrease in efficiency continuously, but strangely enough, a very material increase in the coal burned per hour operating double versus single, sufficiently great to increase capacity to 1.7 its original value, gave no decrease in boiler efficiency. Why is it that with a single stoker an increase of capacity from 1 to 1.3 lowers the efficiency from 1 to 0.8, while increase of capacity from single to double stokers from 1 to 1.7 does not decrease the efficiency at all.

With increase of coal burned under the single stoker, the curve falls continuously and then breaks, starting again at a high point at the beginning of the double-stoker line, along which it again falls. It would seem as if these two curves should join and be continuous, and the fact that they do not, warrants an investigation into the causes. All of the general discussions of boiler efficiency seem to concentrate the conditions for efficiency, and with some degree of reason, on two prime variables; one entering into the structure, the other the operation. The first is the ratio of heating surface to grate surface, and the other is the rate of combustion per square foot of grate surface. With a view to determining how far the ratio of heat surface of itself, independent of other things, might effect boiler efficiency, one of the students at Columbia examined some 300 boiler tests that seemed most authentic and plotted, as in Fig. 1, boiler efficiency against the ratio of heating surface to grate surface.

From these data, it appears that the boiler efficiency lies between 45.4 per cent. and 84 per cent., while the ratio of heating surface to grate surface lies between 14 and 89. The disposition of the points is such as to prevent any conclusion in the form of curves or law of relation, as they do not group themselves in any definite way, but are deposited over what has often been called "a shot-gun diagram", and not a very good one at that. It would thus appear that the ratio of heating surface to grate surface cannot of itself fix boiler efficiency, however much it may seem to be rationally related to it.

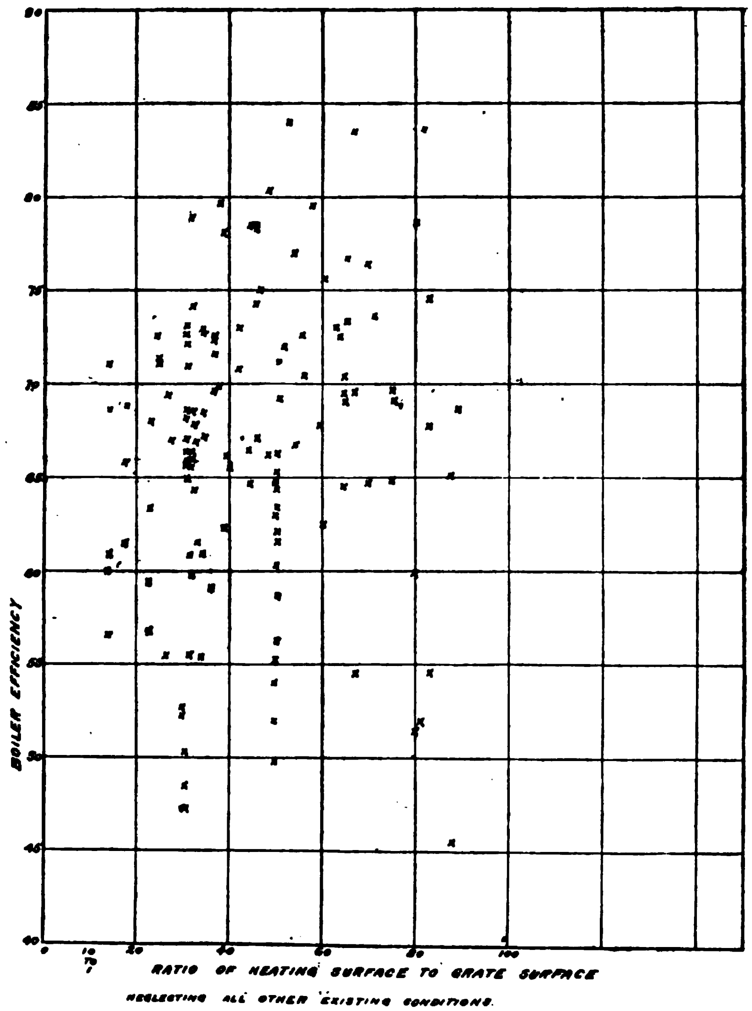

FIG. 1.

The phenomena taking place in a boiler are really quite simple. Any question of boiler efficiency resolves itself into an examination of these phenomena in an attempt to trace the losses. Neglecting all insignificant losses and assuming all coal to be burned, a boiler has an efficiency of less than 100 per cent. because some of the heat is liberated in the fire escapes; first, by radiation in an amount depending chiefly on the mean temperatures of the setting and boiler room; secondly, in the flue gases in an amount depending on their excess of temperature over the atmosphere, their weight and specific heat. To all intents and purposes the mean temperature of the boiler setting of these tests, single and double, may be taken as the same, as may the specific heat of the gases, so that any changes in boiler efficiency that occurred must be charged, assuming all the coal to have been burned, which is reasonable, to a change in the product of excess flue temperature over atmosphere and the weight of gases discharged per pound of coal.

With a given rate of heat liberation in the furnace, it is absolutely certain that the temperature of the gases passing through the boiler will continuously fall as they travel toward the flue. Thus, there might be plotted a falling curve of temperature with the path of these gases through the boiler. A very material increase in rate of heat liberation without change in the weight of air per pound of coal would have the effect of displacing this falling curve completely toward the flue end, or in other words, of raising the temperature at every point in the path and likewise raising the temperature at the flue, so that flue temperature would continuously rise with an increase in rate of combustion, perhaps slowly at first, and faster with the higher rate; boiler efficiency will thus continuously fall with increase in rate of heat liberation or weight of coal burned per hour without any increase of excess air, by reason of this rise in the flue temperature. Admission of more excess air with the higher rates might keep the temperature from rising, but still involve decrease of efficiency. An increased rate of heat liberation or pounds of coal per hour burned may be accomplished by an increase of the draft to raise the rate of combustion per square foot of grate per hour or by increase of surface without increase, perhaps with decrease, of draft. If by reason of a certain stoker construction or by reason of the manipulation of any given stoker, the air supply increases faster than the coal burned per hour, so will also the excess air and the weight of total gases per pound of coal. There is thus a possibility that with increase in rate of combustion per square foot of grate surface there may be also an increase in weight of gases per pound of coal by an increase of excess air, which would tend to decrease the boiler efficiency.

An examination of the results of this test does not indicate from the curve for either the single or the double stoker which factor was more potent in decreasing boiler efficiency with increase of coal burned per hour—the flue-gas temperature or the excess weight of gases, but comparing the double-stoker curve with the single and finding thereby that the same boiler efficiency corresponds to the same rate of combustion

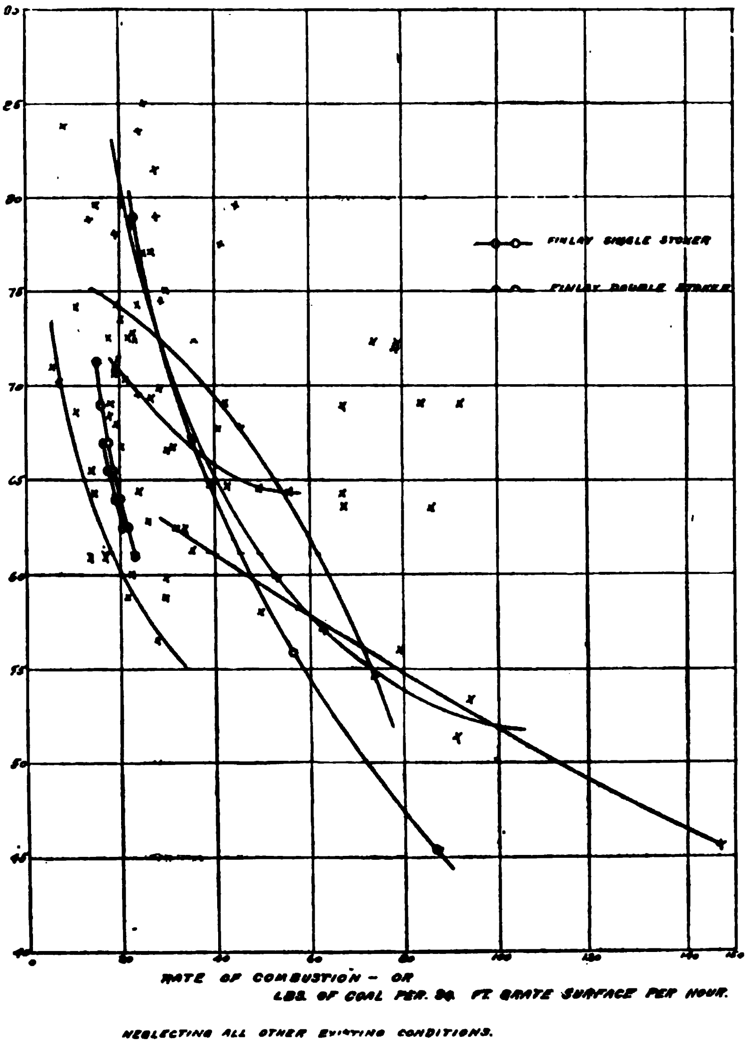

FIG. 2.

per square foot of grate, it would seem that the excess-air factor was more potent than the flue-gas temperature factor. It is inconceivable to me that increasing the coal burned per hour from 2370 for the single stoker to 4100 for the double stoker, or

1.74 times as much, which corresponds to 9.25 evaporation for both cases, there should have been no change in the boiler efficiency if the weight of gas per pound of coal was the same in both cases, especially as with the higher rate the time of contact between gas and boiler tubes is very much less than for the lower rate. The flue temperature for the double-stoker operation must have been higher for the same excess air, and the fact that the efficiency was not any lower seems to indicate that the excess air was less in proportion or that in single-stoker operation, very much more excess air was used than for double-stoker operation. While I believe that two boiler efficiency curves should not be compared except on equal terms, which in this case would be on a basis of equal flue-gas composition, still such a course might be justified if, under the conditions of usual operation, the furnace were such that it could not be operated with the same excess air under different ratings, which would be a most severe criticism of the furnace and not of the boiler. If this is the true explanation, the paper would become a discussion of furnace operation as a function of draft and rate of combustion. The true explanation must depend on the presentation of data on flue-gas composition and flue temperatures.

If on analysis of the efficiency results it should appear that they are due to a comparison of two boiler tests on unequal terms of flue-gas composition, and that for equal flue-gas composition the efficiencies for double-stoker operation are lower than for single at equal capacities, then the conclusions on cost economy might be reversed. For example, if higher flue temperatures result from high capacity of operation, then more economizer surface must be used to attain equivalent plant efficiencies, and discussions of plant cost economies must resolve into a comparison of the commercial value of heating surface in the form of boiler with that of heating surface in the form of economizer.

W F. Wells: The ratio of heating surface to grate surface, although a question of primary importance, is to my mind a matter of secondary consideration. In order to design the most suitable boiler plant for a power house that can be constructed at a minimum cost per kilowatt installed, consideration should first be given to the evaporation possible per square foot of heating surface consistent with commercial economy; and this in turn depends upon the maximum practical rate of combustion of the various fuels available in the local market, their relative costs per ton, cost of handling, and thermal values.

Mr. Finlay's statement that "a considerable increase in boiler capacity can, without great sacrifices in economy, be obtained by proportional increase in grate area" is applicable to most power plants, because until very recently, power house engineers have endeavored to obtain the greatest economies possible from boilers by proportionally increasing the heating surface, so that the average boiler of to-day will give but little more than rating when fired with the so-called " steam coals ". In other words, most boilers, as installed on land, are rated on a basis of 10 sq. ft. heating surface per horse-power and will evaporate but 3.5 pounds of water per square ft. of heating surface, whereas, in marine practice double this amount, or 7 lb. of water, can generally be evaporated per square foot of heating surface; and with closed stoke-hold and forced draft, three times boiler rating, or 10.5 lb. of water, can be evaporated per square foot of heating surface and even greater is sometimes possible.

The following table shows that under the single stoker boiler, referred to in the paper, having a *ratio of* 1 : 56, it is necessary to burn about 20 lb. of coal per square foot of grate, in order to evaporate 3.5 lb. of water per square foot of heating surface, and that by burning 25 lb. of coal, which is about the maximum that can be burned commercially on a mechanical stoker, the boiler will develop only about 20 per cent. above rating. With two stokers under the boiler, making a ratio of 1 : 31, 7 lb. of water can be evaporated per square foot of heating surface, or double boiler rating.

The flat grates originally installed in 1901 under the boilers at the Waterside Station of the New York Edison Company had a ratio of 1 : 74, and in order to obtain boiler rating, it was necessary to burn 35 lb. of No. 3 buckwheat coal per square foot of grate, which necessitated hard firing and great care. The same output could be obtained by firing 28 lb. of No. 1 buckwheat, or 31 lb. of a mixture, consisting of 20 per cent. soft coal and 80 per cent. No. 3 buckwheat. This, however, meant a loss in commercial economy on account of the higher cost per ton of fuel. By extending the fronts of the furnaces under these boilers, and enlarging the grates, thereby reducing the ratio to 1 : 59, it was possible to obtain boiler rating with 25 lb. of No. 3 buckwheat, 22 lb. of No. 1, or 24 lb. of the mixture. With those extended grates, 50 per cent. above rating could be obtained by burning 40 lb. of No. 1 buckwheat per square foot of grate per hour. This firing is possible with forced draft, but great care must be used in order to maintain economy.

In the Sixty-Sixth street station of the Brooklyn Edison Company the grates were originally installed with a ratio of 1 : 68, but last summer the fronts on these furnaces were extended and grates enlarged, giving a ratio of 1 : 53. This increase in grate area was utilized not so much for increased capacity as to give increased economy by burning a cheaper fuel. The economy actually effected by this increase in grate area amounted to 14 per cent. in cost of evaporating 1000 lb. of water.

At our Gold street station, the grates as originally contracted for three years ago were at a ratio of 1 : 76, but before installing the furnace, fronts were extended, thereby reducing the ratio to 1 : 59, and under the boilers installed in 1907 by moving back the bridge-wall, this ratio was still further decreased to 1 : 52. Under boilers proposed for 1908, this ratio has been reduced to 43.

With this ratio of 1 : 43, almost double boiler rating can be obtained, or 7 lb. of water per square foot of heating surface, can be evaporated by burning No. 3 buckwheat, and double rating probably exceeded by burning No. 1 buckwheat or a mixture. This ratio would have been made less but for the physical impossibility of handling a deeper fire box.

It must not be assumed that the least ratio practicable is the best, as there is a possibility of making the grate too large for the heating surface. In addition to the disadvantage of the loss of economy, due to excessive flue temperatures already mentioned, there is the necessity of banking boilers at times of light load, and the loss of time and labor necessary again to bring the fires into condition for steaming.

Walter T. Ray and Henry Kreisinger (by letter):* Perhaps the first inkling that something was wrong came when a number of operating engineers in various places began to explore the interior gas passages of water-tube boilers with thermocouples, and found large dead corners. We have carefully explored many boilers and have never failed to find room for improvement, provided only that it is mechanically feasible to insert gas baffles so as to cause the gases to reach a greater portion of the heating surface, at the same time permitting the gases to travel over the whole surface with at least as high an average velocity as before.

This latter point is important, for practically no benefit would come from inserting baffles such as would cause the gases to flow into dead corners, if at the same time the gas velocity over the old portion of the heating surface were proportionately reduced. The velocity of the gases over, (or past, or along), the heating surface is the active feature which determines how much heat will be imparted to the surface, other things being equal. If the velocity of gas be doubled, the amount of steam produced per second will be nearly doubled. For a fuller discussion of this matter we refer to the Geological Survey's bulletin entitled " A Study of Four Hundred Boiler Tests ".†

The possibility of greatly increasing the rate of heat transmission into boilers will be apparent when it is considered that the amount of heat which can be passed through a thin metal plate is enormous. The heat-resistance of the metal in the case of boilers is insignificant, perhaps ordinarily much less than, $\frac{1}{10}$ of the whole; the seat of resistance is in the layers of scale and soot, and, most of all, probably, in the films of gas

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* We wish it distinctly understood that the United States Geological Survey is in no way officially committed to any of the opinions advanced hereafter. Presented with the permission of the Director of the United States Geological Survey.

† Bulletin No. 325, United States Geological Survey, Washington, D.C.

adhering to the soot and of steam and water adhering to the scale. If these are reduced in thickness by increasing the velocities of the streams of gas and water rubbing against them, the rate of heat transmission will be greatly increased. This is not mere theory, but has been experimentally demonstrated on laboratory models and on large boilers.*

The great increase in capacity in the case cited by Mr. Finlay was undoubtedly due to the increased velocity of the hot gases over the heating surface of the boiler. By burning 80 per cent. more coal, the weight of hot gases generated per second was increased by the same amount. In passing this increased weight of gases through the same boiler the velocity was increased by the same percentage, resulting in an increase of 80 per cent. in capacity.

Mr. Finlay has made only a beginning in working his boilers harder. The Interborough Rapid Transit Company has verified the conclusions experimentally reached mathematically by Professors Reynolds and Perry of England. It is our personal opinion that the boilers under consideration could probably stand five passes instead of three, and that perhaps some other minor changes would be beneficial.

Mr. Finlay's device of putting two stokers under one boiler accomplished the burning of more coal without working the combustion chamber any harder; that is, without increasing the velocity of gases from grate to tubes. Such an increase would have resulted in lessening the time available for the combustion of certain gases. It will be noticed that the distance from the old grate to the entrance into the tubes is only about one third the distance from the new grate to the same entrance; it is therefore likely that the gases from the new stoker are more completely burned, and so it is not surprising that on heavy loads the evaporation per pound of coal was as high as at lower loads on the old stoker alone. The point we wish to emphasize is, that the efficiency of the boiler as a heat absorber is practically constant and independent of the rate of working. The boiler will do its part in meeting increased demands for steam.

In the Jamestown Exposition Plant of the Geological Survey is a 210 h.p. boiler which has been so re-baffled as to cause the gases to pass through the tubes twice instead of once. They pass through a smaller cross-section, nearly twice as far, at a higher average velocity, with the result that about ten per cent. more heat is absorbed, accompanied by no reduction in capacity when using the same draft. When the draft is raised and the boiler made to produce about twice its rated amount of steam, it still retains nearly all of its increased efficiency. Here is a case of greatly increasing the output at a slight cost and at the same time increasing the economical evaporation per pound of coal.

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*See "The Nature of True Boiler Efficiency," by Walter T. Ray and Henry Kreisinger, September 18, 1907, Western Society of Engineers. Chicago.

We see no reason why boilers can not be so designed as to yield several times as much steam per square foot of heating surface as they now do, and with a considerable increase in economical evaporation. One thing seems inevitable—complete resort to forced or induced draft, or, better still, to both.

W. L. Abbott (by letter): Mr. Finlay assumes the cost of a plant to be $125.00 per kilowatt and of this the cost of the building is 35 per cent. or, $43.75, and also that the size of the building is determined by the number of square feet of heating surface in the boilers. He therefore proposes to re-design the plant, using only half as much boiler heating surface, but worked to double the former capacity, thereby effecting a saving of $23.58 per kilowatt in the cost of the plant of which amount $17.50 is due to a reduction of 40 per cent. in the size of the building.

While the foregoing assumptions may have been correct a few years ago, they certainly do not apply to more recent designs for turbine plants using large generating units. In these designs the size of the building is not determined by the number of boilers any more than it is determined by the number of turbines, and the cost of the building, which is about $15.00 per kilowatt, is divided about equally between the boiler room and the rest of the plant. The reduction of 40 per cent. in the cost of the building incident to a reduction by one-half of the boiler heating surface will therefore be applied only to a $7.50 boiler room and not to a $43.75 power house building.

Again, Mr. Finlay allows an additional loss of only 3 per cent. of the fuel when he doubles the rating of a given boiler. This assumption is probably correct for a boiler having an ample economizer, but in the case of a boiler not so supplemented, the additional fuel loss would undoubtedly be as much as 10 per cent., and it should be stated here that the figures given above for cost of boiler room do not allow space for an economizer.

We now have the following approximate figures for power house costs:

With boilers of standard rating	$96.00
" " double " "	$93.00

Both of these prices are without economizers.

Taking these new figures and calculating the data for curves similar to those given by Mr. Finlay, it appears that the total cost of current output will be practically the same in both cases, regardless of the rating at which the boilers are worked.

A. Bement (by letter): It is rather remarkable in the tests described by the author, how nearly constant final efficiency is in steam generation with one and two stokers, and this may be partially explained by the fact that the proportion of the usual type of water tube boiler is such that only a part of the tube surface is acted upon by hot gases, and if a larger volume is forced over the boiler, as would occur with two stokers, their relatively greater body, demanding more space, will extend to portions of the boiler which were practically unused with a single stoker. This has been illustrated elsewhere.*

Referring to Fig. 7, which shows an elevation of boilers and stokers in the Subway power plant, it would appear that a furnace roof has been improvised by the insertion of a baffle between the tubes of the two lower rows of the boiler in the rear. If this be true, it leaves the lower row of tubes exposed to the heat from both stokers for about five-sixths of its length. I would inquire if it has been possible to operate these boilers to to any considerable extent without destroying the tubes of this bottom row by overheating. Even if they have been able to stand such an amount of work, this design of furnace could be very much improved by the use of encircling tiles which are usually made in lengths of 12 in. as have been elsewhere described.† This would not only reduce the amount of work required of the bottom tubes, but would furnish a more satisfactory roof than an inserted baffle does.

F. V. Henshaw (by letter): It may be well to point out that as neither heating surface nor grate surface has fixed value for different designs and conditions, they should be considered in connection with specific cases, and the ratios of the two compared with due regard to all the features of the furnaces and boilers in the different cases. A trifling change in the baffles can greatly alter the value of the heating surface in water-tube boilers, and numerous other variables are obvious.

In designing boiler-plants we have to provide for two distinct operations: first, the chemical operation of burning fuel; secondly, the physical operation of conveying the heat generated to the boiler water. The apparatus for performing these operations is supplied by independent makers. These makers are at times opposed in their requirements. The boiler designer being anxious to secure a high rate of evaporation and rapid circulation, may wish to apply the fire too directly to the boiler, with resultant imperfect combustion and production of cinders and smoke. The fuel value of discharged cinders and smoke is not great, but the deposit from them on tubes reduces the value of the heating surface, and, when emitted from city chimneys, they have a large " injunction and fine ". negative value.

The boiler shown as Fig. 7 is a well known type with a slight change in the baffles. The front furnace is standard, whereas the rear furnace has a longer combustion arch. The grates are much farther below the tubes, and the tubes directly above the grates are covered by a baffle which deflects the flames toward the boiler-front. One would expect the rear furnace to be considerably more efficient, to produce less smoke or cinders, and to require a rather higher draught pressure than

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*Transactions American Society of Mechanical Engineers, Vol. XXVI, p. 626.

† Journal Western Society of Engineers, Vol. XI, p. 752.

the front furnace. We have here, therefore, something more than a simple case of added grate area.

In the curves given, the single stoker doubtless refers to the front furnace. Additional comparisons of each furnace operated singly would be interesting.

It seems to me that the estimate for cost of boilers is somewhat too low, on account of the greater cost of settings for the double-furnace boiler.

W. S. Finlay (by letter): It is evident that the discussion has been productive of possibly more valuable experimental results than are contained in the paper itself, and to attempt to reply to each and every feature of the very long and elaborate criticisms, would be absolutely out of the question. What may be said in reference to these discussions, is said with due respect and recognition of the greater knowledge and experience possessed by the gentlemen whose work determines the value of the subject in hand.

Possibly it was unfortunate that more emphasis was not given to the fact that the specific solution of the problem of increased efficient combustion, namely, the double stoker, was not proffered as a general or sole solution, but was quoted as merely one form, convenient and satisfactory in the case to which it was applied. Neither did the writer desire to give any specific value to the ratio, simply wishing to emphasize the importance of its careful consideration under attendant conditions.

With reference to Dr. Lucke's criticisms, which are chiefly from a theoretical standpoint, a reply should be given from a similar basis. A careful study of the discussion shows that there has been practically but one point brought up, this point being repeated in a number of different ways. In form, the discussion is interrogative, tending to throw a doubtful light upon the experimental data referred to in the paper. A declarative form might be stated as follows:

1. Operation under double-stoker conditions should theoretically conform to operation under single-stoker conditions. With increased total combustion, and increased capacity, economy should decrease regularly, if expressed graphically, in a single continuous curve, whether such increase in capacity be accomplished by increased combustion upon a single stoker, or upon a double stoker.

2. Boiler efficiency is conditioned upon two variables:

a. Ratio of heating surface to grate surface.

b. Rate of combustion per square foot of grate surface.

The question has thus been reduced to a study of: first, that which actually determines boiler efficiency; secondly, the form in which this efficiency varies.

It is a self-evident fact that a diagram, such as the " shot-gun " diagram, based upon results of three hundred tests under all sorts of conditions—boilers, combustion chambers, etc.—is of little or no value, and useless so far as it bears upon theoretical investigation.

The rate of combustion must be recognized as a factor in the " unit " efficiency under practical conditions, but as to its effective value so far as the boiler proper is concerned, it would, in the light of recent investigation, seem highly probable that boiler efficiency decreases but little under conditions of increased rating.

Merely to consider two factors determining boiler efficiency, namely: 1. The ratio of heating to grate surface—primarily a specific feature, which can not be generalized—and, 2. The rate of combustion, would be obviously to neglect certain most elementary and fundamental features in design.

It is inadvisable to attempt completely to discuss all factors entering into boiler and grate efficiency, particularly as certain new features in theory and experiment indicate that knowledge of the subject is not at all complete. However, a summary of recognized factors from both theoretical and practical points of view will serve to indicate the relative effective value of each upon the efficiency of the boiler when considered as a unit consisting of boiler proper, furnace, and grate. Thus, for any given set of conditions, unit efficiency will depend upon the following factors:

1. Grate design, a factor involving in practice relative values of air-space, adaptability to grade of fuel, ease of handling in process of cleaning, with attendant effect due to admission of excess air, etc.

2. Furnace design, which involves complete combustion of gases, and transmission of the same to the heating surface when at their maximum temperature.

3. Method of air supply, which must naturally be considered together with the preceding factors.

4. Boiler design, which may be sub-divided as follows:

a. Relative exposure of heating surface to heat radiation from fire and furnace walls.

b. Design of heating surfaces in relation to direction of quantitative flow of gases.

c. Design of baffling as effective upon flow of gases, with due regard to the effect of such baffling upon soot accumulation, and " dead " space; also to direction of circulation in boiler.

d. Boiler design in respect to rapidity of circulation of water.

5. Boiler proper, maintenance and operation. This factor includes cleanliness in inner and outer surfaces of tubes and drums, together with the condition of all parts of the unit. Operation includes care and handling of fire, together with manipulation to obtain best combustion and lowest practicable flue-gas temperatures.

A number of other governing factors might be quoted, but for purposes of comparison the above will suffice.

A comparison of conditions existing in the single- and double-stoker boilers as influenced by changes in certain of these factors, will serve to explain the apparent discrepancies which

Professor Lucke calls attention to. In the change .rom single to double stokers, the only factors vitally affected, are:

1. Furnace design, in which case the new design undoubtedly favors a more complete combustion of gases, a point in favor of increased efficiency.

2. Grate design, the possibility of increasing combustion per square foot of heating surface without a tendency to force excess air through the fire.

3. Increased exposure of heating surface to radiation from the fire-bed.

4. Greatly increased volume of flow of hot gases; larger portion of the heating surface becoming active, and dead spaces and eddy currents of gases decreasing in number and effect. Heat convection to heating surface is increased by reason of greater speed of gas circulation.

5. Boiler operation is improved by reason of the fact that increased water circulation tends to lessen the formation of scale, as well as improved heat convection inside of tubes.

The above summation of changes in conditions, with their effect upon the unit efficiency, tends to show that curves plotted upon bases of efficiency and rating for the single-stoker boiler and the double-stoker boiler need not be identical, the one a continuation of the other. These curves would necessarily be distinct and individual for each set of conditions.

It is to be noted, in the particular case of the efficiency curves given, that the decrease in efficiency for increase in rating seems to be rather rapid. To lessen the slope of these curves, the self-evident solution is to provide such draught or air-supply conditions that forcing of fires would not be accompanied by excess air supply or undue disturbance of fires.

A move in this direction, with apparently successful results, has already been taken; but the fact remains that the double stoker must retain the all-round higher grate efficiencies accompanying combustion at a lower rate per square foot of grate surface, together with improved furnace conditions. The feasibility of obtaining efficient high boiler output, with due consideration of total plant charges and costs, makes the double-stoker simply one device to obtain certain results, its choice to be based upon ruling conditions.

