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CONTENTS.

MEETING AT FRONTENAC, N. Y., JUNE 28-JULY 1, 1909.

JOINT MEETING AT CLEVELAND WITH N. E. L. P. A. SEPTEMBER 8, 1909.

MEETING AT NEW YORK, OCTOBER 8, 1909.

MEETING AT SAN FRANCISCO, OCTOBER 29, 1909.

MEETING AT NEW YORK, NOVEMBER 12, 1909.

MEETING AT NEW YORK, DECEMBER 16, 1909.

MEETING AT TORONTO, DECEMBER 18, 1908.

APPENDIX.

INDEX.

PAPERS AND DISCUSSIONS.

INDEX OF AUTHORS.

MEETINGS OF THE INSTITUTE.

BUSINESS OF THE INSTITUTE.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

THE RESISTANCE AND REACTANCE OF ARMORED CABLES*

BY J. B. WHITEHEAD

It has been asserted frequently that no form of iron protective covering is permissible for single conductors carrying alternating currents. Experience and simple calculation show this assertion to be well founded with regard to even the thinnest walls, if such walls form a completely closed magnetic circuit about the conductor. In a recent single-phase railway installation it was necessary to carry the trolley circuit across a drawbridge and the nature of the traffic through the draw rendered it advisable to armor the cables, several of which were to be installed for reserve and emergency. Obviously, the use of single-conductor, steel-armored cables was permissible if the reactance and losses in the armor were not prohibitive. There being an apparent absence of data on the subject, and some opinion adverse to the use of such cables, the values of reactance were calculated as explained below. The results showed that even at 60 cycles, and with outgoing and return cables placed close together, the reactance would not be serious; and the subsequent measurements indicate that in cables as manufactured the effect is considerably less than the calculated value, so that for purposes similar to that mentioned the use of the cables is entirely practical.

Calculation. The usual cable consists of a central stranded conductor, surrounded by rubber or paper insulation, covered by tape, lead, jute, and armor in the order named. The armor consists of a number of wires spiralled around the cable; the number of armor wires varies somewhat with the size of cable but is not usually

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*The measurements were made at the Johns Hopkins University. The cables were loaned by the Standard Underground Cable Company.

less than 20. The pitch of the spiral is from 5 to 10 times the diameter of the cable, being fixed by the size of armor wire and the requirement to cover the entire outer surface. The exact expression for the inductance in the armor wires is too unwieldly for direct evaluation. A close approximation to its value may be had by neglecting the spiral, by assuming that the intensity of magnetic force is uniform through the armor and equal to the value at the center of the section of an armor wire, and by assuming that the lines of magnetic intensity are circles concentric about the center of the main conductor.

It is obvious that any increase in the inductance due to the armor will take place almost entirely in the region near the circle passing through the lines of contact between the armor wires. This is borne out by the form of integral which is involved, which shows that 0.8 of the total induction is within an arc of 10 degrees on each side the point of contact, and indicates that the above assumptions yield results only a few per cent greater than the exact value. The problem then resolves itself into a determination of the reluctance of a closed magnetic circuit formed by a number of iron wires placed side by side on the circumference of a circle, the magnetic field being at right angles with the length of the wires. The magnetic field is circular and of uniform intensity in the space occupied by the wires. The approximate calculation is further simplified without serious error if the circle of armor wires be considered as laid out side by side in the plane of a uniform magnetic field.

Consider the reluctance of an elementary portion of the magnetic circuit at a distance x from the line passing through all the points of contact, of a width dx, and length equal to the diameter of the armor wire. The length of path in iron is $2\sqrt{r^2 - x^2}$, and the length in air is $2\ (r - \sqrt{r^2 - x^2})$, r being the radius of the armor wire cross-section. The total reluctance per unit length of cable of the circular element of thickness dx is then

$$R = \frac{2\,n}{d\,x}\left(\frac{\sqrt{r^2 - x^2}}{\mu} + r - \sqrt{r^2 - x^2}\right)$$

in which n is the number of armor wires and μ the permeability. The error in neglecting the curvature of the circle of contacts is rom 1 to 2 per cent for 20 to 30 armor wires.

The total flux in the armor alone is

$$\Phi_i = \frac{4\pi i}{10\,n} \cdot \tfrac{1}{2} \int_{-r}^{+r} \frac{dx}{r+a\,\sqrt{r^2-x^2}}$$

$$= \frac{0.4\,\pi i}{n} \cdot \frac{1}{a} \left\{ \frac{\pi}{2} - \frac{2}{\sqrt{1-a^2}} \tan^{-1} \left(\frac{1-a}{1+a} \right) \right\},$$

in which

$$a = \frac{1-\mu}{\mu}$$

For

$$\mu = 50,\ \Phi_i = 13.8\,\frac{0.4\,\pi i}{n}\cdot$$

$$\mu = 300,\ \Phi_i = 36.7\,\frac{0.4\,\mu i}{n}$$

If there were no armor wire the total magnetic induction in the corresponding air space would be equal to

$$\frac{0.4\,\pi i}{n};$$

consequently the presence of the armor increases the induction in the space occupied by it from 14 to 36 times, according to the value of μ.

The effect of the flux in the armor on the total inductance of the cable will depend on the radius of the central conductor and the distance between it and the return conductor; that is, on the proportion of the total field of force which is occupied by the armor. The data of one of the cables on which measurements were made are as follows:

Single conductor 0 B. & S. gauge; stranded $\frac{8}{32}$ in. of paper, $\frac{1}{8}$ in. of lead, and a jute bedding about $\frac{1}{8}$ in. thick, armored with No. 10 (B. W. G.) steel wires.

Diameter over strand	373	mils.
" over paper insulation	873	"
Diameter over lead sheath	1123	"
Outside diameter, approximate	1500	"

The values of the inductance of this cable per mile of conductor, at different distances, *d*, between ajacent surfaces of parallel cables, assuming the permeability of the armor to be 1, and applying the formula

$$L = \frac{161}{10^3}\left\{2 \log \frac{D}{r} + \tfrac{1}{2}\right\},$$

are as follows:

D = distance between centers of cables
$d = 0$, $L = 0.75$ millihenry
$d = 2$ in., $L = 1.02$ millihenrys
$d = 6$ in., $L = 1.26$ "
$d = 12$ in., $L = 1.45$ "

The value of L for the space inside the armor is 0.69. Consequently the difference, 0.06, between 0.75 and 0.69 is the proportion which is increased by the factors 14 to 36 mentioned above. Calling this factor k, the values of L with armor wires in contact over the entire circumference are got by adding 0.078 $(k - 1)$ to the values given above. For $k = 36$ the values of L are increased by the armor 3.8, 3.1, 2.7, and 2.5 times respectively for the distances of separation given above, and for 6 ft. separation the factor is 2.1. That is, depending on the distance of separation the reactance of the usual single-conductor, steel-armored cable may be from two to four times as great as the reactance of the same cable without steel armor. Obviously the reactance constitutes no objection to the use of such cables in moderate lengths.

The losses in the armor are not subject to simple calculation. As already stated, about 80 per cent of the total induction in the armor is within an arc of 10 degrees on each side of the point of contact of two adjacent wires. For $\mu = 300$ this means an average value of the induction B equal to 166 H within a wall from 0.03 to 0.05 in. thick. At 100 amperes the value of H in the armor of the type of cable under discussion is about 10. It is evident that the resulting losses would not rise to any great value. It is also evident that the assumption that the armor wires are all in contact throughout their length will not be true of the manufactured product. Since the induction in the armor will be greatly decreased for any appreciable air-gap between the individual wires, the reactance and losses should fall below the approximate values as calculated. This conclusion was borne out by the following measurements.

Single-conductor, iron-armored cable. The description of this cable has been already given. The measurements were made on two lengths each 51 ft. long, at different distances apart, with frequencies of 25 and 60 cycles and various values of current. The quantities measured were current, impedance, resistance, and power. The instruments employed were a voltmeter with a range of 0.5 to 3.5 volts and a scale which could be read to 0.005 volt, an electrodynamometer, and a wattmeter. The wattmeter was connected in the 110-volt primary circuit of a special transformer which gave low secondary voltages. The primary current of this transformer was also measured. The net loss in the cable as given in the accompanying table is the wattmeter reading minus the aggregate of the iron and copper losses in the transformer and the copper loss in the leads to the cable. Separate determinations of these values were made at each reading, and the actual or dead resistance—resistance with direct current flowing—measured after each alternating-current reading. The results are given in Table I.

The increase in the impedance with current and with distance between cables is evident but not great. At 60 cycles it varies from 2.2 times the dead resistance, at 67 amperes with the cables close together, to 2.8 times the resistance at 90 amperes with 12 in. between cables. The effective resistance as calculated from the watts lost in the cable is given in column 9 and the effective reactance in column 10. The decrease in effective resistance and the increase in effective reactance with increasing separation is noticeable at 60 cycles, but not important at 25 cycles. At the lower frequency, owing to the saturation of the transformer, the accuracy of the figures for the losses is somewhat impaired. This is reflected in the value of the reactance which is the square root of the difference between two squares of approximately equal value. The order of magnitude, however, is sufficiently indicated.

The reactance per mile of two cables 12 in. apart, as measured at 60 cycles and 90 amperes, is 2.13 ohms; the value calculated as previously explained is 2.73; at 25 cycles the values are 0.80 and 1.14, respectively. The figures for other distances of separation show similar differences, and indicate the measured values to be about 70 per cent of those calculated for the ideal case. As already stated, this is accounted for by the fact that the armor wires are not in contact at all points.

The effective resistance increases with the current density but varies very little with the distance of separation. The value in the cable here investigated increased at 60 cycles and a current density of 1 ampere per 1000 circular mils, to about twice the dead resistance.

TABLE I.

SINGLE-CONDUCTOR CABLE WITH IRON ARMOR.

Two parallel lengths, 51 ft. long each. Conductor No. 0 B. & S. Stranded Armor 29 No. 10 B.W.G. Wires.

	Frequency 60 cycles.								
1 Separation of cables, inches	2 Amperes	3 Volts	4 Impedance	5 Resistance	6 Gross watts	7 Trans. loss watts	8 Net loss in cable watts	9 Effective Resistance	10 Effective Reactance
0	67.2	1.50	0.0223	0.0104	245	160	85	0.0188	0.012
	75.4	1.75	0.0232	0.0104	305	198	107	0.0188	0.0135
	88	2.14	0.0242	0.0105	415	265	150	0.0199	0.0144
2	60.8	1.37	0.0225	0.0102	197	135	62	0.0167	0.0151
	76.28	1.86	0.0244	0.0104	315	208	107	0.0184	0.016
	87.4	2.22	0.0254	0.0103	418	261	157	0.0205	0.0156
6	60.6	1.45	0.0239	0.0103	197	137	60	0.0165	0.0173
	76.25	1.95	0.0255	0.0103	316	212	104	0.0179	0.0181
	86.7	2.31	0.0267	0.0101	411	269	142	0.0189	0.0188
12	59.8	1.49	0.0249	0.0105	196	137	59	0.1064	0.0187
	68.5	1.8	0.0263	0.0104	257	178	79	0.0168	0.020
	89.4	2.53	0.0283	0.0104	447	289	158	0.0192	0.021
	Frequency 25 cycles.								
0	68.7	1.05	0.0153	0.0103	245	173	72	0.1152	0.002
	74.3	1.65	0.0157	0.0103	285	202	83	0.0150	0.003
	84.0	1.375	0.0164	0.0103	381	268	113	0.016	0.003
2	69.6	1.085	0.0156	0.0103	246	175	71	0.0146	0.005
	75.6	1.205	0.0159	0.0102	302	213	89	0.0155	0.004
	83.6	1.375	0.0164	0.0103	371	263	108	0.0155	0.005
6	68.3	1.075	0.0157	0.0103	241	173	68	0.0146	0.005
	75.4	1.220	0.0161	0.0102	294	209	85	0.0150	0.006
	85.8	1.48	0.0172	0.0103	417	296	121	0.0164	0.005
12	70.3	1.17	0.0166	0.0104	258	185	73	0.0147	0.007
	75.5	1.275	0.0169	0.0104	313	220	93	0.0163	0.004
	84.1	1.475	0.0175	0.0104	390	279	111	0.0157	0.008

The effect on the impedance of connecting the lead sheathing at both ends and also connecting the iron armor at both ends, with 12 in. separation, is shown in Table II. It is noticeable that the impedance is reduced by each of these secondary circuits. The increase in impedance with increasing current is less marked, however, indicating the low value of reactance resulting from the presence of the closed secondary circuits. In the same table several values of impedance are given for the case of the return current in the lead sheath. A small value of reactance is indicated at 60 cycles, about one-fifth the value of the dead resistance, assuming the effective resistance to be no greater than the dead resistance. At 25 cycles the difference between impedance and dead resistance is so small as to approach the limits of accuracy to which the instruments could be read.

TABLE II.

Two Single-Conductor Cables with Iron Armor, 12 in. Apart.
Lead sheathings connected at both ends.

60 cycles.				25 cycles.			
Current	Volts	Imped.	Resist.	Current	Volts	Imped.	Resist.
67.5	1.62	0.0240	0.0103	....	....	....	....
77.0	1.89	0.0245	0.0103	80.5	1.375	0.0171	0.0104
84.7	2.1	0.0248	0.0103	90.2	1.59	0.0176	....
Both Sheathings and Armors Connected at Both Ends.							
72.5	1.57	0.0216	0.0105	....	....	....	....
82.7	1.817	0.0219	....	82.1	1.351	0.0164	....
88.6	1.945	0.0219	....	93.7	1.57	0.0167	0.0106
One Cable, with Lead Sheath as Return.							
82.0	1.54	0.0188	0.0185	73.1	1.365	0.0187	0.0187
87.6	1.645	0.0188	0.0186	78.7	1.48	0.0188	0.0188
93.0	1.775	0.0191	0.0187	82.0	1.54	0.0188	0.0188

Single-conductor, copper-armored cable. A series of measurements were made on two 48-ft. lengths of cable similar in all respects to that with steel armor, except that the armor consisted of 24 No. 8 B. & S. hard-drawn copper wires. The impedance was measured at different current densities and with different separations of the cables, with the copper armor connected and disconnected at the ends. The impedance was also measured for a return circuit through the armor wire. The results are given in Table III.

TABLE III.

Single-Conductor Cables with Copper Armor.

60 cycles.

	Armor Open				Armor Connected at ends.			
Separation	Cur.	Volts	Imped.	Resist.	Cur.	Volts	Imped.	Resist.
0	84.7	0.92	0.0108	0.0092	87.8	0.98	0.0111	0.0092
	91.8	1.01	0.011	0.0092	....	....	....	....
2 in.	84.0	1.00	0.0119	0.0093	82.6	1.03	0.0124	0.0093
	87.7	1.05	0.0120	0.0094	....	....	....	....
6 in.	80.0	1.055	0.0132	0.0094	77.5	1.06	0.0137	0.0094
	86.4	1.152	0.0133	0.0094	84.1	1.16	0.0138	0.0094
12 in.	77.1	1.11	0.0144	0.0096				
	84.6	1.24	0.0146	0.0096				

25 cycles.

Separation	Cur.	Volts	Imped.	Resist.	Cur.	Volts	Imped.	Resist.
0	98.8	0.83	0.0095	0.0093	89.0	0.845	0.0095	0.0091
2 in.	87.5	0.855	0.0098	0.0094	86.2	0.86	0.0099	0.0093
6 in.	86.9	0.897	0.0103	0.0094	87.2	0.92	0.0105	0.0094
12 in.	85.1	0.905	0.0106	0.0097	83.5	0.935	0.0112	0.0096

One cable length with return through copper armor.

60 cycles.				25 cycles.			
Current	Bolts	Imped.	Resist.	Current	Volts	Imped.	Resist
71.6	0.500	0.0070	0.0065	65.0	0.42	0.0064	....
83.6	0.595	0.0071	0.0067	71.6	0.48	0.0067	0.0066
89.5	0.6530	0.0070	0.0068	73.5	0.50	0.0068	....

At 60 cycles and 12 in. separation the reactance per mile of double conductor, as calculated from the measured values of impedance and resistance at 82 amperes is 1.19 ohms. As calculated from the value of L given by the formula previously stated, the value is 1.1. This indicates an appreciable eddy-current loss in the copper armor. The readings with the armors of the two cables connected at both ends indicate a small increase in the effective resistance.

Table IV gives the impedance values for a double-conductor, steel-armored cable. The conductors were similar to those in the single-conductor cables and spaced at 0.873 in. between centres. The diameter over the lead sheath was 2.025 in. and the armor consisted of 38 No. 18 B.W.G. steel wires. At 91 amperes and 60 cycles the impedance per mile, as measured, was 1.14 ohms. The value as calculated by means of the formula for L and the measured value of the dead resistance was 1.09 ohms. The difference between measured and calculated values indicates that the increase in impedance of the double-conductor cable also is due to increase in the effective resistance. This increase is probably due to eddy currents in the lead sheath rather than to any effect of the steel armor.

TABLE IV.

Double-Conductor Cable with Iron Armor.

60 cycles				25 cycles.			
Current	Volts	Imped.	Resist.	Current	Volts	Imped.	Resist.
84.6	0.968	0.0113	0.0101	82.9	0.860	0.0104	0.0101
88.5	1.020	.0115	0.0101	86.0	0.905	0.0105	0.0102
91.0	1.050	0.0115	0.0101				

Conclusions. 1. Theoretically the reactance of the usual type of single-conductor, iron-armored power cable may be from 2 to 4 times that of unarmored cable, depending on the distance to return conductor; the factor increases with decreasing distance.

2. In cables as manufactured the reactance is about 0.7 of the maximum theoretical value.

3. The effective resistance as measured varies little with the distance to return conductor and is about 1.6 and 2 times the

dead resistance at 25 and 60 cycles, respectively, and a current density of 1 ampere per 1000 circular mils.

4. The impedance for distances under 12 in. is about 3 times the dead resistance at 60 cycles and 1.7 to 2 times the dead resistance at 25 cycles. With the sheathing and the armor grounded at both ends the impedance is somewhat lessened and is largely of the nature of resistance.

5. The impedance of a double-conductor, iron-armored cable, with conductors located 0.873 in. apart between centers, and at the current density given above, is about 5 per cent greater at 60 cycles and 3 per cent greater at 25 cycles than the calculated value. The increase is in effective resistance, due to eddy currents in the lead sheathing.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y. June 29, 1909.

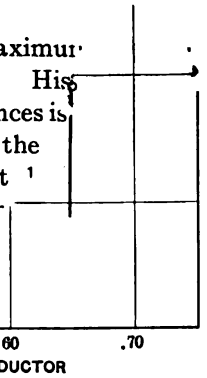
. By A. I. E. E.

LOSSES, INDUCED VOLTS AND AMPERES IN ARMOR AND LEAD COVER OF CABLES

BY H. W. FISHER

Part I of this paper is supplementary to the paper by Professor Whitehead, because the data presented were obtained from measurements made on the same cables prior to Professor Whitehead's tests. The results given cover conditions mostly not considered by Professor Whitehead. Any differences in impedance and losses presented are undoubtedly due to the coiling and uncoiling and shipment of cables, as these would tend to change the relative air-gaps between the armor wires. Slight differences may also have been caused by small differences in the lengths of the cables tested, or by differences in temperature.

Professor Whitehead shows clearly how the maximur
inductance of armored cables can be calculated. His
son between the calculated and measured impedances is
interesting and instructive. It is evident that the
of iron-armored, single-conductor cables cannot
with any degree of certainty, because slight differ
gaps between the armor wires materially affe
of the cable. Moreover the induced volts a
affected by the same cause, hence the resu
iron-armored, single-conductor cable must
proximate in their general application to



The first cable considered will be t
Professor Whitehead's paper; namel
0 B. & S. G., insulated with $\frac{8}{32}$ in. pape
lead with the usual jute bedding and No.
The dimensions are as follows:

thest apart and when the
these conditions, with a
ced volts for 2000 ft. of
e load, a minimum in-

Diameter over copper strand, = 373 mils.
Diameter over paper insulation, = 873 mils.
Diameter over lead sheath, = 1123 mils.
Outside diameter, approximate, = 1500 mils.
Resistance of conductor per 2000 ft. = 0.21
Resistance of lead sheath per 2000 ft. = 0.53
Resistance of armor per 2000 ft. = 0.35

The following symbols are used to designate the different curves shown in Figs. 1 and 2:

A indicates that the distance between centers of cables was 1.5 in.
B " " " " " " " " " 9 in.
C " " " " " " " " " 24 in.

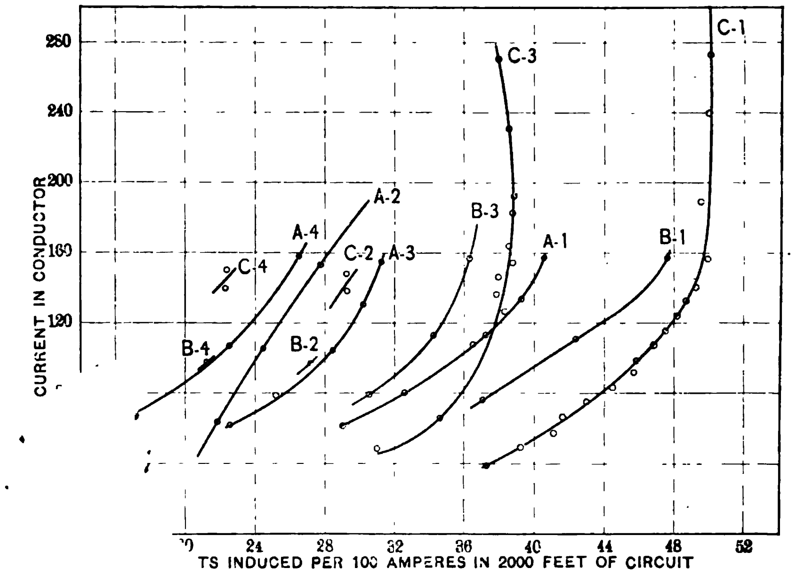


Fig. 1.

'n connection with the above letters indicate

r volts in lead.
volts in lead, the armor being short-
of the cable.
'lts in armor,
volts in armor, the lead being short-cir-
of the cable.
armor and lead, connected in parallel.
ts induced per 100 amperes in 2000 ft. of

circuit. The reason for expressing the volts in terms of 100 amperes in the conductor is to give at sight a general idea of what pressure might be expected with a current somewhat near that used in practice. It will be seen that the induced volts are greatest when the conductors are farthest apart and when the armor is not short-circuited. Under these conditions, with a normal load of about 170 amperes the induced volts for 2000 ft. of circuit would be about 85. For the same load, a minimum in-

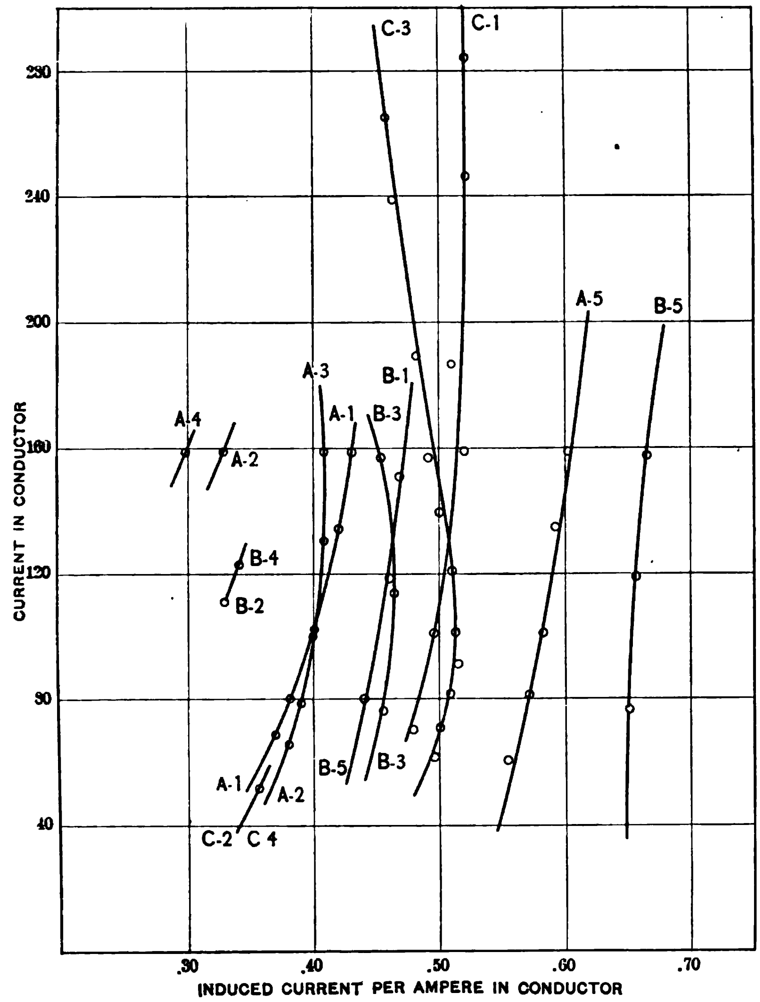


FIG. 2.

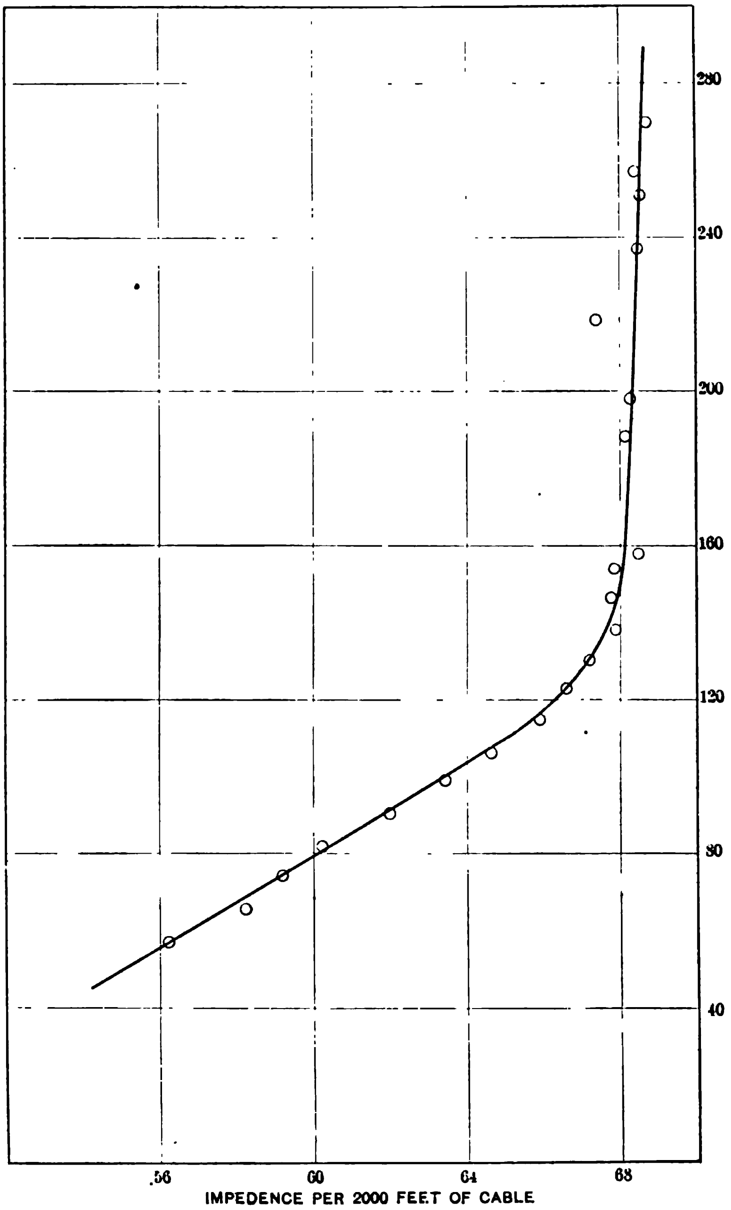


Fig. 3.—Current in conductor

duced electromotive force of 40 volts was obtained on the armor when the lead covers were connected at both ends of the cable. Between these extremes will be found various curves giving the different induced volts corresponding to the various tests that were made. The bends in the curves are characteristic of all circuits containing iron.