Mr. Wells bases his entire discussion upon a premise whose value is exactly the point which originated the question brought up by the writer. He makes the statement:

> Consideration should first be given to the evaporation possible per square foot of heating surface consistent with commercial economy; and this in turn depends upon the maximum practical rate of combustion, etc.

This is just a re-statement of heating surface and furnace relation. However, having made this statement as the fundamental, his development of the subject has unfortunately been merely along lines of hitherto accepted methods of increasing boiler capacity without any consideration of the latest phases of development giving consideration to the possibilities latent in heating surface efficiency.

The discussion by W. T. Ray and H. Kreisinger is peculiarly valuable in view of the fact that it incorporates results of most recent investigation. The writer considers it a most practical verification of what has been said in reply to Dr. Lucke's discussion as well as of the original paper.

It is evidently a misinterpretation of the writer's thought that Messrs. Ray and Kreisinger have emphasized the point of fixed valuations to the ratio of heating to grate surface. The writer fully realizes that such a fixed valuation could not be generally applied, the purpose in view being more particularly a careful consideration of furnace and heating surface relation, as applied to each specific case in the light of results such as have been realized by the very investigations of the United States Geological Survey.

Mr. Abbott objects to considering the size of the boiler plant as practically the determining factor in the size of a plant building. Conservative design, as exemplified in nearly every recent plant of importance, has been on the parallel plan, it being almost uniformly an accepted rule that consideration must be given to plant growth and extension, in addition to uniformity, as necessary to simple operation. The turbo-generator in point of permitting extreme flexibility in adapting turbine room size to boiler room size has been an additional incentive to the development of this system.

Replying to Mr. Bement's first question in reference to the life of the bottom row of tubes, the writer would say that operating results for a period of about three months show most satisfactory results in this regard. Improved circulation and evenness of heating of these tubes result in improved cleanliness and little wear. Mr. Bement's statement in reference to increased utilization of heating surface in the case of the double stoker seems to corroborate the reply to Dr. Lucke's discussion.

Albert A. Cary: Mr. Cary presented a careful analysis of fuel combustion, and the relative distribution of heat losses throughout the process of such combustion, for the particular purpose of emphasizing the need of deliberation and care in the design of furnace and grate in their relation to the boiler. In support of his position, Mr. Cary cited numerous examples and facts gathered during years of wide experience.

J. P. Sparrow: It sems to me that undue prominence is given to the matters of grate area; if the question were the proper relation of boiler heating surface to maximum station output as affecting station design and operating costs, then the matter of grate surface becomes one of obtaining the necessary capacity at the maximum efficiency.

In the ratio of square feet of heating surface to kilowatt capacity there are quite wide variations in practice—variations of from 5 to 1 to 10 to 1; there are also similar variations in the evaporation per square foot of heating surface, every-day practice showing examples of from 2.5 to 8 lb. for land service, and as high as 10 or 12 lb. for marine work.

In the ratio of grate area to heating surface, common practice varies between the limits of 75 to 1 to 35 to 1. In central station service where variable loads are the rule, these variations in heating surface and grate area bear on two points—the economical evaporation per square foot of heating surface, and the economical rate of combustion per square foot of grate. Large grate areas have been advocated for many years, nearly always, however, from the standpoint of capacity.

The performance quoted of a single stoker giving a boiler output of 610 h.p. and an equivalent evaporation of 9.5 lb. represents a combined furnace and boiler efficiency of 64.4%. A comparative performance of the double stoker gives a boiler output of 1050 h.p. for the same equivalent evaporation. To compare with results obtained from other installations, I would quote a performance of a single stoker of the same size and design under a boiler of the same heating surface, of a boiler output of 1070 h.p. with an equivalent evaporation of 11.2 lb. or a combined efficiency of 74.5%. This capacity was obtained with a flue draft of 0.85 in. Mr. Finlay shows only 750 h.p. from a single stoker with same draft.

Taking the curves in Mr. Finlay's paper as a basis, his single stoker developing 600 h.p. burned coal at the rate of 19 lb. of coal per square foot of grate, his double stoker at the rate of 18 lb. at 1000 h.p. while the installation referred to above burned coal at the rate of 28.6 lb. developing 1070 h.p.

On a test of a marine boiler built for the cruiser Cincinnati with a ratio of heating surface to grate surface of 41.7 to 1, coal was burned at a rate of 59.75 lb. per square foot with equivalent evaporation of 9.63 lb. or an efficiency of 64 per cent.

The New York Edison Company has for some time been conducting tests of high rate of combustion of soft coal under forced draft, and have on test burned at the rate of 44 lb. of coal per square foot of grate with a boiler output of 1300 h.p. and a combined efficiency of 73 per cent. With anthracite coal under forced draft burning 24 lb. per square foot, 1,070 h.p. was developed with a combined efficiency of 69 per cent. The evaporation per square foot of heating surface of these various tests and the efficiencies are:

Mr. Finlay's single stoker..........	3.4 lb.	64.4 per cent.
double "	5.7 "	64.4 "
Waterside single "	5.7 "	74.5 "
Waterside forced draft "	7. "	73. "
" " " anthracite	7. "	69. "
U. S. S. Cincinnati.................	9.6 "	64. "

In electric lighting stations where the storm peak demands may be from 60 to 100% above normal, it is most convenient, and I believe most economical, with the commonly accepted ratios of grate to heating surface, to operate boilers at about 15% above rating, relying on the ability to force evaporation to meet the sudden load demands. If this operating routine is correct, then increased grate areas are opposed to good economies. It is practically impossible to burn fuel at low rates of combustion on large grate areas with reasonable economies. We all know the difficulties experienced in checking excess air when operating with a ratio of grate to heating surface of 1 to 60, how much more difficult it will be to operate with ratio of 1 to 32 at the same boiler output.

A very large number of tests conducted by The New York Edison Company with boilers designed with ratios of 10 sq. ft. of heating surface to one boiler horse power have shown conclusively that while there is a falling off of combined efficiency at high rates of evaporation, this decrease of efficiency is not at all serious if the higher rate is maintained only at time of peak load.

The crux of the matter lies in an increase in rate of combustion, this bearing the same relation to construction costs and fixed charges as Mr. Finlay's increase of grate surface. An evaporation of 6 lb. of water per square foot of heating surface is not unreasonable, and as against 3.4 lb. allows a decrease in boilers of 43 per cent. A comparison on this basis with the figures in Mr. Finlay's paper would show:

Maintenance	Evaporation per square foot of heating surface		Evaporation per square foot of heating surface
	3.4 lb.		6 lb.
Boilers	29.5 %	43%	16.82%
Economizers	2.78		2.78
Furnaces	17.29	20%	13.84
Stokers	40.68	20%	32.55
Boiler feed-pumps	5.42		5.42
" " piping	2.20	43%	1.25
" blow-off "	0.44	43%	0.19
Water piping	1.52		1.52
	100.00%		74.37%

or 74.37 : 100 as against Mr. Finlay's 84 : 100.

Operation	3.6		6 lb.
Water tenders	20.82	43%	11.87
Stoker operators	38.09	43	21.72
Assistant stoker operators	15.49	43	8.83
Stoker oilers	2.54	43	1.45
Economizer oilers	5.84		5.84
Feed pump men	5.08		5.08
Boiler cleaners	10.41		10.41
Miscellaneous	1.73		1.73
	100.00%		66.93%

or 66.93 : 100 as against Mr. Finlay's 84 : 100.

As Mr. Finlay has said, the value of specific results obtained lies in their adaptability to existing conditions. These results to be of value must be fairly indicative of results obtainable under normal operating conditions, and I fail to see the warrant for the conclusions drawn on the basis of the results quoted.

J. E. Moultrop: I understand that the installation described by Mr. Finlay was brought about by reason of the necessity of more steam from a boiler house built as large as the location permitted, and completely filled with boilers. Also, that previously to the installation of the double grates, these boilers were run at about their rating, 600 h.p., and that the original grates had an area of 100 sq. ft. These data, together with the evaporation curve in Fig. 4, indicate that the maximum coal consumed per square foot of grate per hour was about 21 lb., not a large amount compared with the consumption of some other large stations. As the curves indicate an ample draft, the natural question is, why was not more coal burned on the original grate? An inspection of the other curves indicates that this could have been done, and practically the same capacity obtained from the original grate as is now obtained from the two grates, but the economy would fall off appreciably.

If this be true, the solution of the problem is not necessarily more grate area under the same boiler. There is nothing in the paper to indicate that any change was made in the heating surface or in the travel of the gases across the heating surface, so it may be assumed that this part of the boiler remained unchanged and that all improvements were made in the furnace. The cross-sectional elevation of the boiler shows two noticeable changes in the furnaces; the ignition arch on the new furnace is longer than in the old, and the combustion chamber is much larger. The new boiler appears to be almost twice the size of the old one. These two modifications are decided improvements, and should be large factors in the improved operation of the boiler. It does not follow that it was necessary to build a second furnace under this same boiler to obtain these improvements, because the original furnace could be re-designed on similar lines, and if necessary a considerably larger grate could be placed in one furnace.

The proposition to reduce the size and cost of the boiler plant is a step in the right direction, but in so doing the utmost simplicity should be maintained, especially in the large stations of to-day. Possibly the scheme adopted at the Interborough station was the best that could be devised in an existing plant for a reasonable cost, but it does not follow that this design is a good one to adopt in laying out a new station.

A vertical-header boiler is more compact, and with 18-ft. tubes, 14 high, will be some 3 ft. shorter and take about 41 sq. ft. less floor space than the inclined-header boiler. Here is a real saving in building space with no disadvantages. Such a boiler can be equipped with as large a single grate as may be conveniently installed under the rear end of the boiler, with the gases passing in the usual way through the heating surface. In other words, install the vertical header boiler in a similar manner to the Interborough boiler with the original furnace omitted. This arrangement incorporates all the real advantages of the double-grate plan with none of the disadvantages of the latter, except possibly one. Both of these plans require a tile roof on the lower row of tubes immediately over the fire, which may prove troublesome to maintain.

A paper presented at the 223d Meeting of the American Institute of Electrical Engineers, New York, December 13, 1907.

AN EXHAUST STEAM TURBINE PLANT

BY HENRY H. WAIT

At the Wisconsin Steel Company's Mill at South Chicago the turbine utilizes the exhaust steam from a reversible engine which drives the blooming rolls. The steam passes first to the receiver which takes out the shock of the puffs of steam, thence to the steam accumulator or " regenerator ", and from there to the turbine and condenser. The general layout of the plant is shown in Fig. 2.

As this is the first plant of this character to be installed in this country, it was subjected to an elaborate series of tests by Mr. A. U. Leonhauser, the chief engineer of the Wisconsin Steel Company, and Mr. F. G. Gasche, mechanical engineer of the Illinois Steel Company. Besides testing the turbine equipment, the arrangement offered an opportunity to test the steam consumption of the primary engine by making a temporary change in the piping, so that the exhaust was led directly to the condenser without passing through the turbine. Mr. Gasche has already published an account of the various tests, giving very interesting continuous indicator diagrams of the engine and charts of the roll-train resistance, etc.*

Primary engine. This is a 42 by 60 double-cylinder engine, of the rolling-mill type. When in normal operation the engine rolls about 19 ingots per hour with 21 passes per ingot, stopping and reversing after each pass with a short interval for the starting of a new ingot, so that it is stopped or practically idle 20% of the time during the cycle required for turning out an ingot. There are other frequent stops for the ordinary manipulation of the mill which last from a few seconds to several minutes.

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*" Power " June 1907.

The average i.h.p. while the engine is actually running is 1010, and, if the total work per hour were distributed evenly over the hour, the average i.h.p. for the hour would be 820. Figuring back from the total steam consumption gives 64 pounds of steam per average i.h.p. for the hour, or 54 pounds during the running period. This large consumption is readily understood when we consider that the engine takes steam for practically the full stroke when starting the passes, and is running on very light load most of the rest of the time. Of course the horse power and especially the torque runs up enormously when the rolls first take hold of the ingot.

FIG. 1

Receiver. This is the vertical drum shown on the left of Fig. 3. When the engine is exhausting directly to the atmosphere and is taking steam at nearly full stroke, the puffs of steam shoot a long distance up in the air and make a noise like a number of big locomotives puffing in unison. The receiver is to relieve the accumulator of the strains and disturbance which would occur if the puffs went directly to it. The receiver consists of a tank with a number of baffle-plates and is provided with drains for water and oil. At the top of the receiver, between it and the vertical exhaust-pipe, used when desired to exhaust directly to

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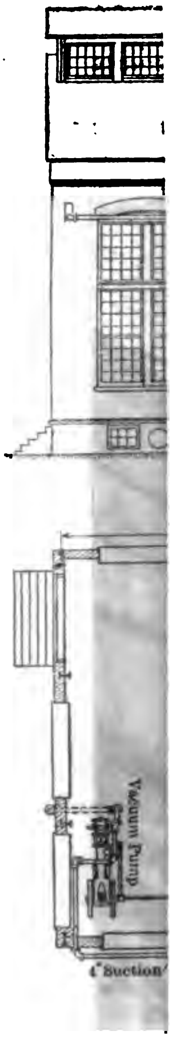

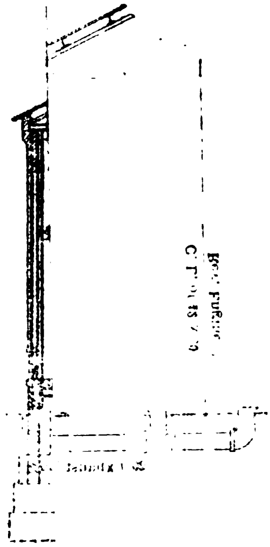

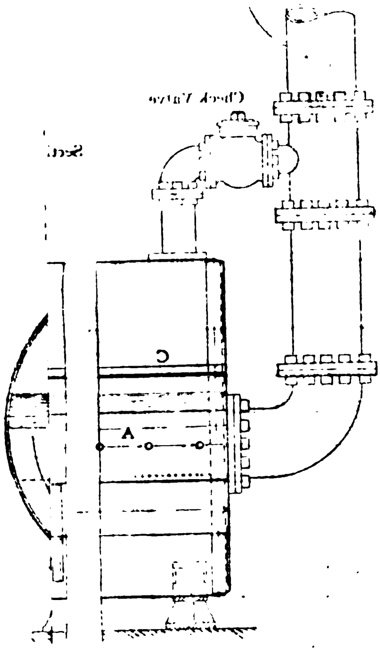

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in Fig. 4. Longitudinal and transverse cross-sections of a small regenerator are shown at the right in Fig. 2.

Principle of operation. The accumulator might be called a heat fly-wheel, absorbing or giving up energy in accordance with the requirements. It might also be likened to a storage-battery floating on the line.

When the engine is running, the exhaust steam comes from the engine through the receiver and is delivered to a number of pipes immersed in the water in the regenerator. These pipes or ducts are perforated with a number of small holes, spraying the steam, so to speak, in through the mass of the water in the regenerator. A greater or less proportion of this steam is condensed in passing through the water and gives up heat to the mass of water in the regenerator.

Fig. 4

It is usual to operate the regenerators at about atmospheric pressure. In other words, the steam coming to the regenerator will usually have a temperature of 212° fahr. and will tend to heat the water to just that temperature. If the engine stops and the supply of exhaust steam discontinues, we will see that we have a large mass of water heated to 212° fahr., and if there is a continuous load on the turbine the flow of steam through the turbine to the condenser will tend to make the pressure fall off slightly in the regenerator, and 212° fahr. will then be slightly above the boiling temperature of water at this lower pressure, so that the mass of water begins to give off steam and act like a boiler running at approximately atmospheric pressure. If, now, the engine starts again, steam will be delivered to the accumulator at a temperature slightly above that to which the water has fallen, due to the cooling effect of the evaporation of the steam for supplying the turbine, and the mass of water will again absorb heat from the exhaust steam.

In actual practice it is more convenient to run the regenerator at a pound or two pressure above the atmosphere, as in this case the piping is not under vacuum so that so much care does not have to be exercised to avoid air leaks. However, in certain cases, it is desirable to run below atmospheric pressure. In this way the power of the primary engine may be augmented by letting it operate at a partial vacuum. Plants are actually running with a delivery pressure to the turbines as low as six pounds below atmosphere.

Details of accumulator. The accumulator at South Chicago, being quite a large one, is divided by a diaphragm in the middle into two decks, each deck having a series of flues similar to those shown in the small regenerator of Fig. 2. The steam generated in the lower deck passes up through steam flues into the upper chamber and passes out with the upper steam through the steam dome.

Water trap. There is a small percentage of the steam delivered to the regenerator which is condensed on account of radiation from the surface of the apparatus and this makes an accumulation of excess water in the regenerator, and this is automatically discharged by the float trap seen at the end of the regenerator. In most plants where such apparatus is used, there is more exhaust steam than is actually required for the turbines so that this condensation does not matter as it is only a small percentage anyhow. But in some plants, where the fullest possible amount of steam needs to be saved, the regenerators are lagged.

Water level. Gauge glasses are shown on each deck, and a series of valves and pipes are shown so that the water level in the upper deck can be set to suit that maintained in the lower deck by the float valve.

Reducing valve. If for any reason the primary engine shuts down for a considerable period, the supply of heat stored in the regenerator will become exhausted and the pressure will fall below a workable amount for the turbines. To take care of this condition, there is an automatic reducing valve which will be seen on the piping just above the scaffold. This valve in the present plant is set so that it will open whenever the pressure falls below atmosphere and deliver live steam through the reducing valve to the regenerator whenever the primary engine is shut down for a long enough period to make it necessary.

In this plant the relief valve is set for three pounds above atmosphere; in other words, whenever there is more steam than is necessary to run the turbine and heat the water in the regenerator to a temperature corresponding to its pressure, the excess steam will pass off to the air through the relief valve. On the other hand, if the engine does not give enough steam to supply the needs of the turbine, the reducing valve will open and let in enough live steam to make up the deficiency.

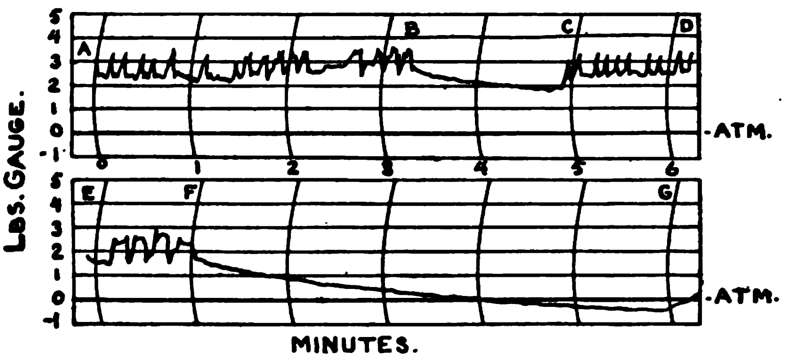


FIG. 5

Fig. 5 shows a typical chart from a recording pressure gauge on a regenerator operating from the exhaust of a roll-train engine. From *A* to *B* the engine is working and the pressure rises and falls as a function of the amount of steam delivered. At *B* the engine stops and the regenerator continues to deliver steam to the turbine so that the pressure begins to fall off down to the point *C*, where the engine begins rolling again. At *F* the engine stops again for a considerable period so that the pressure falls to atmosphere and a little below, until the point *F* is reached, where the pressure has fallen sufficiently to let the automatic reducing valve open and admit live steam, which brings the pressure back up slightly above the atmosphere.

At the Wisconsin Steel Company's plant, during normal operation, the pressure ranges about one or two pounds above atmosphere; when the engine is exhausting heavily it runs up to about three pounds. The lower limit of pressure, when the reducing valve opens, is about atmosphere.

As a matter of fact the regenerator is considerably larger than would be really necessary to regularize the flow of steam to the turbine, as tests show that under the ordinary load conditions the regenerator will keep the turbine running at its average load for about seven minutes after the primary engine shuts down before the reducing valve opens. This would correspond to a period of about five minutes at full load on the turbine.

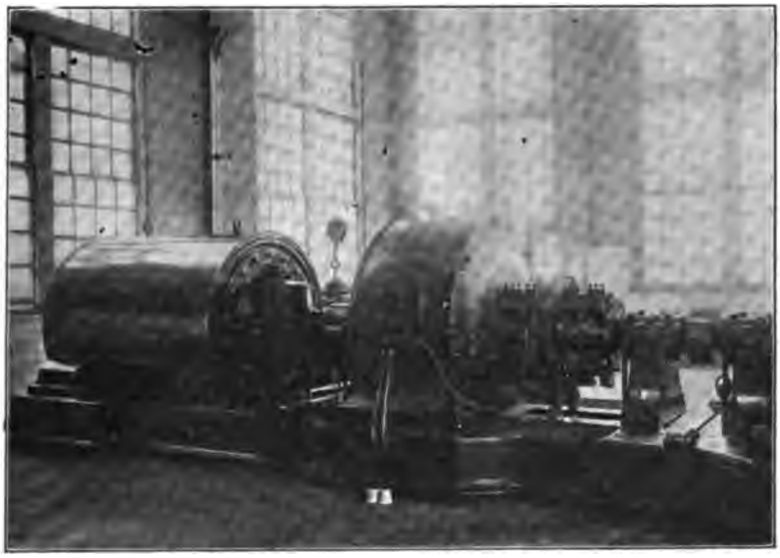


FIG. 6

Turbine. The turbine is of the well-known Rateau type, similar to those of the same character built in Europe, except that on account of American conditions it was necessary to make the construction heavier and stronger. The exterior of the turbine is shown in Figs. 1 and 6.

Wheels. The revolving wheels and their vanes are shown in Fig. 7. The wheels are turned out of solid steel plate with an cross-section increasing toward the center to give them a large factor of safety.

Buckets. The buckets are made of a special alloy of great mechanical strength and rust-resisting qualities. Each bucket resembles a half of a brass shot-gun cartridge sawed in two. The buckets are held against the rim of the wheel by special rivets which have heads formed to fit the shape of the bucket at the bottom. It will be noted that this is an extremely simple and reliable method of securing each bucket independently of the others. The rivets are figured with a very large factor of safety, and there has never been a case of a rivet giving out in all of the large number of Rateau turbines which are running. The buckets are spaced at the periphery by a spacing or shroud-ring which serves to maintain an accurate spacing and acts as a baffle for improper currents of steam.

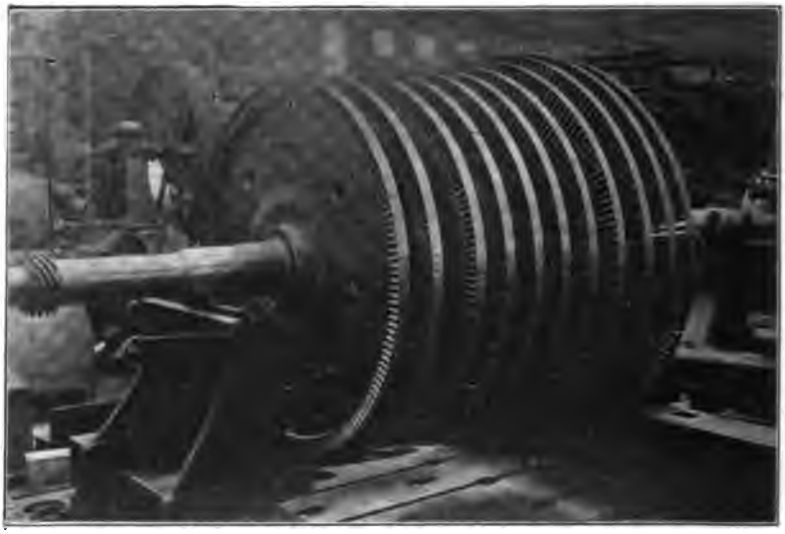


FIG. 7

It will be noted that these rings are made in several pieces. This is for the sake of convenience in manufacture and handling and does not materially affect the strength, as will be seen when it is remembered that at these high peripheral speeds a band of this character would have scarcely the requisite strength to hold itself as a hoop. On the other hand, the buckets must be depended upon to hold it as far as centrifugal force is concerned.

It is of interest to note that as the turbine is divided into so many stages, the steam velocities are very low, so that the impinging jets of steam do not wear away the entering edges of the buckets One of these turbines was examined after being in service for five years and it was found that the marks of grinding on the buckets were still visible, showing that the wear was negligible.

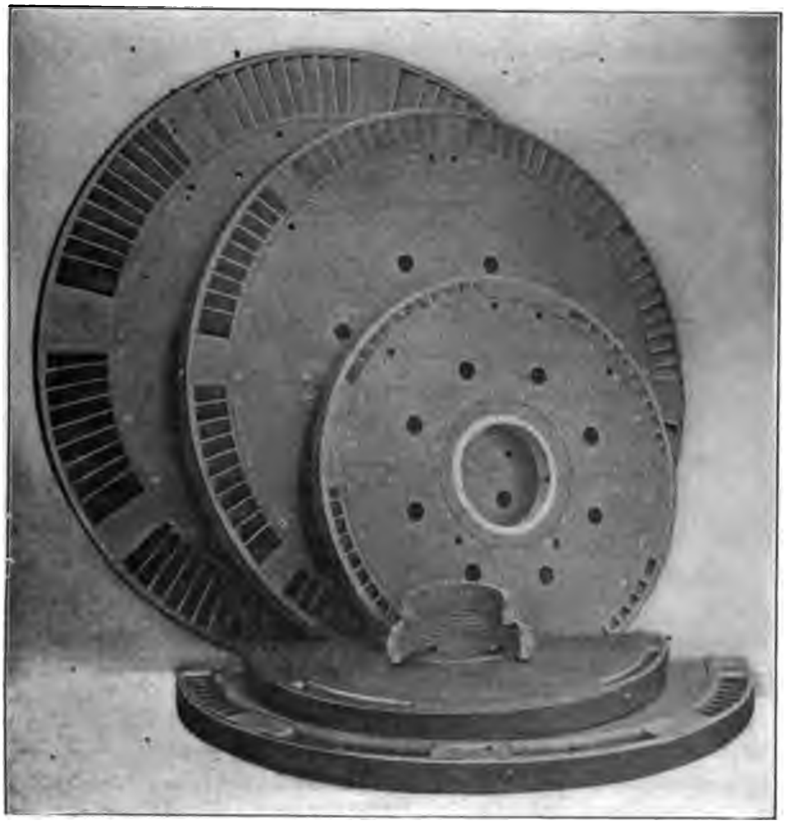


Fig. 8

Diaphragms. The Rateau turbines have fixed diaphragms which extend to the shaft between the wheels, forming a cell in which each wheel operates. There are no photographs of the diaphragms of this particular turbine, but they are of the same character as those shown in Fig. 8.

As the turbine is of the impulse type, the pressure is the same on both sides of the wheel and there is no tendency to leakage of steam through the clearance spaces around the periphery. These clearances can therefore be made as large as desired within reason, without having any material effect on the efficiency.

Governor. The governor is of the spring-balanced, fly-ball type, operating in connection with a dash-pot. It is located in the cylindrical casing on the turbine bearing seen in Fig. 6.

Throttle valve. The governor regulates the speed by throttling, the valve being of the double-beat type, located in the vertical cylinder seen in Fig. 1. Of course it will be realized that the steam admission pipe and the throttle valve have to be of abnormally large dimensions on account of the steam being delivered at such a low pressure.

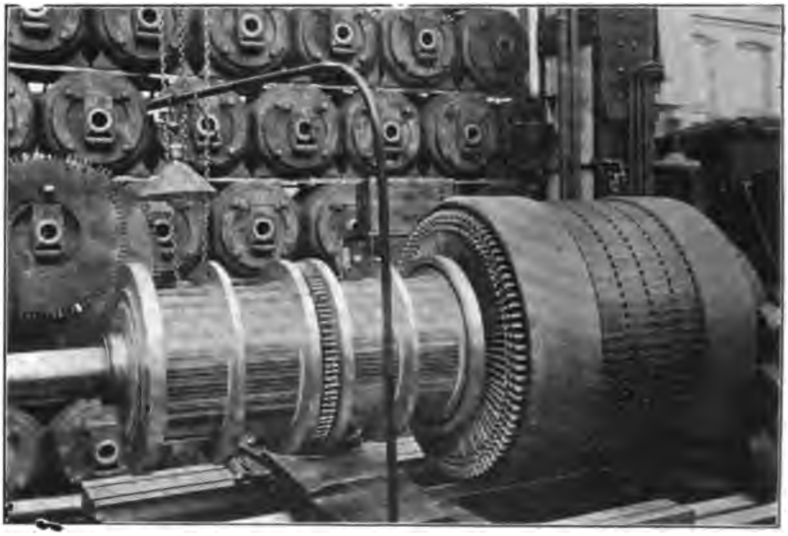


FIG. 9

The governor operates satisfactorily and maintains the speed within the ordinary ranges, either during violent or slow changes of load.

Bearings. The bearings are very simple in construction, as they are practically the same as the ordinary ring-oiled dynamo bearings, except that they have water-jackets to maintain the temperature at the desired value.

The turbine being of the impulse type, there is no end-thrust except that due to slight residual effects, so that only a few thrust-collars are necessary to locate the shaft and these are placed at one end of the governor bearing.

Stuffing-boxes. On low-pressure turbines the stuffing-boxes become a comparatively simple problem; on this turbine they simply consist of a water-seal in chambers bolted to the heads of the turbine.

Dynamos. One of the dynamos is shown in Fig. 6, the armature in Fig. 9, and the fields in Fig. 10.

The design of direct-current dynamos at turbine speeds is the really hard part of the engineering problem connected with such an installation. The turbine itself, being constructed entirely of strong materials, is relatively a simple matter in comparison with the dynamos. The centrifugal force at the periphery of the armature is nearly half a ton per pound of material, and it can be readily understood that the designing of a machine to hold a large number of small insulated coils with an adequate factor of safety, and so placed that they will stay where they are put and not unbalance the machine, is not a problem of the nature of child's play.

FIG. 10

When it was decided to put in this plant we found that direct-current dynamos of the speed and capacity required had not been built in this country and were not obtainable, so it was necessary for us to design the dynamos ourselves. It might also be remarked that although larger direct-current turbine dynamos had been designed in Europe, there were none, as far as we could find out, adapted to the requirements of American steel-mill practice.

In order to make the problem simpler and not run so much risk with abnormally long commutators, it was decided to divide the generating capacity into two direct-current units of 250 kw. each, the pressure being 250 volts.

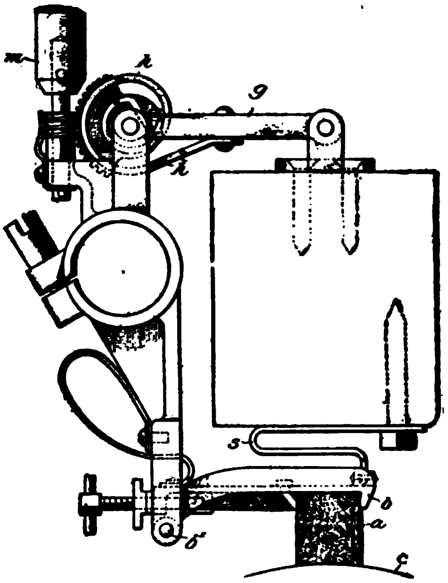


Fig 10*a*

Armature. The armature resembles an ordinary iron-clad armature, except that everything has to be much stronger and the shaft at the center is very large so as to bring the critical speed well above normal. At the ends of the winding, where there are no teeth to hold the coils against centrifugal force, nickel-steel retaining rings are used, which give a very large factor of safety in spite of the enormous strains. These rings revolving in the fringe of the magnetic field from the pole-pieces would, of course, have a large loss in eddy currents generated in them and would overheat and cause loss in efficiency if something were not done to prevent it.

In Fig. 10, just outside the pole pieces will be seen iron rings which serve as magnetic shields to protect the retaining rings from the leakage flux which would otherwise pass through them. These rings of course increase the magnetic leakage of the fields by a small percentage but this can be allowed for once for all by providing a little extra material in the fields and, on the contrary, the shielding of the retaining rings prevents a loss which would be a continuous one during the operation of the machine.

Commutator. Abnormal peripheral speed limits the size of the commutator diametrically, and the great coefficient of expansion of long commutator bars limits the permissible length in a longitudinal direction. The commutator is therefore divided into two sections, as shown in Fig. 9, to avoid expansion troubles. The segments are held against the great centrifugal force by nickel-steel retaining rings which are shrunk in place and give a large factor of safety to the commutators. The two sections of the commutator are united by tangs resembling those ordinarily used at the inner end of commutators.

Fields. In order to overcome the effects of the very high commutating voltages caused by the large current and high speed, it is necessary to use commutating poles. These are well shown in Fig. 10. The rest of the field structure is of the same general character as ordinary machines. On the right of the field frame in Fig. 10 may be seen half of the turbine shell with the diaphragms removed.

Brush-holders. The brush-holders are one of the difficult features of the problem. I think it may be said that some brush holders are worse than others, but there are no perfect ones.

On these high-speed commutators the energy lost in the brush friction is usually a good many times that of the $I^2 R$ loss, so that it is important to keep the brush tension as low as possible. The other horn of the dilemma is that, unless considerable tension is maintained, it is difficult to keep the commutator absolutely true, and even one-thousandth of an inch eccentricity or a high spot will throw the carbons out of contact and make sparking and other troubles. On these machines the problem is handled in a very interesting manner by a novel type of brush holder, Fig. 10*a*. The carbons are held in a clamp swiveled some distance back of the point of contact, and between the carbon and a lead weight is located quite a stiff spring. The lead weight is held by this spring on one end and the swiveled arm at the outer end. A spiral spring adjusts the tension on the weight. The weight acts like the weight of a seismograph and the brush is therefore acted upon by a strong force tending to bring it back in contact if for any reason it has a tendency to be thrown off the commutator by a high spot or otherwise. On the other hand, the adjusting spring behind the weight enables the maintenance of a low average tension on the brush. In this way the natural period of vibration of the brush and its spring acting against the weight can be made a number of times the frequency of revolution. Care must, however, be taken that the natural period of vibration of the inertia weight, vibrating on the inner and outer springs, shall not be such that resonance will be caused by the frequency of rotation.

Ventilation. These high-speed machines cause a considerable whirring noise on account of high peripheral speed, and for this and other reasons the frames are enclosed with end-bells. On the end of the armature in Fig. 9 will be seen the projecting tips of fan-blades which are mounted on the armature. These draw in air through a passage at one end of the frame and force it through the machine down through a passage at the other end and out through the base. This assures adequate ventilation and makes the machines comparatively quiet in operation.

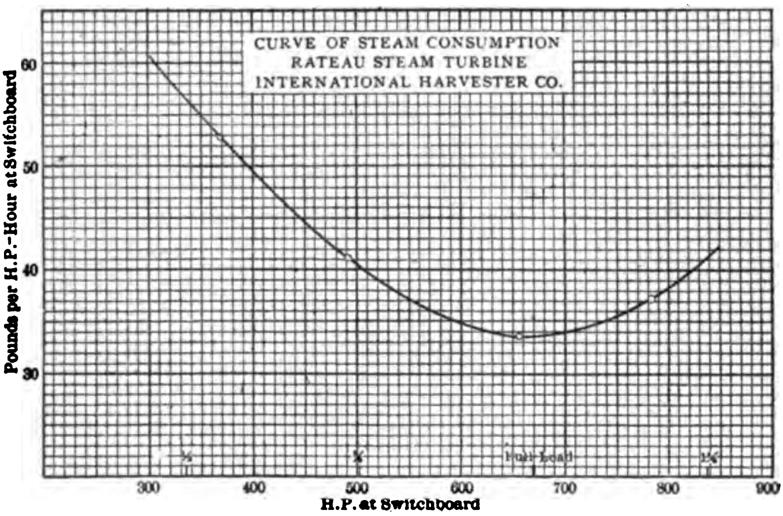
Operation. The general operation of the machines, as regards heating and sparking, is about the same as with ordinary slow-speed dynamos, although it is usual to have slightly higher temperature rises on the high-speed machine, because the losses are concentrated in such small space that it makes the ventilation of abnormal proportions to get down to the limits which are sometimes specified for slow-speed machines.

Regarding the sparking, it may be said that these high-speed machines are quite sensitive to the condition of the commutator surface, as dirt or other causes which tend to keep the brushes out of contact will induce sparking. Sometimes the same cause would not have the same effect on slow-speed machinery. In general it may be said that there is not a great deal of difference in the operation of slow- and high-speed machines.

These machines being equipped with commutating poles, with which the forces to accomplish commutation increase proportionately to the load, have an advantage as compared with ordinary machines in handling temporary overloads, as will be seen from the fact that we have a number of times carried the entire load on one machine for several hours while the other dynamo was running idle.

Condenser. The condenser and air pump are of standard type. It may be remarked that there has been no difficulty in maintaining a good vacuum in normal operation and that the plant is usually run at a vacuum of about 28 inches.

Tests. The tests of the plant have already been referred to. Table I gives the details of the observations. Fig. 11 shows a curve of the steam consumption of the turbine per electrical horse-power at the switchboard. The steam consumption was determined by temporarily putting a Venturi meter in the pipe delivering the condensing water to the condenser and measuring the temperature of the entering and discharged water, in this way using the condenser as a calorimeter to determine the heat rejected from the turbine. It may be well to point out that in order to get suitable temperature ranges and on account of other local conditions obtaining at the time of the test, the vacuums were not as high as the turbine was designed for, so that, although the steam consumption was better than the guarantees, the values given do not represent the actual capabilities of the turbine.



CURVE OF STEAM CONSUMPTION OF TURBINE

FIG. 11

Comparative power of low-pressure turbines. To those not familiar with low-pressure turbines, the query might naturally arise as to how it comes that the low-pressure turbine can get

TABLE I.—RESULTS OF TESTS OF 500-KILOWATT INSTALLATION OF RATEAU TURBINE, STEAM REGENERATOR AND GENERATORS, AT THE SOUTH CHICAGO PLANT OF THE INTERNATIONAL HARVESTER COMPANY

OBSERVED AND DERIVED VALUES	UNIT	TEST NO. 1	TEST NO. 2	TEST NO. 3	TEST NO. 4
Date of trial	1907	Mar. 11	Mar. 11	Mar. 12	Mar. 12
Duration of trial	hours	1.00	2.00	2.00	2.00
CONDENSER					
Average head on Venturi meter	inches	3.48	7.57	14.72	17.77
Average initial temp. of condensing water	° fahr.	38.40	39.30	38.90	39.55
Average final temp. of condensing water	° fahr.	80.00	68.30	61.50	66.55
Average rise of temp. of condensing water	° fahr.	41.60	29.00	22.60	27.00
Average condensing water per min	cu. ft.	151.9	192.8	247.2	295.4
Average condensing water per min	pounds	8,155.0	12,030.0	16,750.0	18,700.0
Average barometer	inches	29.6	29.6	29.2	29.2
REGENERATOR					
Average pressure at turbine, abs	pounds	16.9	16.6	15.9	15.3
Average temp. of steam at turbine	° fahr.	215.5	217.0	216.3	213.2
Average temp. of air	° fahr.	48.0	48.0	64.0	64.0
Average steam delivered per hour	pounds	19,500.0	20,220.0	22,050.0	29,280.0
TURBINE					
Average pressure above controlling valve	inches	32.9	32.4	30.93	29.75
Average pressure under controlling valve	inches	18.6	19.0	21.47	24.85
Average vacuum at exhaust casing	inches	25.31	26.6	26.95	26.40
Average revolutions of turbine ± 15 per min	r.p.m.	1,540.0	1,540.0	1,500.0	1,500.0
Average brake hp. at turbine shaft	hp.	409.0	544.0	727.0	869.0
GENERATORS					
Average ammeter readings	amperes	1,085.0	1,485.0	2,195.0	2.482.0
Average voltmeter readings	volts	245.2	246.9	233.5	238.3
Average current delivery in kilowatts	kilowatts	266.1	366.7	489.2	591.6
Average efficiency of generators	per cent.	90.2	90.2	90.2	90.2
Average hp. at the switchboard	hp.	369.0	491.0	656.0	784.0
DERIVED RESULTS					
Radiation from piping per min	B.t.u.	2,700.0	2,700.0	810.0	810.0
Heat equivalent of work done per min	B.t.u.	17,490.0	23,250.0	31,100.0	37,300.0
Heat delivered to condensing water per min	B.t.u.	339,100.0	349,000.0	395,100.0	498,100.0
Steam per min. to turbine	pounds	326.0	337.0	367.5	488.0
Steam per kilowatt-hour	pounds	73.3	55.2	45.2	49.5
Steam per hp. at switchboard per hour	pounds	52.8	41.2	33.6	37.3
Steam per brake hp. at turbine per hour	pounds	47.7	37.1	30.7	33.7

so much power out of the exhaust steam. It is quite inconvenient to show this by the ordinary pressure volume diagram, Fig. 12, but this diagram readily shows the difficulty of trying to make a piston engine utilize the expansion of the steam down to the volume realizable with the good vacuums maintained with turbines. The diagram is laid out showing the expansion of 4.21 pounds of steam, which is the average amount of steam used per stroke in the primary engine. The dotted curve shows the volume in cubic feet of this amount of steam expanding without condensation from 140 pounds gauge to atmosphere and from there down to a vacuum of something less than 28 inches, the 28-inch point being considerably off the scale of the diagram. The upper cross-hatched portion represents the adiabatic expansion of the steam down to atmospheric pressure and the lower cross-hatched portion, the expansion from atmosphere adiabatically to 28 inches vacuum. It will be seen that the areas of the diagrams, which show the theoretical power in the steam, are approximately equal.

The theoretical steam consumption of a perfect heat engine working between the limits of the absolute initial pressure P and the absolute exhaust pressure p, is given by the following formula:

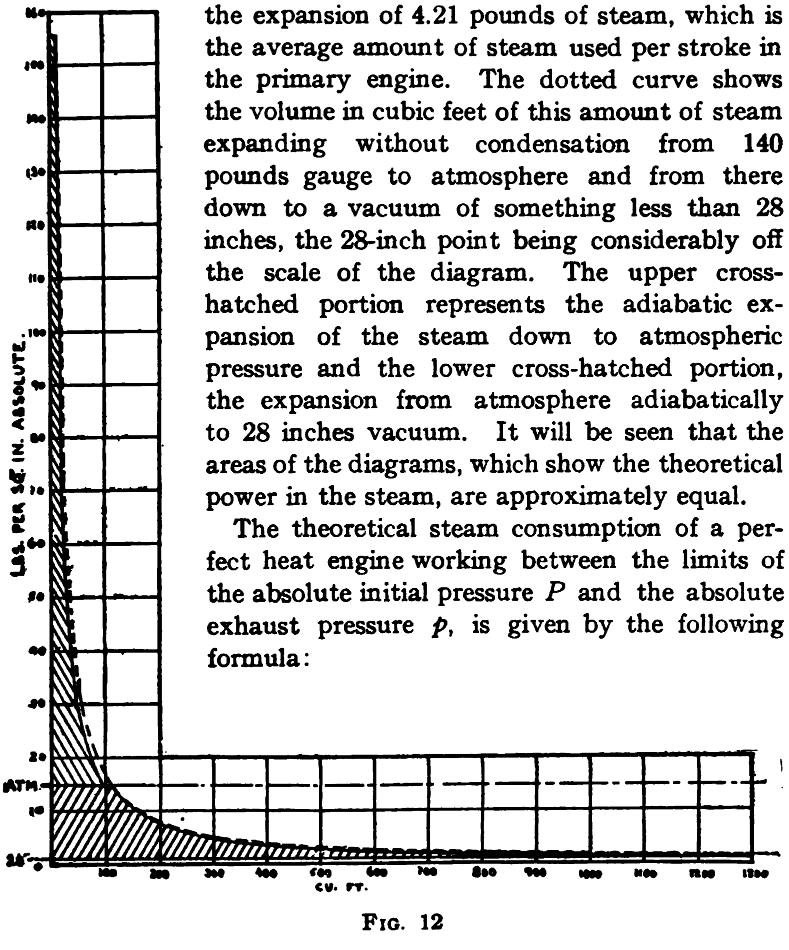


FIG. 12

$$K = 0.85 + \frac{6.95-0.92 \log_{10} P}{\log_{10} P-\log_{10} p} = \text{kg. per hp-hr. for metric units}$$

$$\text{or } K = 1.9 + \frac{17.91-2.05 \log_{10} P}{\log_{10} P-\log_{10} p} = \text{lb. per hp-hr. English units.}$$

If from this we work back and find the pressure at which a perfect heat engine would have to operate in expanding from boiler pressure down to atmosphere in order to consume the same amount of steam as a perfect engine or turbine working from atmosphere down to 28 inches vacuum, we find that the initial pressure would be about 140 pounds.

The temperature-entropy diagram shows this much better than the pressure-volume diagram. In Fig. 13 the upper cross-hatched area represents the energy available in expanding one unit of steam adiabatically to atmosphere, while the lower area shows the available energy in expanding a unit of steam from atmosphere down to 28 inches vacuum. It will be seen at a glance that the energy available in each case is the same.

Further than this, the low-pressure turbine is usually a more efficient heat engine than the primary engine; that is, it turns out a greater percentage of the power theoretically available. Thus it will be seen from the tests that the turbine in this case consumed less than 35 pounds of steam per horse power delivered at the switchboard, while the primary engine consumed 54 pounds per indicated horse power.

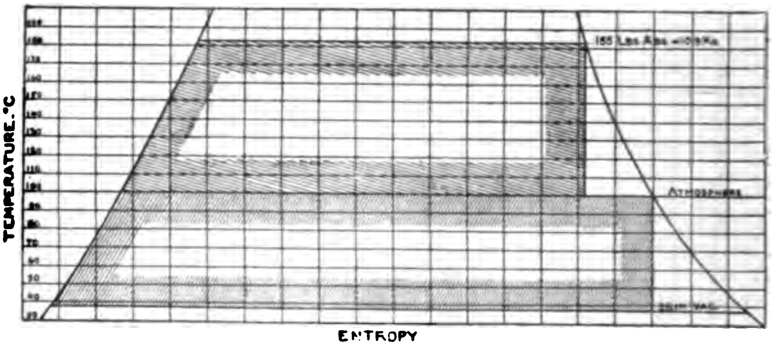


FIG. 13

Condensing engines. The query also arises how the exhaust-steam-turbine plant compares in economy with the primary engine running condensing.

In the first place, it introduces operating difficulties to run reversible engines of this character condensing. Nevertheless, they are being operated this way in a number of instances. We understand that a steam consumption of 25 pounds per indicated h.p.-hour is the best that can be obtained on a compound reversible condensing mill engine and that, when the losses in clearances, condensation, and mechanical efficiency are taken into consideration, the steam consumption per horse power at the shaft would come up to at least 38 pounds.

In comparison we can take the low-pressure turbine plant at the Wisconsin Steel Company as an example. The primary engine delivers to the regenerator an average of 52,400 pounds of steam per hour and develops 1010 indicated horse power. The tests on the turbine showed that it took 33.6 lb. per electrical horse power-hour. This would make available at the switchboard 1560 hp. or a total of 2370 hp., after deducting the engine friction, that is, 22.1 lb. of steam per total horse power at the shaft as against 38 with the condensing engine. In other words, the condensing engine would take about 70% more steam per effective horse power than the combined high-pressure engine and turbine; this result is checked by the experience at the Poensgen Steel Works at Dusseldorf, in which various engines of the plant were connected to a central condensing system which effected a saving of 15% in the amount of steam used. Afterwards one of the Rateau steam regenerator plants was installed, and the exhaust steam put through the turbines. The saving now exceeds 40% as compared with the average of a 15% saving by running all their engines into the condensing system.

The saving in this case is not as great as the example we have just cited, because the engines are not all reversible and are consequently more economical to start with.

In general, it will be found to work out that the combination of a low-pressure turbine with a high-pressure engine is a more economical unit than a condensing engine alone; and it frequently figures out to a lower steam consumption than a high pressure and low-pressure turbine or a high-pressure condensing turbine.

Degree of vacuum. An interesting problem in connection with these plants is what degree of vacuum is most economical. Where the admission pressure to the turbines is so low, the steam consumption is affected to a greater percentage by the vacuum than with high-pressure turbines. In Fig. 14, the Curve *T* shows the theoretical steam consumption per horse power of a perfect heat engine working between an admission pressure equal to atmosphere and an exhaust pressure of the various inches of vacuum set down as abscissas.

The actual steam consumption per brake horse power would be as indicated in Curve *A*, assuming a constant efficiency of the turbine over the range of the curves. This assumption is not strictly correct but is near enough so over the region of the minimum point which is what we are concerned about. It is seen that both the theoretical and actual consumption decrease very rapidly with a better vacuum, so that, for example, about 25% more power can be obtained from the same amount of steam by running at 28 inches vacuum as compared with 26 inches. On the other hand, it will be found that the horse power required to run the circulating pump and the other auxiliaries increases at a very rapid rate with the higher vacuua, although the power of the air pump decreases slightly.

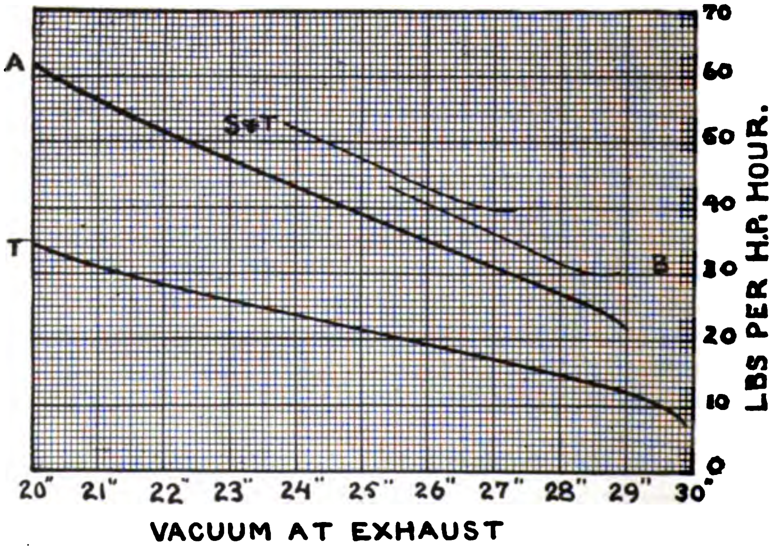


FIG 14—T = Theoretical consumption of perfect engine per horse power-hour A = Actual consumption of turbine per brake horse power-hour. B = Actual consumption of turbine per net electrical horse power-hour with barometric condenser after deducting power for auxiliaries. S and T = Consumption per net electrical horse power-hour with surface condenser and cooling tower after deducting power for auxiliaries.

In order to show the effect of the power consumed in the auxiliaries we have taken as an example such a turbine operated in connection with a barometric condenser and assumed that the circulating pump and air pump were motor-driven by current supplied from the dynamo connected with the turbine. This would not ordinarily be the method of arranging such a plant, as the turbine depends on the vacuum as its source of power and it is inconvenient to get the plant started; but such an example offers a clear way for figuring the net output of the plant.

The Curve *B* shows the pounds of steam per net electrical horse power, the power for operating the auxiliaries first having been deducted. This curve is on the basis of circulating water at 70° fahr., (which can be taken as representing average conditions) and the usual commercial forms of condenser auxiliaries. It will be noted that the curve begins to turn up at the higher vacuua instead of turning down as do the theoretical curve and the actual gross consumption curve.

In steel mills there is usually a large water system for supplying the plant, and it is generally thought best to avoid complication and supply the condensing water for the turbine plant directly from the system, without installing a separate circulating pump. The head of the water systems is usually in the neighborhood of four times the head required for the circulating pump. This extra amount of power, although not needed for the turbine plant, has to be considered in determining the most economical vacuum and has the effect of shifting the minimum point to something over half an inch lower vacuum than indicated on Curve *B*.

Where condensing water is not available, a low-pressure turbine plant can be installed in connection with a cooling-tower equipment.

Curves *S* and *T* show the steam consumption per net electrical horse power in a plant equipped with a surface condenser and cooling tower, after deducting the power which would be consumed in motor-driven air, circulating and hot-well pumps, and in the cooling-tower fan. This curve is made out on the basis of 75° temperature of the air and 70% humidity, which are taken as representing average conditions. It will be noted in this case that the most economical vacuum is practically the maximum vacuum obtainable under the conditions.

With the barometric Curve *B*, it will be noted that a higher temperature of the circulating water would move the most economical point to a lower vacuum and vice versa.

These curves are on the basis of machinery of the character under consideration. It would be well to point out that with larger turbines and with alternating-current generators, the efficiency of the generating set and also that of the auxiliaries would be increased so that the points of minimum net consumption would be shifted downwards and slightly towards the right.

These values refer to steam consumption and the real point in most cases is the minimum cost of current. The cost of current in such a plant is almost entirely represented by the interest on the investment and other fixed charges The intrinsic cost of both the turbine and the condensing equipment increases with the higher degrees ot vacuum so that these factors would tend to shift the point of minimum cost of current a slight amount to the left

Practical results. The general result of the installation of this low-pressure turbine equipment is that it enabled the mill to shut down the two 250 kilowatt engine-driven generators which formerly operated the mill and for a long time the turbine carried the entire electrical load of the steel mill, operating from the exhaust of the blooming engine and not taking any live steam except during abnormal stoppages of the blooming engine.

Recently they have installed some electrical unloading machinery on their docks When this machinery is all in operation the load frequently runs up above the ultimate capacity of the turbine and they have to start up one or more of the engines and run in parallel with the turbine.

The attendance and lubrication items for the turbine plant are very small The turbine is located near the blooming engine, while the other generators are located in the blowing-engine house about a quarter of a mile away. There is but one attendant on duty in the turbine engine room.

At this plant the boilers are supplied principally by gas from the blast furnace, but the supply of gas is quite variable and usually not adequate to give all the steam required, so that more or less coal has to be used. The installation of the turbine, therefore, results in a saving of the coal corresponding to the steam required for operating the dynamo engines. This, as indicated above, is quite a variable quantity but has been variously estimated at from $10,000 to $20,000 per year. In figuring on the installation of the turbine plant, it was estimated that the turbine would effect a considerable saving, even if the supply of gas were generally adequate, as the maintenance of the turbine plant would be considerably less than the corresponding engine and boiler plant, or even a gas-engine plant.

Further, it is well to remember that exhaust steam passing to the atmosphere can be looked upon as the equivalent of a water-power plant and that it usually has the advantage of being near a market for power, besides costing less to develop than a water-power plant would. In other words, the exhaust-steam plant should be able to produce the power cheaper than a corresponding water-power plant.

Cost of power. During three months when the steel plant was running at nearly full capacity. the turbine delivered an average of 188,300 kw-hr. per month, or 51% of the total possible kilowatt-hours if run at its rated load the entire time.

The operating expenses are at the following rates, based on the above output:

Oil, waste, etc.	0.002	cents per kilowatt-hour
Attendance	0.074	" " " "
Maintenance and miscellaneous	0.011	" " " "
Total operating	0 087	" " " "
Fixed charges	0.212	" " " "
Total cost	0.299	" " " "

The fixed charges are figured on the basis of a cost of $80 per kilowatt. This figure would, of course, vary considerably with the conditions, but it can be taken as an average for moderate-size plants. Interest, depreciation etc. are allowed for at 12%. Nothing is allowed for superintendence, as no additional force is required for this item.

The cost being made up so largely of fixed charges, it varies very markedly with the load-factor. In fact, if the plant is run 24 hours a day, the lubrication, attendance, and maintenance are only affected to a slight extent by the amount of load, so that they have almost the same effect as a fixed charge. Of course if the plant were run only during the day shift the operating expenses would go down

The effect of the load-factor on the cost is seen in Fig 15, the load-factor here being taken as the ratio of the actual output, divided by the output if run the entire time at rated load

Metallurgical operations. It will be noted that the cost of power at the larger load-factors is extremely low and would be even more so in a larger plant where the first costs and the other costs would go down considerably

If the exhaust steam turbine plant were used for electric smelting or similar purposes, it is probable that the load-factor could be kept up over 80%, which we see from the curve, gives a cost of 0.19 of a cent per kilowatt-hour.

It might be remarked that the electric smelting processes take, on a very crude average, one kilowatt-hour per pound of metal produced. It will therefore be seen that such plants offer a good opportunity for doing certain kinds of metallurgical or similar work.