Fig. 2 gives the current induced per ampere in the conductor. Here, as would be expected, the greatest current is obtained when both the lead and armor are in parallel. This current amounts to approximately 65 per cent of the current flowing in the conductor. From this it will readily be seen that an armored cable has a tendency to become warmer than an unarmored cable. However, in practice such cables are generally laid in water or in the ground, where the dissipation of heat is readily taken care of.

TABLE I.

Current in conductor	Effective resistance per 2000 ft. of circuit			
	No. 1	No. 2	No. 3	No. 4
60	0.33	0.36	0.36	0.35
100	0.41	0.41	0.40	0.37
160	0.46	0.45	0.44	0.40
240	——	0.48	0.48	0.42

Curve *C*-3 shows that a maximum per cent of induced current is reached with about 100 amperes in the conductor.

Fig. 3 shows how the impedance of the cable is affected by the amount of current. The knee of the curve commences at about 120 amperes; if sufficient current were applied, undoubtedly the impedance would begin to decrease. This will be shown in some curves given later.

Table I gives the effective resistance per 2000 ft. of circuit. The values given were obtained from wattmeter tests made when the cables were 24 in. apart. No. 1 indicates that neither lead nor armor circuit was connected; No. 2 that the lead circuit was connected at each end of the cable; No. 3 that the armor circuit was connected at each end of the cable; No. 4 that both circuits were connected. The conductor resistance to direct current was 0.21 ohms, so it will be seen that the maximum total loss is somewhat greater than double the conductor loss. When the distance between centers was 1.5 in. the losses in the No. 1

column were increased by about 1 per cent. In the Nos. 2, 3, and 4 columns, the losses were less as the distances were decreased. At 1.5 in. separation and with 60 amperes in the conductor, the difference was slight. With 160 amperes the decrease was about 5 per cent.

It will also be seen that the relative losses given in column 1 increase with the amount of current. For any particular current the losses in the several columns are not materially different, but this condition would not necessarily always be the case.

Single-conductor, copper-armored cable. This cable was made up substantially in the same manner as the first mentioned cable, except that the armor consisted of 24 No. 8 B. & S. G., hard-drawn copper wires.

Table II gives the volts induced in 2000 ft. of circuit per 100 amperes. Comparing this table with the curves in Fig. 1, a marked diminution in induced volts is shown.

TABLE II.

VOLTS INDUCED IN 2000 FT. OF CIRCUIT PER 100 AMPERES

Distance between centers	Measured induced volts	
	In lead circuit	In armor circuit
3 in.	8.2	6.6
6 in.	11	9.5
12 in.	14.3	12.6
18 in.	16.2	14.5

Table III gives the current induced per 100 amperes in the conductor. These tables do not call for comment, except that the induced voltage and current are proportional to the current in the conductor.

TABLE III.

CURRENT INDUCED PER 100 AMPERES IN CONDUCTOR

Distance between centers	Measured induced current	
	In lead circuit	In armor circuit
3 in.	14	44
6 in.	18	56
12 in.	23	63
18 in.	25	67

Table IV gives the impedance per 2000 ft. of cable for different distances with different connections of armor and lead. The calculated values are also given. In making these calculations it was necessary to estimate the resistance of the lead and armor circuits. The calculated values in the table are not so close as they would have been had the resistance referred to been accurately measured. The formulas for making these calculations were worked out after the cables had been discarded. The most interesting part of this table is that the impedance is greater when the lead circuit is connected at both ends of the cable than when the lead covers are not connected. This seems so contrary to what would be expected that I asked my chief assistant, Mr. R. W. Atkinson, to investigate the subject mathematically. In Part III of this paper will be found his graphical and mathematical solution of this problem; this solution shows the conditions under which the impedance of the cable may be greater when the lead covers are short-circuited.

TABLE IV

IMPEDANCE PER 2000 FT. OF CABLE

Distance between centers	Measured impedance				Calculated impedance	
	Lead and armor free	Leads connected	Armor connected	Both connected	Lead connected	Armor connected
1.5 in.	—	—	—	—	0.234	0.239
3 in.	0.245	0.255	0.252	0.253	0.262	0.262
6 in.	0.264	0.277	0.264	0.262	0.290	0.276
12 in.	0.288	0.304	0.273	0.271	0.321	0.284
18 in.	0.298	0.319	0.276	0.273	0.339	0.283

PART II.

This part deals with tests made on 100-ft. of steel-tape-armored cable of the following construction:

Size of conductor	No. 0 B. & S. G.
Thickness of paper	$\frac{8}{32}$ in.
Thickness of lead	$\frac{1}{8}$ in.
Diameter over lead	$1\frac{1}{8}$ in.
Diameter over armor	$1\frac{5}{8}$ in.
Dimensions of steel tape	0.039 in by 1.5 in.

Two such tapes were applied in the same direction, overlapping each other.

Resistance of conductor.............0.0103 ohm.
Resistance of lead sheath............0.0300 "
Resistance of armor ....0.150 "

To designate the different curves, the following letters and figures were employed.

A indicates that the cables were 1⅞ in. between centers.
C indicates that the cables were 24 in. " "
1 indicates induced current or volts in lead.
2 indicates induced current or volts in lead, the armor being short-circuited at each end of the cable.
3 indicates induced current or volts in armor,
4 indicates induced current or volts in armor, the lead being short-circuited at each end of the cable.
5 indicates induced current in armor and lead connected in parallel.
6 indicates lead or armor of each cable not connected nor inter-connected.
7 indicates lead short-circuited at each end of the cable, armor free.
8 indicates armor short-circuited at each end of the cable, lead free.
9 indicates lead and armor short-circuited at each end of the cable.

On account of the continuity of the steel armor, which forms almost a closed magnetic circuit, the curves for this cable are radically different from those of the steel-wire-armored cables.

On referring to Fig. 4, which gives the impedance per 2000 ft. at 60 cycles, it will be seen that the impedances are greatest when the armor and lead are not connected, and that a sharply defined maximum is reached with a conductor current of about 80 amperes. There is not much difference in curves A_6 and C_6 except at low current densities, where the greater distance between cables of test C_6 makes the air effect larger proportionally, and hence causes a greater difference of impedance between the two curves.

Short-circuiting the armor at each end of the cable (See A_8 and C_8) decreases the impedance only slightly. However, when both lead and armor are short-circuited (See A_9 and C_9) the impedance is very much reduced and only varies slightly with the amount of current in the conductor. In this kind of cable when the lead and armor are disconnected, the impedance may be 13 times the ohmic resistance. When the lead and armor are short-circuited, which is generally the case in practice, the impedance may be about 3.5 times the ohmic resistance. With larger conductor cables these ratios may be very much increased.

Fig. 5 gives the equivalent resistance per 2000 ft. of circuit. Here a current of about 60 amperes in the conductor seems to produce the maximum resistance. This resistance seems to be virtually independent of the distance between the centers of the cables. It is also striking that curves C_8 and A_8 cross curves C_9 and A_9 at points corresponding to about 40 and 200 amperes respectively, so that for small current densities and very large current densities the equivalent resistance per 2000 ft. of circuit may be less when the lead and armor are not connected than when they are connected. The maximum equivalent resistance is about 8 times the ohmic resistance when the lead and armor are disconnected. Under practical conditions of operation the equivalent resistance would be about 3.5 times the ohmic resistance.

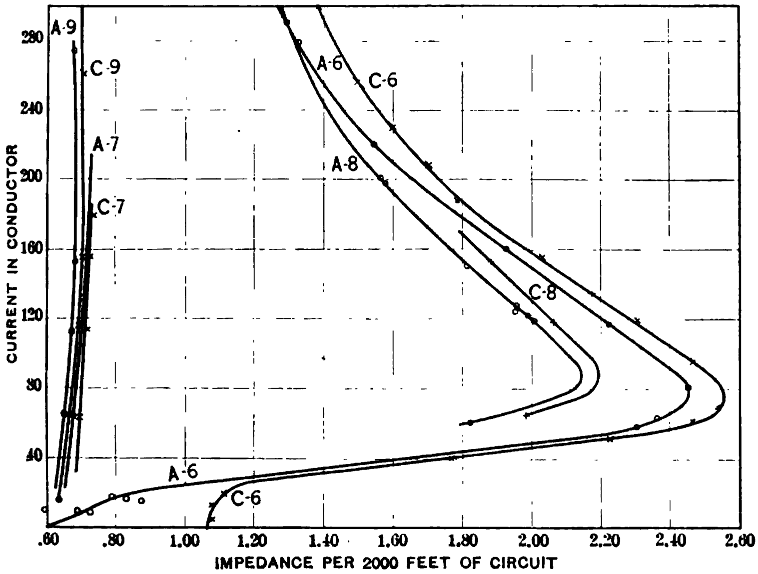


FIG. 4.

All this tends to show how advisable it is to use multiple-conductor cables all under one armor instead of single-conductor armored cables. The equivalent resistances given in Fig. 5 were found by means of wattmeter tests.

Fig. 6 gives the volts induced per 100 amperes in 2000 ft. of circuit. These curves show clearly a maximum rate of induced voltage that corresponds to about 80 amperes in the conductor. As might be expected, the induced voltage is greatest when the cables are farthest apart. At the maximum point the volts per 100 amperes are about 240, or actually about 190 volts. With a load of 170 amperes, the induced volts would be about 290. When the lead is short-circuited the electromotive force on the armor as given by C_4 is very small. The intermediate curves are in the order that one would expect.

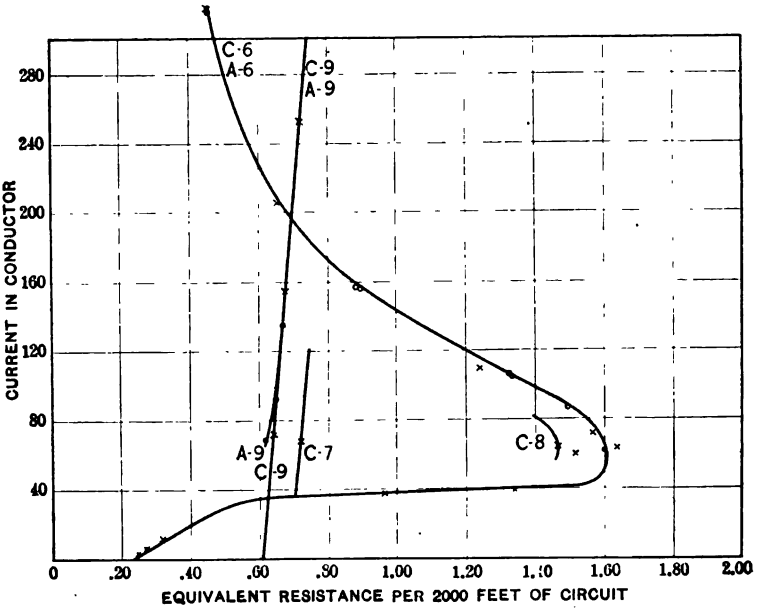


FIG. 5.

The significant fact brought out by these tests is that it is necessary to bond the armor and lead of single-conductor cables like the above, or else arcs may occur betwen the cables, or alternating-current electrolysis may tend to destroy the armor or lead. Even when such cables are laid in water, it would be best to bond the armor and lead occasionally.

Fig. 7 gives the induced current per ampere in conductor. With high current densities the induced current amounts to nearly 85 per cent of the total current. On account of the high resistance of the armor, the current induced therein is small,

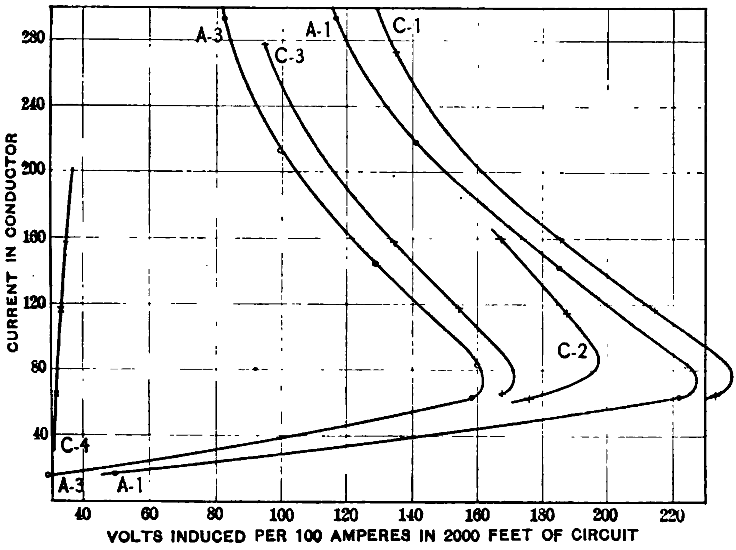

CURRENT IN CONDUCTOR
280
240
200
160
120
80
40
A-3
A-1
C-1
C-3
C-2
C-4
A-3
A-1
40
60
80
100
120
140
160
180
200
220
VOLTS INDUCED PER 100 AMPERES IN 2000 FEET OF CIRCUIT

FIG. 6.

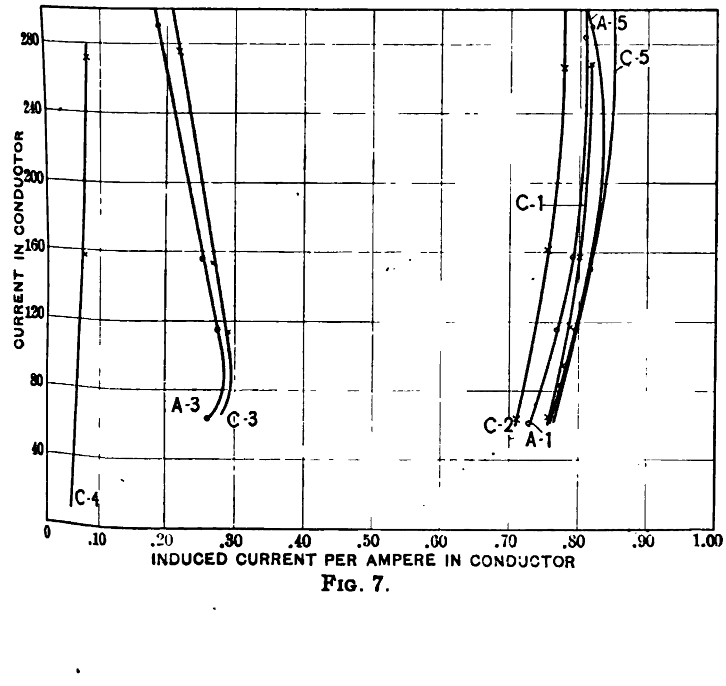

CURRENT IN CONDUCTOR
280
240
200
160
120
80
40
A-5
C-5
C-1
A-3
C-3
C-2
A-1
C-4
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
INDUCED CURRENT PER AMPERE IN CONDUCTOR

FIG. 7.

(See A_3, C_3 and C_4). The other curves are practically close together, and the greatest current is obtained when the cables are operating under practical working conditions with the lead and armor connected.

The large amount of induced current will not only increase the losses of such a cable under operating conditions, but will also, of course, tend to reduce the safe carrying capacity. Therefore, as previously stated, when armored cables have to be employed for alternating currents, all circuits should be placed in one cable. Where it is impossible to do this, the cables will be operated at an increased loss.

A comparison between measured and calculated data is found in Table V. This comparison will be of interest as an illustration of the accuracy of the practical method given at the close of the paper.

TABLE V

Current in conductor	Impedance		Volts induced on lead		Effective resistance		Induced current in lead in per cent of conductor current	
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
300	0.73	0.716	128	126		0.68	0.815	0.83
156	0.72	0.73	187	187		0.716	0.80	0.87
70	—	—	—	—	0.72	—	—	—

In Table V, the impedances and effective resistances are for lead covers short-circuited at each end of the cable. The values given in Table V are per 2000 ft. of circuit. Only one test was made of effective resistance and that with 70 amperes in the conductor.

In order to see if the correction method would give a closer agreement to the measured impedance than the method which is correct for cables without iron armor, the following calculations were made with reference to the steel-wire-armored cable mentioned in Part I. The distance between centers of cables was 1.5 in.

Measured impedance = 0.233
Calculated impedance by correction method = 0.226
Calculated impedance by theoretical method for cables without armor = 0.283
Current in conductor = 140 amperes.

The close agreement of the first and second impedances given shows that the correction method should be used in connection with armored cables.

Comparison calculations between the two methods as applied to the steel-tape-armored cable show a fairly close agreement. This agreement is no doubt due to the fact that the reactance of this cable is so great that the current induced in the lead forms a large part of the conductor current, and a large change in the reactance will only slightly affect the lead current.

Part III.

Calculation of impedance, etc. A graphical method may be used for determining the conditions existing when the armor or lead circuit is completed. The conditions required to be known are the reactance and resistance of the conductor and of the secondary circuit. These may have been measured or calculated.

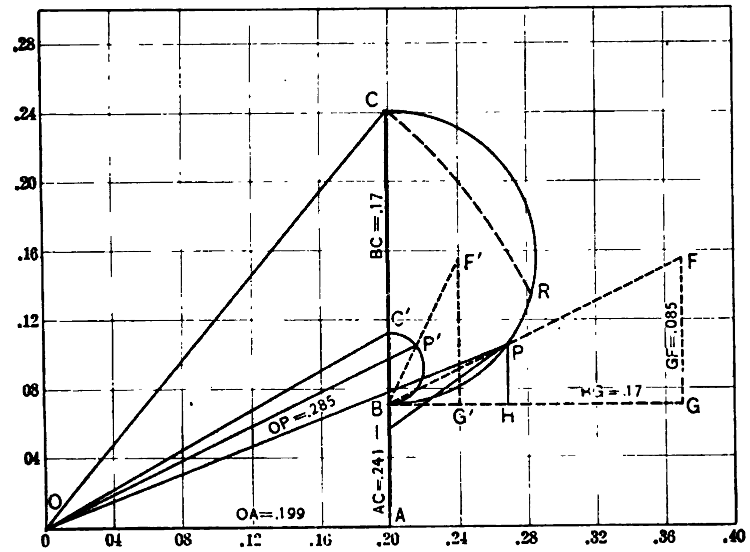


Fig. 8.

Refer to Fig. 8. The following construction has been made. OA is parallel to the X axis and is equal to the conductor resistance. AC is parallel to the Y axis and is equal to the conductor reactance. This may be calculated by formulas 11 and 14. BC is equal to the reactance of the secondary circuit and can be determined by formulas 12 and 14. The circle CPB has been drawn on CB as a diameter. BG has been drawn equal to BC, the reactance of the secondary circuit, and GF equal to r, the resistance of same. BF cuts the circle CPB at the point P.

Then $O\,P$ is the impedance of the conductor when the secondary circuit is closed, OC being the impedance when this circuit is open. As r is varied, the locus of the point P is on the semicircle $C\,P\,B$; and it may readily be seen that the impedance may be greater with the sheath connected than when it is open. The effective resistance is $OA + B\,H$, the effective reactance $A\,B + H\,P$. $B\,F$ is the impedance of the secondary circuit; the current induced in it per ampere in conductor (see formula 7) is equal to $C\,B \div B\,F$. If there be another secondary circuit beneath, whose reactance is $C\,I$, the voltage induced in it is equal to $I\,P$. If the current coil of a wattmeter be in series with the main conductor and the volt coil be connected to the terminals of this circuit, the reading will be the watts lost in the closed secondary circuit.

In the case of an iron-armored cable, where there is considerable loss, it is impossible to calculate the conditions accurately, but the following method has given results in fairly close agreement with actual tests. The open circuit conditions must have been measured or calculated from observations on another cable.

The construction is as follows: (refer to Fig. 9) $O\,A$ equals the conductor resistance; $A\,B$ equals the reactance between sheath and conductor and may be calculated by formulas 13 and 14. $O\,L$ equals loss when the secondary circuit is open; $O\,K$ equals impedance. The circle $B\,K\,C$ is constructed, its center being on $B.C$. $B\,G$ equals $B\,C$. In the diagram as constructed it was necessary to draw $B\,G$ one-fourth size, thus reducing $G\,M$ and $B\,M$ to the same scale, on account of the great length of $G\,M$. This affects no other lines or points. $G\,M$ is perpendicular to $O\,L$. Draw $B\,K\,M$, cutting $M\,G$ in M. Then $O\,K$ is the impedance which would have resulted had there been an imaginary completed circuit of reactance $B\,C$ and resistance $G\,M$ surrounding the conductor so as to have a reactance between itself and the conductor are equal to $A\,B$.

This assumption is actually far from true. A large part of the loss, probably one-half or more, in the tape-armored cable is due to hysteresis. The excuse for the method is that errors in calculations based on it are less than the variations would be between two cables made to the same specifications. For the remainder of the calculation consider this imaginary circuit in parallel with the sheath when the latter is connected. The point P may be located as before, $O\,P$ being the impedance of the cable. The voltage induced in the lead on open circuit is $B\,K$. The current is determined as before, except that the whole current (equals $CB + BF$) may be supposed to divide between the two in accordance with the resistances.

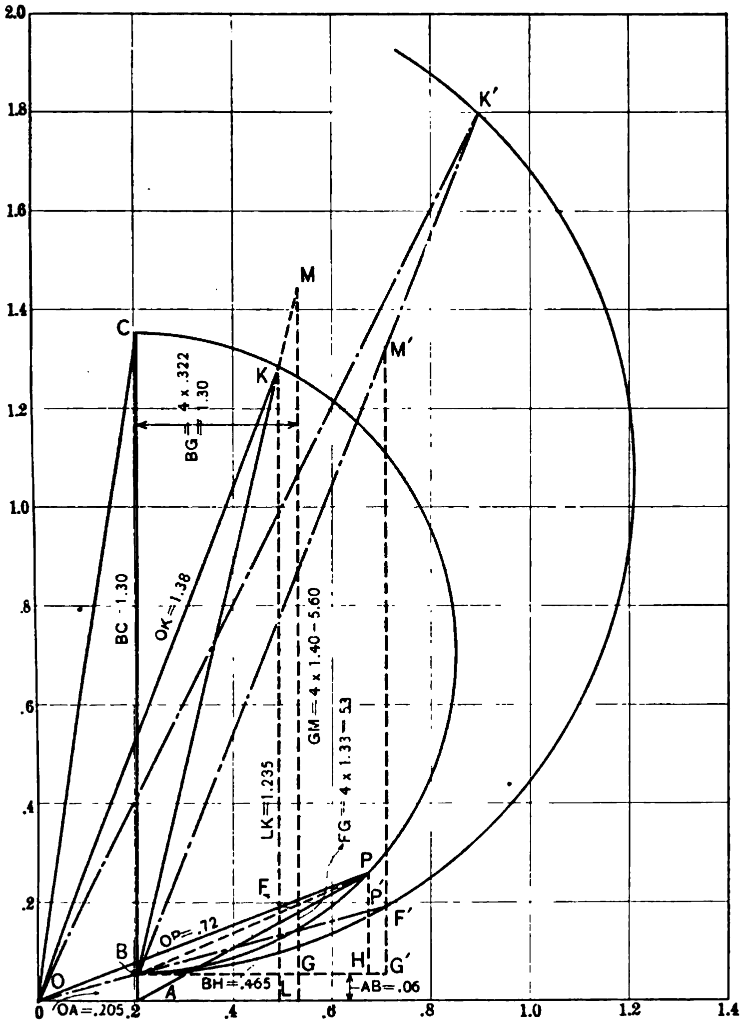


Fig. 9.

It may be noted that the accuracy of any method for calculation of the performance of an iron-armored cable is somewhat reduced, due to the fact that the reactance voltage caused by the iron is far from a sine wave.

In demonstrating the correctness of the construction for the cable without iron the following facts are made use of.

1. The effect on the magnetic field of current flowing in a tube, is the same, at any point outside the tube, as if the current in the tube were concentrated in a conductor at the axis of the tube.*
2. The effect on the field at any point inside the tube is zero.*

From (1) it follows that the electromotive force induced in the tube is the same whether the current be flowing in the tube or in a conductor at the axis of the tube.

The effect of non-uniform distribution of current in the tube when the cables are near each other has been neglected. This effect should be of about the same magnitude as that of the eddy currents produced by the current in the conductor when the secondary circuit is open. This latter effect is, in general, not of great importance.

Let current in conductor = I.
$x+x_1$ = reactance of conductor,
x = reactance of tube (lead or armor).
$x\,I$ = volts induced in tube when tube circuit is open.
r = resistance of tube,
r_1 = resistance of conductor.
i = current induced in tube.
i_1 = component of i in phase with I.
i_2 = component of i at right angles to I.
E = voltage.
E_1 = voltage in phase with I.
E_2 = voltage at right angles to I.

Induced by the flux which cuts both the tube and the conductor when the tube circuit is completed.

Now since the induced voltage is at right angles to the current producing it and is equal to the product of that current by the reactance of the circuit,

$$E_1 = i_2\,x \tag{1}$$

$$E_2 = (I - i_1)\,x \tag{2}$$

Then since E_1 and E_2 are the voltages induced in the tube by the combined action of the current in the conductor and in the

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* See Maxwell, Third Edition, Vol. II, page 316.

tube itself, the current induced is equal to the voltage divided by the resistance, and is in phase with the voltage producing it, or

$$i_1 = \frac{E_1}{r} \tag{3}$$

$$i_2 = \frac{E_2}{r} \tag{4}$$

From equations (1), (2), (3), and (4) we obtain:

$$i_1 = \frac{x^2}{r^2+x^2} I \tag{5}$$

$$i_2 = \frac{x\,r}{r^2+x^2} I \tag{6}$$

$$i = \frac{x}{r^2+x^2} I \tag{7}$$

$$E = \frac{x^2\,r}{r^2+x^2} I \tag{8}$$

$$E_2 = \frac{x\,r^2}{r^2+x^2} I \tag{9}$$

$$\frac{E_1}{E_2} = \frac{x}{r} \tag{10}$$

If I is made equal to 1, these values are in ohms, volts, and amperes. The impedance of the conductor equals the vector sum of E_1, E_2, x, and r.

If r be eliminated between equations (8) and (9), we get an equation between E_1 and E_2, which is that of a circle constructed on the line x as a diameter. This with equation (10) confirms the correctness of the graphical construction. It is possible to calculate the conditions existing when two secondary circuits of different reactances and resistances are connected in parallel, but the formula is very complicated and is of the fourth degree. It is much simpler and generally would be very closely approximate to assume a single circuit having a reactance of about the average of the two. This will always give values of the total loss somewhat lower than the true loss.

Having given the performance of one armored cable with the secondary circuits open, that of another of different dimensions may be easily determined almost as closely as one of the same dimensions, provided only that the size of the armor and the method of construction be the same.

Let a_1 = diameter through the center of the armor of the measured cable, a_2 = same diameter on the cable whose performance it is desired to calculate at a current = I. Then the loss of apparent power in the second cable at I amperes caused by the armor is equal to $\frac{a_2}{a_1}$ times that of the first at $I \frac{a_1}{a_2}$ amperes. The loss to be used in the calculation is the total loss in the cable less the conductor $I^2 r$. To get the impedance due to the armor, subtract from the total impedance (vectorially) the conductor resistance and the reactance calculated for cables of the same size at the same separation without armor. More accurately, that part of the reactance which is produced by the space that would be occupied by the armor should not be subtracted. Neglecting this will make an error of about 5 per cent in the reactance.