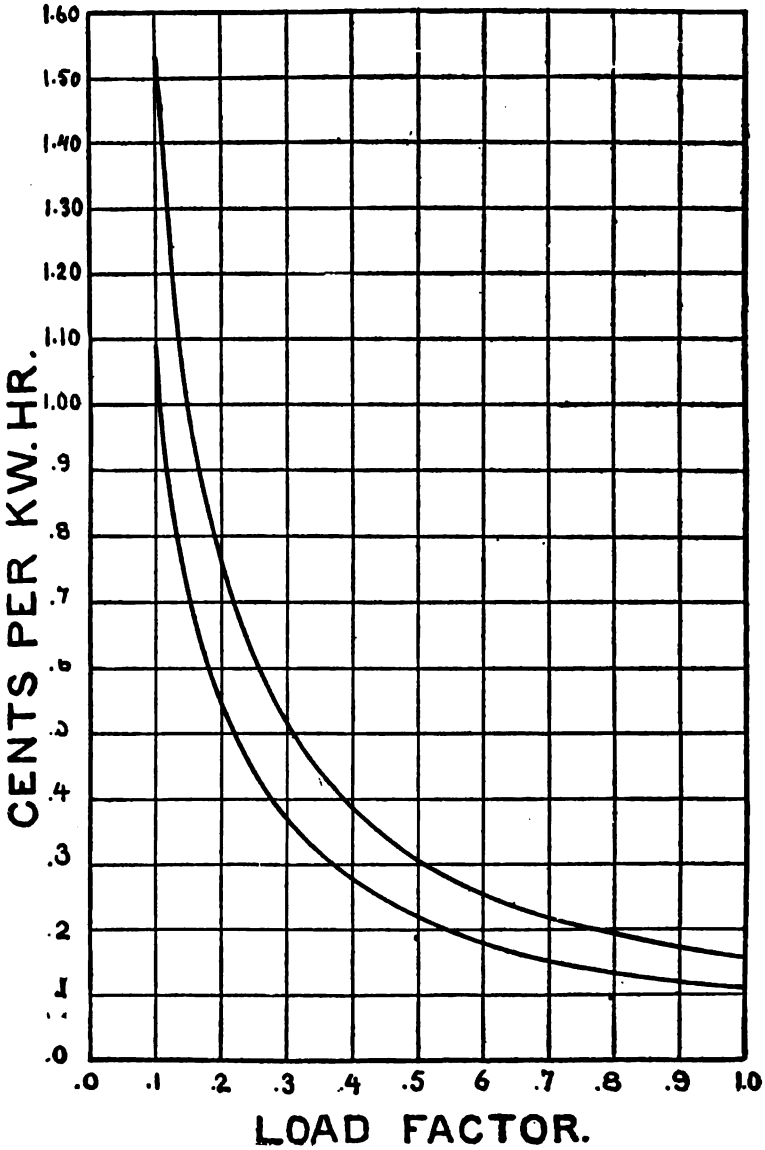


Fig. 15

In the foregoing no value has been assigned to the exhaust steam. In most places where such exhaust steam occurs, there is not a good opportunity to utilize any considerable portion of it in any other ways, so that it would otherwise be a waste product. In case of selling power, it will be seen that either the steam itself or the current produced could be profitably sold to outside parties.

Under these conditions the question of the continuousness of the power would arise. Of course when the primary engine shuts down for more than a few minutes, there is a tendency for the boilers to blow off at the safety valve, so that for short periods it does not mean any more fuel, even if the primary engine is stopped. If the primary engine is stopped altogether, the boilers stand ready to furnish the steam to the turbine and the latter would consume approximately the same amount of steam as non-condensing engines would. If this condition of running with live steam were one that would occur for a considerable time, it would be advisable to install a mixed high-pressure and low-pressure turbine; that is, one which would have a high-pressure section which is automatically fed with high-pressure steam whenever this becomes the normal source of steam. Such plants as this are already operating in a number of places where the primary engine runs only during a day shift and it is necessary to have the electric power day and night.

Field of usefulness. The foregoing remarks apply more particularly to the conditions in a steel plant, but similar conditions occur with large mining hoists; of course any other source of exhaust steam, whether intermittent or not, can be utilized in similar fashion. It has been already pointed out that a great saving can be effected in connection with continuous-running engines, and that such a system can be used to increase the power of such engines and that, even when run condensing, the power and total economy can sometimes be increased by combining a low-pressure turbine and engine.

DISCUSSION ON "AN EXHAUST STEAM TURBINE PLANT", AT NEW YORK, DECEMBER 13, 1907.

Francis Hodgkinson: The combination of a turbine utilizing steam at atmospheric pressure in conjunction with a reciprocating engine is by no means new, although the one described is probably the first installation in this country of such apparatus in conjunction with a Rateau heat accumulator. However, leaving out any value there may be in the heat accumulator, there is no doubt that power plants now operating non-condensing and requiring increased capacity would do well to obtain it by low-pressure turbines so long as means of condensing the exhaust steam are available within reasonable expense. There are many power plants employing high-grade compound reciprocating condensing engines where the total expansion is such that the engines have a higher efficiency ratio when operating non-condensing (efficiency ratio, not steam economy), than when operating condensing. In making this statement I have more in mind high-grade engines for modern power plants, than such prime movers as blooming-mill engines where the expansion when exhausting even to atmosphere is somewhat incomplete. The power-plant engineer, therefore, should not expect to make the large percentages of increase in economy that the author cites in the case of the Wisconsin Steel Company, and the Poensgen steel works, at Dusseldorff.

In the case of the Dusseldorff installation, presumably most of the engines were simple engines, if compounded at all, it was probably with low cylinder ratios. Hence, merely turning the exhaust from these into a condenser would not make material difference in the steam consumption; but exhausting them instead through a low-pressure turbine, and thence into the condenser would, if the power from the turbine be made use of, cut the steam consumption per unit of power to about one-half what it was before.

Low-pressure turbines are not only applicable for working in conjunction with non-condensing reciprocating engines in which the steam expansion is incomplete, but just as much in conjunction with engines designed for operating condensing. A low-pressure turbine can, furthermore, just as well be designed to operate at less than atmospheric initial pressure, should the performance of any given high expansion ratio reciprocating engine show a higher efficiency ratio when exhausting at some pressure less than atmosphere.

One obvious reason for the beneficial results of low-pressure turbines is due to the large temperature drops as low steam pressures are reached, which in the low-pressure cylinder of the reciprocating engine are harmful because of condensation and re-evaporation as the cycles are reversed. This objectionable condition does not exist in the low-pressure turbine.

As an instance of the advantage of low pressure turbines, assume a compound reciprocating engine of cylinder ratios of 3.5 : 1, say of diameters 28 in. and 52 in.; this with 150 lb. initial pressure may be assumed of 1000 kw. economical capacity when running condensing and having a steam consumption of about 22 lb. per kilowatt-hour. This engine, if operated non-condensing, could have valve gears adjusted to develop 1700 i.h.p. when it would consume about 20 lb. of steam per i.h.p. per hour. This gives 30,600 lb. steam available for the turbine, allowing 10 per cent. of moisture in the exhaust of the reciprocating engine. The total amount of steam passing the reciprocating engine, however, being 34,000 lb. 30,600 lb. would develop not less than 1,073 brake horse power in the turbine. Allowing 94 per cent. for the mechanical efficiency of the reciprocating engine, the combined horse power developed would be 2673 brake horse power and the steam consumption of the two units 12.7 lb. per brake horse power-hour, or 18 lb. per kilowatt-hour, which is a remarkable performance for engines of such capacities operating without superheat. Compared with the performance of the reciprocating engine running condensing, this gives 75 per cent. increase of power and 18 per cent. saving of steam.

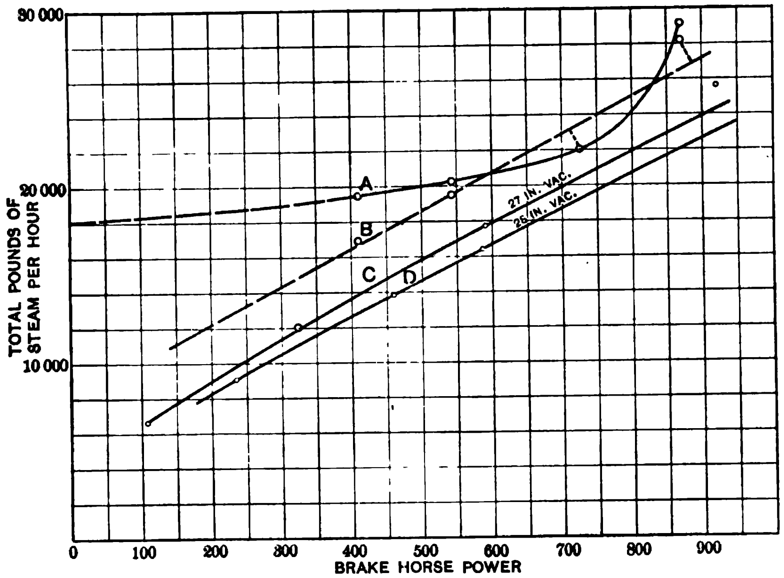


Fig. 1

One very nice feature of low pressure turbines when used in conjunction with reciprocating units where the electric energy from each may be connected to the same bus-bars, is that the turbine need have no governor other than a safety stop. In the case of alternating-current generators, they are locked together, electrically, the steam turbine doing all the work that it can within its pressure limits and in the event of the load becoming light, the available steam will be proportionately reduced by the governors on the reciprocating engines. In the case of direct current units the generators may be shunt wound, which makes them self-regulating in a precisely similar manner, inasmuch as the voltage varies nearly directly as the speed, and the load will divide itself properly between the reciprocating unit and the turbine.

A low-pressure turbine built for such purposes naturally contains very few rows of blades as compared with ordinary turbines, the volume of steam being large permitting generous blade proportions and having neither regulating valve nor governor mechanism, must commend itself as the simplest kind of apparatus imaginable.

Examining the tests which Mr. Wait quotes in detail, we find that the curves show the steam consumption per brake-horsepower per hour. The general characteristics of a turbine are, however, much better exhibited by a curve of total steam consumption; to show it in this case, I submit Fig. 1 where the total steam consumption per hour is shown by curve *A*. It is unfortunate in the tests quoted by the author, that the vacuum was not maintained constant at the various loads, for the line of total steam consumption is very much curved. It is the writer's experience that the line of total steam consumption for low pressure turbines is a straight line, just the same as it is in the case of standard condensing turbines. Of course had the vacuum been kept constant the curve would have been more nearly a straight line. Correcting this curve to constant 27 in. vacuum in accordance with the writer's experience with varying vacuum, indicates the performance of the low pressure turbine to be about as curve *B*.

We note in the tests, the generators have been assumed to have constant efficiency at all loads tested.

Some tests on a low pressure turbine made recently gave the following results:

Steam pressure pounds per square inch absolute. Dry and saturated steam	Vacuum in exhaust inches mercury, referred to 30 in. barometer	Load in brake h.p.	Total steam per hour	Steam consumption brake h.p. hour
17.4	25.98	920	25670	27.9
12.4	25.99	472	17487	37.1
11.8	26.97	592	17720	29.9
7.7	27.03	321	11980	37.3
5.2	26.98	102	6570	64.4
11.6	27.8	586	16400	28.00
8.7	28.00	458	13920	30.4
6.1	27.90	234	9036	38.6
4.5	27.90	114	6248	54.8

It will be observed from the above table that various loads were carried at constant vacuum, and sets of tests were also made with different vacuums. In these particular tests high-pressure steam was used, but care was taken to inject enough water to reduce the superheat at the inlet pressure to zero The results of two of these sets of tests: namely, at 27 in. and 28 in. vacuums, are shown in Fig. 1 and from these were deduced the corrections to constant vacuum which I have applied to the author's test.

Another turbine built to operate in connection with high-pressure reciprocating engines gave the following result in shop test:

Initial steam pressure, 15 lb. absolute.
Superheat 40° fahr.
Vacuum referred to 30 barometer—23 in.
Load 1500 brake h.p.
Pounds steam per brake h.p-hr. 35.5.

In all these tests the exhaust was condensed in a surface condenser, which assures accuracy in measuring the steam consumption.

The author makes some remarks on the subject of condensers as applied to low-pressure turbines and endeavors to show what vacuum it is most expedient to carry with different conditions of temperature, etc. He draws his conclusions largely from the power required to operate the condenser, which he assumes to be motor-driven. Except when motor-driven, the power required to operate the condenser does not necessarily have much bearing on the case. There are many reasons why it is preferable, as is customary in this country, to operate condensers by means of non-condensing steam engines, the exhaust of which is condensed in feed-heaters. So long as this steam is utilized, the thermal efficiency of the engines will be something like 87 per cent., as has already been pointed out by Mr. H. G. Stott, in his paper on " Power Plant Economics ", so that where the exhaust steam is thus profitably used the amount of power required to operate the condenser is almost immaterial.

It is unfortunate we are not given more information regarding the performance of the heat accumulator, especially as to how much energy it is capable of storing up and giving out. We calculate from the published description that the regenerator has normally 100,000 lb. of water in it. Mr. Wait says it blows to atmosphere at three pounds gauge pressure, 222° fahr. The reducing valve admits live steam at atmospheric pressure 212° fahr. and that the regenerator normally works between these limits. This gives a temperature range of 10° and Mr. Wait says the turbine will carry load for 7 min. without exhaust steam from the reciprocating engine or the admission of live steam. With this range of temperature, the regenerator will take up and give out 1,000,000 B.t.u. the equivalent of

$$\frac{1,000,000}{961.8^*} = 1040 \text{ lb. of steam.}$$

which will run the engine $\frac{1040 \times 60}{27,000} = 2.31$ min.

27,000 being the assumed steam consumption of the turbine. The other 4.69 min. to make up the 7 min. quoted by Mr. Wait, requiring 2110 lb. of steam would be accounted for if there were 280,000 cu. ft. contents in the receiver, steam space of regenerator, piping, etc.

I should think that better results would be obtained from the regenerator by having the turbine large enough to carry its load without the reducing valve having to admit live steam until the temperature has fallen to, say 180°, when something like three times the heat will be absorbed and given out by the regenerator.

J. R. Bibbins: It is interesting to note that the steam velocities are reduced to so a low point by subdivision of the expansion into a large number of stages, that no appreciable erosion has resulted from moisture in the steam. This, of course, is an extremely desirable feature, particularly for a low-pressure turbine in which the maximum amount of suspended moisture is found, as compared with the high-pressure element of a complete machine. In a standard complete expansion turbine operating on superheated steam, the so-called " dew point " where moisture begins to appear, may not occur until a considerable number of expansion stages have been transversed by the steam; so that while part of the high-pressure section of the turbine runs in superheated steam, the steam traversing the low-pressure section increases in moisture more or less approximating the adiabatic law. For instance, assuming ideal adiabatic expansion between the limits of 165 lb. absolute and 28 in. vacuum, the moisture in suspension would gradually increase to about 23 per cent. In practice, however, internal heat interchanges, considerably reduces this moisture, perhaps as much as 50 per cent. Thus, the low-pressure turbine is obliged to work with steam containing large amounts of moisture, and the necessity of low steam velocities is apparent, not only as affecting depreciation, but also efficiency.

In actual installations of low-pressure turbines, it is possible to trap out some of the suspended moisture in the engine exhaust and deliver steam approaching a dry saturated condition to the turbine. Here the average moisture encountered in the low-pressure turbine would evidently be lower than in the corresponding expansion stages of a complete expansion turbine operating on saturated steam. Or a heating chamber might be introduced between engine and turbine for the purpose of com-

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* 961.8 is taken as the mean heat of evaporation between steam at 212° and 222°.

pletely drying, or slightly superheating, the low-pressure steam. Owing to the low temperatures at which this could be accomplished, it is possible that some of the waste products of a factory or power station might be utilized to good advantage—hot gases from heating furnaces, possibly boiler-flue gases, in cases where underground flues were employed leading to the chimney.

Although it is true that the impulse or velocity type of turbine may have as large peripheral clearances as desired around the bucket-wheels, it must not be inferred that correspondingly small clearances at the shaft are not necessary to prevent the leakage of steam between the various pressure stages, also that the side clearances between the buckets and nozzles must be small, while in the reaction or pressure type turbine the side or axial clearances may be made as large as desired without affecting the efficiency, owing to the fact that the entire steam space or annulus surrounding the rotor is always filled with working steam.

As low-pressure turbines are usually started under vacuum, provision must be made for flooding the water packing until the turbine picks up its speed sufficiently to provide its own water-seal. This, of course, is easily accomplished from the ordinary water service pressure; otherwise, the vacuum would be seriously interfered with by the air leakage.

A paper presented at the 223d Meeting of the American Institute of Electrical Engineers, New York, December 18, 1907.

A NEW CO_2 RECORDER

BY C. O. MAILLOUX

In the very valuable paper on " Power Plant Economics," presented before this Institute, Jan. 26, 1906, by Mr. H. G. Stott, (Trans. Vol. XXV, pp. 1-27), attention was called to the utility of records of the percentage of CO_2 (carbonic dioxide) present in the flue gases of a boiler plant, as a means of determining and of preventing those fuel losses which might be termed " avoidable ".

Mr. Stott's paper contains curves and data which show quite conclusively that there is an important and close relation between fuel-economy and the percentage of CO_2 contained in the flue-gases. In analyzing the average loss incidental to the conversion of the energy of a pound of coal into electrical energy, he finds, in the case of one of the most efficient plants in existence, that the " loss to the stack " amounts to 22.7 per cent. It is well known that in the majority of cases this loss exceeds 30 per cent. Mr. Stott refers to a case where the loss was approximately 40 per cent. of the thermal value of the coal. The utility of CO_2 records, as a means of locating the " leak ", in a case of this kind, is made apparent by the following statement, quoted from Mr. Stott's paper:

" Fig. 2 shows what improvement may easily be obtained by watching the CO_2 records, and indicates a saving of about 19 per cent. over the previous case."

In the time which has elapsed since the reading of Mr. Stott's paper, the importance of " watching the CO_2 " has been demonstrated in hundreds of cases, here and abroad, in a manner which no longer leaves room for doubt. As an example of a recent appreciation of the utility of complete knowledge of the CO_2, in flue-gases, the following emphatic statement is of interest:

" It cannot be too strongly impressed upon the power-plant owner that CO_2 is the factor upon which depends his very existence under any circumstances of real competition ".

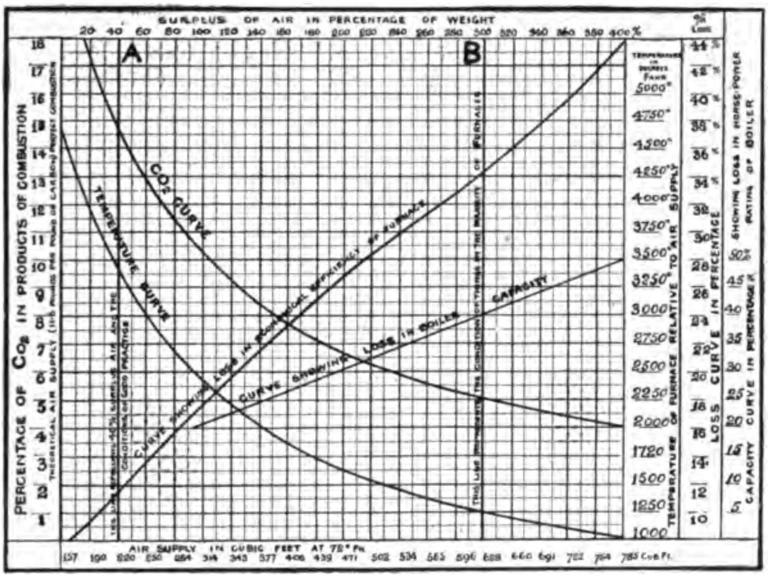
This statement is made by Mr. W. D. Ennis, a leading authority on fuel-economy. It is quoted from the ***Engineering Magazine*** of June, 1907, containing the first of a series of articles by him, on " Efficiency in Fuel Burning ", in which the entire subject is treated exhaustively. Many other citations to the same effect could be made. These will suffice to demonstrate the desirability of CO_2 records, and of satisfactory apparatus for obtaining such records, in the boiler room. Incidentally, they call attention to two sources of reliable information regarding the scientific (chemical and physical) principles on which the value of the percentage of CO_2 as a criterion of the efficiency of a steam boiler depends.

It is not within the scope of this paper to enter into a detailed discussion of these principles. For our purpose, a sufficient idea of these principles and of their consequences may be obtained from the graphical " summary " or " resumé " of them indicated by the curves in Fig. 1, which were prepared and placed at the disposal of the Institute by Mr. H. J. Westover, the inventor of the present CO_2 recorder. The ordinate values of the different curves, at the points where these curves intersect the vertical line *A*, when interpreted by reference to the proper scales of values, represent the condition of " good " practice. The vertical line *B* marks, in the same way, the conditions of " bad " practice.

The average working conditions and the economic results attained, in the majority of steam plants, are such as would correspond to a characteristic vertical line located somewhere between the vertical lines *A* and *B*—as a rule, nearer *B* than *A*. In a few " glorious " examples, that characteristic line is at the *left* of the line *A*. In many " horrible " examples it is at the *right* of the line *B*.

We see, at a glance, in Fig. 1, that high efficiency corresponds to high percentage of CO_2, in the flue-gases. We also see that the falling off in percentage of CO_2 and in the fuel efficiency, is due primarily to *excess* of air. From this, it becomes obvious that the percentage of CO_2 present in the flue-gases, being influenced directly and solely by the conditions of combustion of the fuel, can serve as a criterion of the performance and efficiency of the boiler plant, and as a means of detecting defects and of suggesting improvements in its operation.

This has been known more or less generally, for a long time, and it has been the practice of many experts to make chemical analyses of the flue-gases in connection with boiler tests. The oldest and most widely known form of apparatus used for this purpose is that of Orsat. Since a knowledge of the principle of this apparatus will be of assistance in understanding the operation of a new form of CO_2 recorder to be herein described, a brief reference to it will be made.



Ex. CO_2 14½ shows 36% surplus air with 11½% loss representing 88½% furnace efficiency
CO_2 5 shows 300% surplus air with 34½% loss representing 65½% furnace efficiency

THE DIFFERENCE BETWEEN USUAL AND GOOD PRACTICE IS 22½%

FIG. 1

The Orsat apparatus is represented diagrammatically in Fig. 2. The movable vessel *E*, of glass, containing water, is connected by a flexible (rubber) tube, *F*, with a stationary vessel *G D*, of glass, of the general form shown, having graduations at the upper part of the tubular portion *G*, and connecting, by a small tube, *C*, with a three-way coupling in which are valves or stop-cocks, *A*, *L*, and *M*. The cock *L* controls a connection leading to a receiving vessel *H*, filled with small glass tubes, and connected, at the bottom, by a bent tube, with a supplemental receiver, *I*, which is open to the atmosphere, at the top. The liquid put in the vessels *H* and *I* depends on the particular gas which is to be analyzed. When the apparatus is to be used for determining the percentage (by volume) of CO_2 in flue-gases, the liquid put in these vessels consists of a solution of caustic soda,

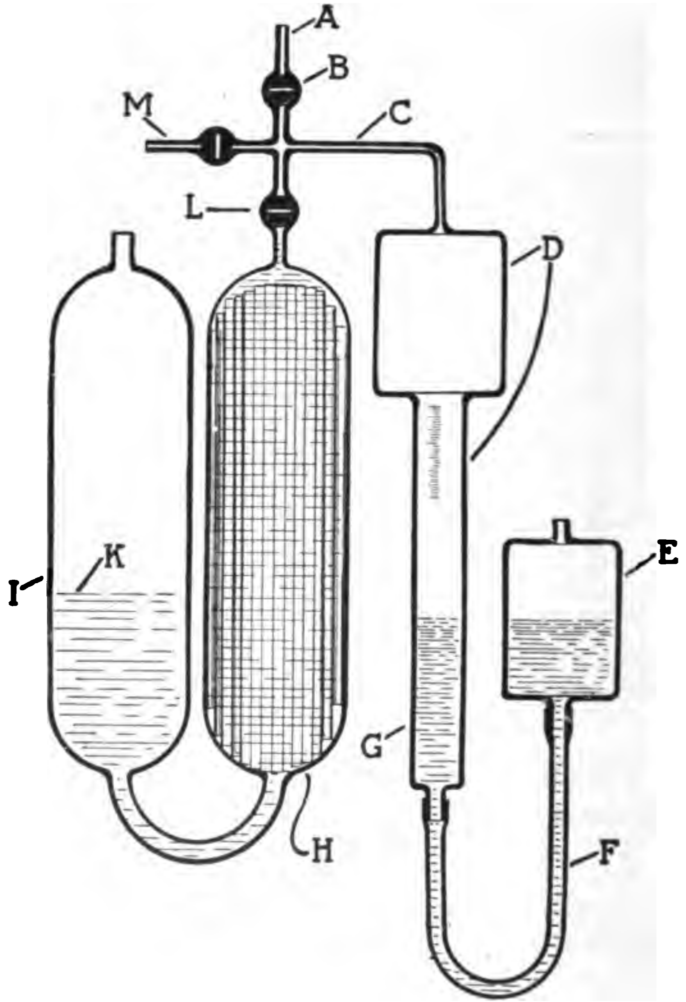


Fig. 2

or caustic potash. The process of making an analysis comprises various manipulations which must be made in proper order, with a certain care, each requiring a certain time. The cocks *M* and *L* being both closed, the cock *B* is opened, leaving a free passage from the receiver *D* to the atmosphere. The movable vessel *E* is then raised, causing the level of the liquid to rise in the vessel *G* and the liquid to fill the portion *D* as far as the small tube *C*. The cock *B* is then closed, and the cock *M*, controlling the connection with the supply of gas, is opened, allowing the gas which is to be analyzed to enter. The vessel *E* is now lowered; and the gas enters and fills the vessel *D* and a part of the vessel *G* as far as desired. The exact quantity of gas allowed to enter is controlled by the position of the movable vessel *E*, which is adjusted carefully, so as to bring the level of the liquid in *G* to a certain mark, corresponding to a definite volume, say 100 c.c. of gas. The cock *M* is then closed and the cock *L* is opened. The vessel *H* is normally left filled with the absorbent liquid, at the end of the preceding test. Therefore, on opening the cock *L*, this liquid begins to fall, in *H*, and the gas begins to enter. The movable vessel *E* is now raised again until the gas has been entirely forced out of the vessel *D* by the rise of the liquid in *G* and *D*. The gas enters the vessel *H*, forcing down the absorbent solution, which is displaced into the vessel *I*. The glass tubes in the vessel *H* present a greatly increased surface, wet with the caustic soda or potash solution, whereby the chemical reaction on which the analysis depends is expedited. This reaction is the absorption of the CO_2 gas contained in the sample of gas forced into the vessel *H*, and its combination with the soda or potash contained in the solution, to form a " carbonate ", of soda or potash, which remains in solution. The volume of the gas in the vessel *H* is diminished in proportion to the amount of CO_2 abstracted from it by this chemical reaction. After a certain time, sufficient for the reaction to be practically ended, the movable vessel *E*, which was held at its upward position during the time allowed for the reaction to take place, is lowered, causing the residue of gas to return into the vessel *D*. The vessel *E* is lowered until the liquid in *H* rises and fills the vessel to the top as far as the cock *L*. If the sample of gas contained no CO_2, it will not have been reduced in volume when it returns into the vessel *D*; and the level of the liquid in this vessel will be at the same mark as it was before the gas was sent into the vessel *H*. If the gas contained CO_2, the volume returned from *H* to *D* will be smaller than it was before; consequently, when the "residue" has all passed out of *H*, the liquid in *G* will stand at a higher mark than before. Suppose, for example, that the initial volume was 100 c.c. and that the residual volume is found to be 92.5 c.c. Then, the percentage (by volume) lost, in passing through the vessel *H*, was $= 100 - 92.5 = 7.5$ per cent. Since the loss in volume was due to the absorption of CO_2 only, it follows that this sample of gas contained 7.5 per cent. of CO_2. If the residue is not to be subjected to further analysis, the cock *B* is opened and the gas is forced out at *A*, by raising the movable vessel *E* and filling the vessel *D*, as before. If it be desired to analyze the residue for some other gas, say oxygen, for example, the pipe *A* is connected with another vessel similar to the vessel *H* and containing a chemical reagent which can absorb the gas whose percentage is to be determined. The reagent used for the oxygen analysis is pyrogallic acid dissolved in a solution of caustic potash. The operation is conducted in substantially the same manner as for the estimation of the percentage of CO_2. The residue of gas is returned to the vessel *D*, its volume is measured, and the loss of volume, if any, is noted, as before. Suppose the volume be now found $= 90$ c.c. Then the percentage of oxygen which was present in the gas was $92.5 - 90 = 2.5$ per cent. A third analysis may serve to determine the percentage of CO (carbon monoxide), present in the sample. The reagent then used is cuprous chloride, dissolved in hydrochloric acid. The residue left after this determination will be substantially all nitrogen. From the data thus obtained it is possible to determine the percentage of CO_2, O, CO, N, and of air, contained in the flue gas.

Various other forms of apparatus for gas analysis have been devised and are known under different names, such as the apparatus of Wilson, Elliott, Hempel, etc.

(Further details and also some bibliographical references concerning methods of flue-gas analysis will be found in Carpenter's "Experimental Engineering", Chapter XIV.)

These different forms of apparatus are all, in reality, transplantations from the chemical laboratory, modified and simplified as far as practicable, to render them more transportable, and more suitable generally, for the purposes of flue-gas analysis. They are only intended and, obviously, would only be suitable, for the purpose of making a few analyses at a time, under "laboratory" conditions.

In order that the results of flue-gas analysis may be of service in the operation of a steam boiler plant, it is necessary that these analyses should be obtained under conditions which satisfy certain indispensable " practical " requirements, including the following: 1st, the apparatus should work automatically, without more care and attention than any ordinary apparatus of " mechanical " character;

2d, it should give results (analyses) quickly and regularly;

3d, it should give a visual indication and record of all the results.

For the purposes of information and guidance, in regard to the economic operation of an average boiler plant, it is not necessary that analyses should be made of *all* the constituents of the flue-gases. This would require a too much complicated apparatus, and would lengthen too much the time required for each operation. Practically, the determination of the percentage of CO_2 is all that is required.

Various forms of automatic CO_2 recorders, which meet the above requirements more or less satisfactorily, have been devised and have been put into commercial use, during the last three or four years. Although some of these CO_2 recorders have done and are still doing good work in many cases, their applicability and usefulness in other cases have been restricted by the presence of conditions and the absence of features which rendered modifications and improvements very desirable.

The present CO_2 recorder, which has recently been perfected, is the result of careful analysis of all the requirements and of a critical study of the weak points and drawbacks of all the preceding forms of CO_2 recorder. The new features especially desirable from the point of view of the boiler room manager are: 1st, to make the apparatus more " rugged " mechanically, and, consequently, less liable to break down or derangement from mechanical causes; 2d, to do away with the necessity for any technical knowledge or skill, and to reduce to a minimum the amount of ordinary care and attention, necessary to keep the outfit in good operative condition; 3d, to reduce to a minimum the time required for each analysis and to increase as much as possible the total number of analyses obtainable per hour; 4th, to increase the accuracy of the apparatus by eliminating all errors due to variations of the temperature, of chemical composition of the reagent, or of barometrical pressure; also all errors due to frictional resistance in the recording mechanism;

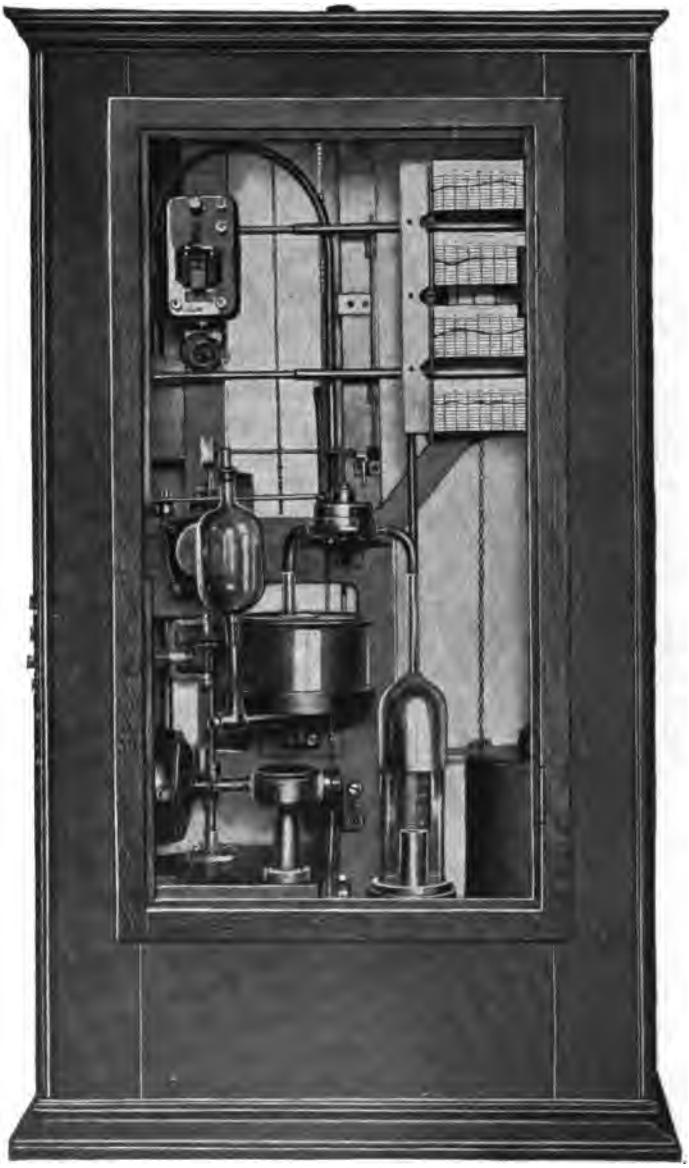


Fig. 3

5th, to make the same apparatus give CO_2 records for several boilers, thereby reducing the cost of equipment per boiler.

Fig. 3 shows this CO_2 recorder arranged to give CO_2 records for a battery of four boilers. Fig. 4 is a theoretical diagram of the apparatus.

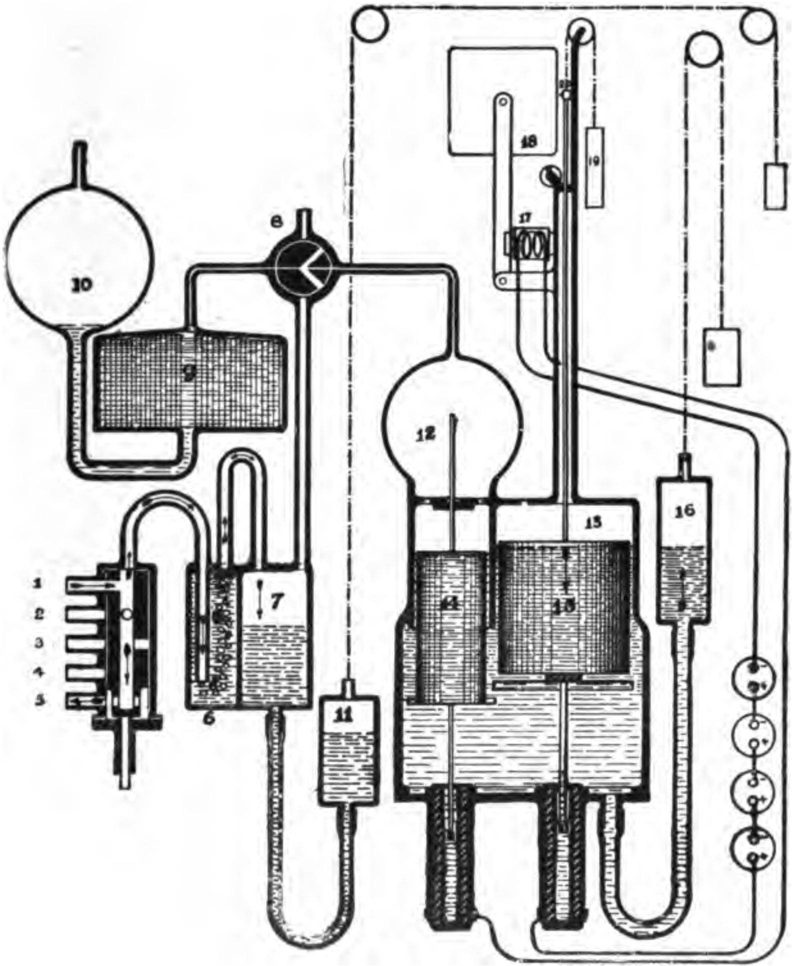


FIG. 4

Each complete analysis of a sample of gas comprises, in this case, a succession of steps or a cycle of operations very similar to those described in connection with the Orast apparatus. All the manipulations are made automatically the work incidental thereto being done by a small constant-speed electric motor partly visible at the lower left hand portion in Fig. 3. This motor drives, through suitable speed-reducing gearing, the mechanism by which all necessary movements of valves, liquids, recording devices, etc., are effected and controlled, in systematic manner.

The function of the movable vessel *E*, in Fig. 2, is performed, in this case, by two movable vessels (11 and 16, Fig. 4), which are counterweighted and which are raised or lowered or held stationary at certain positions and at certain times, by means of ingenious cam-actuated devices driven by the electric motor. One of the movable vessels, 11, serves to displace the sample of gas when it is first received from the boiler-flue. The other movable vessel, 16, serves to displace it during the operations of measuring, " treating ", and remeasuring the gas.

In a case such as indicated in Fig. 4, where the CO_2 recorder serves four boilers, a pipe must be run from the flue of each of these four boilers to the " selector " shown in Fig. 4, at the left side. This selector is provided with a small steam injector and with four valves so operated that only one is open at a time. In Fig. 4, the valve of the " sampling " pipe from boiler No. 1 is shown open, the other valves being closed. The injector causes a stream of gas to be drawn from the particular sampling pipe which happens to be in connection with it, and to flow through the selector and out through the exhaust pipe 5. This insures a rapid motion of the flue-gas in the sampling pipe and, therefore, enables a " sample " of flue gas to be drawn directly from the boiler flue at the very time when it is to be used. The opening of the valve of each sampling pipe is so " timed " by the motor-driven mechanism, that it occurs some seconds before the sample is taken for analysis, thereby allowing the sampling pipe to be first cleared of " stale " samples. This feature overcomes one of the objections which has been found hitherto, namely, that the CO_2 records are sometimes several minutes " behind time ", especially when the sampling pipe is of considerable length. In this case the sample is taken into the recorder, through the receiving vessel, 7. Before the sampling pipe is " cleared ", the movable vessel 11 is raised to its highest position by the action of the cam, thus causing the liquid to fill the vessel 7 and empty it of all gas. When a new sample is to be taken, the vessel 11 descends, causing the liquid in vessel 7 to lower, and consequently, causing a certain volume of gas to be " aspirated " from the selector into vessel 7. This gas is prevented from leaving the vessel 7 by the sealing action of the liquid in the pipe connecting with the selector.

When the vessel 11 has reached its lowest position, it remains stationary, during an interval of time sufficient to allow the valve 8 to be opened by the motor-driven mechanism, and to make connection between the vessel 7 and the measuring vessel 12. The vessel 11 is then caused to rise by the action of the motor-driven cam; the liquid rises in vessel 7 and forces the gas into the measuring vessel 12. The capacity of vessel 7 being from four to six times greater than that of vessel 12, there will be more gas than is necessary for one analysis. The pressure produced by the rising of receiver 11, and the rising of the water level in vessel 7, tend to force the liquid into measuring vessel 12. This pressure would, obviously, compress the gas, were it not that room is made for the gas by the lowering of vessel 16 (which then occurs by the action of the motor-driven cam), and the consequent lowering of the liquid in space 14, until the liquid is about half an inch below the mouth of the measuring vessel 12. Consequently, the surplus gas can escape freely through the vessel 13 and through the vent pipe to the atmosphere or to an exhaust pipe. The vessel 16 remains stationary at its lowest position for a brief interval, during which the valve 8 is moved so as to close the connection between 12 and 7 and open the connection between 12 and 9. The displacement vessel 16 then begins to rise. The consequent rise of the liquid and of the " float " 14, in measuring vessel 12, causes the gas therein to be imprisoned or sealed. The further rise of the displacing vessel 16 and the further rise of the liquid at 14 now cause the liquid to rise in the measuring vessel 12, and the gas to be displaced out of the said measuring vessel, through the valve 8 into the caustic potash vessel or " treating " chamber 9. The liquid in vessel 9 is displaced to make room for the gas, the excess of liquid being forced into the supplemental receiver 10. The chamber 9, being of relatively large diameter and filled with iron-wire netting, presents, as the level of the liquid in it is lowered, a very finely subdivided chemical surface which is wet with the chemical reagent (caustic soda or caustic potash). The amount of surface exposed is approximately 40 times greater than the area of cross-section of the vessel 9; consequently, the rapidity of the absorption of the CO_2 is greatly increased. The presence of this iron netting has the further advantage of stirring and mixing up the solution when it rises again in the vessel 9, which happens when the vessel 16, after having reached the upper end of its "excursion" and having remained there a certain length of time, now descends, allowing the level of the liquid to fall in vessel 14, thereby reducing the pressure exerted on the gas in the vessel 9, causing the unabsorbed gas or "residue" to return from the vessel 9, through the vessel 8, into the measuring vessel 12. This return process is assisted by the simultaneous fall of the level of liquid in the compensating vessel 10, and its rise in vessel 9. It will thus be seen that the residual gas is measured in the same vessel in which the sample was measured before the analysis.

The final step is the estimation of this residual volume of gas as a percentage of the original volume of the sample. This is accomplished in an ingenious manner. There are two cylindrical pivoted floats, 14 and 15, in the vessel 13. Each float carries, at its lower part, an annular electrical contact which forms part of an electric circuit, indicated on the diagram (Fig. 4). Although these floats may revolve on their pivots, as they rise or fall with the liquid, an electric contact will be made by their annular portions whenever these are allowed to touch. The annular contacts are faced with platinum. The "liquid" in which they are placed is "oil". The current which passes when the circuit is completed is only small fraction of an ampere. Therefore, the chances of "failure to connect" are very remote. The contacts are, however, readily accessible, in case of necessity. The electric circuit is controlled at another point by a contact-segment mounted on a revolving disc which is operated by the motor-driven mechanism. The electrical contact at this segment is so "timed" by the mechanism, that it occurs only during the final period of analysis, when the percentage of CO_2 is to be determined and recorded.

When, during this period, the vessel 16 is lowered, causing the residual gas to be returned from the vessel 9 into the vessel 12, for the estimation of its volume, the floats 14 and 15 each tend to follow the levels of the liquids in the respective portions of vessel 13. The float 14 will remain stationary when the residual gas has all been returned from the absorption chamber 9 to the measuring vessel 12. If the original gas contained CO_2, the residual gas will obviously be of smaller volume; consequently, the level will not fall as low as the mouth of the measuring vessel and the float 14, which forms a sort of plunger or piston in the lower part of vessel 12, will remain at a higher position.

When, now, by the continued lowering of the receiving vessel 16, the float 15, in following the level of the liquid, has come down to a point where its annular contact touches the annular contact of float 14 the electric circuit will be closed, the electromagnet 17 will be energized, and the measurement will be recorded on the paper strip 18. It will be seen that when the circuit is closed, both of the floats 14 and 15 are in stable equilibrium because the gases in vessel 12 and in vessel 13 are thus at atmospheric pressure; and the possibility of variations in consequence of errors due to barometric conditions is eliminated.

The recording mechanism, being attached to a stem, rising from float 15, moves therewith. The recording point 21 does not, however, come in contact with the paper strip until the electric circuit is closed in the manner just described. In this manner, the possibility of errors due to the friction of the recording mechanism, and the consequent liability to failure of the float 15 to follow the level of the liquid, is obviated. The weight of the float and of the recording mechanism attached thereto can be accurately counterbalanced by a counter-weight 19. The float 15 can obviously be made to rise or fall to some extent in the liquid, when in a position of equilibrium, by varying the counterweight 19. Advantage is taken of this fact, in making the initial adjustment of the float 15, so as to insure the closing of the circuit at the exact point when the levels of the liquids in vessels 12 and 13 are the same.

In practice, when the same recording apparatus is used for several boilers, the recording point and the recording strips are duplicated. Fig. 3 shows a recording apparatus capable of giving four distinct recording charts, corresponding to four different boilers. In such a case, the float 15 carries and moves four recording points instead of one. The conditions are such, however, that only one of these points can make a record at any one time. In such a case, the driving mechanism of the apparatus automatically makes an analysis for each of the four boilers in succession and makes a record of the analysis on a chart corresponding to that boiler. This is done by a train of gears so arranged that, at the end of each analysis, the "selector" is connected to the sampling pipe of a different boiler. The connections are changed successively, in such a manner, that each sampling pipe in turn becomes connected with the steam jet and with the receiving vessel 7. At the same time, the electric circuit connections with the recording magnets are changed in such a manner that the magnet of the recording apparatus corresponding to that boiler is alone in circuit. The proper coördination of all the moving devices, including the displacement of the vessels 11 and 16, the change of the valve, the change of the electrical connections, etc., is insured, as already stated, by means of positive gearing-mechanism, all driven by the same source of motive power, consisting of a small constant-speed motor, shown in the lower left hand portion of the case, in Fig. 3. In this way, it is practically impossible for any of the different operations which have been described to take place out of their proper turn, or to be " out of phase."

One of the important sources of errors of previous forms of CO_2 recording apparatus was due to the fact that the residual gas was left in the measuring chamber 12 and had to be forced out by a new sample. In this case, at the end of an analysis, the residual gas is positively forced out and the measuring chamber is, so to speak, " cleaned " by the rising of the liquid until it fills, entirely, the measuring chamber. This is done by a preliminary upward " excursion " of the displacing vessel 16 which rises for that specific purpose until the level of the liquid in vessel 12 reaches the top. The only gas that is not displaced is that in the small tube connecting with valve 8. The succeeding analysis begins by the transfer of a new sample into vessel 7, while the residue is being expelled from vessel 12. In this way, a certain amount of time is gained in getting ready for the succeeding test. The design of the treating chamber 9 is such as to reduce to a minimum the time required for the absorption of the CO_2. The recorder can make a complete analysis and record the same inside of one and one-half minutes. Therefore, a recorder serving four boilers can give a record for each of the four boilers once every six minutes or ten times per hour. If the recorder is serving only two boilers, it will give a record for each every three minutes or twenty times per hour.

It is an important advantage of this CO_2 recorder that the measurement of the gas residue does not take place in the treating vessel 9, as it does, practically, in some forms of CO_2 recorder. The present CO_2 recorder, by adhering to the Orsat principle, in this respect, and forcing back the gas residue to the measuring vessel 12 before measuring it, avoids some more or less important causes of error due to changes in the volume of the reagent solution, by reason of changes of temperature and of actual increase due to the absorption of CO_2. In such a case, the error due to a change of temperature will, obviously, be all the more important when the total quantity of solution is large. The expansion of the liquid in vessel 9, either from absorption of CO_2 or from rise of temperature, has no influence on the final result. The vessel 10 with which the vessel 9 is connected, is open to the atmosphere and, consequently, allows adjustment to be made automatically between the two vessels, for change of volume.

The external features which distinguish this recorder from all previous forms, is the liberal use which has been made of *metal* to the exclusion of *glass* in its construction. It can be said, indeed, that glass has been eliminated everywhere except where it is desirable or necessary in order to allow the operation to be *seen* at any point or at any stage.

Damper-control. Mr. Stott, himself, is authority for the statement that the efficiency of a boiler plant can be materially improved by " watching the CO_2 records ". The tests made by him, and by many others since, have shown conclusively, that the CO_2 record gives accurate information regarding the efficiency of a steam boiler. For a boiler working constantly at the highest possible theoretical efficiency, the CO_2 record would be a straight line, corresponding to a little over 20% of CO_2. In practice, such high CO_2 values are seldom attained, even momentarily. Occasionally, the records may " make a jump " to 16, 17, or even 18%; but even those results are infrequent and of very short duration, and may be considered abnormal, since they correspond to conditions of combustion which cannot be maintained for any great length of time without affecting the output, or steam-capacity, of the boiler.

The above-mentioned CO_2 record corresponds to the condition of perfect combustion, in which only the quantity of air theoretically necessary for perfect combustion is admitted into the furnace. We all know that this ideal or theoretical condition could not be satisfied in practice. There always is, and, indeed, there must always be, a certain excess of air, as there are always some parts of the fire which have a deficiency of air even when there is an excess of air in the rest of the fire. The consequence is, that, practically, the highest efficiency attainable corresponds to a CO_2 record which is seldom higher than 15%, and is usually considerably lower, being as low as 9, or even 8 per cent., in some cases. This highest attainable line depends upon the design of the boiler plant, and, especially, upon the kind and quality of coal and the way in which it is burnt. For the very lowest grades of " culm ", the line of highest attainable practical efficiency probably could not be higher than 8%.

The desideratum, in any boiler plant, then, is a CO_2 record which is as nearly as possible a straight line, representing an average value of CO_2 which is as high as is consistent and possible, with the particular conditions of design and operation, for that plant. That line is the line of highest attainable efficiency for that plant; and there is a similar line for every plant. The examination of CO_2 records obtained even in those boiler plants which may be considered " well regulated " to the highest degree, indicates that the CO_2 " curve " is far from being a straight line; but shows " lapses from grace " or losses of efficiency which occur in somewhat erratic, unexpected, and oftentimes apparently unaccountable manner.

Now, what Mr. Stott means by " watching the CO_2 records ", is, that the careful study of such " lapses " of the CO_2 records from the line of highest practical efficiency for that particular plant, will, in nearly all if not all cases, lead to the discovery of the reasons for them; and these reasons are almost always related to the method of firing and the damper-control. The CO_2 record, obviously, renders a great service by calling attention to discrepancies or irregularities in the method of firing or to improper methods of damper-control. When the fault is discovered and remedied, the CO_2 records bear testimony to that fact by showing a decided improvement, because the CO_2 curve does not then have so many and such large breaks or notches in it.

One of the important lessons which the CO_2 recorder has taught the boiler-room expert, is that the damper must be adjusted much more *often*, and usually much *less at a time*, than it has been hitherto, if we expect to get very near the maximum efficiency obtainable in any particular plant. In the case of boiler-plants which are operated at more or less constant load, and with automatic stokers, the damper-adjustment may not need to be so frequently changed; but, in the case of boilers which are hand-fired and which supply steam for variable loads, it sometimes seems, judging from the CO_2 records, as if the damper-adjustment ought to be changed every few moments. Even in the most favorable cases, however, it ought really be changed much more often than it is.

If we admit the necessity and desirability of frequent changes of damper-adjustment, the question of finding ways and means of doing it properly and cheaply assumes some importance. In several cases the problem has been partly solved, and with satisfactory results, by making the fireman himself watch the CO_2 records, and adjust and readjust the dampers accordingly. In some cases, in large boiler plants, it might even be profitable, to have a special attendant for the purpose of watching the CO_2 records and of adjusting and readjusting the dampers. The ideal solution of this problem is, obviously, automatic damper-control.

It being evident that automatic damper-control could render valuable service, by increasing the fuel-efficiency, in a large number of steam plants, work has been done on this problem systematically, in the last year. While it seemed simple enough to let the CO_2 recorder close an electric circuit, which would start a motor that moved the damper, yet, the solution did not prove to be quite so simple as that. The truth is, that, in this case, as in the cases of all automatic apparatus, the apparatus must be so organized that it can, if not entirely replace, at least assist, human intelligence instead of counteracting its result. There being limitations to the capabilities of automatic apparatus, as there are to the limitations of the human intelligence that is at hand in the boiler room, it is necessary to exercise great foresight and to make provision, in the automatic device, for all contingencies, even that of bringing human intelligence to the " rescue ", when circumstances arise which cannot be successfully dealt with by a machine, but which require more or less prompt application and exercise of human intelligence. It is needless to say that these circumstances are of frequent occurrence in the furnace of the steam boiler, and it is obvious that an automatic device which failed to do the right thing, or which did the wrong thing, at a critical moment, would be very inadvisable, to say the least. It should be so organized that it will not, at least, put the boiler out of commission, or prevent it from doing its work, even temporarily.

The practical results which have already been obtained are satisfactory and encouraging. A detailed reference cannot be made here, at the present time, for obvious reasons. It is hoped and expected, however, that full publicity can be given to the method and the results obtainable by it, within the next few months.

DISCUSSION ON "A NEW CO_2 RECORDER", AT NEW YORK, DECEMBER 13, 1907.

A. A. Adler (by letter): The CO_2 determinations are not the only determinations to be made in the proper estimation of furnace efficiency, as a low percentage of CO_2 may be due either to too much, or too little air. When too much air is admitted through the furnace, the O determinations will show a high percentage; when too little air is admitted, the carbon burns to CO and CO_2, and no oxygen will be found in the analysis. The CO_2 recorder, therefore, only indicates that there is something wrong, and leaves it for the attendant to find the real cause.

Again there is great difficulty in obtaining the proper sample to be analyzed, and the exact location cannot be determined at random. In the opinion of the writer, it should be taken before it enters the flue on the " boiler side " of the damper, so as to eliminate the errors due to infiltration of air, when natural or induced draft are used. Frequently the infiltrated air produces combustion in the flue, when CO is present, and the temperature of the flue gas rises at the far end of the flue. Such an occurrence shows an erroneous CO_2 determination, as that combustion does not benefit the boiler.

[A report presented by the Committee on a Code of Ethics at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.
Revised by the Committee and considered at a meeting of the Board of Directors of the Institute, at New York, August 30, 1907. Ordered printed and submitted to the membership for suggestions.]

PROPOSED CODE OF ETHICS.

PRINCIPLES OF PROFESSIONAL CONDUCT FOR THE GUIDANCE OF THE ELECTRICAL ENGINEER.

A. General Principles.

B. Relations of the electrical engineer to his employer, customer, or client.

C. Relations of the electrical engineer to the ownership of the records of his work.

D. Relations of the electrical engineer to the public.

E. Relations of the electrical engineer to the engineering fraternity.

F. Relations of the electrical engineer to the standards of his profession.

A. General Principles.

1. In both his professional and his business relations the electrical engineer should follow strictly the same ethical principles that are recognized in the social relations of every-day life. He should consider himself personally responsible for the character of the enterprises with which he is associated professionally.

2. Before entering into professional relations, it is therefore the duty of the electrical engineer to satisfy himself that the enterprises with which he connects himself are of a legitimate character. If, after becoming associated, he finds them to be of a questionable nature he should sever his connection as soon as possible. It should not be considered an excuse that his connection extends only to legitimate engineering work.

3. An electrical engineer permitting the use of his name in any enterprise or exploitation becomes morally responsible for its character. He should therefore not allow the use of his name in connection with anything upon which he is not qualified by training and experience to exercise competent judgment.

4. The electrical engineer should take care that credit for engineering work is attributed to those who, as far as his knowledge of the matter goes, are the real authors of such work.

5. The electrical engineer should incline toward and not away from standards of all kinds, since standardization is peculiarly essential to the general progress of the profession. This applies to construction, meas-

urement and expression or nomenclature, as well as to conduct, or ethics. Even the tendency to give individuality by providing special construction may usually be avoided with advantage.

B. RELATIONS OF THE ELECTRICAL ENGINEER TO HIS EMPLOYER, CUSTOMER, OR CLIENT.

7. The electrical engineer should consider the protection of his client's interests as his first obligation, and therefore should avoid every act that would be contrary to this duty; if any other consideration such as professional obligations or restrictions interfere with his so acting, in accordance with the expectation of his client, he should inform him of the situation.

8. The electrical engineer, whether consulting, designing, or operating, may not accept financial or other compensation, directly or indirectly, from more than one side or party interested in the same matter.

9. Electrical engineers in a position to decide on the use of inventions, apparatus, etc., should not be financially interested in their use, as by receiving a royalty, etc., unless the matter is clearly understood by the client or employer

10. Electrical engineers should not accept employment while financially interested in a rival concern except with the express permission of both parties. An electrical engineer may be employed by more than one party, as in the case of a consulting engineer, when the interests of the parties do not conflict and it is understood, as is usual in such cases, that he is not expected to devote his entire time to the work of one party but is free to enter into other engagements. A consulting engineer permanently retained by a party should notify other prospective employers of this affiliation before entering into relations with them. A consulting engineer when not exclusively retained by one side may advise rival concerns, with the full knowledge of all of them and upon taking care that the interests of the parties do not conflict in the particular matter handled.

11. Operating engineers should consider themselves responsible for defects in apparatus or dangerous conditions of operation, should bring the same to the attention of their employers and insist upon the removal of the causes of danger as soon as feasible.

12. An electrical engineer should in general be considered directly responsible to his employer or client for the successful fulfilment of the work upon which he has been engaged and for its satisfactory performance as a whole. It should therefore be clearly understood at the outset just what the extent or the limitations of responsibility of the engineer are to be. Whether he has been employed merely as designer or whether he is retained to design and to superintend construction; whether to design only the chief features, or also to pass upon all details of the apparatus that is to be installed. Attention should be directed to the fact that defects in the manufacture of material or apparatus is a matter distinct from the matters of design or installation. An engineer should not be held responsible for the unsatisfactory performance of a plant resulting from defective apparatus furnished, unless he has undertaken to include this subject.

C. RELATIONS OF THE ELECTRICAL ENGINEER TO THE OWNERSHIP OF THE RECORDS OF HIS WORK:

15. If in executing his work, the electrical engineer uses data or information which are not common and public property, but which he receives, directly or indirectly from his employer, or if the problem solved by the engineer is met in the pursuit of his work for his employer, and is not of such character that his attention would have been directed to it regardless of his relations to his employer, the products of his work, in the form of inventions, plans, designs, etc., are not his private property, but the property of his employer.

16. If in the execution of the work the consulting engineer uses only his own knowledge or data or information which are public property by prior publication, etc., and receives no engineering data from his employer or customer, except performance specifications, the results of the work, such as inventions, plans, designs, etc. are the private property of the engineer, and his employer or customer is entitled to their use only in the specified case.

17. All the work done by the engineer in the form of inventions, plans, designs, etc., which are outside of the field of engineering for which his employer has retained him, are the engineer's private property.