The formulas used to obtain calculated results given in this paper are as follows:

Inductance of a cable:

$$L = l \frac{15.24 + 140.5 \log 10 \frac{d}{r}}{10^9} \qquad (11)$$

l = length of cable in feet.
d = distance between centers and
r = radius of conductor.

$$\text{For tubes—inductance} = l \frac{140.5 \log_{10} \frac{d}{r}}{10^9} = L \qquad (12)$$

This is strictly true only for an infinitely thin tube. Inductance of a circuit consisting of a tube and solid conductor

$$= L = l \frac{15.24 + 140.5 \log_{10} \frac{r_1}{r}}{10^9} \qquad (13)$$

r_1 being the radius of the tube.
The reactance = $2 \pi f L$ (14)
Where f = the frequency.

In Fig. 8 the construction resulting in the determination of the impedance *O P* was for the 1/0 copper armored cable, distance between centers being 18 in. The impedance *O P′* is that of the same cable, the distance between centers being 1.5 in. Both these impedances were determined with the armor short-circuited at each end of the cable.

The construction of Fig. 9 is based on a conductor current of 300 amperes and 24 in. between centers of the steel-tape armored cable. The incompleted semicircle *B F′ K′* is the construction for 156 amperes. It is interesting to note the relative increase of reactance compared with ohmic resistance, which is much greater in Fig. 9 than in Fig. 8.

DISCUSSION ON "LOSSES, INDUCED VOLTS AND AMPERES IN ARMOR AND LEAD COVER OF CABLES." FRONTENAC, N. Y. JUNE 29, 1909.

Ralph D. Mershon: Once I asked Mr. Fisher to make some measurements on three-conductor, three-phase cables, measurements which would show whether there were any losses in the lead sheath. I knew of a case where some three-conductor cables showed after installation higher losses and higher drops than the calculations had indicated. I do not remember the results of these measurements and it will be interesting to hear them in connection with this paper.

H. W. Fisher: I made tests to determine the lead and copper losses due to eddy currents in a piece of 500,000 cir. mils lead-covered cable. First of all, the total losses were measured and the $I^2 R$ losses subtracted to get the total eddy-current losses. Then the lead cover was removed and the same test repeated to obtain the eddy-current losses in the conductor. The frequency was 60 cycles. The total eddy-current loss was 13 per cent of the $I^2 R$ loss, and was divided as follows; lead loss 6 per cent; copper loss 7 per cent.

John B. Whitehead: Mr. Fisher has spoken of the advisability of putting all the conductors into one sheath wherever it is possible. There is one class of circuit—an instance of which led to the paper which I gave this morning—in which there is necessity for insulating only one side, the case of a single-phase trolley carried through a drawbridge. It is unnecessary to insulate the grounded conductor. Double-conductor cables cost 50 per cent more, and by putting in single-conductor cables more may be put in for the same money and additional reserve capacity obtained. The reactance of short lengths is no difficulty, nor are the losses great enough to cause trouble.

Charles P. Steinmetz: This paper brings out strongly the fact that in steel-armored, single-conductor cables we may get heating and effective resistance and impedance many times greater than these corresponding to the conductor copper. It also brings out the fact that the increase of effective resistance and impedance cannot be expressed in any simple manner, but varies over an enormous range for changes of current with changes of arrangement, with the manner and character of applying the steel armor, etc. Incidentally, this impedance curve of the cable has a close similarity to the permeability curves of iron, as is to be expected. It therefore appears to me that the single-conductor, steel-armored cable is unsafe to use, and should be avoided as far as possible; where it is used, it is not safe merely to make a few measurements and tests of impedance and resistance to determine its probable behavior, but the investigation must be extended over the entire range of operating conditions which the cable may meet under normal as well as abnormal conditions of service. I would rather use two-conductor cable even if unarmored. With single-conductor cables of higher voltages, in addition to the phenomena of losses, and possibly related to them, there appear a number of very high frequency disruptive effects, some of them unexplained, which have in a number of instances of station wiring led to the abandonment of armored cables, and even of lead-covered, single-conductor cables in favor of unarmored cables. I believe, in general, the conclusion is that a single-conductor cable, whether lead sheathed or steel armored, is not safe in electrical systems.

J. B. Whitehead (by letter): Consider a double-conductor submarine armored cable connected for carrying the track and trolley circuits across a drawbridge. The conductor in the track circuit has in parallel with it all possible ground paths between the two sections of track on opposite sides of the draw. The track is usually well grounded at such points, either by the bridge and supports or frequently by intention by means of ground plates in good water bottom. A steel cable or a chain is also often installed as a protection against dragging anchors. The armor and lead cover of the cables also contribute their conductivity. If all these grounded circuits are tied in together it is not difficult to imagine a considerable diminution if not extinction of current in the track conductor of the cable. The cable thus operates more or less completely as a single conductor concentric cable, and it would be difficult to prevent its doing so.

Three single-conductor armored cables 200 ft. long have been in service in the trolley circuit of a 6600-volt, single-phase road for over a year, under widely varied conditions of load and have given no evidence of trouble.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

CORONA PHENOMENA IN AIR AND OIL AND THEIR RELATION TO TRANSFORMER DESIGN

BY W. S. MOODY AND G. FACCIOLI

Several experimenters have investigated the phenomena of corona and published very complete results of their investigations, which, however, have been confined almost entirely to the conditions found in transmission lines. The experiments recently made by the authors, some of which will be described in this paper, were not undertaken with any idea to add to the available information applicable to transmission lines, but rather with reference to apparatus, and especially static transformers.

In transmission lines we have the simplest form of condenser to consider in studying the corona effects. In apparatus, the forms of condenser that must be considered are evidently very much more complex, because of the relatively shorter length of the dielectric, the irregular shapes of the condenser surfaces, and the combination of solid, liquid, and gaseous dielectrics.

No attempt will be made to make the paper an exhaustive treatise on the subject; in fact, the experiments have shown so many unexpected results that it would be quite impossible to do so from the experiments so far completed. It is hoped simply to bring out some confirmation of existing knowledge and some distinctly new observations, to point out the very complex nature of the study, and how essential further knowledge will become with the increasing demand for apparatus generating 100,000 volts and over.

The first series of tests were made on apparatus consisting of a cylindrical conductor parallel to a plate. Let us briefly recall the theory giving the distribution of the electric field in a condenser of this type.

The capacity of such a condenser is

$$C = \frac{1}{2 \log_n \frac{2D}{\rho}} \text{ c.g.s.}$$

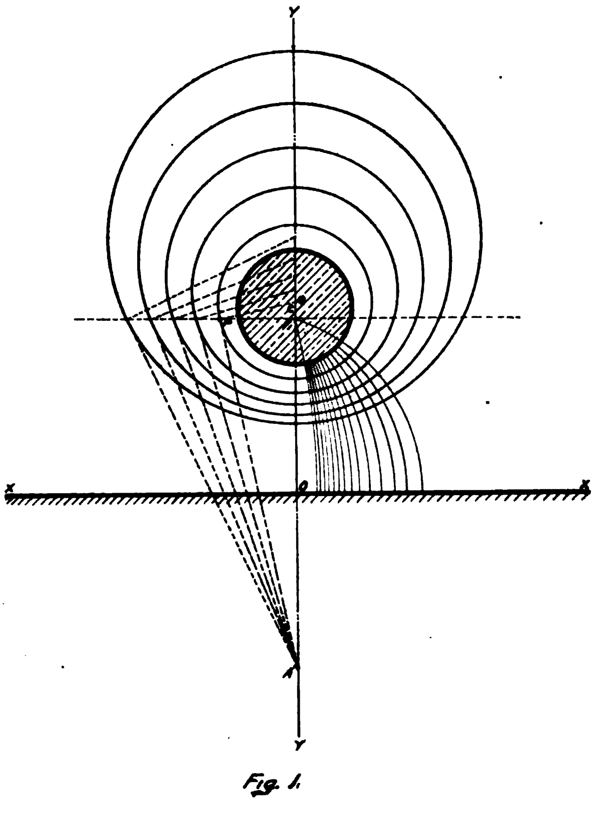

Fig. 1.

electrostatic units per unit length, where ρ is the radius of the conductor and D is the distance between the center of the conductor and the plate. This formula is sufficiently accurate if ρ is small with reference to D.

Fig. 1 represents such a condenser. The plate $x\,x$ is at a distance $C\,O$ from the cylindrical conductor. The diameter of the conductor has been chosen comparatively large in proportion to the distance from the plate in order to have a distinct picture of the equipotential surface, etc. The lines of force are circles with their centers on $x\,x$ and all pass through the points $A\ A'$, such that $O\,A = O\,A'$ and $C\,A = D - \sqrt{D^2 - \rho^2}$

The equipotential surfaces are represented in cross-section by a series of circles perpendicular to the lines of force and with their centers along the axis $Y\ Y$. If we imagine these equipotential surfaces materialized and metallic, we do not change the distribution of the electric field in the condenser. If, therefore, we wish to know the potential existing at a point P, we can imagine that the condenser formed by the conductor and the equipotential surface passing through P, is in series with the condenser formed by this equipotential surface and the plate $x\,x$.

The capacity between the cylindrical surface passing through P, and the plate $x\,x$ is given by

$$c' = \frac{1}{2 \log_n \dfrac{2\,D}{m}}$$

where m is the radius of the equipotential cylindrical surface passing through P, m being supposed to be small with reference to D. The potential at the point P will then be

$$E' = E\frac{C}{c'} = \frac{E \log_n \dfrac{2\,D}{m}}{\log_n \dfrac{2\,D}{\rho}}$$

The potential of $x\,x$ is assumed as zero, and E is the potential applied to the cylindrical conductor. This formula is general and gives the potential of any point P in the field, provided m be small with reference to D.

If we want the potential gradient κ at any point P, we must take the first derivative of the potential and we arrive at

$$\kappa = \frac{1}{m} \quad \frac{E}{\log_n \dfrac{2\,D}{\rho}}$$

and using the decimal logarithm we have

$$\kappa = \frac{1}{m} \quad \frac{0.434\,E}{\log_{10} \dfrac{2\,D}{\rho}}$$

It is very important to know at which point of the field this potential gradient κ is maximum. Obviously κ is maximum for $m = \rho$, and the maximum gradient is therefore

$$\kappa_{max} = \frac{0.434\,E}{\rho \log_{10} \dfrac{2\,D}{\rho}}$$

The potential gradient is then a maximum at the surface of the conductor, and when κ maximum is higher than the resisting power of air, corona will appear on the conductor. From a number of experiments the maximum permissible stress in air at atmospheric pressure seems to be 100,000 volts per inch. The voltage at which corona will appear on a cylindrical conductor is therefore given by

$$E = \frac{100000}{0.434}\,\rho \log_{10} \frac{2\,D}{\rho} = 230000\,\rho \log_{10} \frac{2\,D}{\rho}$$

and using the effective value

$$E_{eff.} = 160000\,\rho \log_{10} \frac{2\,D}{\rho}$$

this being true for a sine wave.

Applying this formula to distances $D = 9$ in., 12 in., and 18 in., for diameters of conductors of ⅛ in., ¼ in., ⅜ in., and ½ in., we obtain the following table of voltages necessary to establish corona under different conditions:

D	Diameter of conductor			
	0.125 in.	0.25 in.	0.375 in.	0.50 in.
9 in.	24600	43200	59400	74400
12 in.	25800	45600	63000	79200
18 in.	27600	49200	68400	86400

We must note that this formula does not take into consideration the temperature, barometric pressure and the vapor product; *i.e.*, it is assumed that the constant, 100,000 volts per inch, is regardless of temperature, barometric pressure or vapor product. To check the results of this formula experimentally the apparatus outlined in Fig. 2 was used. A rod 45 in. long is suspended by small bare copper wires *A C* and *B D* from pieces of treated wood hanging from the ceiling. A large iron plate 69 in. long and 27 in. wide, grounded, is brought at a distance *D* from the rod. The points *C* and *D* are connected by bare copper wire; the potential is brought in the wire *M* from the terminal of a transformer whose other terminal is grounded. The volts are read across the secondary of a transformer which is excited by a 60-cycle sine-wave generator. The capacity of the transformer is 100 kw. and by properly grouping the secondary coils, different ratios of transformation are obtainable.

The results given below are the average readings taken repeatedly over a period of two months. The readings taken at different times under the same conditions agree remarkably well. The variations of temperature and barometric pressure were very small, the average temperature being 23 degrees cent., and the average barometric pressure 28.9 in.

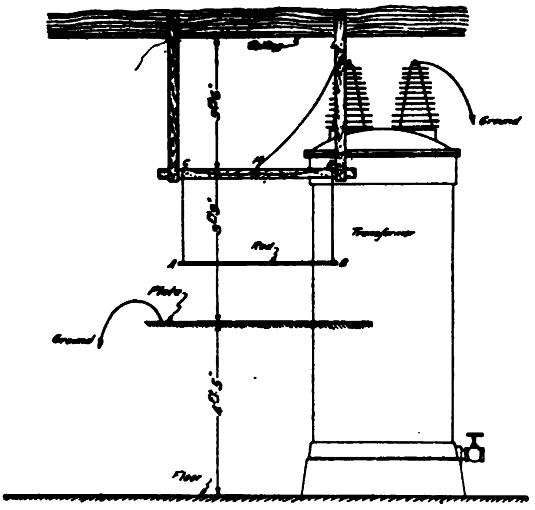

FIG. 2

It must be noted at this point that corona appears on the conductor very abruptly; furthermore, the luminous phenomenon is accompanied by the well-known characteristic noise, so that there is little chance for errors of observation.

The following table gives the voltages at which corona appears on the center of the rod in the apparatus illustrated in Figure 2.

D	Diameter of conductor			
	1.8 in.	0.25 in.	0.375 in.	0.50 in.
9 in.	35600	54500	69800	85000
12 in.	38000	57000	75000	90750
18 in.	41200	61000	80500	95000

The results are plotted in Fig. 3. The curve obtained from the tests is in all cases fairly parallel to the calculated theoretical curve, and the test values may be represented by the formula

$$E = 160000\, \rho \log_{10} \frac{2D}{\rho} + f$$

where f is a constant, whose value is 12000 volts. It is not surprising that this relatively small correction should be found necessary when attempting to apply a formula, which has been evolved for transmission lines, to such extreme conditions as existed in these experiments.

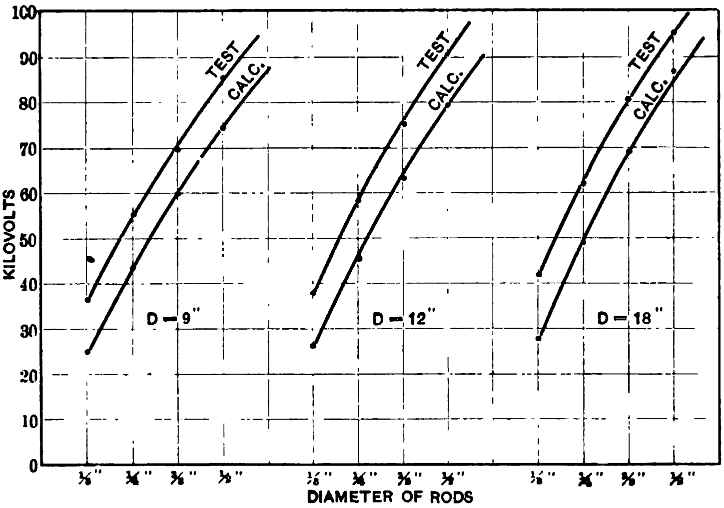

FIG. 3

Professor Ryan has given a formula to determine the conditions necessary for corona between two parallel cylindrical conductors. The maximum value of the voltage at which corona appears, according to this formula is

$$E_{max} = \frac{17.94b}{459.2+t}\, 350000\, (\rho + 0.07) \log_{10} \frac{s}{\rho}$$

where b is the barometric pressure in inches, t is the temperature in degrees Fahrenheit, ρ is the radius of the conductors and s the distance between conductors.

To apply this formula to our case we must divide E_{max} by 2; we will then have the voltage between one of the conductors and the neutral plane. The correction factor for pressure and temperature is 0.97, and using the effective value of the voltage we finally arrive at

$$E_{eff} = 120000\ (\rho+0.07) \log_{10} \frac{2\,D}{\rho\,\text{[illegible]}}$$

This formula is supposed to apply only to conductors ¼ in. in diameter and upward. We will, therefore, exclude from the following table the values referring to a rod ⅛ in. in diameter. The corona voltages, according to Ryan's formula, are then

D	Diameter of conductor		
	0.25 in.	0.375 in.	0.50 in.
9 in.	50500	61200	71500
12 in.	53500	65000	76500
18 in.	57700	70300	83000

Comparing these results obtained by Professor Ryan's formula with the results obtained experimentally, it will be seen that for the rod 0.25-in. in diameter the calculated results are higher than the test values. For the 0.375-in. rod the calculated results are still high, but nearer to test values, while for the 0.50-in. rod the calculated results are lower than the test values.

Without making any attempt to reconcile the departures which have been observed from the published formulas and constants, we will proceed to describe some of the experiments which have shown that so many conditions are to be considered in studying this phenomenon, in connection with apparatus, that it is apparently hopeless to evolve any formula which will be broad enough to be given general application. All the tests were made with a grounded plate as one electrode. It seemed advisable to do this, as it so simplified the problem as compared with the double condenser formed by the plate, conductor and earth, if the plate were ungrounded. The plate used, as before stated, was about 70 in. by 30 in. However, no material variation in results was obtained when a 13-in. disc was substituted for this plate.

In order to obtain consistent results it is, of course, but necessary to know the voltage wave-form which is used in the experiments, as the corona depends on the maximum rather than the average effective voltage as shown by a voltmeter. An attempt was made to determine the voltage by a spark-gap in parallel with the apparatus under test, but the results obtained were very variable, and the attempt was given up for the following reasons:

If the gap was located in the small dark room in which the experiments were performed, the ionization of the air, resulting from the brush discharges, would affect the striking distance considerably.

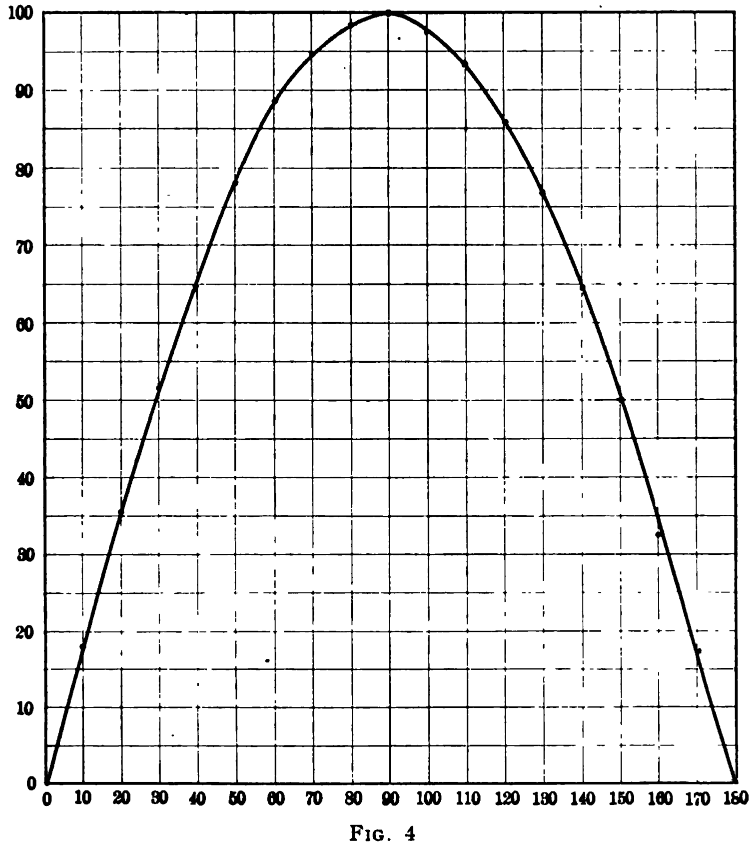

Fig. 4

If the gap was brought outside the dark room, then a source of error was introduced by the long leads required.

There are reasons to suppose that between the gap and the condenser under test some internal oscillations, which upset the results, are set up.

It was therefore thought better to take some oscillograms of electromotive force, reproduced in Figs. 4 and 5, to be sure that the wave-form was the sine wave that it was supposed to be. Fig. 4 represents the electromotive force across the terminals of the high-potential windings of the transformer used in the experiments. It was taken at no load and at 80,000 effective volts, with one terminal of the transformer grounded. The curves show a substantially perfect sine wave.

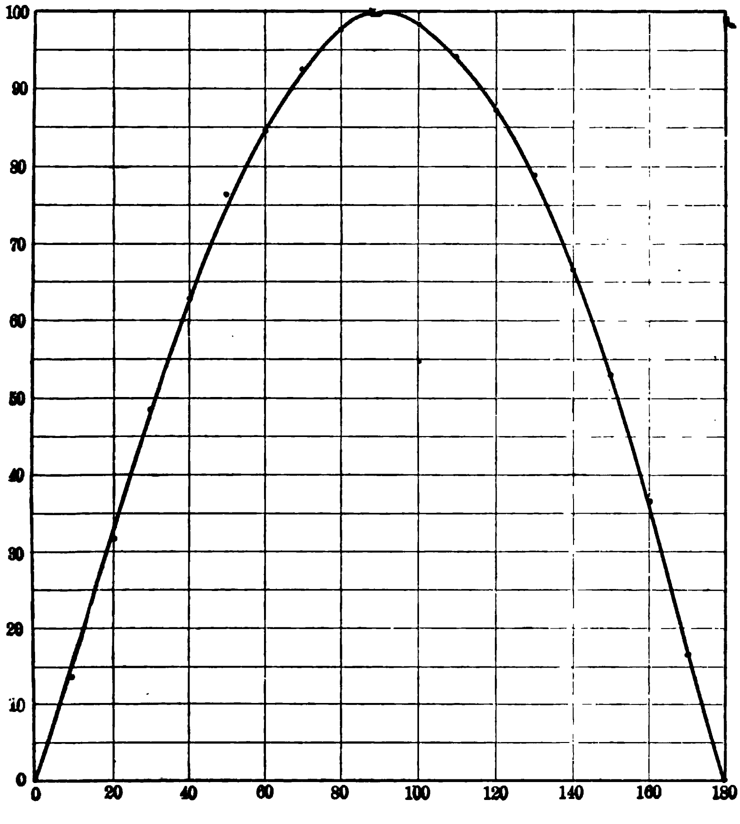

FIG. 5

Fig. 5 gives the shape of the wave of the electromotive force across the high-potential windings of the same transformer, with one terminal grounded at 60,000 volts, when the 0.25-in. rod is connected to the ungrounded terminal and the large iron plate is connected to the grounded terminal, the distance between the plate and the rod being 12 in. The change in the wave form is very small and the effective value is 0.698, the maximum value. It is known, therefore, that the tests were made with substantially sine waves.

Another very important point affecting results was found to be the condition of the surface of the conductor. Assuming, as we know to be the case, that the maximum potential gradient occurs at the surface of the conductor, and that the corona starts from the surface, it is obvious that any irregularity in the surface will have the effect of reducing the diameter of the conductor at that point. Consistent results can therefore only be obtained when the surface is free from any such rough spots or foreign material.

A rough metallic spot, constituting a point on the conductor, will naturally begin to glow at much lower voltage than the conductor itself on account of the much higher potential gradient at that point. These isolated points give a brilliant white light and they are easily distinguished from the regular corona and must be eliminated with great care, to obtain constant and consistent results.

More common, however, are spots of insulating material on the surface of the rod. These spots act quite differently from metallic spots; they also begin to glow, generally before the point of regular corona is reached, but they emit a blue, unsteady brush different in shape and color from the brilliant steady light given by a metallic point. A very peculiar characteristic of these brushes is the fact that they do not die out at the same voltage at which they are originally established, but to extinguish them the voltage must be lowered considerably from the original value.

If, for instance, we take the 0.375-in. rod parallel to the grounded plate, as shown in Fig. 2, and, in order to magnify the phenomenon we slip a piece of rubber tube 3 in. long on the rod and then increase gradually the potential of the rod, we find that at 78,500 volts each edge of the rubber tube gives a blue, silent, unsteady brush, which increases in length and volume with increasing potential. If the voltage is lowered below 78,500 volts, the brushes do not die out until 68,000 volts is reached. To reëstablish the brushes after they have been extinguished 78,500 volts are again necessary.

In order to obtain consistent results, great care was taken during the tests to work with clean, uniform surfaces of conductors, which condition is not easily obtained. But the effect of insulation on the conductor appeared so peculiar that an investigation of this matter was started and very interesting results were gathered.

If in the test just mentioned, we raise the potential above 78,500 volts, the brushes at the edge of the rubber tube increase, as has been said, in length and volume until they span the whole distance between the rod and the plate. Increasing the potential still further, the color of the brushes changes from blue to purple and finally the spark jumps from the rod to the plate through the mass of one of the brushes. If no insulation were on the rod, the break-down would have occurred at one of the ends of the rod, but the presence of the rubber tube changed the conditions and brought the weakest point of the system to the edge of the insulation. This phenomenon obtained with a piece of rubber tube can be reproduced by using any kind of insulating material on the surface of the rod. A thin coat of paraffin on the rod will produce the phenomenon as well as a glass or mica tube, a knot of varnished cambric tape, a rubber cork, a disc of sulphur, or the like.

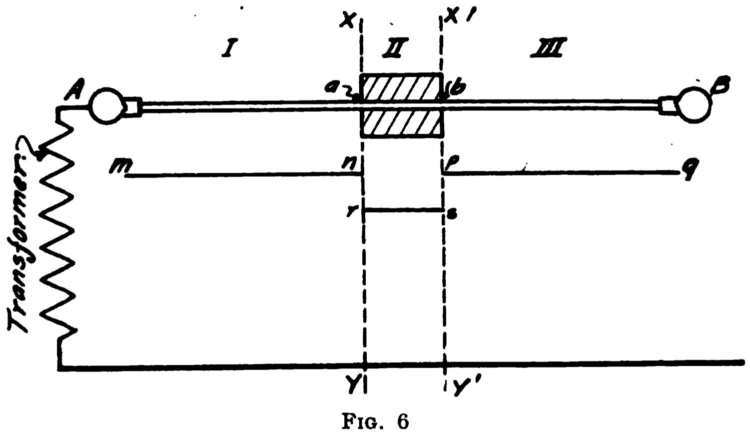

FIG. 6

Referring to Fig. 6, *A B* is a rod 0.25-in. in diameter, ended by two spheres 2 in. in diameter and brought 12 in. away from a plate. If we apply a difference of potential between the rod and plate, the system will break down at one of the spheres at 144,000 volts. If a rubber cork ¾ in. in diameter and 1 in. in length is slipped on the center of the rod, the system breaks down at one of the edges of the cork at 141,000 volts. If the cork is removed and replaced by varnished cambric tape wound on the rod, the system breaks down from the edge of the varnished cambric insulation at 135,000 volts. We see, therefore, that not only the edge of the insulation has become the weakest point of the system, but that the value of the breaking-down point has also been decreased. It would be superfluous to state the many tests performed on this point but they all agree and confirm the results already given.

An explanation of these results will be simple, we believe, if the disturbances in the field of electric forces, which take place on the introduction of the insulating material around the center of the rod *A B*, are investigated in the following way: Let us imagine the system of conductors and insulations in Fig. 6 divided up into three contiguous condensers I, II, III. If we attempt to draw any one of the equipotential surfaces of the system, we will see that in the condensers I and III, the sections of the equipotential surface are represented by the lines *m n* and *p q* at the same distance from *A B*. But in the condenser II, which has a material of high specific inductive capacity near the rod, the trace of the equipotential surface will be lower than *m n* and *p q*, say *r s*.