18. When an engineer or manufacturer builds apparatus from engineering designs supplied to him by his customer, the designs remain the property of the customer and should not be duplicated for other customers without express permission. When the engineer or manufacturer and his customer are jointly to work out designs and plans or develop inventions, a clear understanding should be arrived at before the beginning of the work regarding the proportionate rights of ownership in any inventions, designs, etc., that may result, since in such case both parties should be considered to have rights therein.

19. Any engineering data or information which an electrical engineer obtains, directly or indirectly, from his employer or customer, or which he creates as a result of such information, must be considered by the engineer as confidential; and while the engineer is justified in using such data or experience in his own practice as going towards his education, the publication thereof without express permission is improper, as is also its use in producing for other parties, work that is characteristic of the original customer or employer.

20. Designs, data, records and notes made during his engagement by an engineer employed on salary under permanent engagement, and referring to his work, are his employer's property. The same matter in the case of a consulting electrical engineer paid by fee or by commission, are the property of the consulting engineer.

21. A customer, in buying apparatus, does not acquire any right in its design beyond the use in the apparatus purchased. A customer of a consulting engineer does no acquire any right to the plans made by the consulting engineer except for the specific case for which the apparatus was built or the plans made.

D. RELATIONS OF THE ELECTRICAL ENGINEER TO THE GENERAL PUBLIC.

22. The electrical engineer should endeavor to assist the public to a fair and correct general understanding ot engineering matters, spread the general knowledge of electrical engineering, and discourage wrong or exaggerated statements on engineering subjects published in the press or otherwise, especially if these statements are made for the purpose of, or may lead to inducing the public to participate in unworthy schemes.

23. Controversies on engineering questions, however, should never be carried on in the public press, but should be confined to the technical press and the engineering societies.

24. First publication of inventions or other engineering advances should not be made through the public press but rather through the engineering societies and the technical press or through trade bulletins.

25. The publications which an electrical engineer is justified in making through the public press should therefore be of a historical, educational, instructive or similar character and should not relate to controversies between engineers or on engineering questions, to new inventions, etc., nor contain technical criticisms of fellow engineers, and it should be considered unprofessional to give opinions without being fully informed on all the facts relating to the question, and on the purpose for which the opinion is asked, with a full statement of the conditions under which the opinion applies.

26. In giving expert testimony before judicial bodies, the electrical engineer should confine himself to brief and clear statements on engineering or historical facts. He should not give personal opinions without so expressly stating, and should avoid pleading on one side or the other.

E. RELATIONS OF THE ELECTRICAL ENGINEER TO THE ENGINEERING FRATERNITY.

30. The electrical engineer should take interest in and show due regard for the electrical engineering societies and the technical press, and should assist his fellow engineers by exchange of general information, experience, etc. through them.

32. He should not seek a position held by another electrical engineer.

33. Where engineering work is in charge of an electrical engineer, no other electrical engineer should undertake the work except on request of or in coöperation with the electrical engineer who had charge of the work before, unless the latter's connection with it has already terminated.

35. In engineering work in charge of a board of engineers, the respective limitations of the authority of each should be decided at the outset, and each electrical engineer should give full and complete information on his part to the other engineers and insist on this being reciprocated.

F. RELATIONS OF THE ELECTRICAL ENGINEER TO THE STANDARDS OF HIS PROFESSION.

40. The title " electrician " should be applied to those having practical training sufficient to enable them to carry on intelligently certain classes of electrical work, such as the installation of electric lights and bells, and the operation of small electric plants.

41. The title " electrical engineer " should be applied only to graduates from electrical engineering schools of recognized standing, and such men as possess an equivalent knowledge of electrical engineering. Letters usually employed to denote college degrees should be used only by those holding such degrees.

42. The title " consulting electrical engineer " should be applied only to those electrical engineers who are engaged in consulting work, and who possess such knowledge and experience in electrical engineering as would qualify them to full membership in the American Institute of Electrical Engineers.

Signed,

Charles P. Steinmetz,
Harold W. Buck,
Schuyler Skaats Wheeler.
Chairman.

Committee on a
Code of Ethics.

STANDARDIZATION RULES OF THE A. I. E. E.

New York, June 17, 1907.

Dr. Samuel Sheldon,
President, American Institute Electrical Engineers,
33 West 39th Street,
New York City.

Dear Sir:—

In accordance with a motion made by Dr. Steinmetz, and duly carried at the last Annual Convention of the Institute, at Milwaukee, the Standardization Rules have been revised in form and wording and in accordance with various suggestions received from members of the Institute. This work has been accomplished by the Standards Committee which has held monthly meetings beginning in September last.

Dr. Steinmetz' motion provided that the Standardization Rules when completed by the Committee should be submitted to the Board of Directors for final adoption and promulgation. I therefore submit the revised Standardization Rules through you to the Board of Directors, and request that they be formally approved and adopted.

Respectfully yours,
(Signed) Francis B. Crocker,
Chairman, Standards Committee.

STANDARDS COMMITTEE.

FRANCIS B. CROCKER, Chairman, Columbia University, New York, N. Y.

ARTHUR W. BERRESFORD, Milwaukee.
DUGALD C. JACKSON, Boston, Mass.
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HENRY G. STOTT, New York, N. Y.
CHARLES P. STEINMETZ, Schenectady.
SAMUEL W. STRATTON, Washington, D.C
ELIHU THOMSON, Lynn, Mass.

Approved by vote of the Board of Directors, June 21, 1907.
RALPH W. POPE,
Secretary.

New York, June 21, 1907.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

GENERAL PLAN.

I. DEFINITIONS AND TECHNICAL DATA — Paragraph

II. PERFORMANCE SPECIFICATIONS AND TESTS

III. VOLTAGES AND FREQUENCIES

V. APPENDICES AND TABULAR DATA

I. DEFINITIONS AND TECHNICAL DATA.

1 ***Note*: The following definitions and classifications are intended to be practically descriptive and not scientifically rigid.**

A. DEFINITIONS. CURRENTS.

2 A Direct Current is a unidirectional current.

3 A Continuous Current is a steady, or non-pulsating, direct current.

4 A Pulsating Current is a current equivalent to the superposition of an alternating current upon a continuous current.

5 An Alternating Current is a current which, when plotted, consists of half-waves of equal area in successively opposite directions from the zero line.

6 An Oscillating Current is a current alternating in direction, and of decreasing amplitude.

B. DEFINITIONS. ROTATING MACHINES.

7 A Generator transforms mechanical power into electrical power.

8 A Direct-Current Generator produces a direct current that may or may not be continuous.

9 An Alternator or Alternating-Current Generator produces alternating current, either single-phase or polyphase.

10 A Polyphase Generator produces currents differing symmetrically in phase: such as two-phase currents, in which the terminal voltages on the two circuits differ in phase by 90 degrees; or three-phase currents, in which the terminal voltages on the three circuits differ in phase by 120 degrees.

11 A Double-Current Generator produces both direct and alternating currents.

12 A Motor transforms electrical into mechanical power.

13 A Booster is a machine inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

14 A Motor-Generator is a transforming device consisting of a motor mechanically connected to one or more generators.

15 A Dynamotor is a transforming device combining both motor and generator action in one magnetic field, with two armatures; or with an armature having two separate windings and independent commutators.

16 A Converter is a machine employing mechanical rotation in changing electrical energy from one form into another. A converter may belong to either of several types, as follows:

17 *a*. A Direct-Current Converter converts from a direct current to a direct current.

18 *b*. A Synchronous Converter (commonly called a rotary converter) converts from an alternating to a direct current, or *vice versa*.

19 *c*. A Motor-Converter is a combination of an induction motor with a synchronous converter, the secondary of the former feeding the armature of the latter with current at some frequency other than the impressed frequency; *i.e.*, it is a synchronous converter concatenated with an induction motor.

20 *d*. A Frequency-Converter converts from an alternating-current system of one frequency to an alternating-current system of another frequency, with or without a change in the number of phases or in voltages.

21 *e*. A Rotary Phase Converter converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

C. DEFINITIONS. STATIONARY INDUCTION APPARATUS.

22 **Stationary Induction Apparatus** change electric energy to electric energy through the medium of magnetic energy. They comprise several forms, distinguished as follows:

23 *a*. In **Transformers** the primary and secondary windings are insulated from one another.

24 *b*. In **Auto-Transformers**, also called compensators, a part of the primary winding is used as a secondary winding, or conversely.

25 *c*. In **Potential Regulators** a coil is in shunt and a coil is in series with the circuit, so arranged that the ratio of transformation between them is variable at will. They are of the following three classes:

26 (*a*) **Compensator Potential Regulators** in which a number of turns of one of the coils are adjustable.

27 (*b*) **Induction Potential Regulators** in which the relative positions of the primary and secondary coils are adjustable.

28 (*c*) **Magneto Potential Regulators** in which the direction of the magnetic flux with respect to the coils is adjustable.

29 *d*. **Reactors**, or **Reactance Coils**, formerly called choking coils, are a form of stationary induction apparatus used to produce reactance or phase displacement.

D. GENERAL CLASSIFICATION OF APPARATUS.

30 **Commutating Machines**. Under this head may be classed the following: Direct-current generators; direct-current motors; direct-current boosters; motor-generators; dynamotors; converters, compensators or balancers; closed-coil arc machines, and alternating-current commutating motors.

31 Commutating machines may be further classified as follows:

32 *a*. **Direct-Current Commutating Machines**, which comprise a magnetic field of constant polarity, a closed-coil armature, and a multisegmental commutator connected therewith.

33 *b*. **Alternating-Current Commutating Machines**, which comprise a magnetic field of alternating polarity, a closed-coil armature, and a multisegmental commutator connected therewith.

34 *c*. **Synchronous Commutating Machines**, which comprise synchronous converters, motor converters and double-current generators.

35 **Synchronous Machines**, which comprise a constant magnetic field, and an armature receiving or delivering alternating-currents in synchronism with the motion of the machine; *i.e.*, having a frequency equal to the product of the number of pairs of poles and the speed of the machine in revolutions per second.

36 **Stationary Induction Apparatus**, which include transformers, autotransformers, potential regulators, and reactors or reactance coils.

37 **Rotary Induction Apparatus**, or **Induction Machines**, which include apparatus wherein the primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, frequency converters, and rotary phase converters.

38 **Unipolar** or **Acyclic Machines**, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

39 **Rectifying Apparatus, Pulsating-Current Generators.**

40 **Electrostatic Apparatus**, such as condensers, etc.

41 **Electrochemical Apparatus**, such as batteries, etc.

42 **Electrothermal Apparatus**, such as rheostats, heaters, etc.

43 **Protective Apparatus**, such as fuses, lightning arresters, etc.

44 **Luminous Sources.**

E. MOTORS. SPEED CLASSIFICATION.

45 **Motors** may, for convenience, be classified with reference to their speed characteristics as follows:

46 *a*. **Constant-speed Motors**, in which the speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

47 *b.* **Multispeed Motors** (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load, such as motors with two armature windings.

48 *c.* **Adjustable-speed Motors**, in which the speed can be varied gradually over a considerable range; but when once adjusted remains practically unaffected by the load, such as shunt motors designed for a considerable range of field variation.

49 *d.* **Varying-Speed Motors**, or motors in which the speed varies with the load, decreasing when the load increases; such as series motors.

F. DEFINITION AND EXPLANATION OF TERMS.

(I) *LOAD FACTOR.*

50 The **Load Factor** of a machine, plant or system is the ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain interval of time, such as a day or a year, and the maximum is taken over a short interval of the maximum load within that interval.

51 In each case the interval of maximum load should be definitely specified. The proper interval is usually dependent upon local conditions and upon the purpose for which load factor is to be determined.

(II) *NON-INDUCTIVE LOAD AND INDUCTIVE LOAD.*

52 A non-inductive load is a load in which the current is in phase with the voltage across the load.

53 An inductive load is a load in which the current lags behind the voltage across the load. A load in which the current leads the voltage across the load is sometimes called an anti-inductive load.

(III) *POWER-FACTOR AND REACTIVE FACTOR.*

54 The **Power-Factor** in alternating-current circuits or apparatus is the ratio of the electric power in watts to the apparent power in volt-amperes. It may be expressed as follows:

$$\frac{\text{true power}}{\text{apparent power}} = \frac{\text{watts}}{\text{volt-amperes}} = \frac{\text{energy current}}{\text{total current}} = \frac{\text{energy voltage}}{\text{total voltage}}$$

55 The **Reactive Factor** is the ratio of the wattless volt-amperes (*i.e.*, the product of the wattless component of current by voltage, or wattless component of voltage by current) to the total amperes. It may be expressed as follows:

$$\frac{\text{wattless volt-amperes}}{\text{total volt-amperes}} = \frac{\text{wattless current}}{\text{total current}} = \frac{\text{wattless voltage}}{\text{total voltage}}$$

56 **Power-Factor** and **Reactive Factor** are related as follows:
If p = power-factor, q = reactive-factor, then with sine waves of voltage and current,

$$p^2+q^2 = 1$$

With distorted waves of voltage and current,

$$p^2+q^2 = \text{ or } < 1$$

(IV) *SATURATION-FACTOR.*

57 The **Saturation-Factor** of a machine is the ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. The saturation factor is, therefore, a criterion of the degree of saturation attained in the magnetic circuits at any excitation selected. Unless otherwise specified, however, the saturation factor of a machine refers to the excitation existing at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

58 The **Percentage of Saturation** of a machine at any excitation may be found from its saturation curve of generated voltage as ordinates, against excitation as abscissas, by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percentage, is the percentage of saturation and is independent of the scale selected for excitation and voltage. This ratio is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity. Thus, if f be the saturation factor and p the percentage of saturation ratio,

$$p = 1 - \frac{1}{f}$$

(V) *VARIATION AND PULSATION.*

59 The Variation in Prime Movers which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360°.

60 The Pulsation in Prime Movers is the ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

61 The Variation in Alternators or alternating-current circuits in general is the maximum difference in phase of the generated voltage wave from a wave of absolutely constant frequency, expressed in electrical degrees (one cycle equals 360 degrees) and may be due to the variation of the prime mover.

62 The Pulsation in Alternators or alternating-current circuits, in general, is the ratio of the difference between maximum and minimum frequency during an engine cycle to the average frequency.

63 Relation of Variation in prime mover and alternator.

64 If n = number of pairs of poles, the variation of an alternator is n times the variation of its prime mover, if direct-connected, and n/p times the variation of the prime mover if rigidly connected thereto in the velocity ratio p.

II. PERFORMANCE SPECIFICATIONS AND TESTS.

A. RATING.

65 Rating by Output. All electrical apparatus should be rated by output and not by input. Generators, transformers, etc., should be rated by electrical output: motors by mechanical output.

66 Rating in Kilowatts. Electrical power should be expressed in kilowatts, except when otherwise specified.

67 Apparent Power, Kilovolt-Amperes. Apparent power in alternating-current circuits should be expressed in kilovolt-amperes as distinguished from real power in kilowatts. When the power factor is 100 per cent., the apparent power in kilovolt-amperes is equal to the kilowatts.

68 The Rated (Full-Load) Current is that current which, with the rated terminal voltage, gives the rated kilowatts, or the rated kilovolt-amperes. In machines in which the rated voltage differs from the no-load voltage, the rated current should refer to the former.

69 Determination of Rated Current. The rated current may be determined as follows: If P = rating in watts, or apparent watts if the power factor be other than 100 per cent., and E = full-load terminal voltage, the rated current per terminal is:

70 $I = \frac{P}{E}$ in a direct-current machine or single-phase alternator.

71 $I = \frac{1}{\sqrt{3}} \frac{P}{E}$ in a three-phase alternator.

72 $I = \frac{1}{2} \frac{P}{E}$ in a two-phase alternator

73 NORMAL CONDITIONS. The rating of machines or apparatus should be based upon certain normal conditions to be assumed as standard, or to be specified. These conditions include voltage, current, power-factor, frequency, wave shape and speed; or such of them as may apply in each particular case. Performance tests should be made under these standard conditions unless otherwise specified.

74 *a*. POWER FACTOR. Alternating-current apparatus should be rated in kilowatts, at 100 per cent. power factor; *i.e.*, with current in phase with terminal voltage, unless a phase displacement is inherent in the apparatus or is specified. If a power factor other than 100 per cent. is specified, the rating should be expressed in kilovolt-amperes and power factor, at rated load.

75 *b*. WAVE SHAPE. In determining the rating of alternating-current machines or apparatus, a sine wave shape of alternating current and voltage is assumed, except where a distorted wave shape is inherent to the apparatus. See Secs. 79-83.

76 FUSES. The rating of a fuse should be the maximum current which it will continuously carry.

77 CIRCUIT-BREAKERS. The rating of a circuit-breaker should be the maximum current which it is designed to carry continuously.

78 *a*. NOTE. In addition thereto, the maximum current and voltage at which a fuse or a circuit-breaker will open the circuit should be specified. It is to be noted that the behavior of fuses and of circuit-breakers is much influenced by the amount of electric power available on the circuit.

B. WAVE SHAPE.

79 The SINE WAVE should be considered as standard, except where a difference in the wave form from the sinusoidal is inherent in the operation of the apparatus.

80 A MAXIMUM DEVIATION of the wave from sinusoidal shape not exceeding 10 per cent. is permissible, except when otherwise specified.

81 The DEVIATION of wave form from the sinusoidal is measured by determining the form by oscillograph or wave meter, computing therefrom the equivalent sine wave of equal length, superposing the latter upon the observed wave in such a manner as to give least difference, and then dividing the maximum difference at any ordinate by the maximum value of the equivalent sine wave.

82 The EQUIVALENT SINE WAVE is a sine wave having the same frequency and the same effective or r.m.s. (root of mean square) value as the actual wave.

83 NON-SINE WAVES. The phase displacement between two waves which are not sine waves, is that phase displacement between their equivalent sine waves which would give the same average product of instantaneous values as the actual waves; *i.e.*, the same electro-dynamometer reading.

C. EFFICIENCY.

(I) *DEFINITIONS.*

84 The EFFICIENCY of an apparatus is the ratio of its net power output to its gross power input.

85 *a*. NOTE. An exception should be noted in the case of storage batteries or apparatus for storing energy in which the efficiency, unless otherwise qualified, should be understood as the ratio of the energy output to the energy intake in a normal cycle. An exception should also be noted in the case of luminous sources.

86 APPARENT EFFICIENCY. In apparatus in which a phase displacement is inherent to their operation, apparent efficiency should be understood as the ratio of net power output to volt-ampere input.

87 *a*. NOTE. Such apparatus comprise induction motors, reactive synchronous converters, synchronous converters controlling the voltage of an alternating-current system, self-exciting synchronous motors, potential regulators and open magnetic circuit transformers, etc.

88 *b*. NOTE. Since the apparent efficiency of apparatus delivering electric power depends upon the power-factor of the load, the apparent efficiency, unless otherwise specified, should be referred to a load power-factor of unity.

(II) *DETERMINATION OF EFFICIENCY.*

89 Methods. Efficiency may be determined by either of two methods, viz.: by measurement of input and output; or, by measurement of losses.

90 *a.* Method of Input and Output. The input and output may both be measured directly. The ratio of the latter to the former is the efficiency.

91 *b.* Method by Losses. The losses may be measured either collectively or individually. The total losses may be added to the output to derive the input, or subtracted from the input to derive the output.

92 Comparison of Methods. The output and input method is preferable with small machines. When, however, as in the case of large machines, it is impracticable to measure the output and input; or when the percentage of power loss is small and the efficiency is nearly unity, the method of determining efficiency by measuring the losses should be followed.

93 Electric Power should be measured at the terminals of the apparatus. In tests of polyphase machines, the measurement of power should not be confined to a single circuit but should be extended to all the circuits in order to avoid errors of unbalanced loading.

94 Mechanical Power in machines should be measured at the pulley, gearing, coupling, etc., thus excluding the loss of power in said pulley, gearing or coupling, but including the bearing friction and windage. The magnitude of bearing friction and windage may be considered, with constant speed, as independent of the load. The loss of power in the belt and the increase of bearing friction due to belt tension should be excluded. Where, however, a machine is mounted upon the shaft of a prime mover, in such a manner that it cannot be separated therefrom, the frictional losses in bearings and in windage, which ought, by definition, to be included in determining the efficiency, should be excluded, owing to the practical impossibility of determining them satisfactorily.

95 In Auxiliary Apparatus, such as an exciter, the power lost in the auxiliary apparatus should not be charged to the principal machine, but to the plant consisting of principal machine and auxiliary apparatus taken together. The plant efficiency in such cases should be distinguished from the machine efficiency.

96 Normal Conditions. Efficiency tests should be made under normal conditions herein set forth and which are to be assumed as standard. These conditions include voltage, current, power-factor, frequency, wave shape, speed and barometric pressure, temperature, or such of them as may apply in each particular case. Performance tests should be made under these standard conditions unless otherwise specified. See Secs. 73-75.

97 *a.* Temperature. The efficiency of all apparatus, except such as may be intended for intermittent service, should be either measured at, or reduced to, the temperature which the apparatus assumes under continuous operation at rated load, referred to a room temperature of 25° C. See Secs. 267–292.

98 With apparatus intended for intermittent service, the efficiency should be determined at the temperature assumed under specified conditions.

99 *b.* Power Factor. In determining the efficiency of alternating-current apparatus, the electric power should be measured when the current is in phase with the voltage, unless otherwise specified, except when a definite phase difference is inherent in the apparatus, as in induction motors, induction generators, frequency converters, etc.

100 *c.* Wave Shape. In electrical apparatus, the sine wave should be considered as standard, except where a difference in the wave form from the sinusoidal is inherent in the operation of the apparatus. See Secs. 79–83.

(III) *MEASUREMENT OF LOSSES.*

101 Losses. The usual sources of losses in electrical apparatus and the methods of determining these losses are as follows:

102 (*A*) Bearing Friction and Windage.

The magnitude of bearing friction and windage (which may be considered as independent of the load) is conveniently measured by driving the machine from an independent motor, the output of which may be suitably determined. See Sec. 94.

(*B*) COMMUTATOR BRUSH FRICTION.

103 The magnitude of the commutator brush friction (which may be considered as independent of the load) is determined by measuring the difference in power required for driving the machine with brushes on and with brushes off (the field being unexcited).

(*C*) COLLECTOR-RING BRUSH FRICTION.

104 Collector-ring brush friction may be determined in the same manner as commutator brush friction. It is usually negligible.

(*D*) MOLECULAR MAGNETIC FRICTION AND EDDY CURRENTS.

105 These losses include those due to molecular magnetic friction and eddy currents in iron and copper and other metallic parts, also the losses due to currents in the cross-connections of cross-connected armatures.

106 In MACHINES these losses should be determined on open circuit and at a voltage equal to the rated voltage $+I\ r$ in a generator, and $-I\ r$ in a motor, where I denotes the current strength and r denotes the internal resistance of the machine. They should be measured at the correct speed and voltage, since they do not usually vary in any definite proportion to the speed or to the voltage.

107 NOTE. The TOTAL LOSSES in bearing friction and windage, brush friction, magnetic friction and eddy currents can, in general, be determined by a single measurement by driving the machine with the field excited, either as a motor, or by means of an independent motor.

108 RETARDATION METHOD. The no-load iron, friction, and windage losses may be segregated by the Retardation Method, in which the generator should be brought up to full speed (or, if possible, to about 10 per cent. above full speed) as a motor, and, after cutting off the driving power and excitation, frequent readings should be taken of speed and time, as the machine slows down, from which a speed-time curve can be plotted. A second curve should be taken in the same manner, but with full field excitation; from the second curve the iron losses may be found by subtracting the losses found in the first curve.

109 The speed-time curves can be plotted automatically by belting a small separately excited generator (say 1/10 kw.) to the generator shaft and connecting it to a recording voltmeter. When the retardation method is not feasible, the frictional losses in bearings and in windage, which ought, by definition, to be included in determining the efficiency, may be excluded; but this should be expressly stated.

(*E*) ARMATURE-RESISTANCE LOSS.

110 This loss may be expressed by $p\ I^2\ r$; where r = resistance of one armature circuit or branch, I = the current in such armature circuit or branch, and p = the number of armature circuits or branches.

(*F*) COMMUTATOR BRUSH AND BRUSH-CONTACT RESISTANCE LOSS.

111 It is desirable to point out that with carbon brushes these losses may be considerable in low-voltage machines.

(*G*) COLLECTOR-RING AND BRUSH-CONTACT RESISTANCE LOSS.

112 This loss is usually negligible, except in machines of extremely low voltage or in unipolar machines.

(*H*) FIELD EXCITATION LOSS.

113 With separately excited fields, the loss of power in the resistance of the field coils alone should be considered. With either shunt- or series-field windings, however, the loss of power in the accompanying rheostat should also be included, the said rheostat being considered as an essential part of the machine, and not as separate auxiliary apparatus.

114 (*I*) LOAD LOSSES.

The load losses may be considered as the difference between the total losses under load and the sum of the losses above specified.

115 *a.* In Commutating Machines of small field distortion, the load losses are usually trivial and may, therefore, be neglected. When, however, the field distortion is large, as is shown, for instance, by the necessity for shifting the brushes between no load and full load, or with variations of load, these load losses may be considerable, and should be taken into account. In this case the efficiency may be determined either by input and output measurements, or the load losses may be estimated by the method of Sec. 116.

116 *b.* Estimation of Load Losses. While the load losses cannot well be determined individually, they may be considerable and, therefore, their joint influence should be determined by observation. This can be done by operating the machine on short-circuit and at full-load current, that is, by determining what may be called the "short-circuit core loss." With the low field intensity and great lag of current existing in this case, the load losses are usually greatly exaggerated.

117 One-third of the short-circuit core loss may, as an approximation, and in the absence of more accurate information, be assumed as the load loss.

(IV) *EFFICIENCY OF DIFFERENT TYPES OF APPARATUS.*

(*A*) Direct-Current Commutating Machines.

118 In Direct-Current Commutating Machines the losses are:

119 *a.* Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

120 *b.* Molecular Magnetic Friction and Eddy Currents. See Measurement of Losses (*D*), Sec. 105.

121 *c.* Armature Resistance Losses. See Measurement of Losses (*E*), Sec. 110.

122 *d.* Commutator Brush Friction. See Measurement of Losses (*B*), Sec. 103.

123 *e.* Commutator Brush and Brush Contact Resistance. See Measurement of Losses (*F*), Sec. 111.

124 *f.* Field Excitation Loss. See Measurement of Losses (*H*), Sec. 113.

125 *g.* Load Losses. See Measurement of Losses (*I*), Sec. 114.

126 Note. *b* and *c* are losses in the armature or "armature losses"; *d* and *e* "commutator losses"; *f* "field losses."

(*B*) Alternating-Current Commutating Machines.

127 In Alternating-Current Commutating Machines, the losses are:

128 *a.* Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

129 *b.* Rotation Loss, measured with the machine at open circuit, the brushes on the commutator, and the field excited by alternating current when driving the machine by a motor.

130 This loss includes molecular magnetic friction, and eddy currents, caused by rotation through the magnetic field, I^2r losses in cross-connections of cross-connected armatures, I^2r and other losses in armature-coils and armature-leads which are short-circuited by the brushes as far as these losses are due to rotation.

131 *c.* Alternating or Transformer Loss. These losses are measured by wattmeter in the field circuit, under the conditions of test *b.* They include molecular magnetic friction and eddy-currents due to the alternation of the magnetic field, I^2r losses in cross-connections of cross-connected armatures, I^2r and other losses in armature coil and commutator leads which are short-circuited by the brushes, as far as these losses are due to the alternation of the magnetic flux.

132 The losses in armature-coils and commutator leads short-circuited by the brushes, can be separated in *b*, and *c*, from the other losses, by running the machine with and without brushes on the commutator.

133 *d.* I^2r Loss, Other Load Losses in armature and compensating winding and I^2r loss of brushes, measured by wattmeter connected across the armature and compensating winding.

134 *e.* Field Excitation Loss. See Measurement of Losses (*H*), Sec. 113.

135 *f.* **Commutator Brush-Friction.** See Measurement of Losses (*B*), Sec. 103.

(*C*) Synchronous Commutating Machines.

136 1. In Double-Current Generators, the efficiency of the machine should be determined as a direct-current generator, and also as an alternating-current generator. The two values of efficiency may be different, and should be clearly distinguished.

137 2. In Converters the losses should be determined when driving the machine by a motor. These losses are:

138 *a.* Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

139 *b.* Molecular Magnetic Friction and Eddy Currents. See Measurement of losses (D) Sec. 105.

140 *c.* Armature Resistance Loss. This loss in the armature is qI^2r, where I = direct current in armature, r = armature resistance and q, a factor which is equal to 1.47 in single-circuit single-phase, 1.15 in double-circuit single-phase, 0.59 in three-phase, 0.39 in two-phase, and 0.27 in six-phase converters.