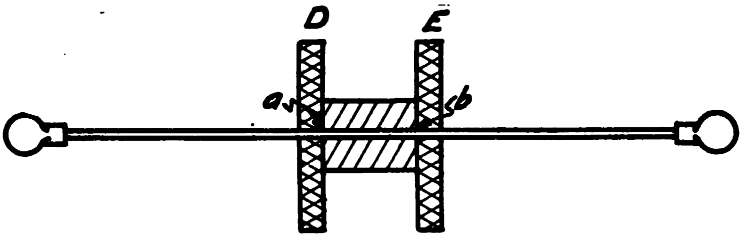

FIG. 7

In the vertical planes *X Y* and *X′ Y′*, the conditions of the field are very peculiar, inasmuch as the voltage of each point along these lines. considered as a part of condenser I, is different from the voltage of the same point considered as a part of condenser II. The result, we believe, therefore, shows the existence of a transverse stress along the lines *X Y* and *X′ Y′*, which causes the appearance of the brushes and the final breakdown.

If this is correct we should be able to stop the formation of brushes in *a b* by equalizing the potential along the planes *n r* and *p s* by metallic surfaces. If we slip on either side of the insulation two metallic discs (Fig. 7) having diameters as large, or larger, than the insulation, we should expect that we would eliminate the brushes *a b*. Tests show this to be the result. Two tinfoil discs 2 in. in diameter were put on the rod, as shown in Fig. 7. The edges of the insulation were entirely free from brush discharge and the condenser broke down at one of the spheres at 144,000 volts.

It is to be noted that although the metallic discs were nearer to the plate than the ends of the rod, still these ends remained the weakest point of the apparatus. But we would expect even more from the metallic discs. If we apply the same methods of reasoning used before, and we picture to ourselves the equipotential surfaces of the condenser, we would expect that the introduction of these discs on the rod would have the effect of relieving the stress from a certain length of the rod on each side of the discs. The test proves that this assumption is correct.

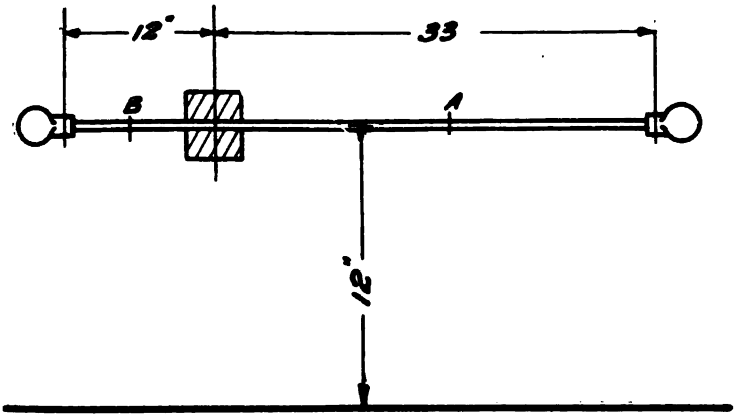

FIG. 8

We have seen that a rod, 0.25-in. in diameter and 45 in. long, parallel to a grounded plate, and 12 in. away from it, begins to glow at 57,000 volts. If we wrap tin-foil in the center of the rod, making a little cylinder 3 in. long and 1 in. in diameter, corona will appear in the middle of the two sections of the rod at 62,300 volts. Let us shift our tin-foil cylinder on the rod so that the two sections will be of different length. Then, as shown in Fig. 8, the middle of the longer section *A* glows at 59,250 volts, while the middle of the shorter section *B* does not glow until 76,500 volts is reached.

If we put on the same rod two cylinders of tin foil, spaced as shown in Fig. 9 the center of the middle section *B* glows at 69,750 volts, while the centers of the other two sections *A* and *C* glow simultaneously at 75,750 volts. This test shows conclusively that the metallic cylinders cast, so to speak, a shadow on the conductor on each side, protecting a certain length of it, and increasing, if properly spaced, the effective diameter of the rod.

Figs. 10, 11, 12 will serve as a summary of what we have seen regarding the influence of the condition of the surface of the conductors. Fig. 10 shows a 0.25-in. rod 88 in. long having a regularly distributed corona against the ground plate 12 in. from it. The photograph was taken at 85,000 volts. Fig. 11 shows the same rod in exactly the same conditions as before, at the same voltage, but a piece of varnished cambric tape is wrapped on the center of the rod and a strong brush is produced at this point. In Fig. 12 we have the same rod as before at the same voltage but with three tinfoil discs 2 in. in diameter equally spaced on the rod. The corona is very small and limited and very different from the one shown in Fig. 10.

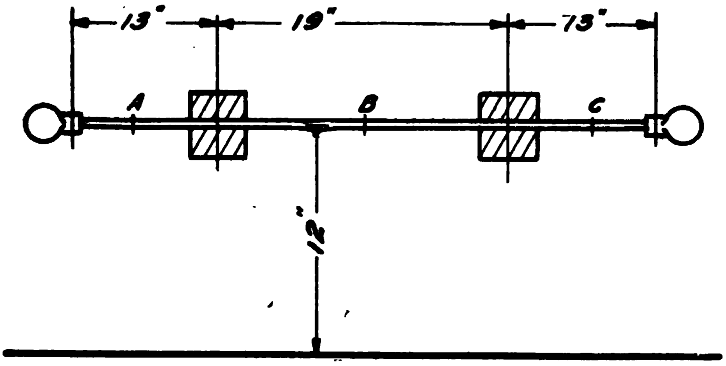

FIG. 9

A very interesting point was brought out in further study of the results obtained with the combinations shown in Figs. 8 and 9. When the voltages at which corona appeared on different portions of this apparatus are tabulated with reference to the free length of the conductor *A B* we find the following:

Free length of rod	Glowing point
45 in.	57,000 volts
31.5 in.	59,250 "
21 in.	62,300 "
16 in.	69,750 "
11.5 in.	75,750 "
10.5 in.	76,500 "

This shows that it takes an increasing voltage to establish corona the shorter the length of the rod. In other words, corona is not a fixed quantity for a given voltage and diameter of rod, unless the length of the rod is great and the diameter uniform. In order thoroughly to demonstrate this point, three rods ½ in. in diameter were experimented with. The rods were of different length, all the other conditions of the test being identical. The arrangement was the one represented in Fig. 2 and the distance between the rod and the grounded plate was 12 in. The results of the test are as follows:

Fig. 10

Length of rod	Corona voltage
45 in.	57000 volts
23 in.	68000 "
12 in.	83500 "

These results are plotted in Fig. 13.

We see immediately that the values of this table differ from the corresponding values of the preceding table. We must realize, however, that the conditions of the test are somewhat different in the two cases and that the " suspension " of the rod might influence the results.

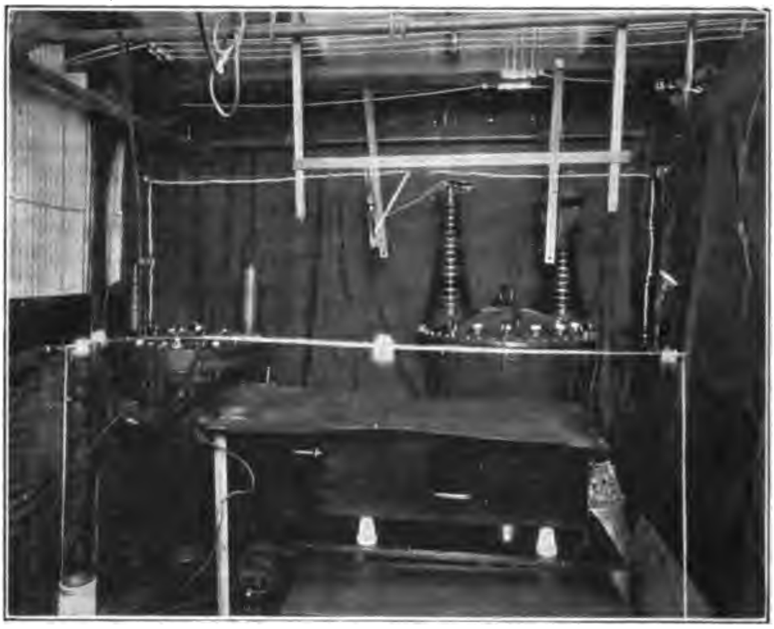

FIG. 11

Let us return to our apparatus as represented in Fig. 2, where the rod is suspended by copper wires and the suspension wires are connected together by the wire *C D*. Let us observe accurately what happens when we gradually raise the potential of the rod, which is 45 in. long, 0.25-in. in diameter and 12 in. away from the grounded plate.

At 57,000 volts the rod was dark.

At 58,000 volts the center of the rod glowed.

Theoretically we would expect that as soon as the critical voltage is reached corona would appear over the whole length of the rod. This is because we assume that the intensity of the field is constant all along the rod and the equipotential surfaces in the immediate neighborhood of the rod are cylinders practically concentric with it. This test shows, however, that the intensity of the field is not uniform throughout the length of the rod.

If we measure the exact location and length of corona at different voltages, and note its spreading with increasing potential, we will have an idea of the distribution of the field in the different parts of the rod. At 58,000 volts the length of the glowing portion of the rod is 15 in., exactly in the center. At 80,000 volts its length becomes 33.5 in.; that is, the whole rod glows, except 6 in. near the suspension points. The system breaks down at 113,000 volts from one end of the rod, although even at this voltage the portion of the rod near the suspension wires remains dark.

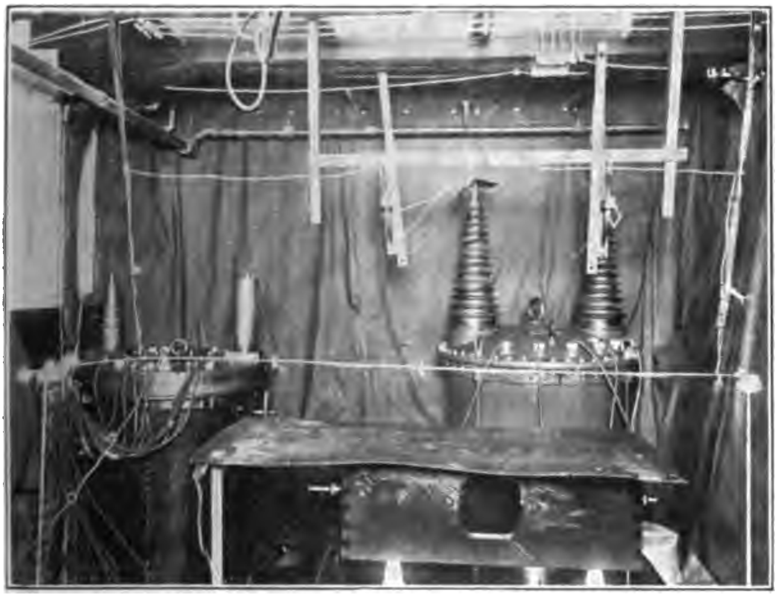

FIG. 12

Now let us repeat this test, but let us modify the suspension slightly. We eliminate the bridging wire *C D* and bring the high potential lead to *C*. The suspension wire *B D* is, therefore, connected to the rod only.

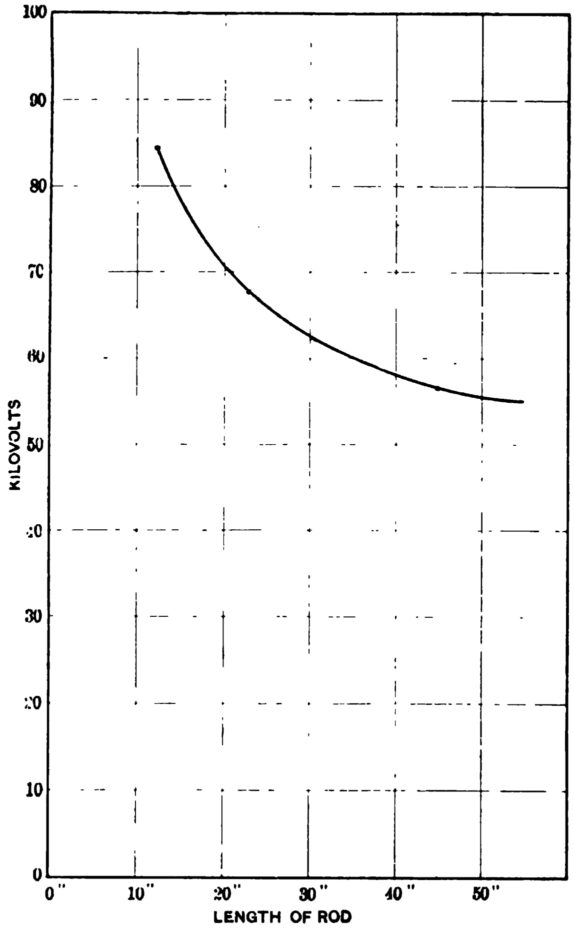

Fig. 13

At 54,000 volts the rod was dark.
At 55,000 " corona was 15 in. long in the center.
At 60,000 " " " 22 " "
At 80,000 " " " 33 " "
At 100,000 " " " 35 " "
At 112,000 volts the system broke down from one of the ends to the plate.

We have changed the value of the voltage at which corona starts, although we have not changed practically the spreading of corona at high voltage. Finally let us remove the copper wire $B\ D$ and replace it by silk tape. In this case the results are as follows:

At 50,000 volts the rod was dark.

At 51,000 volts, the portion of the rod near B, or near the silk tape suspension, glowed for the length of 21 in. measured from B; in other words, the rod was divided into two sections, of which 24 in. near A were dark and 21 in. near B glowed. Increasing the voltage, the corona approached more and more to the point A.

At 60,000 volts the corona was 33 in. long.

At 80,000 volts the corona was 40 in. long, or 5 in. near A remained dark.

At 90,000 volts the corona was 41 in. long, or 4 in. near A were dark.

At 105,000 volts the corona was again 41 in. long and at 112,000 volts a spark jumped from A to the plate.

The phenomenon is so delicate that it actually makes a difference whether the silk ribbon is tied in a knot around the rod or whether the rod is placed in a loop made by the ribbon. The knot gives a brush, while the loop originates a silent glowing on the rod near B before corona starts. The results obtained with the insulating suspension are not, generally speaking, so certain and constant as those obtained with the suspension represented in Fig. 2. This is the reason why the latter suspension has been chosen to perform comparative tests.

We must note that in all these experiments the " ends " of the rod do not affect the character of the phenomena. In fact similar results are obtained whether the rods are ended by spheres of large diameter or not. The curves in Fig. 14 represent the voltages and the corresponding lengths of corona in the three cases mentioned above. Curve 1 refers to the suspension shown in Fig. 2. Curve 2 refers to the same suspension without the bridging wire $C\ D$. Curve 3 refers to the silk-tape suspension.

A doubt may arise in connection with the results of these experiments, as one might suppose that the dimensions and the position of the grounded plate might affect the location and spreading of corona. This, however, is not the case. If the grounded plate is removed and the rod is left in the same place, forming a condenser with the floor, ceiling, walls, etc., of the room, the same results are obtained.

The voltage at which corona starts is naturally different, but the general appearance of the phenomenon is the same as before. If both ends of the rod are suspended by copper wires the center of the rod will glow first and the parts in the immediate neighborhood of the suspension points will not glow at the highest voltage. If one end of the rod is suspended by insulating material, this end will glow first and the corona gradually approach the excited end.

In conclusion, we have seen that the corona voltage is affected by many conditions which can hardly be taken care of in a formula. We have shown the influence of the following:

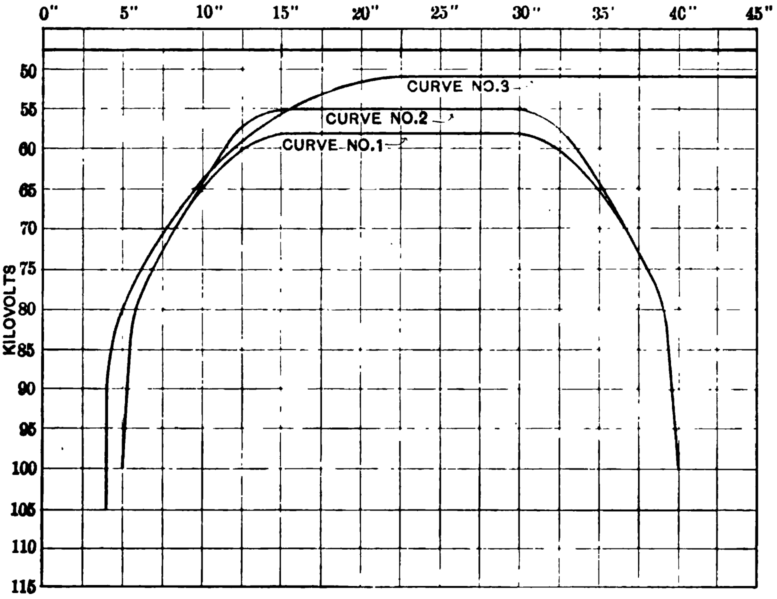

FIG. 14

1. Grounding the plate.
2. Wave form.
3. Conditions of surface, and effect of insulating and metallic discs.
4. Length of rod.
5. Suspension and consequent localizations and spreading of corona.

Before we leave this apparatus—a cylindrical conductor parallel to a plate—we might attempt to check, in a general way, the theoretical law which gives the corona voltage as a function of the diameter of the rod and its distance from the plate. If we take a rod of radius ρ' at a distance D' from the plate, and another rod of radius ρ'' at a distance D'' from the plate, the two rods ought to glow at the same voltage, if

$$\rho' \frac{\log 2\,D'}{\rho'} = \rho'' \frac{\log 2\,D''}{\rho''}$$

Unfortunately the change in the distance required by a small change in diameter is very large. For instance, if we take two rods, one 0.25 in. in diameter, and the other 0.375 in. in diameter,

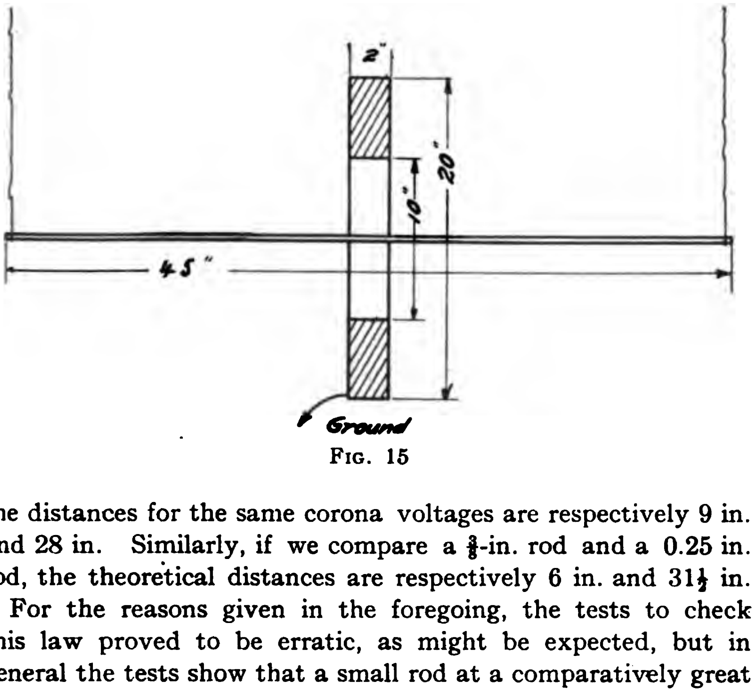

FIG. 15

the distances for the same corona voltages are respectively 9 in. and 28 in. Similarly, if we compare a ⅜-in. rod and a 0.25 in. rod, the theoretical distances are respectively 6 in. and 31½ in.

For the reasons given in the foregoing, the tests to check this law proved to be erratic, as might be expected, but in general the tests show that a small rod at a comparatively great distance from the plate requires a higher voltage than a large rod at a correspondingly small distance from the plate. However, on account of the great difference in distances, it is almost impossible to reproduce exactly the same conditions of test in both cases, and, from what we have seen, the behavior of the electric field is so sensitive that we would not be surprised at the apparent inconsistency between theory and test.

The second type of condenser on which experiments were performed is illustrated in Fig. 15. Different rods 45 in. long, suspended at both ends by copper wires, were located in the center of a metallic disc. The dimensions of the ring are 10 in. inside diameter, 20 in. outside diameter and 2 in. long. The disc and the portion of the rod covered by it constitute a condenser whose theory we will briefly recall.

Fig. 16 represents a condenser of this type, C being the inside conductor of radius ρ'', G being the outside cylinder of radius ρ'. The lines of force of such a condenser are along the radii, and the cross-sections of the equipotential surfaces are circumferences concentric with the plates. If we wish to find the potential of a point P at a distance m from the center we can imagine the equipotential surface passing through P materialized and metallic, as we did before.

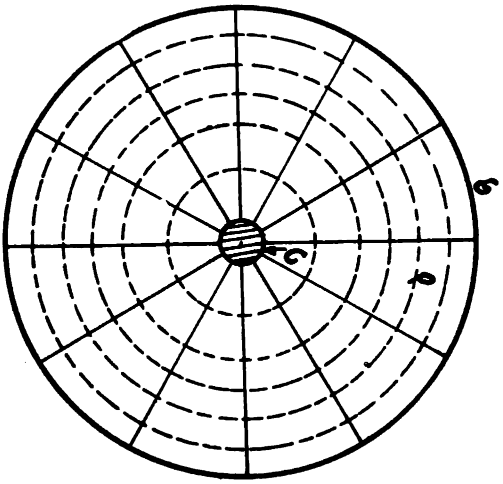

FIG. 16

Now the condenser made by the conductor C and the cylinder G is equivalent to two condensers in series, one from the conductor C to the equipotential surface P, the other from this surface to the cylinder G. If we call C the capacity between the conductor C and the cylinder G, C' the capacity between the equipotential surface P and the cylinder G, zero the potential of G, E the potential of C, E' the potential of P, we have

$$E' = \frac{C}{C'} E$$

$$\text{But } C = \frac{1}{2\log\dfrac{\rho'}{\rho}}, \text{ per unit length}$$

$$C' = \frac{1}{2\log_n\dfrac{\rho'}{m}} \text{ per unit length}$$

Therefore:

$$E' = \frac{\log_n\dfrac{\rho'}{m}}{\log_n\dfrac{\rho'}{\rho}}$$

The potential gradient at P is

$$\frac{dE}{dm} = \kappa = \frac{0.434\,E}{m\log_{10}\dfrac{\rho'}{m}}$$

It is evident that the maximum potential gradient occurs when $m = \rho$, and is given by

$$\kappa_{max} = \frac{.434\,E}{\rho\log_{10}\dfrac{\rho'}{\rho}},$$

and the effective voltage at which corona will appear on the inside conductor is, in volts

$$E_{eff} = 160000\,\rho\log_{10}\frac{\rho'}{\rho}$$

If we apply this formula to the case of Fig. 15 for $\rho' = 5$ in. and for diameters of rods ⅛ in., ¼ in., ⅜ in., ½ in., we have

Radius of conductor	Corona voltage
0.0625 in.	19000
0.125 in.	32000
0.187 in.	42600
0.250 in.	52000

In attempting to check these calculations with the apparatus shown in Fig. 15, the metallic cylinder was grounded and the rod connected to one of the terminals of the testing transformer, whose other terminal was grounded. The rod was 45 in. long and the cylinder 2 in. long, the latter being located in the center of the rod. The following results were obtained:

Radius of conductor	Corona voltage
0.0625 in.	26500
0.125 in.	40500
0.187 in.	52000
0.250 in.	62000

The tested values are again higher than the calculated values, but their difference is not constant. The discrepancies between tests and theories are undoubtedly explained by the fact that the formula applies to cylinders of indefinite length, whereas one cylinder in this case was very short and consequently the disturbing influences of the ends of the cylinder were proportionately very great.

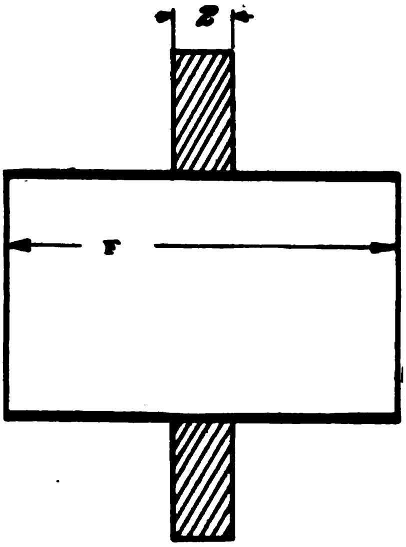

FIG. 17

Just how the length of the outside ring influences the results can be easily seen from the further tests made with apparatus as shown in Fig. 17. Metallic tubes of different lengths were inserted and supported by the cylinder previously used, and the following results were obtained with different lengths *F*:

Radius of rod	2 in. long	6 in. long	18 in. long
0.0625 in.	26500	25200	24000
0.125 in.	40500	38500	36500
0.187 in.	52000	48500	47500
0.250 in.	62000	——	54500

The longer the cylinder the lower is the corona voltage, which shows a more uniformly distributed field in the center of the apparatus; that is, the longer the cylinder the nearer we approach the theoretical results.

On the other hand, with the arrangement shown in Fig. 15, if the length of the rod is decreased, the voltage at which corona appears is increased, as shown by the following table:

Length of rod	Corona voltage
45 in.	40500
23 in.	41500
12 in.	44000

We obtain identical results if instead of using shorter rods, we shift the suspension wires nearer together so that the free lengths of the rod between the suspension points are respectively 45 in., 24 in., and 12 in. We see here again, as in the other type of condenser, the protecting influence of the suspension wires, which relieve the stress for a considerable length on the surface of the rod.

We would expect also to find that the cross-section of the ring has a pronounced influence on the results. If we take a pipe 1 in. in diameter, bend it in a ring 10 in. in diameter, pass through its center rods 45 in. long and of varying diameters, we then obtain the following results:

Radius of rod	Corona voltage
0.0625 in.	29600
0.125 in.	45000
0.187 in.	58000

The corona voltage has been increased considerably. It should be borne in mind, however, that we have not only changed the cross-section of the ring, but we have also decreased its length, the pipe used being only 1 in. in diameter.

The results of all these tests show that conditions existing in the field between the ring and the rod are very different from those assumed in our theory. The lines of force have commonly been thought of as perpendicular to the surfaces of the outside cylinder and uniformly distributed along its length. Evidently this cannot be the case when the length of the cylinder is short. The density of the field is a maximum in the central part of the rod and decreases in intensity towards the ends. This can be clearly shown by observing the fact that when the rod is excited from both ends the middle begins to glow at very much lower voltage than is required to distribute this glow upon the entire length of the rod. In fact, with the proper combination of apparatus, the voltage applied can be quite accurately determined by the length of the rod that glows. The following results were obtained by again using a 0.25-in. rod in the apparatus shown in Fig. 15.