141 *d.* Commutator-Brush Friction. See Measurement of Losses (*B*), Sec. 103.

142 *e.* Collector-Ring Brush Friction. See Measurement of Losses (*C*), Sec. 104.

143 *f.* Commutator-Brush and Brush-Contact Resistance Loss. See Measurement of Losses (*F*), Sec. 111.

144 *g.* Collector-Ring Brush-Contact Resistance Loss. See Measurement of Losses (*G*), Sec. 112.

145 *h.* Field Excitation Loss. See Measurement of Losses (*H*), Sec. 109.

146 *i.* Load Losses. These can generally be neglected, owing to the absence of field distortion.

147 3. The Efficiency of Two Similar Converters may be determined by operating one machine as a converter from direct to alternating, and the other as a converter from alternating to direct, connecting the alternating sides together, and measuring the difference between the direct-current input, and the direct-current output. This process may be modified by returning the output of the second machine through two boosters into the first machine and measuring the losses. Another modification is to supply the losses by an alternator between the two machines, using potential regulators.

(*D*) Synchronous Machines.

148 In Synchronous Machines the losses are:

149 *a.* Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

150 *b.* Molecular Magnetic Friction and Eddy Currents. See Measurement of Lossess (*D*), Sec. 105.

151 *c.* Armature Resistance Loss. See Measurement of Losses (*E*), Sec. 110.

152 *d.* Collector-Ring Brush Friction. See Measurement of Losses (*C*), Sec. 104.

153 *e.* Collector-Ring Brush Contact Resistance Loss. See Measurement of Losses (*G*), Sec. 112.

154 *f* Field Excitation Loss. See Measurement of Losses (*H*), Sec. 113.

155 *g.* Load Losses. See Measurement of Losses (*I*), Sec. 114.

(*E*) Stationary Induction Apparatus.

156 In Stationary Induction Apparatus, the losses are:

157 *a.* Molecular Magnetic Friction and Eddy Currents measured at open secondary circuit, rated frequency, and at rated voltage — Ir, where I = rated current, r = resistance of primary circuit.

158 *b.* Resistance Losses, the sum of the I^2r losses in the primary and in the secondary windings of a transformer, or in the two sections of the coil in a compensator or auto-transformer, where I = rated current in the coil or section of coil, and r = resistance.

159 *c.* Load Losses, *i.e.*, eddy currents in the iron and especially in the copper conductors, caused by the current at rated load. For practical

purposes they may be determined by short-circuiting the secondary of the transformer and impressing upon the primary a voltage sufficient to send rated load current through the transformer. The loss in the transformer under these conditions measured by wattmeter gives the load losses $+I^2 r$ losses in both primary and secondary coils.

160 In CLOSED MAGNETIC CIRCUIT TRANSFORMERS, either of the two circuits may be used as primary when determining the efficiency.

161 In POTENTIAL REGULATORS, the efficiency should be taken at the maximum voltage for which the apparatus is designed, and with non-inductive load, unless otherwise specified.

(*F*) ROTARY INDUCTION APPARATUS, OR INDUCTION MACHINES.

162 In ROTARY INDUCTION APPARATUS, the losses are:

163 *a*. BEARING FRICTION AND WINDAGE. See Measurement of Losses (*A*), Sec. 102.

164 *b*. MOLECULAR MAGNETIC FRICTION AND EDDY CURRENTS in iron, copper and other metallic parts; also $I^2 r$ losses which may exist in multiple-circuit windings. *a* and *b* together are determined by running the motor without load at rated voltage, and measuring the power input.

165 *c*. PRIMARY $I^2 R$ LOSS, which may be determined by measurement of the current and the resistance.

166 *d*. SECONDARY $I^2 R$ LOSS, which may be determined as in the primary. when feasible; otherwise, as in squirrel-cage secondaries, this loss is measured as part of *e*.

167 *e*. LOAD LOSSES; *i.e.*, molecular magnetic friction, and eddy currents in iron, copper, etc., caused by the stray field of primary and secondary currents, and secondary $I^2 R$ loss when undeterminable under (*d*). These losses may for practical purposes be determined by measuring the total power, with the rotor short-circuited at standstill and a current in the primary circuit equal to the primary energy current at full load. The loss in the motor under these conditions may be assumed to be equal to the load losses $+I^2 r$ losses in both primary and secondary coils.

(*G*) UNIPOLAR OR ACYCLIC MACHINES.

168 In UNIPOLAR MACHINES, the losses are:

169 (*a*) BEARING FRICTION AND WINDAGE. See Measurement of Losses (*A*), Sec. 102.

170 (*b*) MOLECULAR MAGNETIC FRICTION AND EDDY CURRENTS. See Measurement of Losses (*E*), Sec. 106.

171 (*c*) ARMATURE RESISTANCE LOSSES. See Measurement of Losses (*E*), Sec. 110.

172 (*d*) COLLECTOR BRUSH FRICTION. See Measurement of Losses (*C*), Sec. 104.

173 (*e*) COLLECTOR BRUSH CONTACT RESISTANCE. See Measurement of Losses (*G*), Sec. 112.

174 (*f*) FIELD-EXCITATION as in Sec. 113. See Measurement of Losses (*H*), Sec. 113.

175 (*g*) LOAD LOSSES. See Measurement of Losses (*I*), Sec. 114.

(*H*) RECTIFYING APPARATUS, PULSATING-CURRENT GENERATORS.

176 THIS DIVISION INCLUDES: open-coil arc machines and mechanical and other rectifiers.

177 In RECTIFIERS the most satisfactory method of determining the efficiency is to measure both electric input and electric output by wattmeter. The input is usually inductive, owing to phase displacement and to wave distortion. For this reason the power factor and the apparent efficiency should also be considered, since the latter may be much lower than the true efficiency. The power consumed by auxiliary devices, such as the synchronous motor or cooling devices, should be included in the electric input.

178 In CONSTANT-CURRENT RECTIFIERS, transforming from constant potential alternating to constant direct current, by means of constant-current transforming devices and rectifying devices, the losses in the transforming devices are to be included in determining the efficiency and have to be measured when operating the rectifier, since in this case the losses may be greater than when feeding an alternating secondary circuit. In constant-current transforming devices, the load losses may be considerable, and, therefore, should not be neglected.

179 In OPEN COIL ARC MACHINES, the losses are essentially the same as in direct-current (closed coil) commutating machines. In this case, however, the load losses are usually greater, and the efficiency should preferably be measured by input- and output-test, using wattmeters for measuring the output. In alternating-current rectifiers, the output should, in general, be measured by wattmeter and not by voltmeter and ammeter, since owing to pulsation of current and voltage, a considerable discrepancy may exist between watts and volt-amperes. If, however, a direct-current and an alternating-current meter in the rectified circuit (either a voltmeter or an ammeter) give the same reading, the output may be measured by direct-current voltmeter and ammeter. The type of alternating-current instrument here referred to should indicate the effective or root-of-mean-square value and the type of direct-current instrument the arithmetical mean value, which would be zero on an alternating-current circuit.

(*I*) TRANSMISSION LINES.

180 The EFFICIENCY of transmission lines should be measured with non-inductive load at the receiving end, with the rated receiving voltage and frequency, also with sinusoidal impressed wave form, except where expressly specified otherwise, and with the exclusion of transformers or other apparatus at the ends of the line.

(*J*) PHASE-DISPLACING APPARATUS.

181 In APPARATUS PRODUCING PHASE DISPLACEMENT as, for example, synchronous compensators, exciters of induction generators, reactors, condensers, polarization cells, etc., the efficiency should be understood to be the ratio of the volt-amperes minus power loss to the volt-amperes.

182 The EFFICIENCY may be calculated by determining the losses, subtracting them from the volt-amperes, and then dividing the difference by the volt-amperes.

183 In SYNCHRONOUS COMPENSATORS and exciters of induction generators, the determination of losses is the same as in other synchronous machines.

184 In REACTORS the losses are molecular magnetic friction, eddy losses and $I^2 r$ loss. They should be measured by wattmeter. The efficiency of reactors should be determined with a sine wave of impressed voltage except where expressly specified otherwise.

185 In CONDENSERS, the losses are due to dielectric hysteresis and leakage, and should be determined by wattmeter with a sine wave of voltage.

186 In POLARIZATION CELLS, the losses are those due to electric resistivity and a loss in the electrolyte of the nature of chemical hysteresis. These losses may be considerable. They depend upon the frequency, voltage and temperature, and should be determined with a sine wave of impressed voltage, except where expressly specified otherwise.

D. REGULATION.

(I) *DEFINITIONS.*

187 DEFINITION. The regulation of a machine or apparatus in regard to some characteristic quantity (such as terminal voltage, current or speed) is the ratio of the deviation of that quantity from its normal value at rated load to the normal rated load value. The term "regulation," therefore, has the same meaning as the term "inherent regulation," occasionally used.

188 CONSTANT STANDARD. If the characteristic quantity is intended to remain constant (*e.g.*, constant voltage, constant speed, etc.) between rated load and no load, the regulation is the ratio of the maximum variation from the rated load value to the no-load value.

189 VARYING STANDARD. If the characteristic quantity is intended to vary in a definite manner between rated load and no load, the regulation is the ratio of the maximum variation from the specified condition to the normal rated-load value.

190 (*a*) NOTE. If the law of the variation (in voltage, current, speed, etc.) between rated load and no load is not specified, it should be assumed to be a simple linear relation; *i.e.*, one undergoing uniform variation between rated load and no load.

191 (*b*) NOTE. The regulation of an apparatus may, therefore differ according to its qualification for use. Thus, the regulation of a compound-wound generator specified as a constant-potential generator, will be different from that which it possesses when specified as an over-compounded generator.

192 In CONSTANT-POTENTIAL MACHINES, the regulation is the ratio of the maximum difference of terminal voltage from the rated-load value (occurring within the range from rated load to open circuit) to the rated load terminal voltage.

193 In CONSTANT-CURRENT MACHINES, the regulation is the ratio of the maximum difference of current from the rated load value (occurring within the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

194 In CONSTANT-POWER APPARATUS, the regulation is the ratio of maximum difference of power from the rated load value (occurring within the range of operation specified) to the rated power.

195 In CONSTANT-SPEED DIRECT-CURRENT MOTORS and INDUCTION MOTORS the regulation is the ratio of the maximum variation of speed from its rated load value (occurring within the range from rated load to no-load) to the rated load speed.

196 The regulation of an induction motor is, therefore, not identical with the slip of the motor, which is the ratio of the drop in speed from synchronism, to the synchronous speed.

197 In CONSTANT-POTENTIAL TRANSFORMERS, the regulation is the ratio of the rise of secondary terminal voltage from rated non-inductive load to no-load (at constant primary impressed terminal voltage) to the secondary terminal voltage at rated load.

198 In OVER-COMPOUNDED MACHINES, the regulation is the ratio of the maximum difference in voltage from a straight line connecting the no-load and rated-load values of terminal voltage as function of the load current, to the rated-load terminal voltage.

199 In CONVERTERS, DYNAMOTORS, MOTOR-GENERATORS AND FREQUENCY CONVERTERS, the regulation is the ratio of the maximum difference of terminal voltage at the output side from the rated-load voltage, to the rated-load voltage on the output side.

200 In TRANSMISSION LINES, FEEDERS, ETC., the regulation is the ratio of the maximum voltage difference at the receiving end, between rated non-inductive load and no load to the rated-load voltage at the receiving end (with constant voltage impressed upon the sending end).

201 In STEAM ENGINES, the regulation is the ratio of the maximum variation of speed in passing slowly from rated-load to no-load (with constant steam pressure at the throttle) to the rated-load speed. For variation and pulsation see Secs. 59-64.

202 In a HYDRAULIC TURBINE or OTHER WATER-MOTOR, the regulation is the ratio of the maximum variation of speed in passing slowly from rated-load to no-load (at constant head of water; *i.e.*, at constant difference of level between tail race and head race), to the rated-load speed. For variation and pulsation see Secs. 59-64.

203 In a GENERATOR-UNIT, consisting of a generator united with a prime-mover, the regulation should be determined at constant conditions of the prime-mover; *i.e.*, constant steam pressure, head, etc. It includes the inherent speed variations of the prime-mover. For this reason the regulation of a generator-unit is to be distinguished from the regulation of either the prime-mover, or of the generator contained in it, when taken separately.

(II) *CONDITIONS FOR AND TESTS OF REGULATION.*

204 SPEED. The REGULATION OF GENERATORS is to be determined at constant speed, and of alternating apparatus at constant impressed frequency.

205 NON-INDUCTIVE LOAD. In apparatus generating, transforming or trans-

mitting alternating currents, regulation should be understood to refer to non-inductive load, that is, to a load in which the current is in phase with the e.m.f. at the output side of the apparatus, except where expressly specified otherwise.

206 **Wave Form.** In alternating apparatus receiving electric power, regulation should refer to a sine wave of e.m.f., except where expressly specified otherwise.

207 **Excitation.** In commutating machines, rectifying machines, and synchronous machines, such as direct-current generators and motors, alternating-current and polyphase generators, the regulation is to be determined under the following conditions:

(1) At constant excitation in separately excited fields.
(2) With constant resistance in shunt-field circuits, and
(3) With constant resistance shunting series-field circuits; *i.e.*, the field adjustment should remain constant, and should be so chosen as to give the required full-load voltage at full-load current.

208 **Impedance Ratio.** In alternating-current apparatus, in addition to the non-inductive regulation, the impedance ratio of the apparatus should be specified; *i.e.*, the ratio of the voltage consumed by the total internal impedance of the apparatus at full-load current, to its rated full-load voltage. As far as possible, a sinusoidal current should be used.

209 **Computation of Regulation.** When in synchronous machines the regulation is computed from the terminal voltage and impedance voltage, the exciting ampere-turns corresponding to terminal voltage plus armature-resistance-drop, and the ampere-turns at short-circuit corresponding to the armature-impedance-drop, should be combined vectorially to obtain the resultant ampere-turns, and the corresponding internal e.m.f. should be taken from the saturation curve.

E. INSULATION.

(I) *INSULATION RESISTANCE.*

210 **Insulation Resistance** is the ohmic resistance offered by an insulating coating, cover, material or support to an impressed voltage, tending to produce a leakage of current through the same.

211 **Ohmic Resistance and Dielectric Strength.** The ohmic resistance of the insulation is of secondary importance only, as compared with the dielectric strength, or resistance to rupture by high voltage. Since the ohmic resistance of the insulation can be very greatly increased by baking, but the dielectric strength is liable to be weakened thereby, it is preferable to specify a high dielectric strength rather than a high insulation resistance. The high-voltage test for dielectric strength should always be applied.

212 **Recommended Value of Resistance.** The insulation resistance of complete apparatus should be such that the rated voltage of the apparatus will not send more than $\frac{1}{1{,}000{,}000}$ of the rated-load current, at the rated terminal voltage, through the insulation. Where the value found in this way exceeds 1 megohm, it is usually sufficient.

213 **Insulation Resistance Tests** should, if possible, be made at the pressure for which the apparatus is designed.

(II) *DIELECTRIC STRENGTH.*

(*A*) Test Voltages.

214 **Definition.** The dielectric strength of an insulating wall coating, cover or path is measured by the voltage which must be applied to it in order to effect a disruptive discharge through the same

215 **Basis for Determining Test Voltages.** The test voltage which should be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the apparatus and its normal operating voltage, upon the nature of the service in which it is to be used, and the severity of the mechanical and electrical stresses to

which it may be subjected. The voltages and other conditions of test which are recommended have been determined as reasonable and proper for the great majority of cases and are proposed for general adoption, except when specific reasons make a modification desirable.

216 CONDITION OF APPARATUS TO BE TESTED. Commercial tests should, in general, be made with the completely assembled apparatus and not with individual parts. The apparatus should be in good condition and high-voltage tests, unless otherwise specified, should be applied before the machine is put into commercial service, and should not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests should, in general, be made at the temperature assumed under normal operation. High-voltage tests considerably in excess of the normal voltages to determine whether specifications are fulfilled are admissible on new machines only.

217 POINTS OF APPLICATION OF VOLTAGE. The test voltage should be successively applied between each electric circuit and all other electric circuits including conducting material in the apparatus.

218 The FREQUENCY of the alternating-current test voltage is, in general, immaterial within commercial ranges. When, however, the frequency has an appreciable effect, as in alternating-current apparatus of high voltage and considerable capacity, the rated frequency of the apparatus should be used.

219 TABLE OF TESTING VOLTAGES. The following voltages are recommended for testing all apparatus, lines and cables, by a continued application for one minute. The test should be with alternating voltage having an effective value (or root mean square referred to a sine wave of voltage) given in the table and preferably for tests of alternating apparatus at the normal frequency of the apparatus.

Rated Terminal Voltage of Circuit.	Rated Output.	Testing Voltage.
220 Not exceeding 400 volts	Under 10 kw	1,000 volts.
" " "	10 kw. and over	1,500 "
400 and over, but less than 800 volts	Under 10 kw	1,500 "
" " " " "	10 kw. and over	2,000 "
800 " " " 1,200 "	Any	3,500 "
1,200 " " " 2,500 "	Any	5,000 "
2,500 " "	Any	Double the normal rated voltages.

221 EXCEPTION.—TRANSFORMERS. Transformers having primary pressures of from 550 to 5,000 volts, the secondaries of which are directly connected to consumption circuits, should have a testing voltage of 10,000 volts, to be applied between the primary and secondary windings, and also between the primary winding and the core.

222 EXCEPTION.—FIELD WINDINGS. The tests for field windings should be based on the rated voltage of the exciter and the rated output of the machine of which the coils are a part. Field windings of synchronous motors and converters, which are to be started by applying alternating current to the armature when the field is not excited and a high voltage is induced in the field windings, should be tested at 5,000 volts.

223 RATED TERMINAL VOLTAGE.—DEFINITION. The rated terminal voltage of circuit in the above table, means the voltage between the conductors of the circuit to which the apparatus to be tested is to be connected,—for instance, in three-phase circuits the delta voltage should be taken. In the following specific cases, the rated terminal voltage of the circuit is to be determined as specified in ascertaining the testing voltage:

224 (*a*) TRANSFORMERS. The test of the insulation between the primary and secondary windings of transformers, is to be the same as that between the high-voltage windings and core, and both tests should be made simultaneously by connecting the low-tension winding and core together during the test. If a voltage equal to the specified testing voltage be induced in the high-tension winding of a transformer it may be used for insulation tests instead of an independently induced voltage. These tests should be made first with one end and then with the other end of the high-tension winding connected to the low-tension winding and to the core

225 (*b*) CONSTANT-CURRENT APPARATUS. The testing voltage is to be based upon a rated terminal voltage equal to the maximum voltage which may exist at open or closed circuit.

226 (*c*) APPARATUS IN SERIES. For tests of machines or apparatus to be operated in series, so as to employ the sum of their separate voltages the testing voltage is to be based upon a rated terminal voltage equal to the sum of the separate voltages except where the frames of the machines are separately insulated, both from the ground and from each other, in which case the test for insulation between machines should be based upon the voltage of one machine, and the test between each machine and ground to be based upon the total voltage of the series.

(*B*) METHODS OF TESTING.

227 CLASSES OF TESTS. Tests for dielectric strength cover such a wide range in voltage that the apparatus, methods and precautions which are essential in certain cases do not apply to others. For convenience, the tests will be separated into two classes:

228 CLASS 1. This class includes all apparatus for which the test voltage deos not exceed 10 kilovolts, unless the apparatus is of very large static capacity, *e.g.*, a large cable system This class also includes all apparatus of small static capacity, such as line insulators, switches and the like, for all test voltages.

229 METHOD OF TEST FOR CLASS 1. The test voltage is to be continuously applied for the prescribed interval,—(one minute unless otherwise specified). The test voltage may be taken from a constant-potential source and applied directly to the apparatus to be tested, or it may be raised gradually as specified for tests under Class 2.

230 CLASS 2. This class includes all apparatus not included in Class 1.

231 METHOD OF TEST FOR CLASS 2. The test voltage is to be raised to the required value smoothly and without sudden large increments and is then to be continuously applied for the prescribed interval,—(one minute, unless otherwise specified), and then gradually decreased.

232 CONDITIONS AND PRECAUTIONS FOR CLASS 1 and CLASS 2. The following apply to all tests:

233 The WAVE SHAPE should be approximately sinusoidal and the apparatus in the testing circuits should not materially distort this wave.

234 The SUPPLY CIRCUIT should have ample current-supply capacity so that the charging current which may be taken by the apparatus under test will not materially alter the wave form nor materially affect the test voltage. The circuit should be free from accidental interruptions.

235 RESISTANCE OR INDUCTANCE in series with the primary of a raising transformer for the purpose of controlling its voltage is liable seriously to affect the wave form, thereby causing the maximum value of the voltage to bear a different and unknown ratio to the root mean square value. This method of voltage adjustment is, therefore, in general, undesirable. It may be noted that if a resistance or inductance is employed to limit the current when burning out a fault, such resistance or inductance should be short circuited during the regular voltage test.

236 The INSULATION under test should be in normal condition as to dryness and the temperature should when possible be that reached in normal service.

237 ADDITIONAL CONDITIONS AND PRECAUTIONS FOR CLASS 2. The following conditions and precautions, in addition to the foregoing, apply to tests of apparatus included in Class 2.

238 SUDDEN INCREMENT OF TESTING VOLTAGE on the apparatus under test should be avoided, particularly at high voltages and with apparatus having considerable capacity, as a momentarily excessive rise in testing voltage will result.

239 SUDDEN VARIATIONS IN TESTING VOLTAGE of the circuit supplying the voltage during the test should be avoided as they are likely to set up injurious oscillation.

240 GOOD CONNECTIONS in the circuits supplying the test voltage are essential in order to prevent injurious high frequency disturbances from being set up. When a heavy current is carried by a small water rheostat,

arcing may occur, causing high-frequency disturbances which should be carefully avoided.

241 TRANSFORMER COILS. In high-tension transformers, the low-tension coil should preferably be connected to the core and to the ground when the high-tension test is being made, in order to avoid the stress from low-tension to core, which would otherwise result through condenser action. The various terminals of each winding of the high-tension transformer under test should be connected together during the test in order to prevent undue stress on the insulation between turns or sections of the winding in case the high-voltage test causes a break-down.

(*C*) METHODS FOR MEASURING THE TEST VOLTAGE.

242 FOR MEASURING THE TEST VOLTAGE, two instruments are in common use, (1) the spark gap and (2) the voltmeter.

243 1. THE SPARK GAP is ordinarily adjusted so that it will break down with a certain predetermined voltage, and is connected in parallel with the insulation under test. It ensures that the voltage applied to the insulation is not greater than the break-down voltage of the spark gap. A given setting of the spark gap is a measure of one definite voltage, and, as its operation depends upon the maximum value of the voltage wave, it is independent of wave form and is a limit on the maximum stress to which the insulation is subjected. The spark gap is not conveniently adapted for comparatively low voltages.

244 In SPARK-GAP MEASUREMENTS, the spark gap may be set for the required voltage and the auxiliary apparatus adjusted to give a voltage at which this spark gap just breaks down. The spark gap should then be adjusted for, say, 10 per cent. higher voltage, and the auxiliary apparatus again adjusted to give the voltage of the former breakdown, which is to be the assumed voltage for the test. This voltage is to be maintained for the required interval.

245 The SPARK POINTS should consist of new sewing needles, supported axially at the ends of linear conductors which are each at least twice the length of the gap. There should be no extraneous body near the gap within a radius of twice its length. A table of approximate striking distances is given in Appendix D. This table should be used in connection with tests made by the spark-gap methods.

246 A NON-INDUCTIVE RESISTANCE of about one-half ohm per volt should be inserted in series with each terminal of the gap so as to keep the discharge current between the limits of one-quarter ampere and 2 amperes. The purpose of the resistance is to limit the current in order to prevent the surges which might otherwise occur at the time of break-down.

247 2. The VOLTMETER gives a direct reading, and the different values of the voltage can be read during the application and duration of the test. It is suitable for all voltages, and does not introduce disturbances into the test circuit.

248 In VOLTMETER MEASUREMENTS, the voltmeter should, in general, derive its voltage from the high-tension testing circuit either directly or through an auxiliary ratio transformer. It is permissible, however, to measure the voltage at other places,—for example, on the primary of the transformer, provided the ratio of transformation does not materially vary during the test; or that proper account is taken thereof.

249 SPARK GAP AND VOLTMETER. The spark gap may be employed as a check upon the voltmeter used in high-tension tests in order to determine the transformation ratio of the transformer, the variation from the sine wave form and the like. It is also useful in conjunction with voltmeter measurements to limit the stress applied to the insulating material.

(*D*) APPARATUS FOR SUPPLYING TEST VOLTAGE.

250 The GENERATOR OR CIRCUIT supplying voltage for the test should have ample current carrying capacity, so that the current which may be taken for charging the apparatus to be tested will not materially alter the wave form nor otherwise materially change the voltage.

The TESTING TRANSFORMER should be such that its ratio of transformation does not vary more than 10 per cent. when delivering the charging current required by the apparatus under test. (This may be determined by short-circuiting the secondary or high voltage winding testing transformer and supplying 1/10 of the primary voltage to the primary under this condition. The primary current that flows under this condition is the maximum which should be permitted in regular dielectric tests.)

251 The VOLTAGE CONTROL may be secured in either of several ways, which, in order of preference, are as follows:

252 1. By generator field circuit.
253 2. By magnetic commutation.
254 3. By change in transformer ratio.
255 4. By resistance or choke coils.

256 In GENERATOR VOLTAGE CONTROL, the voltage of the generator should preferably be about its approximate normal rated-load value when the full testing voltage is attained, which requires that the ratio of the raising transformer be such that the full testing voltage is reached when the generator voltage is normal. This avoids the instability in the generator which may occur if a considerable leading current is taken from it when it has low voltage and low field current.

257 In MAGNETIC COMMUTATION, the control is effected by shunting the magnetic flux through a secondary coil so as to vary the induction through the coil and the voltage induced in it. The shunting should be effected smoothly, thus avoiding sudden changes in the induced voltage.

258 In TRANSFORMER VOLTAGE CONTROL, by change of ratio, it is necessary that the transition from one step to another be made without interruption of the test voltage, and by steps sufficiently small to prevent surges in the testing circuit. The necessity of this precaution is greater as the inductance or the static capacity of the apparatus in the testing circuit under test is greater.

259 When RESISTANCE COILS OR REACTORS are used for voltage control, it is desirable that the testing voltage should be secured when the controlling resistance or reactance is very nearly or entirely out of circuit in order that the disturbing effect upon the wave form which results may be negligible at the highest voltage.

F. CONDUCTIVITY.

260 COPPER. The conductivity of copper in electric wires and cables should not be less than 98% of Matthiessen's standard of conductivity, as defined in the Copper Wire Table of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

G. RISE OF TEMPERATURE.

(I) *MEASUREMENT OF TEMPERATURE.*

(*A*) METHODS.

261 There are two methods in common use for determining the rise in temperature, viz.: (1) by thermometer, and (2) by increase in resistance of an electric circuit.

262 1. By THERMOMETER. The following precautions should be observed in the use of thermometers:

263 *a.* PROTECTION. The thermometers indicating the room temperature should be protected from thermal radiation emitted by heated bodies, or from draughts of air or from temporary fluctuations of temperature. Several room thermometers should be used. In using the thermometer by applying it to a heated part, care should be taken so to protect its bulb as to prevent radiation from it, and, at the same time, not to interfere seriously with the normal radiation from the part to which it is applied.

264 *b.* BULB. When a thermometer is applied to the free surface of a machine, it is desirable that the bulb of the thermometer should be covered by a pad of definite area. A convenient pad may be formed of cotton waste in a shallow circular box about one and a half inches in diameter, through a slot in the side in which the thermometer bulb is inserted. An unduly large pad over the thermometer tends to interfere with the natural liberation of heat from the surface to which the thermometer is applied.

265 2. By **Increase in Resistance.** The resistance may be measured either by Wheatstone bridge, or by drop-of potential method. A temperature coefficient of 0.42 per cent. per degree C., from and at 0° C., may be assumed for copper.

The temperature-coefficients from and at each degree cent. between 0° C. and 50° C. are given in Appendix E. The temperature rise may be determined either (1) by dividing the percentage increase of initial resistance by the temperature-coefficient for the initial temperature expressed in per cent.; or (2) by multiplying the increase in per cent. of the initial resistance by 238.1 plus the initial temperature in degrees C., and then dividing the product by 100.