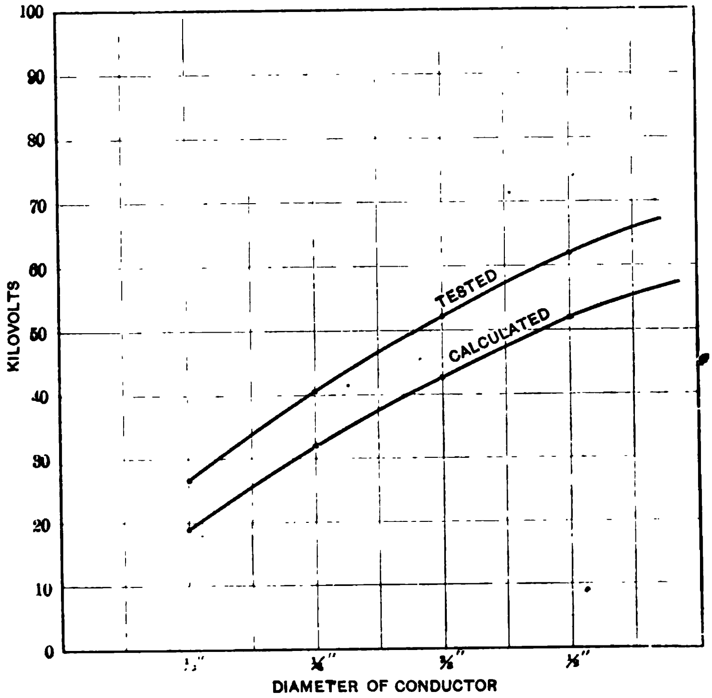

FIG. 18

At 40,000 volts the rod was dark.

At 40,500 the corona appeared in the center under the ring but the glowing portion was shorter than 2 in., which is the length of the outside cylinder.

At 45,000 volts the corona was 7 in. long in the center of the rod; protruding 2.8 in. on each side of the ring.

At 50,000 volts corona was 10 in. long
At 55,000 " " " 15 in. "
At 60,000 " " " 16 in. "
At 65,000 " " " 23 in. "
At 70,000 " " " 26 in. "

At 75,000 volts the apparatus broke down from the rod to the ring. Then at 40,500 volts the intensity of the field was not uniform under the cylinder, but was a maximum in the exact center of the rod. At 45,000 volts the critical value was reached over a portion of the rod much longer than the cylinder itself.

If we observe the glowing part of the rod at 70,000 volts, we will notice that its apparent diameter is constant for about 11 in. in the center, then it decreases gradually toward each end. But at comparatively large distances from the ring and at high potential, the surrounding bodies may have considerable disturbing influence on the glowing of the rod. If we change our suspension, using some insulating material at one end, or if we modify the conditions of the ends of the rod by using spheres of large diameter, the results are not affected, and the potential at which corona appears and the positions of corona on the conductor are unaltered.

On the other hand, the effect of insulation and metallic sleeves on the conductor is the same as in the case of a rod against a plate. If we tie a piece of varnished cambric tape in the center of the 0.25-in. rod shown in Fig. 14, brushes will appear at the edges of the knot at 30,700 volts and the apparatus will break down at 40,500 volts from the insulation to the ring.

If we shift the knot of insulating tape to a distance of 3 in. from the edge of the ring, corona will appear on the conductor under the disc at the usual voltage—40,500 volts. But at 33,000 volts a brush has appeared at the edge of the insulating material facing the ring. Increasing the potential, the brush increases in strength, and at 45,000 volts a spark jumps from the insulation to the ring.

Let us shift the insulation knot 6 in. away from the edges of the ring. A brush will appear simultaneously with corona at 40,500 volts, and at 64,000 volts the system will break down again from the insulation to the ring. If we shift the varnished cambric tape still further away from the ring, say 12 in., the brush starts at 41,000 volts, but, in this case, the apparatus breaks down from the center of the rod to the ring at 75,000 volts. This is the voltage at which the system would have broken down if we had had no insulation on the rod.

It was necessary to remove the knot of varnished cambric 12 in. away from the ring to counteract the effect of insulation on the surface of the conductor. The breaking-down point was lowered considerably by the presence of the varnished cambric, and the remarkable short-circuiting effect of the brush caused the spark to strike through a much longer distance than the shortest path between the two plates of the condenser.

Metallic sleeves, we have seen, have the opposite effect. If two brass sleeves 0.5 in. outside diameter and 1 in. long are placed on the rod near its suspension points, the center point of the rod glows at 40,500 volts. If we shift the two brass cylinders nearer together so that each one is 12 in. away from the ring, the rod will glow again at 40,500 volts. If we bring the brass cylinders 3 in. away from the edge of the ring, corona will appear in the center of the rod at 41,500 volts. When the brass cylinders are placed 1 in. away from the edges of the ring the center of the rod begins to glow at 47,500 volts. If we bring the two brass cylinders still nearer, so that they are 2 in. apart, corona will appear only at 50,000 volts. The presence of the two metallic sleeves, therefore, does increase the apparent diameter of the rod, as far as corona is concerned, for a considerable distance on either side of the disc. In the last test the corona voltage was 50,000 instead of 40,500, which is equivalent to increasing the diameter of the rod from 0.25 in. to 0.375 in.

From all these experiments we can draw the general conclusion that the voltage at which corona appears in apparatus of limited dimensions, not only depends on the dimensions of the apparatus itself and the mutual action of the different parts, but is also a complex function of several quantities and conditions. Therefore, the formula which takes into consideration only the principal dimensions of the condenser between which the electric stress exists could not give correct results.

Before closing, we wish to say a few words with reference to corona as it exists under oil. We have often heard it said that the use of oil eliminates corona, but such is not the case in our opinion. There are some distinct differences in the manifestation of corona in air and in oil, but, so far as our present rather limited experimentation goes, we believe there is no essential difference in this manifestation in the two substances.

If we submerge two needles 12 in. apart in oil, and raise the difference of potential between them, there is no noticeable glow given off up to 100,000 volts, but with 1000 volts more, the glowing is very perceptible in the shape of a small steady brush, noiseless and green in color. We have here, then, not only a corona, but the same characteristic that is found in air corona; namely, that a very slight difference exists between the voltage at which there is no corona and that at which it appears.

If we raise the potential still further, the brushes increase in size and eventually touch each other and soon after cause a disruption of the oil. If the needles, instead of being 12 in. apart, are only 6 in. apart, the corona will be established at about 78,000 volts; if the needles are 3 in. apart, the corona will start at about 72,000 volts.

If before breakdown takes place, we decrease the difference of potential between the needles, the corona will disappear at the same voltage at which it started. Furthermore, the oil that is in the gap is set in violent motion, which is maintained so long as a stress exists. Analogous results can be obtained by using the needle opposed to the plate; that is, at a certain voltage the point will emit a steady luminous brush, which is similar to the brushes obtained in air.

Experiments were made on a condenser consisting of a cylindrical conductor and a plate under oil, as follows: A wire 0.02 in. in diameter and 15 in. long was stretched between two brass supports and a plate was placed 6.5 in. from the wire and parallel to it. One terminal of the transformer was connected to the wire and the other to the plate, and all were submerged in oil. At 49,000 volts everything was dark, at 50,000 volts the small wire glowed; when the potential was raised, the glow became more and more pronounced. The thickness of the corona appeared to be considerably more than in air and was more unsteady.

If, instead of 0.02 in. wire, we use 0.04 in. wire, the corona will not appear until 60,000 volts. In this case, the corona is made up of a large number of contiguous and unsteady brushes which cover the whole length of the wire. Using a wire 0.05 in. in diameter under the same condition, corona does not appear until 80,000 volts. In this case we obtain no regular glow, but very unsteady distinct brushes that shift their position along the wire. If we use 0.125-in. wire, the brush will appear at about 100,000 volts, and if we raise the potential, the brush will appear and disappear again irregularly; that is, we have an intermittent luminous phenomenon, which represents more of an interrupted arc then the regular corona. In explanation of this phenomenon, we would suggest that the very violent movement of oil under such dielectric strains may account for the unsteady nature of the corona at these higher potentials. It would seem, therefore, that the larger the diameter of the wire, and, consequently, the higher the voltage required for corona, the more the phenomenon under oil differs from the phenomenon in air.

With our present knowledge, the comparison of values between corona voltage in air and under oil is very difficult and unsatisfactory. Under oil it is only with wires of small diameter that the corona voltage is sufficiently abrupt and constant to be measured consistently, while in air it is the small wires with which it is difficult to get consistent results. Such small wires in air depart markedly from the law that expresses the corona phenomenon on larger wires. The larger wires under oil, as we have said, give very unsteady and therefore, unsatisfactory results.

Similar tests were tried with wires located in the center of a 10-in. cylinder under oil, but the same conditions were met with. With wires above 0.125 in. in diameter, the point at which the corona started under oil was very uncertain and the luminous phenomenon was intermittent or irregular. Distances between wires and plates up to 4 ft. and potentials up to 400,000 volts were used, but the appearance of the phenomenon was always irregular.

Conclusions. We have selected in the foregoing, only a few of the interesting experiments in an incomplete investigation. We trust however that they will be sufficient to stimulate other investigators in this largely unexplored field.

Commercial transformers are now being extensively built to use for voltages where these complex laws of the corona must be generally, if not exactly, known, if their design is to be correctly worked out.

Of course it has been generally appreciated for some years that corona discharges must be avoided, even more in transformers than on the transmission line to which they are connected. When in transformer design only the simple law of the diameter of the conductor and the corresponding corona voltage are considered, and the effects of such factors as the length of the conductor, changes in its diameter and the solid insulation necessary on parts of the conductor are neglected, then these experiments show that it is not surprising that designs apparently similar, have given very different results in service.

DISCUSSION ON "CORONA PHENOMENA IN AIR AND OIL AND THEIR RELATION TO TRANSFORMER DESIGN."

FRONTENAC, N. Y., JUNE 29, 1909

John B. Whitehead: I wish to say a word about the sentence which reads as follows:

> From a number of experiments the maximum permissible stress in air at atmospheric pressure seems to be 100,000 volts per inch.

Dr. Steinmetz has sometimes placed this figure as high as 120,000 volts. Mr. Berg used 100,000 volts in one of his Institute papers; also in his book " Electrical Energy ", in which he included a table giving the calculated values at which transmission lines may be expected to discharge between wires. There is a wide discrepancy between the calculated values given by Berg and those observed by Mershon, in fact Mershon's values are 30 per cent lower than those calculated by Berg. I have figured this discrepancy for two cases. Berg gives a figure of 104,000 volts approximately for one of the cases investigated by Mershon, whereas Mershon's value lies between 62,000 and 74,000 volts, according to the vapor product. In another case Mershon gives 42,000 and Berg 60,000 volts. Mr. Moody finds that the values he observed are even higher than the calculated values using 100,000 volts as the intensity at which air may be expected to break down. He is, therefore, further than Berg from Mershon's values. All of these conclusions are on the assumption that Mershon's critical point is the point at which the corona becomes visible. I understand this is true, although I should like to have it confirmed. At any rate, we now have quite a discrepancy, about 50 per cent, in values of voltage at which discharge takes place.

In beginning some work on this subject, I have recently had occasion to calculate the potential gradient necessary to start corona discharge, with various assumptions as to the nature of the phenomenon. J. J. Thomson has developed a theory of spark discharge. The experimental results have shown that one cannot get a spark in air at any pressure at a lower value than about 350 volts, and moreover at atmospheric pressure 0.01 of a millimeter is the shortest gap for this voltage. There is a constant minimum spark potential and a minimum spark length dependent on the pressure. Applying Thomson's theory to the case of transmission lines, we find it will not serve, for the value at which the air in the vicinity of the wire may be expected to break down, according to this theory, works out to be about 500,000 volts per centimeter.

Taking another theory as to the nature of the phenomenon; Hobbs has shown that corpuscles or elementary negative charges may be drawn from the material of the wire at a potential gradient corresponding to 100 volts acting over 10^{-4} cm. Applying this to the potential gradient in the vicinity of the wire, which is calculable, we again find a value of different order of magnitude from that observed; namely, about 800,000 volts.

Townsend has shown that ionization by collision, which causes conductivity, will take place at lower values of potential gradient even than that necessary to start and maintain a discharge; and if we take his results, and those of Von Schweidler, we find 30,000 volts per centimeter indicated as the potential gradient at which the intensity is sufficient to start secondary ionization. As 30,000 volts per centimeter is about 75,000 volts per inch, I submit that the formulas and observations would be brought into better accord if 75,000 volts per inch were taken as the potential gradient at which air may be expected to break down in the neighborhood of conductors; and further that secondary ionization is the immediate cause of the breakdown.

One of the most interesting things in Mr. Moody's paper is the clearness with which he shows how sensitive the whole phenomenon of corona discharge is, how easily it is affected by the surrounding conductors, and the presence of metal or dielectrics in the field. The immediate effect upon corona of the manner in which the lead wires are brought in is most important. Mr. Moody suggests that perhaps his observed values differ from the calculated values because of the surrounding and shortness of his wire, and the proximity of neighboring conductors. I think this is also the probable explanation of the wide difference between his values and those of Mershon and others.

J. C. Lincoln: I ask Mr. Moody if he made any measurements at all of the energy required by the wire when it is in the condition of corona discharge? There is, doubtless, energy dissipated from the wire when the discharge is taking place. I also ask if any energy is dissipated by the wire at the potential just below the point at which the corona appears? The next paper to be presented speaks of one case where there is a difference of 1000 volts between the point where darkness is obtained and where the corona appears. Is any energy dissipated from the wire at the lower voltage? or is the difference between the disspiation of energy and the non-dissipation of energy as closely related as the appearance and disappearance of the corona?

Ralph D. Mershon: Dr. Whitehead and Mr. Lincoln have both raised a very interesting point which is touched upon by some information Mr. Faccioli sent me a few days ago. It is the question as to the relation between the critical point and the point at which corona discharge begins. Professor Ryan, I believe, came to the conclusion that they were identical. In my work I had no means of determining whether or not they were identical, because my investigation work was done on overhead lines in a place always more or less illuminated, arc lights some distance away, and the illumination was much too great to determine any corona effect. It would not have been practicable to get indoors a sufficient length of line to measure the loss by the method of measurement I employed.

I have pretty nearly come to the conclusion that the two are not identical, that there has to be a considerable amount of loss before there is any visible manifestation. It would seem reasonable to assume that is the case; that an instrument would probably detect the critical point before the eye would. I feel quite sure that the critical point is affected by the conditions of moisture in the atmosphere, and the results I have obtained seem to show that there is a definite relation between that point and what I call the vapor product. On the other hand, Mr. Moody and Mr. Faccioli kindly endeavored, at my request, to find a relation between vapor product and corona, and were unable to find such relation. I was surprised that this should be the case, but after thinking it over have hit upon a possible explanation as to why there should be no relation between corona and variations of such atmospheric moisture as would ordinarily obtain. If the corona effect is a phenomenon of the air itself, which we assume it is, it is conceivable that the addition of moisture to the air would, up to a certain point, play a part comparable to that of a resistance in shunt to an arc. So long as the resistance is at a high value one will not be able to observe, usually, any difference in the behavior of the arc, but if the value of the resistance is progressively decreased the time will come when there would be an appreciable effect. Now, if the amount of moisture in the atmosphere is low enough, it seems to me it will not affect the corona at all, whereas if the atmosphere is heavily enough laden with moisture the corona may be affected.

I think the apparent discrepancy between my results and those of Professor Ryan and the authors of this paper is due to the fact that the critical point as we have been defining it is not coincident with the point at which corona is visible.

S. B. Charters, Jr.: Following out Mr. Moody's suggestion, or probably preceding his ideas, Professor Ryan has already built at Stanford University what he calls a corona voltmeter, which is used to indicate pressure by corona formation. It has a tapered brass rod inserted in a wire cylinder of uniform diameter and produces fairly reliable results. We have observed that it makes a difference in what manner the leading-in wires are attached. The instrument can be thrown out of calibration by bringing the leading-in wire at some other point than the one at which the calibration has been made. Our results in general are in agreement with Mr. Mershon's. The greatest use for this instrument has been in observing transient phenomena, because the corona will follow all sorts of variable phenomena such as the surging introduced by switching. This spring we incidentally checked, in a very small way, the results obtained by the addition of insulators to conductors; while we did not attempt to make any experiments, our results were in accordance with the results here obtained.

We tried a few experiments on corona under oil, getting results which agreed with the above. I wish to emphasize the point of the tremendous mechanical strains to which the oil and wire are subjected under these conditions. We used a No. 34 wire inside a 4-in. cylinder; and the vibration of the wire was sufficient, when under strain, to shake, not only the stands, but to move a weight of several pounds of iron. We moved the whole stand and iron bodily, simply by the vibration of the small wire under the static strains.

W. S. Moody: I think the only answer needed is to the question which Mr. Lincoln asked; that is, whether we attempted to determine the energy used in creating the corona, and whether we could distinguish between the power required to produce a visible corona and the power required for invisible corona, if such exist.

I tried to make it plain that we did not attempt to make any measurements of the power required to produce corona, for the reason that it was impracticable to erect within a dark room of any practical size sufficient highly insulated wire to get a loss from corona of such an amount as would be measureable with any ordinary wattmeter.

Harris J. Ryan (by letter): Through the facts brought out in this paper, the papers and contributions of Mershon, Watson, and others, we are now prepared to understand the practical significance of the conducting character of the normal atmosphere as determined and expressed by J. J. Thomson and other able physicists. They have found that the normal atmosphere contained in a closed vessel conducts a little even under the smallest electric intensities; *i.e.*, kilovolts per inch; that such conductivity is due to the total number of free ions mixed with the volume of air employed; that the origin of the free ions is due to some external ionizing emanations from the walls of the atmosphere container and the conductors employed or from the outer terestial solar or cosmic sources now known to be numerous; that the value of the current which the atmosphere will thus conduct increases, first regularly with the increase from zero of the electric intensity, then less in proportion until saturation is reached. when the current no longer increases as the electric intensity increases until a critical value is attained: whereas, if exceeded, the atomic structure of the atmosphere is broken, ionization extends from the electrodes and the current is increased at a greatly accelerating rate as the electric intensity is further increased, resulting in the formation of strong coronas or arcs dependent upon circumstances.

For the present purpose we may call the current which is due to the free ions mixed with the atmosphere the *free ion-loss current*, naming *corona-loss current*, that which is due to active ionization. The value of the free ion-loss current depends upon the total number of ions present in the volume of atmosphere employed. When the container is large the free ion-loss current will be large; again when the source of free ions is prolific, the free ion-loss current will be correspondingly great. It is reasonable to expect that with actual line conditions out of doors, because of the vastly greater atmospheric volumes and numerous sources of free ions, especially in great industrial regions, the free ion-loss current would occur in far greater proportions, totally changing its characteristic relation to the initial corona loss current. At Ithaca in 1903–4, by the methods and under the indoor atmospheric conditions there employed, it seemed conclusive that the atmosphere losses are neglibibly small for clean conductors at pressures under the visible corona-forming values.

The earlier results of Mershon in the Rocky Mountains, of Harold B. Smith at Worcester, the results obtained at Ithaca, and the recent continuous current results obtained by Watson at Manchester, England, are in fair agreement as to this point. The more recent results obtained by Mershon at Niagara Falls are not in accord in this respect, and this may be due to the out-of-door character of that region. That is to say, the coincidence or non-coincidence of the electric intensities at which critical loss and visible corona occur may depend considerably upon local conditions; or, to put it another way, when conditions are such as to cause the free ion-loss current to be relatively large, the critical value of the loss current may possibly occur at a decidedly lower pressure than that which will start the visible corona.

As to the volts per inch at which the normal atmosphere is ruptured: J. J. Thomson is likewise authority for the value of 30,000 per centimetre at which active ionization occurs; this corresponds to 76,200 volts per inch. In the work at Cornell alternating pressures that start coronas on conductors having diameters ranging from 0.05 in. to 0.65 in. were found to produce an electric intensity in the atmosphere next to the conductor surface ranging from 190,000 volts per inch for clean conductors with diameters at 0.05 in. down to 90,000 volts per in. for conductor diameters of 0.65 in. All results, however, pointed to the correctness of an idea advanced some years earlier by Steinmetz; namely, that there exists a thin atmospheric zone adjacent to conductors that will endure greater electric intensities than the normal atmosphere beyond. A process was then found for locating the thickness of these zones beyond which the normal atmosphere would break first on the application of the corona forming electric intensity. The values of such critical electric intensities could then be estimated by the method illustrated in the following example:

Beyond the surface of a clean brass conductor 0.65 in. in diameter, the normal atmosphere broke into corona at a distance of 0.07 in., at a dielectric flux density of $170,000 \times 10^{-13}$ coulombs per inch cube. The coulombs per inch cube per volt established in the normal atmosphere are 2.244×10^{-13}.

It follows, therefore, that the volts per inch of electric intensity that ruptured the zone of normal atmosphere about this conductor was found to be

$$\frac{170{,}000 \times 10^{-13}}{2.244 \times 10^{-13}} = 75{,}700,$$

a value that is in accord with the authoritative conclusion of leading physicists and that submitted above by Dr. Whitehead. This value of 76,000 was obtained for all sizes of conductor from 0.65 in. down to 0.2 in.; below that the results gave an increase,—from what cause was not determined. It may possibly be due to the lack of free ions emanating from the surface of the small conductor, or to some related cause.

As to the corona voltmeter mentioned by Professor Charters. It was made about two and a half years ago and has been used so far only for lecture work. It is heartily recommended to those who want to observe transient phenomena on high-pressure circuits, by direct vision or through a revolving mirror, for it is really also a sort of corona oscillograph. At this writing I am compelled to give the dimensions of the instrument and its range from memory. However, the values are throughout about right as given, because the recollection of them is clear.

The instruments consists of a tapered brass rod. 7 ft. long, ⅜ in. diameter at the larger end and uniform for 1 ft., then tapering uniformly, to a diameter of ¼ in., at the opposite end. At the center of a 0.5 in. square galvanized steel wire net cylinder of the same length and 15.5 in. inner diameter, suitably insulated, the tapered rod is mounted. When put in the dark, and alternating pressure applied between rod and cylinder, the corona first appears at the small end of the rod, when ordinary barometric pressures and temperatures obtain, at about 25,000 effective sine-wave volts and extends the length of the rod as the pressure is elevated, reaching its full tapered length at about 55,000 volts. For greater ranges the dimensions must be increased in proportion or instruments of this size must be balanced in series across the circuit. It has not as yet been used in work of investigation. However, for some such purposes it will be useful.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

SURGES ON A CABLE SYSTEM WITH AN ALUMINUM SURGE PROTECTOR

EXPERIMENTAL INVESTIGATION OF THE SURGES ON AN UNDERGROUND ALTERNATING-CURRENT DISTRIBUTION SYSTEM, AND THE PROTECTION BY ALUMINUM CELLS

BY E. E. F. CREIGHTON AND S. D. SPRONG

The investigations referred to later in this paper were begun by the authors early in the summer of 1908 and covered a period of from eight to ten weeks. The system of the United Electric Light & Power Company, of New York City, seemed particularly desirable for this class of investigation, as it is the largest alternating-current light and power system that is entirely underground and therefore subject to the particular class of phenomena treated by the paper; moreover, it is without the variations that might be encountered in a system having a part of its lines overhead.

The system of the company does not differ substantially from others distributing alternating current underground, but as there are certain minor departures from the usual practice it may be desirable to give here a brief description, so that any small differences can be taken into proper account in a study of the application of the suggested solution to other systems.

The Island of Manhattan, over which the company's system extends, is divided into two approximately equal districts, which are operated independently north and south of Fifty-ninth street. More or less centrally located in either district is a sub-station supplied at 7500 volts, 60 cycles, three-phase, from the Waterside Station of the New York Edison Company. In the sub-station this current is stepped down by 2750-kw. air-cooled transformers to 2250 volts, two-phase, and is distributed on the three-wire, two-phase system. All the lighting load and about one-half of the power load are carried on the two outer primary conductors at 3000 volts, thereby nearly doubling the efficiency of the primary distribution and simplifying the question of feeder regulation, which resolves itself into the regulation of the voltage on the outer conductors only.

Each feeder carries an independent district of its own, aggregating about 800 kw. at the peak load. The feeder potential is regulated by an 85-kw., motor-operated, two-phase, air-cooled induction regulator. As only the two outer conductors of the feeder pass through the regulator, as shown in Fig. 1, its effect, as described above, is to increase or decrease the length of each side of the right-angle or quarterphase potentials. This arrangement gives a concentrated inductance in series with the capacity of the feeder, and it is at this point that the problem is met of protection from surge and other abnormal potentials. The potential regulator produces a constant potential of about 250 volts across its secondary, which gives a plus or minus regulation, depending on its phase-angle with the main electromotive force. This phase-angle is regulated by the mechanical movement of the motor-operated primary. The constant secondary potential is particularly suited to the application of the aluminum bypass cells, as will be described later.

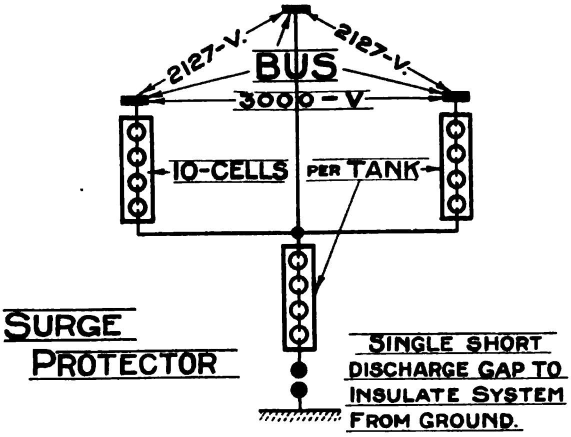

FIG. 1—Connections of the surge protector to the bus bars

The operating experience of the United Electric Light & Power Company, covering a period of some years, has frequently indicated the presence of abnormal potentials which were evidently due to surges. This was shown by punctures on other cables occurring simultaneously or shortly after the grounding of some one feeder. Breakdowns, which usually follow the grounding of a feeder, sometimes happened in one or more of the feeder regulators. This was due, as will be explained, to what may be called the banking up of the potential against the regulator on the feeder side of its reactance.

The total amount of primary cable connected to the bus-bar of each sub-station was about 170 miles during the period of test. This mileage of cable was divided into 14 approximately equal and independent sections, each supplied by a three-conductor feeder on the radial system; that is, the network of primary distributing conductors covering a particular district, is supplied at its approximate load center by a three-conductor feeder direct from the sub-station bus-bar. The capacity current per feeder. with its distributors is about 2 amperes per leg, and this capacity, in series with the high reactance of the induction regulators, gives a combination that is dangerous under a wide variety of disturbances.

It may occasion surprise to some that any company would deliberately undertake the hazard of causing surges on its working system, but in considering this point, it should be kept in mind that the United company has the largest alternating-current system that is entirely underground and, therefore has been among the first to observe the results of the phenomena involved and felt compelled in the absence of any other source of reliable information to resort to a practical investigation on its own system. It was decided that, because of the frequency of breakdowns and the variety of conditions under which they occurred, the point was being reached when to prevent the conditions becoming still more acute the case needed not so much a desperate remedy as an extreme method of diagnosis While the method adopted was no doubt radical, it seemed the only possible way to attack the problem with any chance of satisfactory results. The experimental work was undertaken with caution, in that but one step in the dark was taken at a time after which all the data were correlated, including the development of the oscillograph film, so that the drift of the experiment could be checked before the hazard was multiplied further.

It seems hardly necessary to add that these precautions included the application of the aluminum surge protector to the bus-bars at all times, as shown in Fig. 2, and also the use of needle gaps at different points of the system in an endeavor to indicate potentials before they became hazardous. Earlier experiences of the company while operating the uptown and downtown systems in parallel, showed a more extended damage to other feeders when one developed a fault. This bears out the results of the tests showing that extensions of the system lower its natural frequency to such a value as to bring it within the range of the harmonics of the generator. While the expedient of separating the whole distributing network into two districts postponed the possibility of resonant troubles, the system is a growing one, and as further division is not advisable it was necessary to consider the possible extension of some one district to the point where the frequency would come within the range of the usual generator harmonics. The problem lay in either keeping a high natural frequency of the system by subdivision or using some means of absorbing the energy of abnormal potentials.