266 3. **Comparison of Methods.** In electrical conductors, the rise of temperature should be determined by their increase of resistance where practicable. Temperature elevations measured in this way are usually in excess of temperature elevations measured by thermometers. In very low resistance circuits, thermometer measurements are frequently more reliable than measurements by the resistance method. Where a thermometer applied to a coil or winding, indicates a higher temperature elevation than that shown by resistance measurement, the thermometer indication should be accepted.

(*B*) NORMAL CONDITIONS FOR TESTS.

267 1. **Duration of Tests.** The temperature should be measured after a run of sufficient duration for the apparatus to reach a practically constant temperature. This is usually from 6 to 18 hours, according to the size and construction of the apparatus. It is permissible, however, to shorten the time of the test by running a lesser time on an overload in current and voltage, then reducing the load to normal, and maintaining it thus until the temperature has become constant.

268 2. **Room Temperature.** The rise of temperature should be referred to the standard condition of a room temperature of 25° C.

269 **Temperature Correction.** If the room temperature during the test differs from 25° C., correction on account of difference in resistance should be made by changing the observed rise of temperature by one-half per cent. for each degree C. Thus with a room temperature of 35° C., the observed rise of temperature has to be decreased by 5 per cent., and with a room temperature of 15° C., the observed rise of temperature has to be increased by 5 per cent. In certain cases, such as shunt-field circuits without rheostat, the current strength will be changed by a change of room temperature. The heat-production and dissipation may be thereby affected. Correction for this should be made by changing the observed rise in temperature in proportion as the $I^2 R$ loss in the resistance of the apparatus is altered owing to the difference in room temperature.

270 3. **Barometric Pressure. Ventilation.** A barometric pressure of 760 mm. and normal conditions of ventilation should be considered as standard, and the apparatus under test should neither be exposed to draught nor enclosed, except where expressly specified. The barometric pressure needs to be considered only when differing greatly from 760 mm.

271 **Barometric Pressure Correction.** When the barometric pressure differs greatly from the standard pressure of 760 mm. of mercury, as at high altitudes, a correction should be applied. In the absence of more accurate data, a correction of 1% of the observed rise in temperature for each 10 mm. deviation from the 760 m.m. standard is recommended. For example at a barometric pressure of 680 mm. the observed rise of temperature is to be reduced by $\frac{760-680}{10} = 8\%$

(II) *LIMITING TEMPERATURE RISE.*

272 **General.** The temperature of electrical machinery under regular service conditions, should never be allowed to remain at a point at which permanent deterioration of its insulating material takes place.

273 **Limits Recommended.** It is recommended that the following maximum

values of temperature elevation, referred to a standard room temperature of 25 degrees centigrade, at rated load under normal conditions of ventilation or cooling, should not be exceeded.

(*A*) Machines in General.

274 In commutating machines, rectifying machines, pulsating-current generators, synchronous machines, synchronous commutating machines and unipolar machines, the temperature rise in the parts specified should not exceed the following:

275 Field and armature, 50° C.

276 Commutator and brushes, by thermometer, 55° C.

277 Collector rings, 65° C.

278 Bearings and other parts of machine, by thermometer, 40° C.

279 (*B*) Rotary Induction Apparatus. The temperature rise should not exceed the following:

280 Electric circuits, 50° C., by resistance.

281 Bearings and other parts of the machine 40° C., by thermometer.

282 In squirrel-cage or short-circuited armatures, 55° C., by thermometer, may be allowed.

(*C*) Stationary Induction Apparatus.

283 *a*. Transformers for Continuous Service. The temperature rise should not exceed 50 degrees centigrade in electric circuits, by resistance; and in other parts, by thermometer.

284 *b*. Transformers for Intermittent Service. In the case of transformers intended for intermittent service, or not operating continuously at rated load, but continuously in circuit, as in the ordinary case of lighting transformers, the temperature elevation above the surrounding air-temperature should not exceed 50° C., by resistance in electric circuits and by thermometer in other parts, after the period corresponding to the term of rated load. In this instance, the test load should not be applied until the transformer has been in circuit for a sufficient time to attain the temperature elevation due to core loss. With transformers for commercial lighting, the duration of the rated-load test may be taken as three hours, unless otherwise specified.

285 *c*. Reactors, induction- and magneto-regulators—electric circuits by resistance and other parts by thermometer, 50° C.

286 *a*. Large Apparatus. Large generators, motors, transformers, or other apparatus in which reliability and reserve overload capacity are important, are frequently specified not to rise in temperature more than 40 degrees centigrade under rated load and 55 degrees centigrade at rated overload. It is, however, ordinarily undesirable to specify lower temperature elevations than 40 degrees centigrade at rated load, measured as above.

(*D*) Rheostats.

287 In Rheostats, Heaters and other electrothermal apparatus, no combustible or inflammable part or material, or portion liable to come in contact with such material, should rise more than 50° C. above the surrounding air under the service conditions for which it is designed.

288 *a*. Parts of Rheostats. Parts of rheostats and similar apparatus rising in temperature, under the specified service conditions, more than 50° C., should not contain any combustible material, and should be arranged or installed in such a manner that neither they, nor the hot air issuing from them, can come in contact with combustible material.

(*E*) Limits Recommended in Special Cases.

289 *a*. Heat Resisting Insulation. With apparatus in which the insulating materials have special heat resisting qualities a higher temperature elevation is permissible

290 *b* High Air Temperature In apparatus intended for service in places of abnormally high temperature a lower temperature elevation should be specified

291 *c* Apparatus Subject to Overload. In apparatus which by the nature of its service may be exposed to overload, or is to be used in very high voltage circuits, a smaller rise of temperature is desirable than in apparatus not liable to overloads or in low-voltage apparatus. In apparatus built for conditions of limited space, as railway motors, a higher rise of temperature must be allowed.

292 *d.* APPARATUS FOR INTERMITTENT SERVICE. In the case of apparatus intended for intermittent service, except railway motors, the temperature elevation which is attained at the end of the period corresponding to the term of rated load, should not exceed the values specified for machines in general. In such apparatus the temperature elevation, including railway motors, should be measured after operation, under as nearly as possible the conditions of service for which the apparatus is intended, and the conditions of the test should be specified.

H. OVERLOAD CAPACITIES.

293 PERFORMANCE WITH OVERLOAD. All apparatus should be able to carry the overload hereinafter specified without serious injury by heating, sparking, mechanical weakness, etc., and with an additional temperature rise not exceeding 15° C., above those specified for rated loads. the overload being applied after the apparatus has acquired the temperature corresponding to rated load continuous operation. Rheostats to which no temperature rise limits are attached are naturally exempt from this additional temperature rise of 15° C. under overload specified in these rules.

294 NORMAL CONDITIONS. Overload guarantees should refer to normal conditions of operation regarding speed, frequency, voltage, etc., and to non-inductive conditions in alternating apparatus, except where a phase displacement is inherent in the apparatus.

295 OVERLOAD CAPACITIES RECOMMENDED. The following overload capacities are recommended:

296 *a.* GENERATORS. Direct-current generators and alternating-current generators, 25 per cent. for two hours.

297 *b.* MOTORS. Direct-current motors, induction motors and synchronous motors, not including railway and other motors intended for intermittent service, 25 per cent. for two hours, and 50 per cent. for one minute.

298 *c.* CONVERTERS. Synchronous converters, 25 per cent. for two hours, 50 per cent. for one-half hour.

299 *d.* TRANSFORMERS AND RECTIFIERS. Constant-potential transformers and rectifiers, 25 per cent. for two hours; except in transformers connected to apparatus for which a different overload is guaranteed, in which case the same guarantees shall apply for the transformers as for the apparatus connected thereto.

300 *e.* EXCITERS. Exciters of alternators and other synchronous machines, 10 per cent. more overload than is required for the excitation of the synchronous machine at its guaranteed overload, and for the same period of time. All exciters of alternating-current, single-phase or polyphase generators should be able to give at its rated speed, sufficient voltage and current to excite the alternator, at the rated speed, to the full-load terminal voltage, at the rated output in kilovolt-amperes and with 50 per cent. power factor.

301 *f.* A CONTINUOUS-SERVICE RHEOSTAT, such as an armature- or field-regulating rheostat, should be capable of carrying without injury for two hours, a current 25 per cent. greater than that at which it is rated. It should also be capable of carrying for one minute a current 50 per cent. greater than its rated load current, without injury. This excess of capacity is intended for testing purposes only, and this margin of capacity should not be relied upon in the selection of the rheostat.

302 *g.* An INTERMITTENT SERVICE OR MOTOR-STARTING RHEOSTAT is used for starting a motor from rest and accelerating it to rated speed. Under ordinary conditions of service, and unless expressly stated otherwise, a motor is assumed to start in fifteen seconds and with 150% of rated current strength. A motor-starter should be capable of starting the motor under these conditions once every four minutes for one hour.

303 (*a*) This TEST may be carried out either by starting the motor at four-minute intervals, or by placing the starter at normal temperature across the maximum voltage for which it is marked, and moving the lever uniformly and gradually from the first to the last position during a period of fifteen seconds, the current being maintained substantially constant at said 50% excess by introducing resistance in series or by other suitable means.

304 (*b*) Other Rheostats for Intermittent-Service are employed under such special and varied conditions, that no general rules are applicable to them.

III. VOLTAGES AND FREQUENCIES.

A. VOLTAGES.

305 Direct-Current Generators. In direct-current, low-voltage generators, the following average terminal voltages are in general use and are recommended:

125 volts. 250 volts. 550 to 600 volts.

306 Low-Voltage Circuits. In direct-current and alternating-current low-voltage circuits, the following average terminal voltages are in general use and are recommended:

110 volts. 220 volts.

307 Primary Distribution Circuits. In alternating-current, constant-potential, primary-distribution circuits, an average voltage of 2,200 volts, with step-down transformer ratios 1/10 and 1/20, is in general use, and is recommended.

308 Transmission Circuits. In alternating-current constant-potential transmission circuits, the following average voltages are recommended.

6,600 11,000 22,000 33,000 44,000 66,000 88,000

309 Transformer Ratio. It is recommended that the standard transformer ratios should be such as to transform between the standard voltages above named. The ratio will, therefore, usually be an exact multiple of 5 or 10, *e. g.*, 2,200 to 11,000; 2,200 to 44,000.

310 Range in Voltage. In alternating-current generators, or generating systems, a range of terminal voltage should be provided from rated voltage at no load to 10 per cent. in excess thereof, to cover drop in transmission. If a greater range than ten per cent. is specified, the generator should be considered as special.

B. FREQUENCIES.

311 In Alternating-Current Circuits, the following frequencies are standard:

25~ 60~

312 These frequencies are already in extensive use and it is deemed advisable to adhere to them as closely as possible.

IV. GENERAL RECOMMENDATIONS.

313 Name Plates. All electrical apparatus should be provided with a name plate giving the manufacturer's name, the voltage and the current in amperes for which it is designed. Where practicable, the kilowatt capacity, character of current, speed, frequency, type, designation and serial number should be added.

314 Diagrams of Connections. All electrical apparatus when leaving the factory should be accompanied by a diagram showing the electrical connections and the relation of the different parts in sufficient detail to give the necessary information for proper installation.

315 Rheostat Data. Every rheostat should be clearly and permanently marked with the voltage and amperes, or range of amperes, for which it is designed.

316 Colored Indicating Lights. When using colored indicating lights on switch-boards, red should denote danger such as "switch closed." or "circuit alive"; green should denote safety, such as "switch open," or "circuit dead."

317 When white lights are used a light turned on should denote danger, such as "switch closed" or "circuit alive"; while the light out should denote safety such as 'switch open.' or 'circuit dead.' Low-efficiency lamps should be used

318 The use of colored lights is recommended as safer than white lights.

319 GROUNDING METAL WORK It is desirable that all metal work near high potential circuits be grounded

320 CIRCUIT OPENING DEVICES The following definitions are recommended.

321 *a*. A CIRCUIT-BREAKER is an apparatus for breaking a circuit at the highest current which it may be called upon to carry.

322 *b*. A DISCONNECTING SWITCH is an apparatus designed to open a circuit only when carrying little or no current.

323 *c*. An AUTOMATIC CIRCUIT-BREAKER is an apparatus for breaking a circuit automatically under an excessive strength of current. It should be capable of breaking the circuit repeatedly at rated voltage and at the maximum current which it may be called upon to carry.

V. APPENDICES AND TABULAR DATA.

APPENDIX A. NOTATION.

The following notation is recommended:

324 E, e, voltage, e.m.f., potential difference
I, i, current
P, power
Φ, magnetic flux
$\mathfrak{B}$, B, magnetic density
R, r, resistance
x, reactance
Z, z, impedance
L, l, inductance
C, c, capacity
Y, y, admittance
b, susceptance
G, g, conductance

Vector quantities when used should be denoted by capital italics.

APPENDIX B.—RAILWAY MOTORS.

(I) *RATING.*

325 INTRODUCTORY NOTE ON RATING. Railway motors usually operate in a service in which both the speed and the torque developed by the motor are varying almost continually. The average requirements, however, during successive hours in a given class of service are fairly uniform. On account of the wide variation of the instantaneous loads, it is impracticable to assign any simple and definite rating to a motor which will indicate accurately the absolute capacity of a given motor or the relative capacity of different motors under service conditions. It is also impracticable to select a motor for a particular service without much fuller data with regard both to the motor and to the service than is required, for example, in the case of stationary motors which run at constant speeds.

326 SCOPE OF NOMINAL RATING. It is common usage to give railway motors a nominal rating in horse power on the basis of a one-hour test. As above explained, a simple rating of this kind is not a proper measure of service capacity. This nominal rating, however, indicates approximately the maximum output which the motor should ordinarily be called upon to develop during acceleration. Methods of determining the continuous capacity of a railway motor for service requirements are given under a subsequent heading.

327 The NOMINAL RATING of a railway motor is the horse-power output at the car-axle, that is, including gear and other transmission losses, which gives a rise of temperature above the surrounding air (referred to a room temperature of 25 degrees cent.) not exceeding 90 degrees cent. at the commutator and 75 degrees Cent. at any other part after one hour's continuous run at its rated voltage (and frequency, in the case of an alternating-current motor) on a stand, with the motor-covers removed, and with natural ventilation. The rise in temperature is to be determined by thermometer, but the resistance of no electrical circuit in the motor shall increase more than 40% during the test.

(II) *SELECTION OF MOTOR FOR SPECIFIED SERVICE.*

328 General Requirements. The suitability of a railway motor for a specified service depends upon the following considerations:

329 *a*. Mechanical ability to develop the requisite torque and speeds as given by its speed-torque curve.

330 *b*. Ability to commutate successfully the current demanded.

331 *c*. Ability to operate in service without occasioning a temperature rise in any part which will endanger the life of the insulation.

332 Operating Conditions, Typical Run. The operating conditions which are important in the selection of a motor include the weight of load, the schedule speed, the distance between stops, the duration of stops, the rate of acceleration and of braking retardation, the grades and the curves. With these data at hand, the outputs which are required of the motor may be determined, provided the service requirements are within the limits of the speed-torque curve of the motor. These outputs may be expressed in the form of curves giving the instantaneous values of current and of voltage which must be applied to the motor. Such curves may be laid out for the entire line, but they are usually constructed only for a certain average or typical run, which is fairly representative of the conditions of service. To determine whether the motor has sufficient capacity to perform the service safely, further tests or investigations must be made.

333 Capacity Test of Railway Motor in Service. The capacity of a railway motor to deliver the necessary output may be determined by measurement of its temperature after it has reached a maximum in service. If a running test cannot be made under the actual conditions of service, an equivalent test may be made in a typical run back and forth, under such conditions of schedule speed, length of run, rate of acceleration, etc., that the test cycle of motor losses and conditions of ventilation are essentially the same as would be obtained in the specified service.

334 Methods of Comparing Motor Capacity with Service Requirements. Where it is not convenient to test motors under actual service conditions or in an equivalent typical run, recourse may be had to one of the two following methods of determining temperature rise now in general use:

335 1. Method by Losses and Thermal Capacity Curves. The heat developed in a railway motor is carried partly by conduction through the several parts and partly by convection through the air to the motor-frame whence it is distributed to the outside air. As the temperature of the several parts is thus dependent not only upon their own internal losses but also upon the temperature of neighboring parts, it becomes necessary to determine accurately the actual value and distribution of losses in a railway motor for a given service and reproduce them in an equivalent test-run. The results of a series of typical runs expressed in the form of thermal capacity curves will give the relation between degrees rise per watt loss in the armature and in the field for all ratios of losses between them met with in the commercial application of a given motor.

336 This method consists, therefore, in calculating the several internal motor losses in a specified service and determining the temperature rise with these losses from thermal capacity curves giving the degrees rise per watt loss as obtained in experimental track tests made under the same conditions of ventilation.

337 The following motor losses cause its heating and should be carefully determined for a given service: $I^2 R$ in the field; $I^2 R$ in the armature; $I^2 R$ in the brush contacts, core loss and brush friction.

338 The loss in the bearings (in the case of geared motors) also adds somewhat to the motor-heating, but owing to the variable nature of such losses they are generally neglected in making calculations.

339 2. METHOD BY CONTINUOUS CAPACITY OF MOTOR. The essential losses in the motor as found in the typical run, are in most cases those in the motor windings and in the core. The mean service conditions may be expressed in terms of the current which would produce the same losses in the motor windings and the voltage which, with that current, would produce the same core losses as the average in service. The continuous capacity of the motor is given in terms of the amperes which it will carry when run on a testing stand—with covers on or off, as specified—at different voltages, say, 40, 60, 80 and 100 per cent. of the rated voltage—with a temperature rise not exceeding 90 degrees at the commutator and 75 degrees at any other part, provided the resistance of no electric circuit in the motor increases more than 40 per cent. A comparison of the equivalent service conditions with the continuous capacity of the motor will determine whether the service requirements are within the safe capacity of the motor.

340 This method affords a ready means of determining whether a specified service is within the capacity of a given motor and it is also a convenient approximate method for comparing the service capacities of different motors.

APPENDIX C. PHOTOMETRY AND LAMPS.

341 CANDLE-POWER. The luminous intensity of sources of light is expressed in candle-power. The unit of candle-power should be derived from the standards maintained by the National Bureau of Standards at Washington, D. C., which standard unit of candle-power equals 100/88 of the Hefner unit under Reichsanstalt standard conditions for the Hefner. In practical measurements seasoned and carefully standardized incandescent lamps are more reliable and accurate than the primary standard.

342 CANDLE-LUMEN. The total flux of light from a source is equal to its mean spherical intensity multiplied by 4π. The unit of flux is called the candle-lumen. A candle lumen is the $\frac{1}{4\pi}$th part of the total flux of light emitted by a source having a mean spherical intensity of one candle-power.

343 CANDLE-METER. The unit of illumination is the candle-meter. This is the normal illumination produced by one unit of candle-power at a distance of one metre.

344 *a*. CANDLE-FOOT. Illumination is occasionally expressed in candle-feet. A candle-foot is the normal illumination produced by one unit of candle-power at a distance of one foot.

345 1 candle-foot = 10.764 candle-metres.

The use of the candle-metre unit is preferable and is recommended.

346 The EFFICIENCY OF ELECTRIC LAMPS is properly stated in terms of mean spherical candle-power per watt at lamp terminals. This use of the term efficiency is to be considered as special, and not to be confused with the generally accepted definition of efficiency in Sec. 85.

347 *a*. EFFICIENCY, AUXILIARY DEVICES. In illuminants requiring auxiliary power-consuming devices outside of the luminous body, such as steadying resistances in constant potential arc lamps, a distinction should be made between the net efficiency of the luminous source and the gross efficiency of the lamp. This distinction should always be stated. The gross efficiency should include the power consumed in the auxiliary resistance, etc. The net efficiency should, however, include the power consumed in the controlling mechanism of the lamp itself. Comparison between such sources of light should be made on the basis of gross efficiency, since the power consumed in the auxiliary device is essential to the operation.

348 *b*. A STANDARD CIRCUIT VOLTAGE of 110 volts, or a multiple thereof may be assumed, except where expressly stated otherwise.

349 WATTS PER CANDLE. The specific consumption of an electric lamp is its watt consumption per mean spherical candle-power. " Watts per candle " is the term used commercially in connection with incandescent lamps, and denotes, watts per mean horizontal candle-power.

350 PHOTOMETRIC TESTS in which the results are stated in candle-power should always be made at such a distance from the source of light that

the latter may be regarded as practically a point. Where tests are made at shorter distances, as for example in the measurement of lamps with reflectors, the results should always be given as " apparent candle-power " at the distance employed, which distance should always be specifically stated.

351 Basis for Comparison. Either the total flux of light in candle-lumens, or the mean spherical candle-power, should always be used as the basis for comparing various luminous sources with each other, unless there is a clear understanding or statement to the contrary.

352 Incandescent Lamps, Rating. It is customary to rate incandescent lamps on the basis of their mean horizontal candle-power; but in comparing incandescent lamps in which the relative distribution of luminous intensity differs, the comparison should be based on their total flux of light measured in lumens, or on their mean spherical candle-power.

353 The Spherical Reduction-Factor of a lamp

$$= \frac{\text{mean spherical candle-power}}{\text{mean horizontal candle-power}}$$

354 The Total Flux of light in candle-lumens emitted by a lamp $= 4\pi \times$ mean horizontal candle-power $\times$ spherical reduction-factor.

355 The Spherical Reduction-Factor should only be used when properly determined for the particular type and characteristics of each lamp. The spherical reduction-factor permits of substantially accurate comparisons being made between the mean spherical candle-powers of different types of incandescent lamps, and may be used in the absence of proper facilities for direct measurement of mean spherical intensity.

356 " Reading Distance." Where standard photometric measurements are impracticable, approximate measurements of illuminants such as street lamps may be made by comparing their "reading distances; " *i.e.*, by determining alternately the distances at which an ordinary size of reading print can just be read, by the same person or persons, when all other light is screened. The angle below the horizontal at which the measurement is made should be specified when it exceeds 15°.

357 In Comparing Different Luminous Sources not only should their candle-power be compared, but also their relative form, intrinsic brilliancy, distribution of illumination and character of light.

APPENDIX D. SPARKING DISTANCES.

358 Table of Sparking Distances in Air between Opposed Sharp Needle-Points, for Various Effective Sinusoidal Voltages, in inches and in centimetres. The table applies to the conditions specified in Secs. 240-246.

359

Kilovolts Sq Root of Mean Square	Distance.	
	Inches	Cms.
5	0.225	0.57
10	0.47	1.19
15	0.725	1.84
20	1.0	2.54
25	1.3	3.3
30	1.625	4.1
35	2.0	5.1
40	2.45	6.2
45	2.95	7.5
50	3.55	9.0
60	4.65	11.8
70	5.85	14.9
80	7.1	18.0
90	8.35	21.2
100	9.6	24.4
110	10.75	27.3
120	11 85	30.1
130	12.90	32.8
140	13.95	35.4
150	15.0	38.1
160	16.05	40.7
170	17.10	43.4
180	18.15	46.1
190	19.20	48.8
200	20.25	51.4
210	21.30	54.1
220	22.35	56.8
230	23.40	59.4
240	24.45	62.1
250	25.50	64.7
260	26.50	67.3
270	27.50	69.8
280	28.50	72.4
290	29.50	74.9
300	30.50	77.4

APPENDIX E. TEMPERATURE COEFFICIENTS.

860 Table of Temperature Coefficients of Resistivity in Copper at Different Initial Temperatures Centigrade.

Initial temperature cent. i	Temp. coefficient. in percent. per degree cent.	Initial temperature cent. i	Temp. coefficient. in percent. per degree cent.
0	0.4200	26	0.3786
1	0.4182	27	0.3772
2	0.4165	28	0.3758
3	0.4148	29	0.3744
4	0.4131	30	0.3730
5	0.4114	31	0.3716
6	0.4097	32	0.3702
7	0.4080	33	0.3689
8	0.4063	34	0.3675
9	0.4047	35	0.3662
10	0.4031	36	0.3648
11	0.4015	37	0.3635
12	0.3999	38	0.3622
13	0.3983	39	0.3609
14	0.3967	40	0.3596
15	0.3951	41	0.3583
16	0.3936	42	0.3570
17	0.3920	43	0.3557
18	0.3905	44	0.3545
19	0.3890	45	0.3532
20	0.3875	46	0.3520
21	0.3860	47	0.3508
22	0.3845	48	0.3495
23	0.3830	49	0.3483
24	0.3815	50	0.3471
25	0.3801		

The fundamental relation between the increase of resistance in copper and the rise of temperature may be taken as

$$R_t = R_0\,(1+0.0042\,t)$$

where R_0 is the resistance of the copper conductor at 0° C. and R_t is the corresponding resistance at t° C. This is equivalent to taking a temperature coefficient of 0.42% per deg. C. temperature rise above 0° C. For initial temperatures other than 0° C., a similar formula may be used substituting the coefficients in the above table corresponding to the actual initial temperature. The formula thus becomes at 25° C.

$$R_{i+r} = R_i\,\left(1+\frac{0.3801\,r}{100}\right)$$

where R_i is the initial resistance at 25° C. R_{i+r} the final resistance [illegible] r the temperature rise above 25° C.

In order to find the temperature rise in degrees cent. from the initial resistance R_i at the initial temperature i° C. and the final resistance R_{i+r} we may use the formula

$$r = (238.1 + i)\left(\frac{R_{i+r}}{R_i} - 1\right) \text{ degrees C.}$$

See Sec. 265.

HISTORY OF THE STANDARDIZATION RULES.

In Connection with the Presentation of the Standardization Rules to the American Institute of Electrical Engineers at the 23d Annual Convention Held at Niagara Falls, June 27. 1907.

The first step taken by the Institute toward the standardization of electrical apparatus and methods was a topical discussion on "The Standardization of Generators, Motors and Transformers," which took place simultaneously in New York and Chicago on the evening of January 26, 1898. This discussion appears in the Institute TRANSACTIONS, Vol. XV, pages 3 to 32. The opinions expressed were generally favorable to the scheme of standardization of electrical appratus, although some members feared that difficulties might arise. As a result of this discussion, a Committee on Standardization was appointed by the Council ot the Institute, consisting of the following members:

Francis B Crocker, *Chairman*.

Cary T. Hutchinson	Charles P. Steinmetz
Arthur E. Kennelly	Lewis B Stillwell
John W. Lieb, Jr.	Elihu Thomson

After a careful consideration of the matter and consultation with the members of the Institute and interested parties generally, a "Report of the Committee on Standardization," was presented and accepted by the Institute, June 26, 1899. These original rules appeared in the Institute TRANSACTIONS, Vol. XVI, pages 255 to 268.

As a result of changes and developments in the electric art, it was subsequently found necessary to revise the original report, this work being carried out by the following Committee on Standardization:

Francis B. Crocker, *Chairman*.

Arthur E. Kennelly	Charles P. Steinmetz
John W. Lieb, Jr.	Lewis B Stillwell
C. O. Mailloux	Elihu Thomson

This revised report was adopted at the 19th Annual Convention at Great Barrington, Mass., on June 20, 1902, and appears in the Institute Transactions, Vol. XIX, pages 1075 to 1092.

In consequence of still further change and development in electrical apparatus and methods, it was decided in September, 1905 that a second revision was needed, and the following Committee was appointed to do this work.

Francis B. Crocker, *Chairman.*
Arthur E. Kennelly, *Secretary.*

Henry S. Carhart
John W. Lieb, Jr.
C. O. Mailloux
Robert B. Owens
Charles F. Scott
Charles P. Steinmetz
Henry G. Stott
S. W. Stratton

This Committee held monthly meetings and carried on extensive correspondence with manufacturers, consulting and operating engineers and other interested parties, and as a result, presented its report at the 23d Annual Convention, held at Milwaukee, May 28-30, 1906. After considerable discussion the report was accepted and referred back to the Committee for amendment and rearrangement in form. It was then to be submitted to the Board of Directors for final adoption. In September, 1906, the following Standardization Committee was appointed:

Francis B. Crocker *Chairman.*
Arthur E. Kennelly, *Secretary.*

A. W. Berresford
Dugald C. Jackson
C. O. Mailloux
R. B. Owens
Charles F. Scott
Charles P. Steinmetz
Henry G. Stott
S. W. Stratton
Elihu Thomson

This Committee held monthly meetings, also sub-committee meetings, and carefully referred the rules as a whole, and each part of them, to the members of the Institute The rules were also entirely rearranged as to form, and put in shape to facilitate ready reference to them and enable future revisions to be made without breaking up the logical arrangement. Thus amended the rules were submitted to the Board of Directors and approved by it on June 21, 1907. The Board also directed that the rules should be presented, as accepted by the Board, at the Annual Convention held at Niagara Falls, June 24 to 27, 1907, which action was taken by President Sheldon on June 26, 1905. By the Constitution which went into effect on June 10, 1907, this Committee has been made a standing Committee with the title "Standards Committee," consisting of nine members.

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