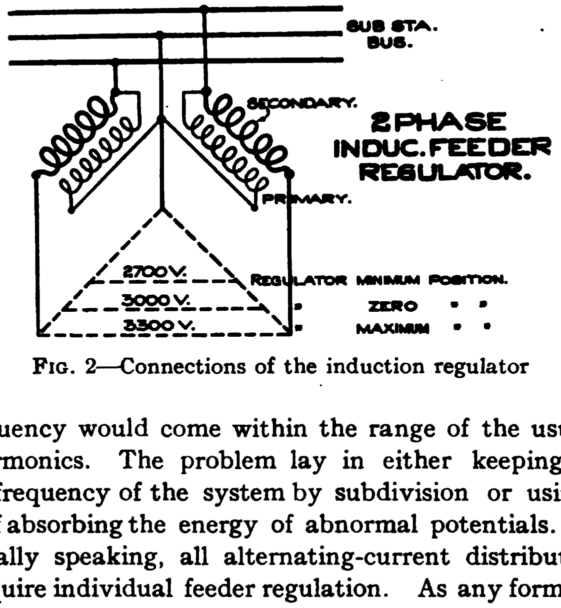

FIG. 2—Connections of the induction regulator

Generally speaking, all alternating-current distributing systems require individual feeder regulation. As any form of regulator must involve reactance, it follows that there will always be the probability of abnormal and often dangerous potentials, as a result of the feeder capacity and regulator reactance. This brings us, then, to the necessity of either taking care of the excess potential on the feeder side of each regulator individually, or by-passing it around the regulator to the station bus-bar, thus making it possible for a single protective equipment to take care of all feeders.

The latter method is preferable, as it reduces to a minimum the investment and bulk of equipment to be provided for in the station. It also provides a way to locate instantly the particular feeder in trouble. As a third advantage, it prevents the piling up of the surge potential on the end-turns of the regulator coils. A further advantage is that by-passing the reactance of the regulator very greatly increases the frequency of the surge and therefore raises it above any possibility of resonance with any of the generator harmonics.

It should be noted in this connection that by-passing a reactance with an aluminum cell almost entirely eliminates such reactance from the circuit. It is for this reason, as described below, that the frequency of a feeder goes much higher than the range of the oscillograph. In other words, by the elimination of the reactance by means of the aluminum by-pass cells, the feeder then oscillates at its natural frequency and the concentrated reactance of the regulator becomes an insignificant factor in its period. It is quite possible that this principle may be employed for other uses than the one covered by this paper.

The first series of tests were carried out with the use of one cable only and its potential regulator. The natural frequency of oscillation, due to a grounded phase through an arc, was of the order of 3000 cycles. Knowing the capacity of this cable, the inductance to correspond to this frequency was calculated and was found to be in the neighborhood of 0.001 henry. This low value of inductance shows that the inductance of the distributing transformers on the circuit with open secondaries is not a factor in this oscillation, since the value of such inductance would be many times greater than the requisite value. The inductance calculated by a short-circuited regulation from tests on the potential regulators gave the value desired of about 0.001 henry. In other words, the oscillation recorded by the oscillograph shows that the energy of the static charge of the cable passes into electro-magnetic energy in the potential regulator and is re-transformed from one to the other until dissipated.

Later tests were made with an increasing number of feeders from the same bus-bar. It was found that the natural frequency of oscillation, as recorded by the oscillograph, diminished with each additional feeder. With twelve feeders on a circuit, the natural frequency of oscillation had decreased from about

1800 to 680, which is about eleven times the generator frequency. In other words, this system of twelve feeders would resonate with the eleventh harmonic of the generator wave if such an harmonic existed. The potentials across the line coil of the potential regulator showed increasingly higher values as the number of feeders on the system was increased. So far as the oscillograms show directly, these values of surge potential reached the dangerous zone.

By indirect calculation it can be shown that the natural frequency of a cable oscillating by itself may be as high as 25,000 cycles, and such a frequency could not possibly be shown by the oscillograph since the natural frequency of an oscillograph is seldom over 8000 cycles. On careful examination of the oscillogram it is found that the initial deflection when the surge takes place is as instantaneous as the inertia of the moving part of the oscillograph can record. In other words, the discharge from the cable strikes the end-turns of the potential regulator and piles up the potential there. Subsequently the surges " ooze " through the inductance of the regulator and produce thereby a lower frequency at potentials, which, for the simple grounded phase, are less hazardous to the total insulation of the regulator.

What may take place when a grounded phase combines with a short-circuit, as frequently happens, is impossible actually to test, but there is every reason to believe that the potentials will reach a far more dangerous total value across the coils of the potential regulator. The evidence seems to point to the conclusion that the grounded phase does not instantly damage the end-turns where the surge potential piles up, but that the injury is caused by long-sustained surges. Each surge probably causes a small amount of sparking between turns of the coil or between layers, and the dynamic potential difference across the spark is not sufficient to maintain an arc. Each one of these spark discharges probably causes some disintegration of the insulation between turns or layers, and it is only after continued stresses of this kind that the trouble develops gradually into a short-circuited condition of the turns of the potential regulator.

The best means of protecting the potential regulator will be to apply aluminum cells across the regulator coils. This was done in the test, and the oscillogram of the current in the cells circuit showed a maximum rise of over 50 amperes from a normal current of about 0.1 ampere. This test was made with a current transformer in series with the cell, which in itself reduces the natural frequency through the cell circuit. Observations on the cells, without the current transformer in circuit, showed an unusual activity. In fact, never in any test made in the laboratory or in service have the plates shown an equal amount of luminosity on the surface nor have they given out as loud a sound.

OSCILLOGRAPHIC RECORDS.

General comments. While these records are very clear in the film, it is found impracticable to obtain good reproductions unless the curves are intensified. Where so many high-frequency waves appear, the most practicable method of intensification is by means of a pen and ink working under a magnifying glass. In these records this inking has been done with care, although without the engraver's experience. In general the ink lines follow the records. Two things are lost by inking: first, occasionally on the waves are higher harmonics which can be shown only by the fine lines of the record; secondly, due to unsteadiness of the hand and width of ink line, a record of an almost instantaneous change, which appears as a thin vertical line, loses this definiteness. These refinements of analysis are in general not important. Some of the lost effects will be referred to in particular in the comments on individual oscillograms.

The oscillograph used in these tests had three vibrators. It will aid in studying these oscillograms to know that two of the vibrators were, with few exceptions, kept in the same part of the circuit. The vibrator giving the middle record was placed between a phase and ground and was maintained in this position in every case where a ground was produced. The last two oscillograms shown, Figs. 23 and 24, are the only ones without a ground. The vibrator giving the lower record was placed in the ground leg of the surge protector, except in Fig. 13. The vibrator giving the upper curve was placed successively in different positions; viz., potential of bus-bars, potential between line and ground, and across the coils of different regulators, both on the grounded phase and the non-grounded phase. In most cases only one factor was changed at a time. These relations are brought out in the *List of comparative oscillograms* given later.

The three wires of Fig. 2 are named as follows: A_2 the middle wire, and B_1 and B_2 the outer wires.

Fig. 3 shows the general connections for test. Under each oscillogram the specific connections are given. Cable No. 109 was grounded in every case except those of the last two records. In these two, Figs. 21 and 22, cable No. 126 was grounded. In all the tests on No. 109, B_2 phase was grounded, but in the tests using cable No. 126, B_1 phase was grounded.

Needle gaps with series fuses and a resistance sufficient to limit the dynamic current to 0.5 ampere, were placed across both the bus-bar and the cable that was grounded. The object of these gaps was to record any possible peaks of potential that were too short in duration to affect the oscillograph. The line potential was 3000 volts and the gap-length equivalent to 6250 volts, but in no case during the test did the gaps spark over. These needle gaps will be referred to again later under the heading *Oscillations under normal operations.*

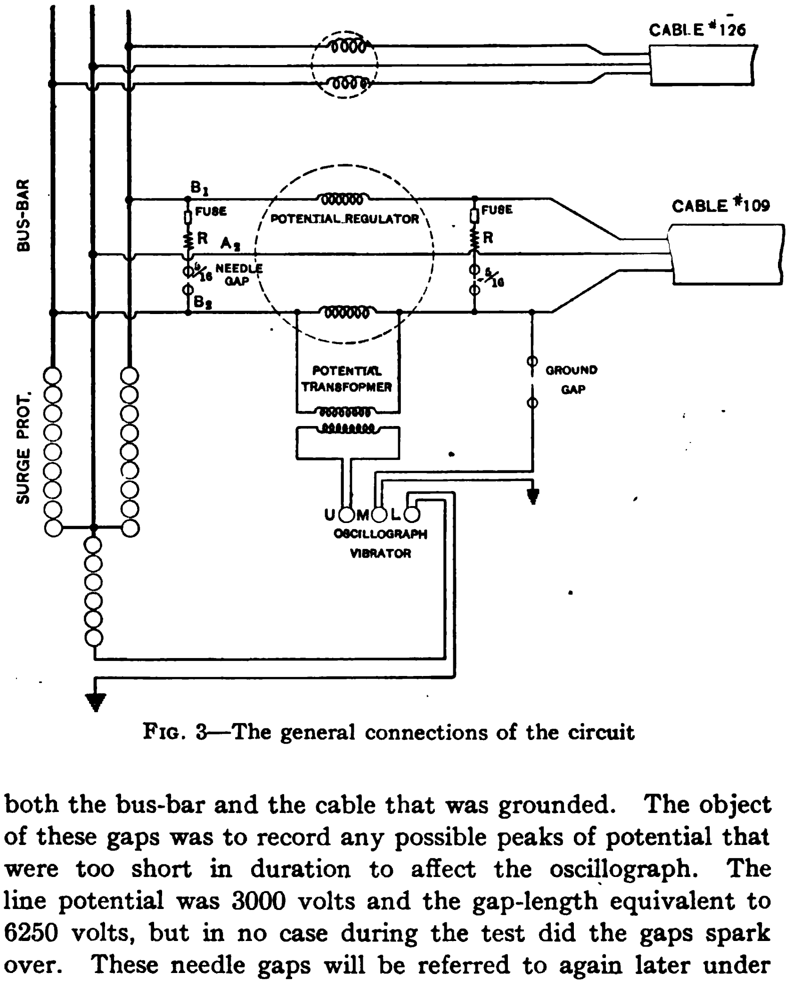

FIG. 3—The general connections of the circuit

In Fig. 4, oscillogram 504, with only cable 109 in circuit,

B_2 leg is grounded through an arc. The middle record shows this current. The rise of current was 68 amperes, although the capacity current is normally only about 2 amperes. This current oscillates during three half-waves of the natural period of the circuit. The gap between line and ground was set at its maximum sparking value and, furthermore, there seemed to have been some rectifying action at the gap which was sufficient to prevent the sparking of the gap when the generator wave reversed. This gives a discharge only at every second peak value.

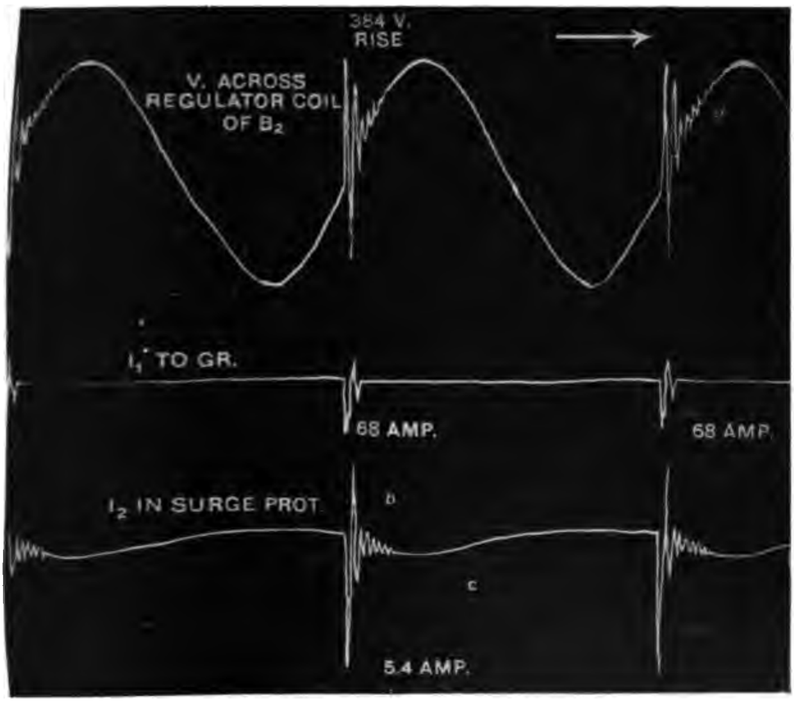

FIG. 4

The upper record is the potential across the B_2 coil of the potential regulator. This is the leg that is grounded. Owing to the mechanical position of the regulator, its zero potential corresponds to the maximum across the phase; therefore the discharge occurs near the zero value of the potential of the regulator. There is a sudden rise of 384 volts, which oscillates for three half-cycles corresponding to the current to ground. This frequency is approximately 1800 cycles per second. After the arc to ground is extinguished, the system continues to oscillate. but at a higher frequency; namely, 3000 cycles per second. This point is shown at *a* and *b*.

The lower record in Fig. 4 is the current through the aluminum surge protector to ground. It shows at *b* two rates of vibration the same as the voltage wave. After the second oscillation ceased, the current continued to flow to ground through the surge protector as shown at *c*. The arcing ground reduced the B_2 leg to ground potential and thus left the system out of symmetry with the zero potential of the ground. Since the surge protector was the only connection to ground, it carried the quantity of electricity necessary to charge up the ground phase. This change took place through a half-cycle of the generator wave and is shown at *c*. The first half-cycle of the discharge through the surge protector took a longer time than the second half-cycle. This is not true of the oscillations through the regulator coil on the upper record.

One of the characteristics lost in printing is in current discharge through the surge protector. The current starts very abruptly but on reaching 1.35 amperes, stops and recedes a little and then increases more gradually to its peak value of 5.4 amperes. This perhaps is due to the nature of the circuit. At the place where the cable is grounded, on one side is the distributed capacity of the cable and on the other side the inductance of the regulator. The different parts of the system have different rates of discharge due to their natural frequencies, and at any one point these discharges may be moving in opposite directions. Apparently this condition gives the variation in discharge through the surge protector. When more cables are added the results are sufficiently pronounced to be seen. The lower record in Fig. 14 with three cables connected to the bus-bars shows two distinct loops in the rise of the current in the surge protector. In the middle record showing current to ground, there is a hook in the wave of the first half-cycle just after the peak value is reached. When more cables are added this hook disappears.

Fig. 13 shows that the potential across the potential regulator recorded by the oscillograph is not the potential on the end turns, but is less.

In the first set of tests (oscillograms 500 to 517) the arc was produced by opening a knife-switch by hand. In the remaining tests a screw gap was used in an endeavor to produce an arc of constant length. The movement of the screw was controlled by cords attached to an arm and its travel limited by adjustable stops.

In Fig. 5, oscillogram 505, upper record, with one cable in circuit, B_2 leg is again grounded, but the potential is now measured across the B_1 phase of the same regulator. The middle record is the current to ground and the lower record the current in the surge protector. The latter two are identical with the previous oscillogram but the upper record differs in the following particulars:

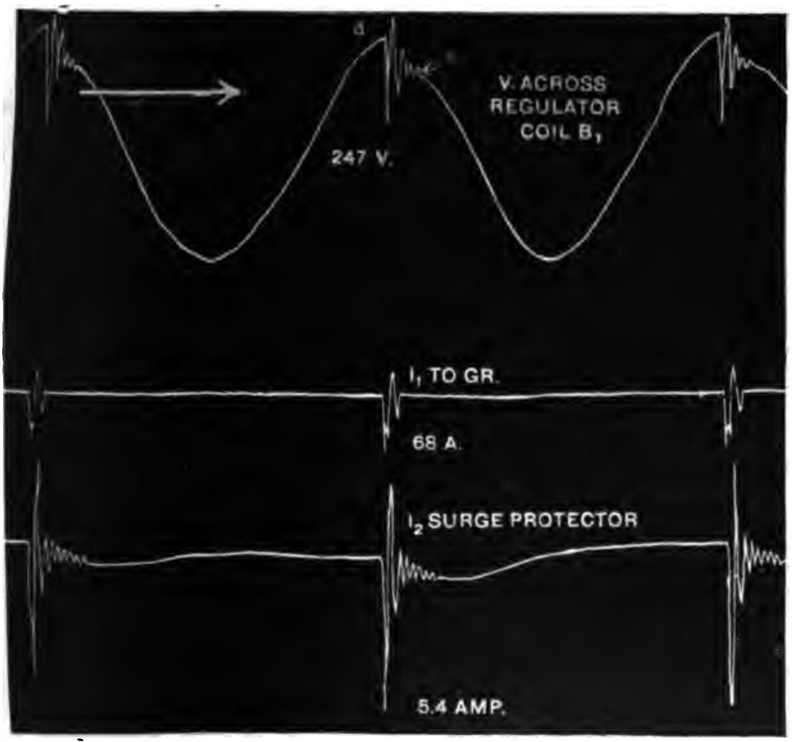

Fig. 5

1. This regulator coil is in the other phase of the two-phase circuit and, therefore, with the same mechanical position of the regulator, the potential must be either 90 degrees ahead or

behind; therefore, the discharge takes place during the peak value of the potential across the regulator.

2. The currents in the B_2 coil (Fig. 4, oscillogram 504) and the B_1 coil (Fig. 5, oscillogram 505) are in the opposite directions. In Fig. 4 the surge potential rises with the rising potential across the regulator coil; but in Fig. 5, the reverse is true. Before the ground took place the B_1 phase was approximately 1500 volts effective above the ground, but after the B_2 leg was grounded this potential of B_1 was about 3000 volts above ground. The quantity of electricity to do this was taken through the regulator coils.

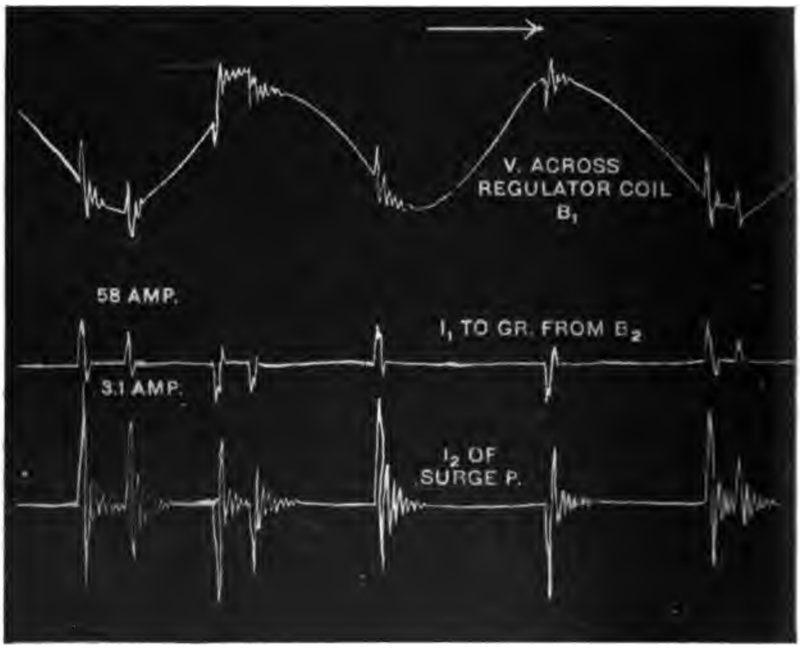

Fig. 6

3. The symmetrical form of the main wave in oscillogram 505 is destroyed by the oscillations. A mean line drawn through the oscillations shows a total drop from the main curve which is not recovered until after the oscillation ceases.

In Fig. 6, oscillogram 506, with one cable in circuit, the same circuit conditions exist as in Fig. 5; viz. the upper record shows the voltage across the B_1 coil of the regulator, the middle record shows the current from B_2 to the ground and the lower record shows the current in the surge protector. The changes are as follows: The scale of the potential wave has been altered to give a smaller record and the gap length between B_2 and the ground is shorter than in the previous test. In consequence of the smaller gap the phase is grounded more frequently and the potential across the gap at the instant of discharge is correspondingly less.

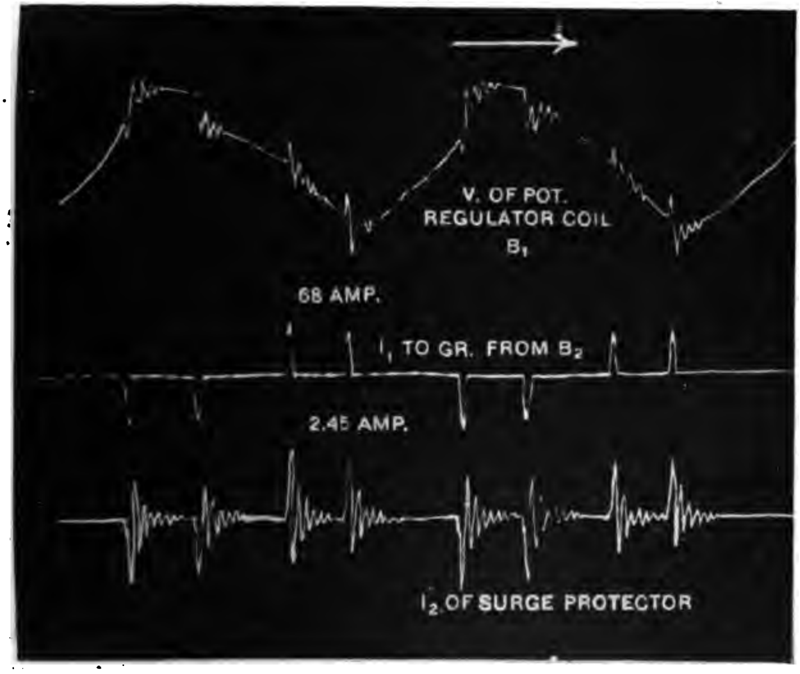

FIG. 7

Fig. 6, oscillogram 506, shows that the distortion of the wave of potential across the B_1 phase of the regulator depends on the condition of the charge of electricity left by the arcing ground. Compare the number of half-waves and the height of the final half-wave of each of the oscillations in the middle record with the corresponding disturbance in the potential record.

In Fig. 7, oscillogram 507, with two cables in circuit, the arc length is about the same as in the previous oscillogram, the only change being in the increase from one to two cables. This oscillogram does not lend itself readily to the calculations of frequency. The following values are given, however: The time of discharge to ground is represented by 1 m.m. equal to 1/2450 second, to which the time of discharge through the surge protector corresponds. Assuming that this wave is not greatly distorted, the frequency should be about 1225 cycles per second. After the ground arc breaks, the remaining oscillations are about doubly rapid; namely, 2450 cycles per second.

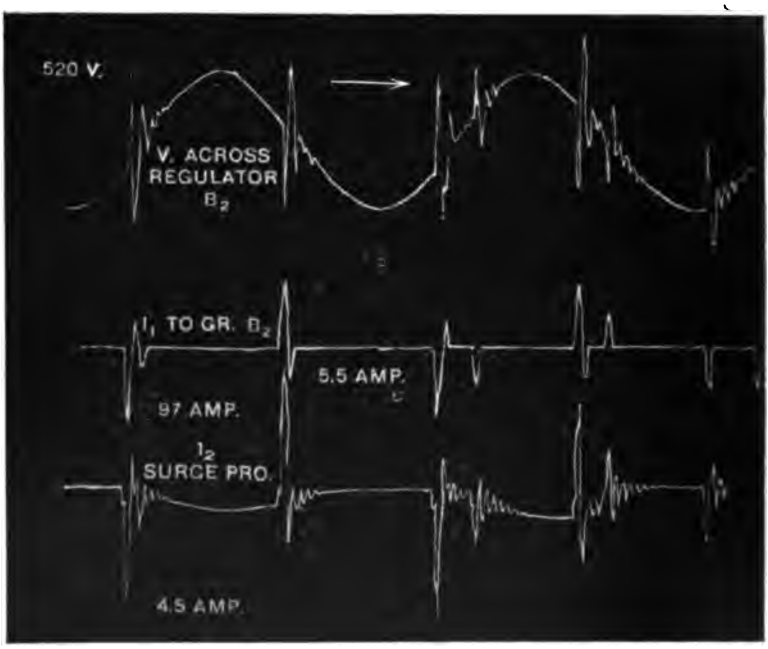

FIG. 8

By the addition of the second cable, little change has been made in the surges. What little change there was lowered the surges. This is shown by the lesser discharge through the surge protector.

In Fig. 8. oscillogram 508, with two cables in circuit, the only change made from the previous test was the transference of the potential vibrator from the B_1 phase to the B_2 phase of the regulator. Inadvertently the arc was a little longer, and in consequence the surge currents were greater and the occurrence less frequent. It is important to note that although the surge current to ground increased from 68 amperes to 97 amperes—only 42 per cent—the surge protector was required to discharge 4.5 amperes, an 82 per cent increase, comparing oscillograms 507 and 508 Figs. 7 and 8.

Except for the difference in arc length and scale for the upper record, Fig. 8, is comparable to Fig. 4, where but one cable was in circuit.

In Fig. 9, oscillogram 509, with two cables in circuit, the circuit connections are the same as in the previous test, but the arc to ground is made of short length. This results in a more frequent discharge to ground; in fact the frequency of discharge is about seventeen times the frequency of the circuit. This is noteworthy and is commented upon later, under the heading of *Artificial Harmonics*. Other than the danger of resonance these surges are less harmful than those due to longer arcs. Fig. 9 is comparable to Fig. 8 for the effect of long and short arcs to ground.

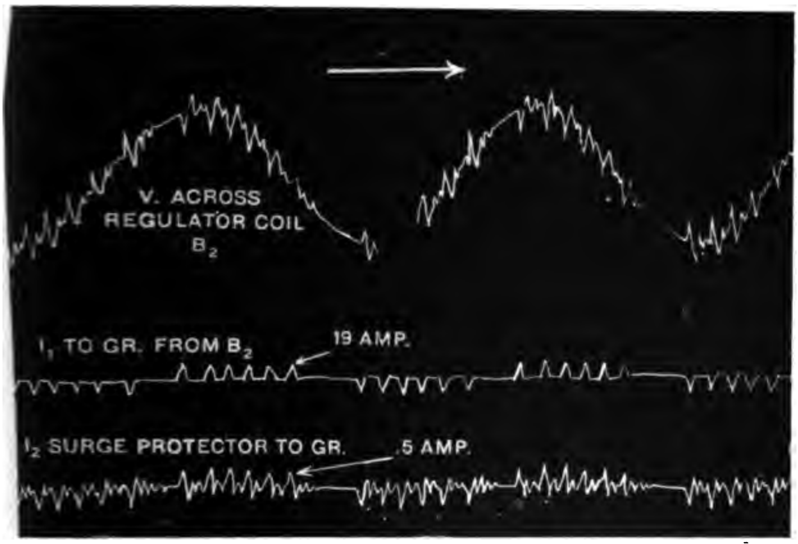

Fig. 9

In Fig. 10, oscillogram 510, with three cables in circuit, the circuit conditions remain the same; namely, voltage across

B_2, coil of the regulator, current to ground, and current through the surge protector. For a comparison of the effect of increasing the number of cables, Figs. 4, 8 and 10 may be used. The general effect is an increase in current to ground and maximum potential across the regulator, but, due apparently to the lower frequency, the surge protector is not called upon for a corresponding increase in discharge.

One cycle of the discharge to ground takes place at the rate of 1120 cycles per second. As closely as can be measured, the frequency after the arc to ground ceases is about double this; that is, 2240 cycles per second.

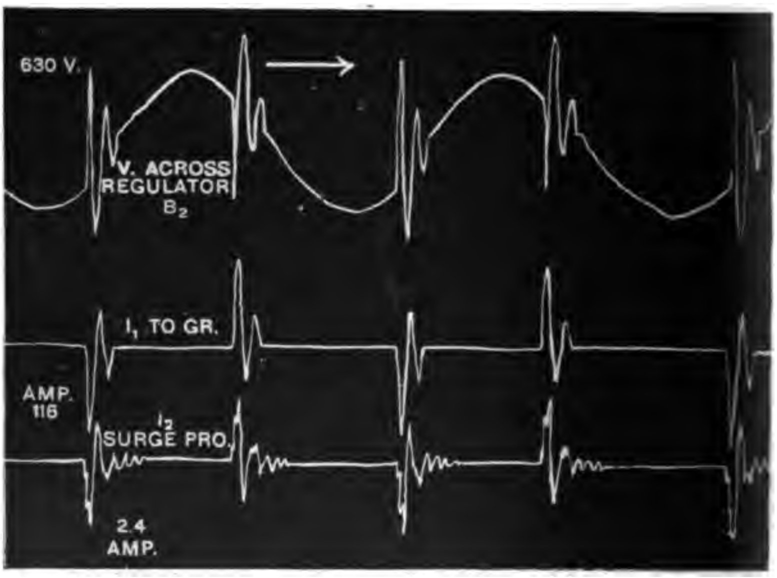

FIG. 10

In Fig. 11, oscillogram 511, with four cables in circuit, the circuit conditions remain the same as in Fig. 10. The voltage rise across the regulator coil and the current to ground have again increased over the condition of three cables. In this case the current in the surge protector has also materially increased. With the increase in current to ground there is a marked tendency for the arc to hold over more than a half cycle. From another standpoint this is a dangerous feature, as it allows of a longer arc—if the arc length were variable—which would produce a heavier surge. The approximately measured frequency is now 920 cycles per second for the oscillation to ground and, as near as can be measured, double this when the ground connection is broken.

In Fig. 12, oscillogram 514, with four cables still in circuit, the potential vibrator has been transferred to the grounded B_2 leg of another (No. 126) regulator. The other conditions remain the same as in 511 (middle record current to ground and lower record current through surge protector.) Oscillograms 514 and 511 give a comparison of the surges in two regulators when the cable of one is grounded. In this case the surges in the grounded potential regulator are more than ten times as great as in the other regulator. Aluminum by-pass cells had been placed across the coils of the grounded regulator No. 109; subsequently the fuse in series with the by-pass cell in the grounded phase was found melted. It is unknown whether this

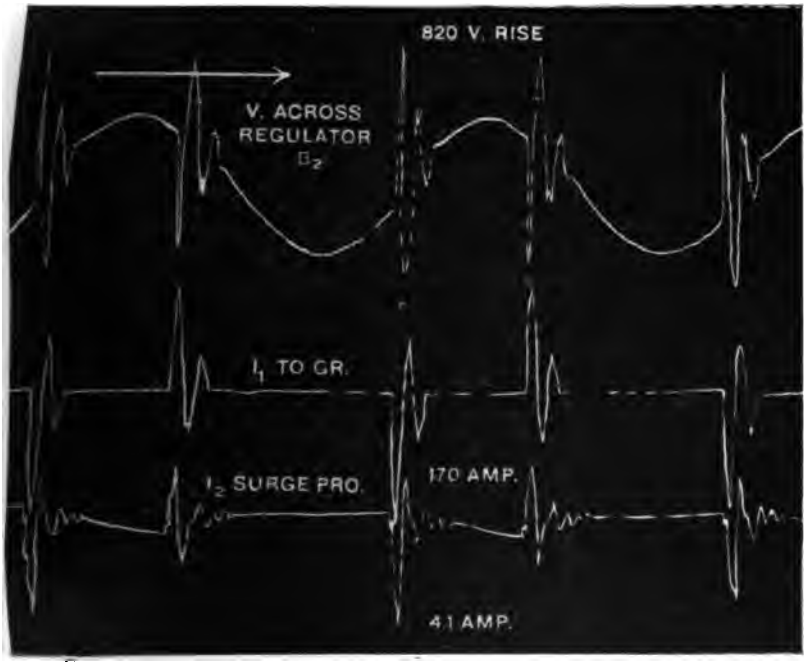

Fig. 11

took place before or after the oscillogram was taken; presumably it fused before the exposure.

The greater values of current in the two lower records of 514 are due probably to a slightly greater length of arc between the line and ground.

In Fig. 13, oscillogram 516, four cables are still in circuit. The potential is again across the grounded phase of the non-grounded regulator. The middle record is the current to ground. The vibrator on the lower record, however. has been changed. An aluminum by-pass cell shunts each side of the regulator (109) that is grounded; in series with the cell in the grounded phase B_2, a current transformer is placed, the secondary of which gives the lower record. Since the natural frequency of the cable with its regulator shunted must be extremely high (over 20,000 cycles per sec.), the oscillograph, with its own period of only 5,000 to 8,000 cycles per sec., cannot be expected to follow faithfully the variations in the circuit.

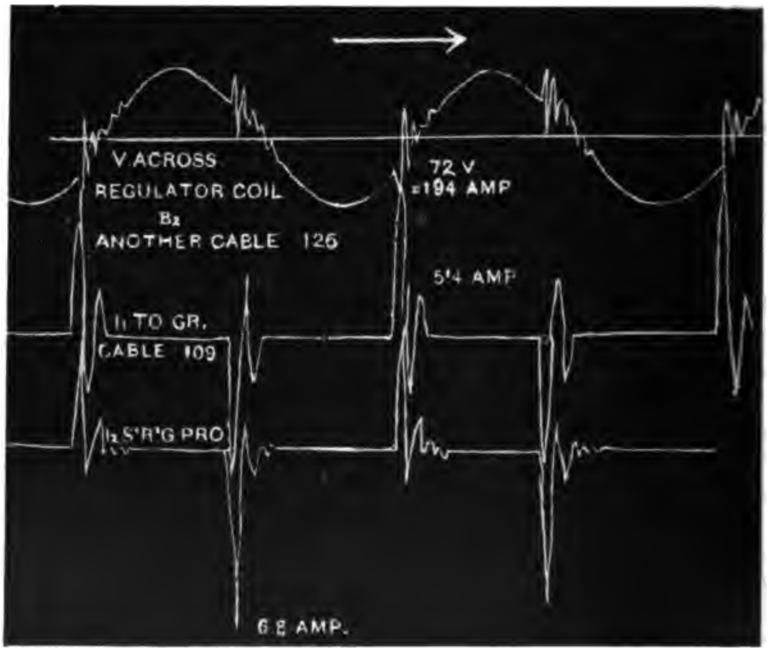

Fig. 12

The inaccuracies of the vibrator will consist in falling short of the maximum current; but in spite of this it is sufficiently surprising to get a record of 57 amperes in the cell. Another feature is the form of this current wave. The current rises rapidly to a peak value, descends as rapidly, crosses the zero, rises to a considerable value in the opposite direction—all before the current to ground has completed its first half-cycle, and maintains a flat top wave before it again reaches zero.

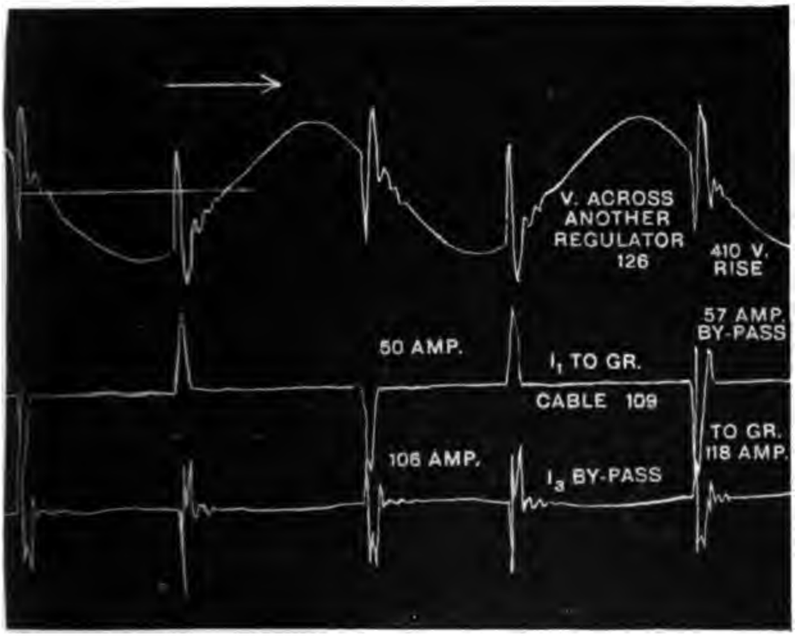

FIG. 13

The potential across the regulator (126) now takes a larger proportion of the total surge.

Another noteworthy condition in this record of current to ground is that the arc is extinguished at the end of the first half-cycle. The only reason apparent for this briefer duration is the presence of the by-pass cells.

In Figs. 14 to 20, seven oscillograms are shown which were taken three days later. The first four, 517, 518, 519, 521, were taken with three cables in circuit with different position of the potential regulator. The last three, 524, 526, 530, of the seven were taken with an increasing number of cables in circuit.

The conditions then for 517 are: three cables in circuit. The upper record is the potential between phase and ground of the grounded phase; in other words, the potential across the arc to ground. The middle record is again the current to ground. The vibrator giving the lower record is changed back to the usual position; namely, current in the ground leg of the surge protector.

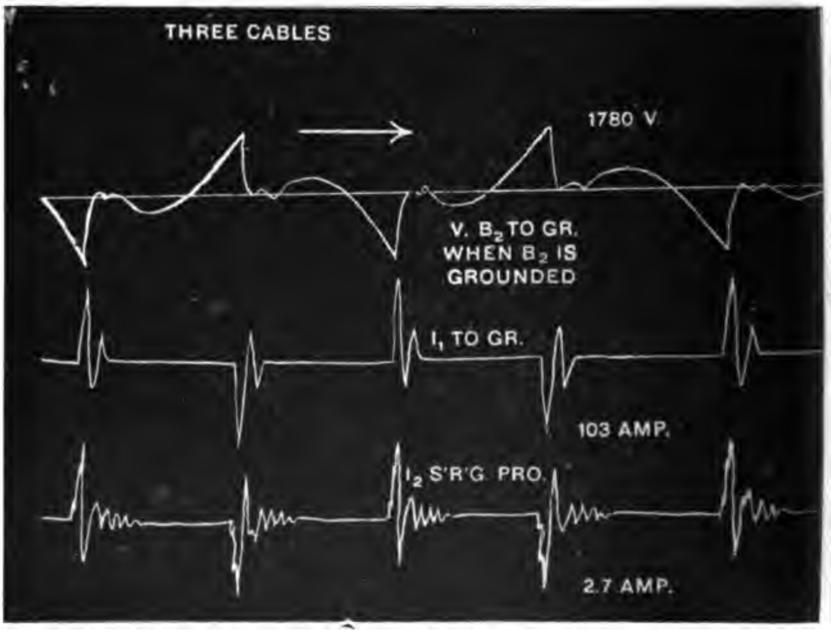

FIG. 14

Commenting on the oscillogram, it may be said that the potential across the gap rises normally to 1780 volts, which is the spark potential; it then drops quickly, but not instantly, to zero, and oscillates slightly across zero while the arc plays. After the arc goes out, the system gradually assumes its normal symmetrical condition of potential, and thus continues until the next arc takes place. (Due to faintness of the lines, one loop of potential was erroneously inked in above the zero. By comparison with the upper record this error will be evident.) The current to ground shows the usual form of discharge, but the current in the surge protector shows *two* distinct halts in rising to its peak value in the first half wave. This same form was shown in oscillogram 510 with three cables in circuit.

In Fig. 15, oscillogram 518 is directly comparable to oscillogram 517 in Fig. 14. The potential vibrator is now between the other phase B_1 and ground. Since this phase is 90 degrees from the grounded phase B_2, and since it takes a charge from the earth corresponding to the increase of potential above the earth, the wave-form is entirely different from both oscillograms 517 and 510, in Figs. 14 and 10, respectively.

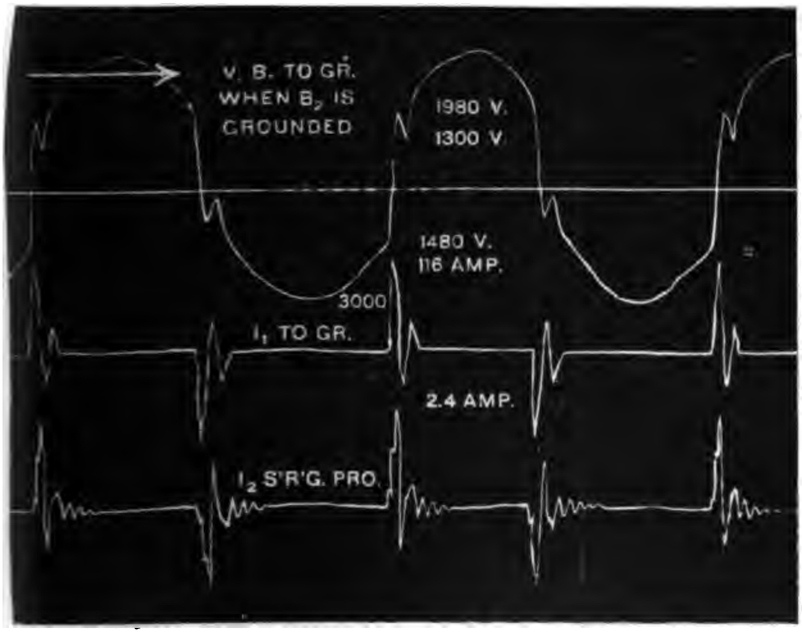

Fig. 15

The potential change of the non-grounded phase does not reverse during the first half-cycle of discharge to ground, as it always does *across* the grounded coil of the regulator. The potential of the non-grounded phase gradually changes in one direction so long as the current to ground is in one direction, regardless of whether it is increasing or decreasing, but the potential across the regulator coil has the form of a potential induced by electromagnetic transformation.

The maximum potential in the negative direction is 3000 volts and in the positive direction is 3660. The maximum possible is 3000 × 1.4 = 4200 volts. Any value less than this is due to the fact that after the grounded arc is extinguished the system has not time to regain its symmetrical relation of potential to the ground, which is 4200 volts maximum.

In Fig. 16, oscillogram 519, the records are directly comparable to those in Figs. 14 and 15. The disturbance in the potential wave between the two phases B_1 and B_2 during the grounding period is noteworthy. Although this disturbance appears relatively unimportant, it is actually a rise of 850 volts corresponding to the voltage added by the surge through the regulator.

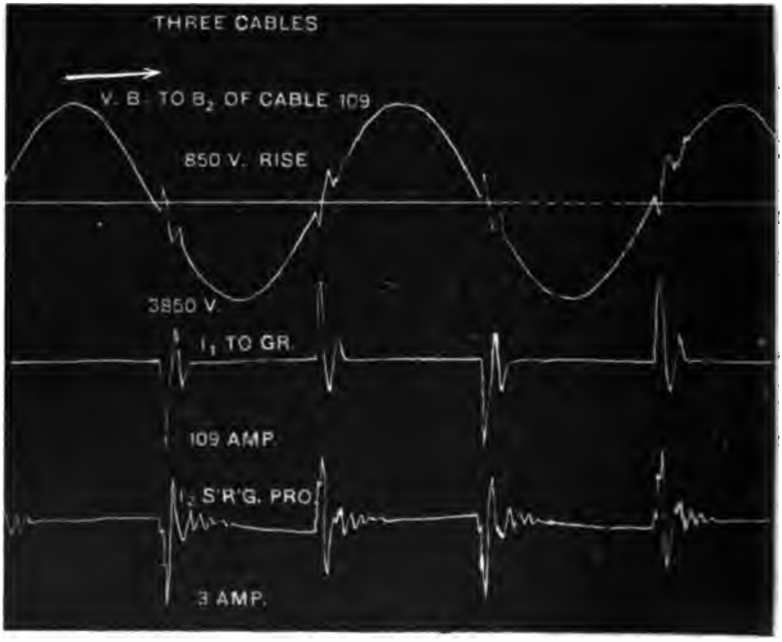

FIG. 16

In Fig. 17, oscillogram 521, the records are directly comparable to those in Fig. 16. The potential is now taken across B_1 to B_2 on the bus-bars where the surge protector is connected. The disturbance in the potential wave, during the period of grounding, is reduced to about one-third the surge potential across the phases of the cable.

In Fig. 18, oscillogram 524, five cables are in circuit. The records are, respectively: voltage across the regulator coil of the grounded phase B_2; current to ground; and current in the surge protector to ground. The maximum voltage rise is 407 volts; the first peak value of the current to ground is 111 amperes; and the first peak value of the current in the surge protector to ground is 1.7 amperes. This oscillogram is comparable especially to others with a lesser number of cables in circuit.

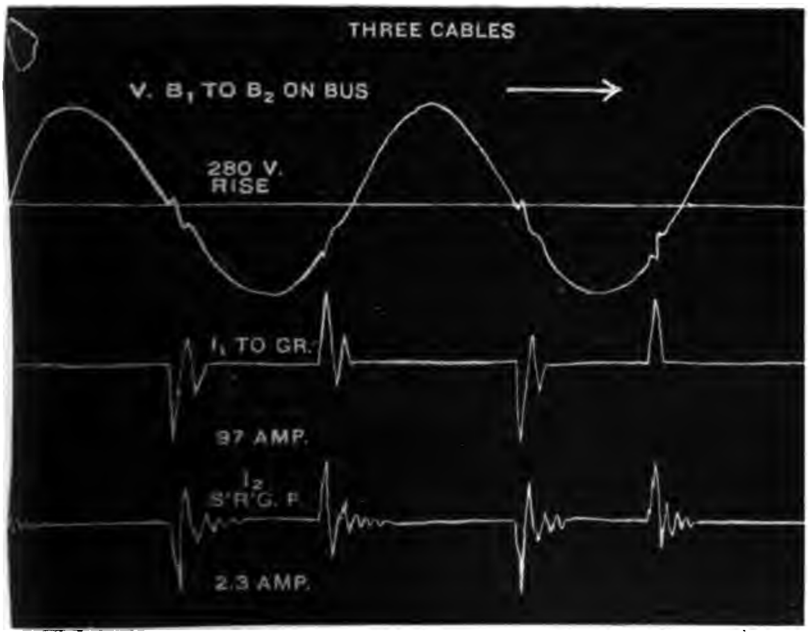

Fig. 17

Making calculations of the natural frequency from the middle record—the current to ground—the following values are obtained.

From	the	first half-cycle	725 cycles per sec.
“	“	second “	1000 “ “ “
“	“	third and last “	690 “ “ “
“	“	first complete cycle	875 “ “ “

The last value is the one used in previous measurements and the one which seems correct to use for comparisons. When not grounded the system oscillates with a frequency about twice as great; viz., 1740 cycles per second.

In Fig. 19, oscillogram 526, six cables are in circuit. The records are, respectively: voltage across the regulator coil of the grounded phase B_2; current to ground; and current in the surge protector to ground. The maximum voltage rise is 615 volts; the corresponding maximum current to ground is 175 amperes; and the corresponding maximum current in the surge protector is 2.4 amperes. This ocillogram is comparable especially to others with a lesser number of cables in circuit. The addition of this cable—No. 120— brings down the measured frequency comparatively little; viz., 875 to 855.

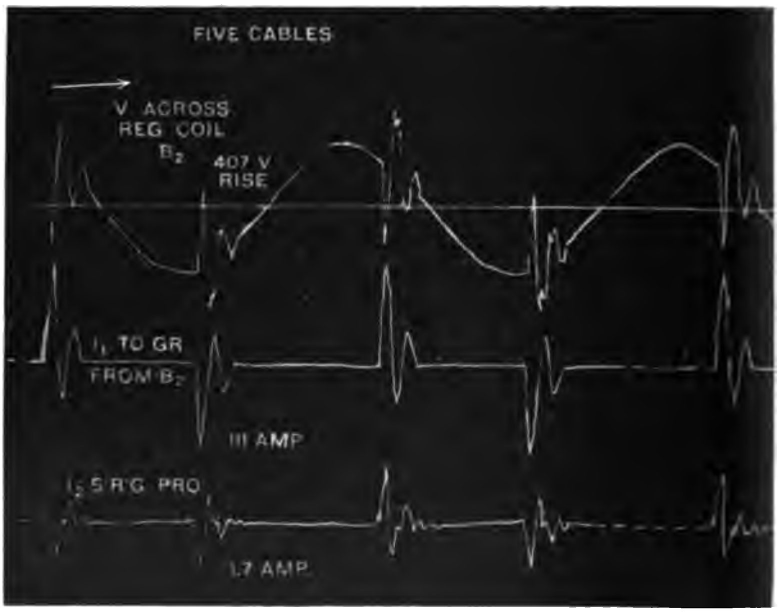

Fig. 18

In Fig. 20, oscillogram 530, seven cables are in circuit. The records are respectively: voltage across the regulator coil of the grounded phase B_2; current to ground; current in the surge protector to ground. The maximum voltage rise is 484 volts; the corresponding maximum current is 135 amperes; and the corresponding current in the surge protector to ground is 1.4

amperes. These maximum values were affected by the arc length, which was not always the same.

Again making detailed calculations of the frequencies represented by the discharge current to ground, the following values are obtained:

From the first half-cycle	645 cycles per sec.
" " second "	990 " " "
" " third and last "	590 " " "
" " first complete cycle	844 " " "

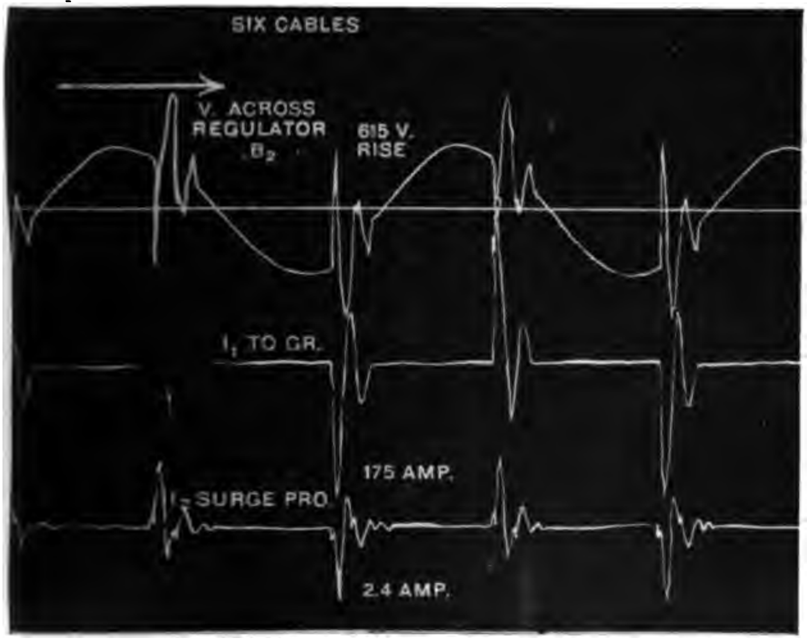

FIG. 19

The last value corresponds to the one used in the previous measurements.

In Fig. 21, oscillogram 576, four cables are in circuit. The next two oscillograms shown were taken one week later. Instead of cable 109, cable 126 was grounded. The records are, respectively: voltage across the regulator coil of the grounded phase B_1; current to ground; and current in the surge protector to ground. The maximum voltage rise is 520 volts; the corresponding current to ground is 92 amperes; and the corresponding current in the surge protector is 1.4 amperes. The estimated frequency is less than 1290 cycles per second—taken from a cycle of the current in the surge protector.

In Fig. 22, oscillogram 582, twelve cables are in circuit. The records are, respectively, voltage across the regulator coil of the grounded phase B_1 of cable 126; and current to ground. In this oscillogram a new shunt on the vibrator in the surge protector circuit gave a deflection too small to reproduce. The maximum voltage was over 1080 volts across the regulator, which carries normally 250 volts effective. The current to ground was 336 amperes maximum.

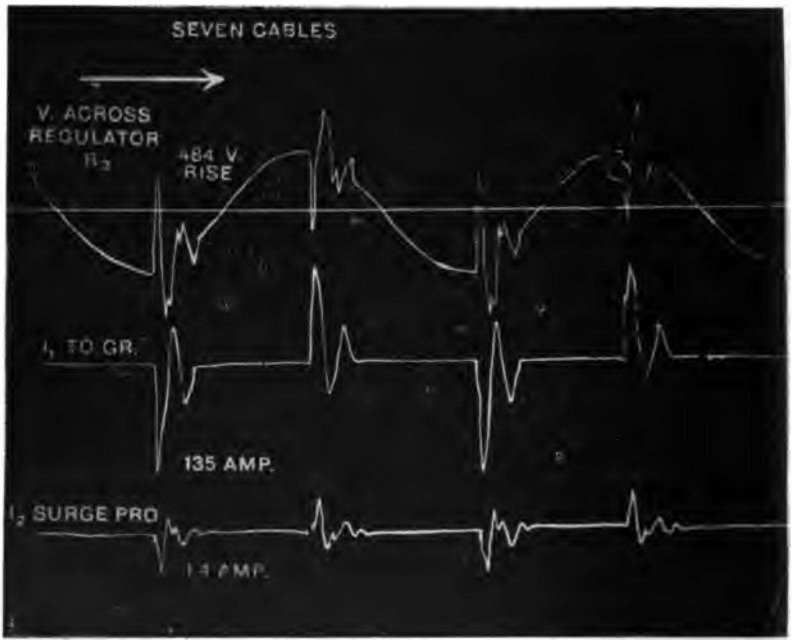

Fig. 20

Again making detailed calculations of the frequencies represented by the discharge current to ground we have:

From the first half-cycle	545 cycles per sec.
" " second "	870 " " "
" " third "	500 " " "
" " first complete cycle	670 " " "

The two oscillograms, shown in Figs. 23 and 24, were taken on a single generator on another system, that of the Brooklyn Edison Company, and are reproduced through their courtesy.

This generator wave shows very strongly the superposition of higher harmonics. Fig. 24 shows the current and potential of the same generator as in Fig. 23 when the generator is attached to the cable system. The capacity so magnifies the harmonics that they predominate over the fundamental. The principal harmonic is the thirteenth, corresponding to N ± 1 teeth; *i.e.*, twelve teeth per pair of poles.

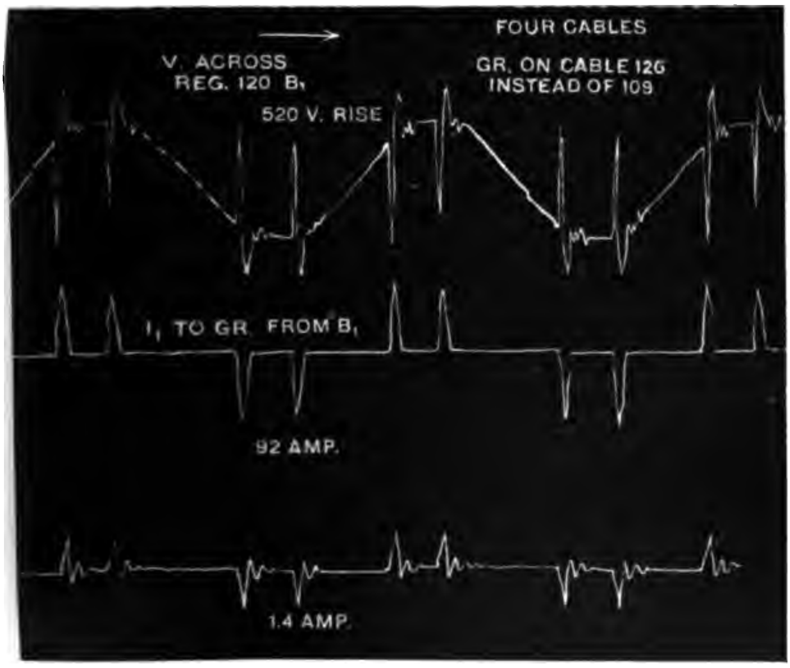

Fig. 21

The oscillogram in Fig. 24 is reproduced to illustrate what resonant conditions might develop. If this generator produced 60 cycles the frequency of the thirteenth harmonic would be 780 cycles per second, and would resonate when placed on a system with conditions equivalent to those of the United Electric Light & Power Co. with eight cables in circuit. This is a graphical illustration of the dangers that may attend the variation or extensions of any electrical transmission system.

Notes. Not all long arcs are necessarily the same length. An endeavor was made to maintain a constant length, but due to inequalities in the crater rims some variations occurred; therefore, there will be corresponding variations in the current and potential values independent of the other controlling factors, such, for example, as the number of cables in circuit.

In brief, the tabulations tend to show the following:

1. A gradual decrease in the natural frequency of the circuit as the number of cables in circuit is increased—see the following tabulation and Fig. 26.

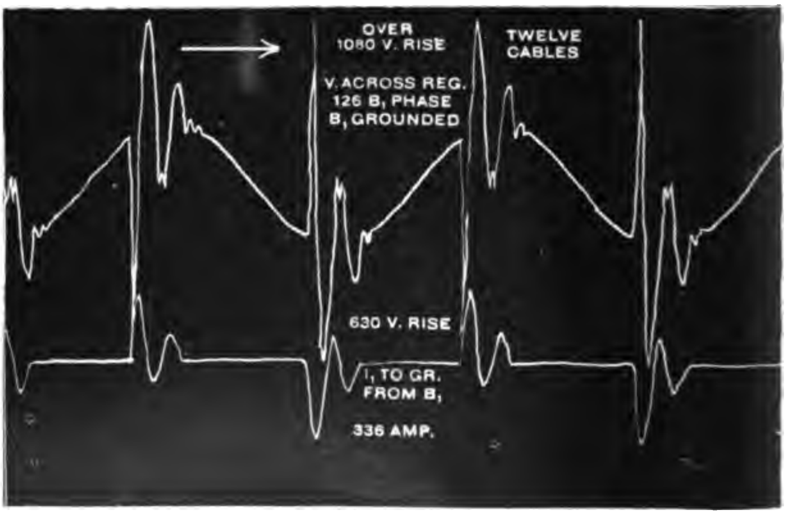

Fig. 22

2. An upper limit of three half-cycles of current from the grounded phase to ground, which was limited probably by the length of arc combined with the value of current and the value of natural frequency relative to the generator frequency. There are fewer numbers of half-cycles than three for shorter arcs.

3. A general increase in the current through the arc to ground with an increase in the number of cables.

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* The authors are indebted to Mr. R. H. Marvin for manipulating the oscillograph.

TABULATION OF GENERAL OSCILLOGRAPHIC DATA
THE GROUPINGS BY HORIZONTAL LINES CORRESPOND TO DIFFERENT DATES
(FOR MORE COMPLETE INFORMATION OF THE CIRCUIT CONNECTIONS THE PREVIOUS DETAILED NOTES SHOULD BE CONSULTED)

Fig. No.	Oscillogram No.	No. of feeders	Frequency to ground	Half cycles to ground	Current to ground	Current in surge protector	Maximum voltage rise	Relative arc length	Discharges per cycle	
4	504	1	1800	3	68	5.4	384	Long	1	Voltage across regulator coil (B_3) grounded phase (*A*)
5	505	1	1800	3	68	5.4	247	"	1	" " " " Non-grounded " (*B*)
6	506	1	....	1–2–3	58	3.1	148	Medium	4	" " " " " "
7	507	2	1225	1–2	68	2.45	70	"	4	" " " " " " "
8	508	2	1225	1–2–3	97	4.5	520	"	4 2	" " " " Grounded " (*A*)
9	509	2	....	1	19	0.5	84	Short	12	" " " " " " "
10	510	3	1120	3	116	2.4	630	Long	2	" " " " " " "
11	511	4	920	3	170	4.1	820	"	2	" " " " " " "
12	514	4	....	3	194	5.4	72	"	2	Another regulator and cells. (*C*)
13	516	4	....	1–2	106	(57.)	410	"	2	(*C*) and *I* by-pass. (*D*)
14	517	3	....	3	103	2.7	Drop	"	2	Voltage between B_2 and ground when B_2 is grounded (*E*)
15	518	3	1020	3	116	2.4	(3465)	"	2	" " B_1 " " " " " " (*F*)
16	519	3	....	3	109	3.0	850	"	2	" " phases (B_1 and B_2) (*G*)
17	521	3	....	3	97	2.3	280	"	2	" " " " " " on bus. (*H*)
18	524	5	875	3	111	1.7	407	"	2	" across regulator coil of grounded phase (B_2) (*A*)
19	526	6	855	3	175	2.4	615	"	2	" " " " " " " " "
20	530	7	844	3	135	1.4	484	"	2	" " " " " " " " "
21	576	4	....	1	92	1.4	520	Medium	4	(*A*) on other cable (*A′*)
22	582	12	670	3	336	....	1100	Long	2	" " " " "
23 24	554 556	Not directly comparable, see oscillograms.								

4. An increase in the current to ground with an increase of spark voltage to ground, which is controlled mostly by the gap length.

5. A variable duty required of the surge protector, which duty apparently depends on the suddenness of the discharge. In general, the duty between line and ground is lessened by addition of cables, but there are some notable exceptions.*

6. A by-pass cell on a potential regulator is called upon to give a high discharge in order to protect the regulator.

7. The maximum surge voltage across the grounded phase of a regulator coil is directly proportional to the maximum surge current to ground. (Although the ratio on different dates is not identical, each makes a straight line; see Fig. 25).

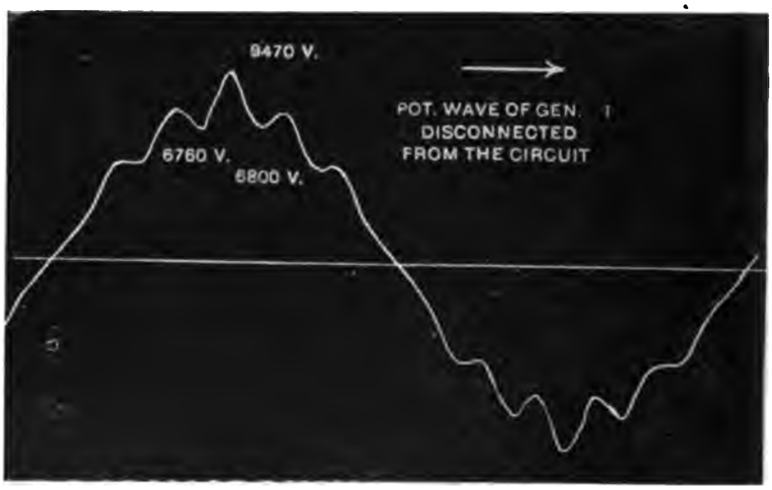

FIG. 23

8. The number of half-cycles of potential across a regulator coil is always one more than the number of half-cycles of discharge current through the arc to ground. This is explained by the fundamental law that the induced potential always opposes a change in the current. Therefore, as the surge current increases in the regulator coil, the potential is in the negative

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* Only surges to ground through the surge protector were measured. The surges from line to line during a disturbance are more severe since they will blow a 10-ampere fuse.

direction, but becomes positive as soon as the current begins to diminish.

9. The gap length determines the voltage, and therefore the current, of the static charge to the cable. The shorter the gap length, the greater the number of discharges for each alternation of the generator wave.

Relations between the frequency and number of cables. The frequency involves two factors; namely, the capacity and inductance. The capacity varies directly with the cable length, but the inductance depends upon four factors; namely, 1, the length of three-conductor cable; 2, the length of single-conductor cable; 3, the inductance in the regulator; and 4, the inductance in the transformers. In view of the difficulty of separating these factors in the several cables, the assumption is made in the curve shown in Fig. 26, that both capacity and inductance are proportional to the length of cable.

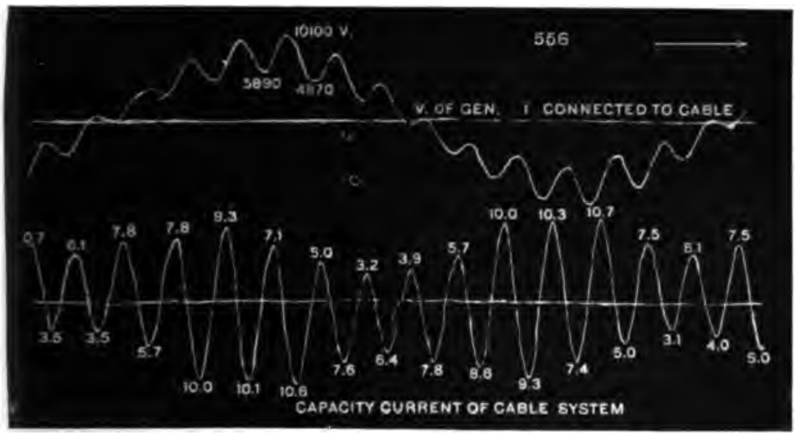


FIG. 24

Artificial harmonics. Impulses may be given to the circuit by the variation from a simple sine curve in the main wave—the harmonics—; or, secondly the circuit may get impulses either by electrostatic induction or electro-magnetic induction from an external source. Thirdly, from either of the above sources impulses may be given to the circuit by unbalancing the system relative to the normal neutral. Such an impulse comes from the accidental grounding of one phase through an arc. The arc forms every time the voltage across the gap reaches the spark value and is extinguished as soon as the current dies down. The frequency of the repetition of these impulses will depend greatly upon the length of gap, the conditions of capacity and damping, and the rate of change of potential. As already pointed out in the discussion of Fig. 9 the danger of these short arc frequent impulses or *artificial harmonics* lies in the possibility of their frequency coinciding with the natural frequency of some part of the circuit.

Guide to Further Comparison of Oscillograms.

To compare the effect of lengths of arc to ground use the oscillograms shown in Figs. 5 and 6, with one cable in circuit, or Figs. 8 and 9 with two cables in circuit.

TABLE OF OSCILLOGRAPHIC DATA RELATIVE TO THE NUMBER OF CABLES IN CIRCUIT

No. of oscillogram	No. of cables	Frequency grounded	Current to ground	Current in surge protected	Maximum voltage rise	Feet cable lengths
504	1	1800	68	5.4	384	38,700
508	2	1225	97	4.5	520	76,800
510	3	1020	116	2.4	630	130,400
511	4	920	170	4.1	820	179,400
524	5	875	111	1.7	407	216,200
526	6	855	175	2.4	615	263,600
530	7	844	135	1.4	484	301,300
576	12	670	336	....	1100	715,400

To compare the surges in the two phases of the potential regulator, that is, the grounded and the non-grounded phase, use Figs. 4 and 5, with one cable in circuit; also Figs. 7 and 8, with two cables in circuit.

To compare the voltage between phase and ground of the grounded and non-grounded phases, use Figs. 14 and 15.

To compare the surges between phases on the bus-bar side of the regulator to the corresponding surges on the cable side, use Figs. 16 and 17.

To compare the effect of the number of cables in circuit on the surges in the non-grounded phase of the regulator, use Figs. 6 and 7.

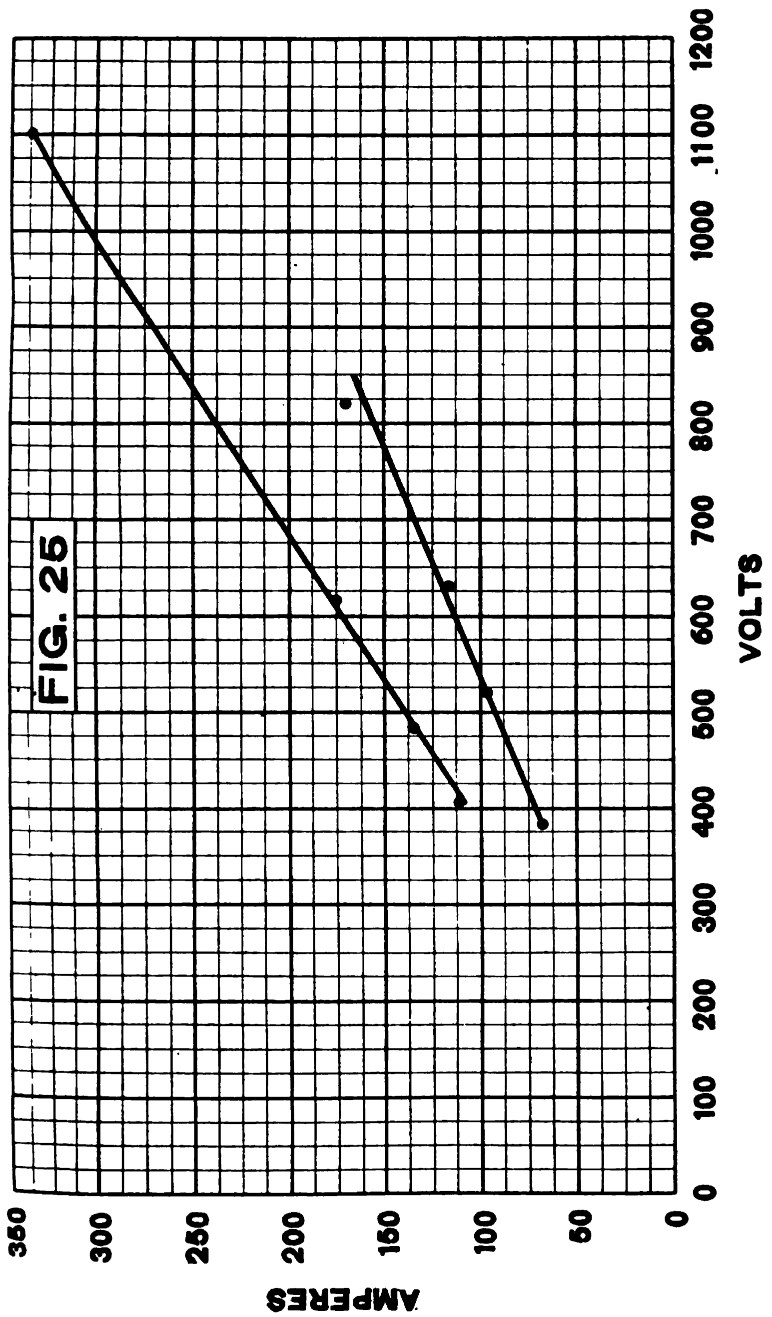


FIG. 25—Relation between the discharge current to ground and the simultaneous potential across a regulator coil

FIG. 26

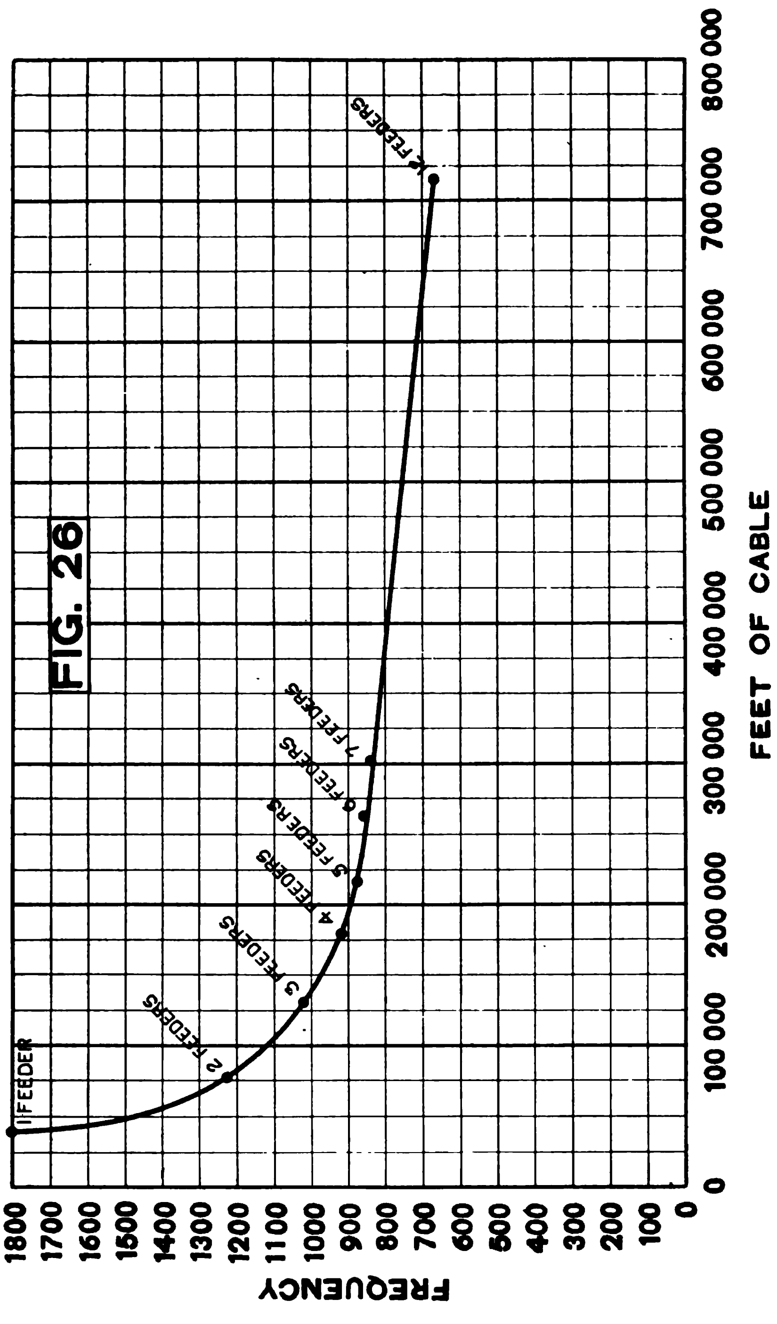


Fig. 26—Relation between the natural frequency and the length of cables in circuit

To compare the surges in the same phase in different regulators use Figs. 11 and 12. There is some question of the exact circuit condition in Fig. 12.

To compare the effect of grounding different cables use Figs. 11 and 13, noting that there is a variable between them in the arc lengths.

Surges during normal operation. In all the foregoing the surges were caused by producing an arc between one phase and the ground. During these tests the surge protector was constantly in circuit. Also needle gaps were placed between phases both inside and outside the regulator. The normal voltage between phases is 3000 and the needle gaps were set on 6250 volts. These needle gaps were installed some time before the surge protector was connected and the tests were started. The needle gaps sparked over twice before the tests but not at all during the tests, in spite of the heavy disturbances.

The sources of these disturbances during normal operations is the subject of further investigations. These surges have been observed on other systems. They seldom reach potentials much greater than twice the normal.

DISCUSSION ON "SURGES ON CABLE SYSTEMS WITH ALUMINUM CELL PROTECTION." FRONTENAC, N. Y., JUNE 29, 1909

J. L. R. Hayden: To investigate how the aluminum cell protects apparatus against high-voltage disturbances, a number of oscillograms were taken, some of which are given in the following.

A standard 5-kw. lighting transformer, shown as *T* in Fig. 1, was connected, with its low-potential coil as primary, to the 60-cycle city supply of Schenectady, and high-voltage impulses were sent into the secondary . These high-voltage oscillations were produced by the discharge of a large mica condenser *C*, Fig. 1, through a series of reactive coils *x* and over a spark-gap *S*. An air-blast across the spark-gap *S* gave abruptness to the discharge. The reactances *x* were chosen so large as to bring the frequency of the discharge—about 1000 cycles—well within the range of the oscillograph.

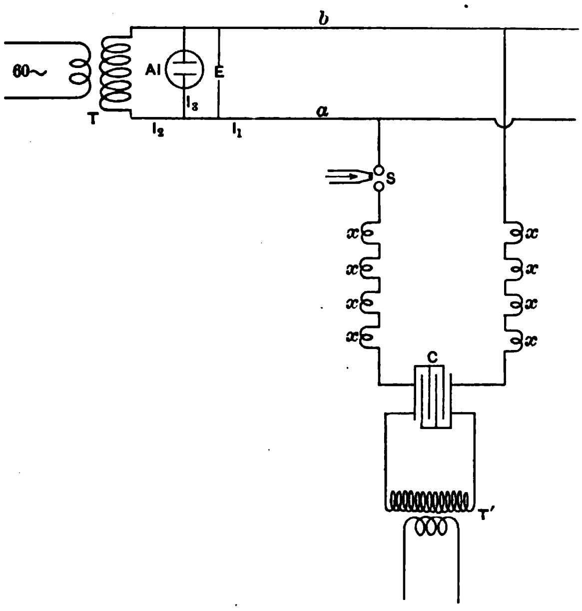


FIG. 1

The condenser C was charged by a 30,000-volt transformer *T'*.

As often as the voltage at the condenser *C* rises sufficiently high to break over the spark-gap *S*, it sends an oscillatory discharge or high-voltage impulse into the line *a b* and the transformer *T*, and the arrangement thus represents the condition of a step-up transformer continuously receiving high-voltage impulses from a transmission line (as by an arcing ground on the line).

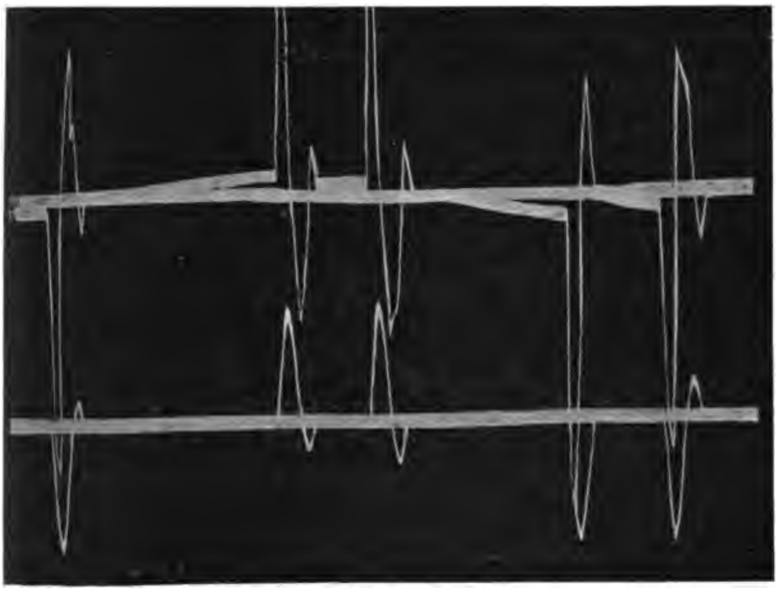


FIG. 2

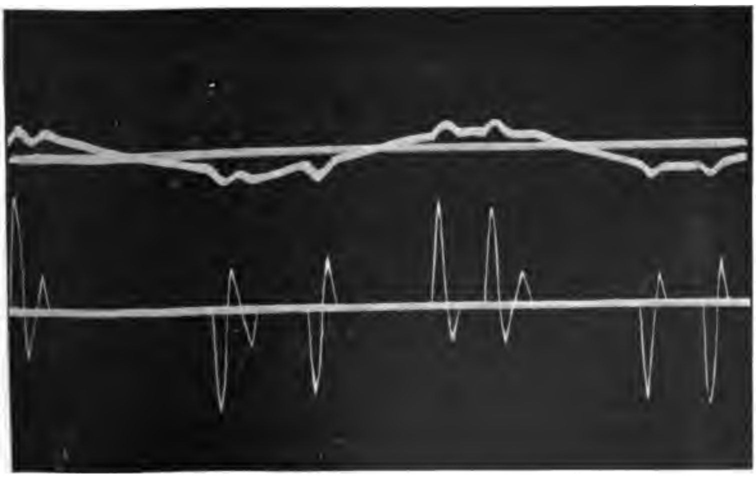


FIG. 3

The oscillogram in Fig. 2 shows the voltage *E* at the transformer terminals, and the current *I* in the line and the transformer, without aluminum cell protection.

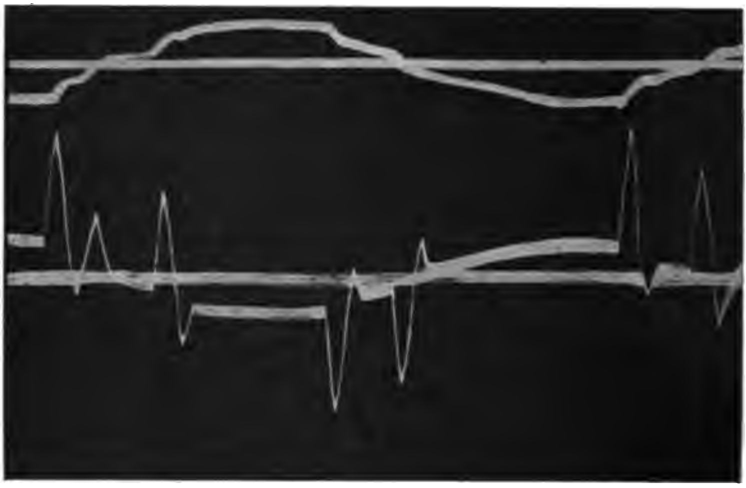


FIG. 4

The low sine-wave in the upper curve is the normal 60-cycle voltage of the transforner, and the oscillatory impulses carry the voltage up to ten or fifteen times the normal value. Of this excess voltage much is probably concentrated at the end-turns of the transformer. In the lower curve, no 60-cycle sine-wave appears, as the secondary *a b* of the transformer was not loaded. It is interesting to note here and in the following

FIG. 5

voltage oscillograms the appearance of higher harmonics in the wave-shape of the oscillations.

An aluminum cell was connected across the transformer terminals, at *a b* in Fig. 1. The oscillograms of voltage E and current I, under these conditions are given in Fig. 3.

The current impulse coming from the line *a b* appears unchanged, but the high voltage peaks of Fig. 2 have entirely disappeared, and only slight rounded kinks show where they would have occurred without the aluminum cell.

To see what becomes of the oscillating current I, oscillograms were taken of the current I_2 in the transformer and the current I_3 in the aluminum cell. These are shown in Fig. 4.

The entire current impulse passes through the aluminum cell, the lower curve in Fig. 4, while the transformer current shows only a very slight kink at these points, less even than the voltage curve in Fig. 3.

FIG. 6

Figs. 5 and 6 show oscillograms of the voltage E at the transformer, with and without the aluminum cell, the latter being shown on a larger scale. As will be seen, the enormous sharp voltage peaks entirely disappear owing to the presence of the aluminum cell. The latter thus protects the transformer without causing any disturbance in the system.

H. W. Fisher: Mr. Sprong has told me that he started these experiments with some misgiving. If he had obtained voltages approximating ten or fifteen times the normal voltage, as I believe Dr. Steinmetz predicted on some of the experiments on the Manhattan Railway cables, great damage might have been done to the system. We probably do not realize the risk taken in putting these surges and oscillations on the lines, and for a paper of this kind, giving the results of tests made for the purpose of observation to improve our systems and methods of operation, I think the Institute is especially indebted to the person and company who took that risk.

John B. Taylor: I think there is little question at to the effectiveness of the aluminum-cell arrester. It seems to be the closest we have come in electrical circuits to approximating the safety valve on the steam boiler. Doubtless while many improvements will be made in its form and the materials of which it is made, the idea seems to be distinctly the proper one for protecting electrical circuits from abnormal rises of potential.

I do not understand the basis on which is figured such a marked reduction in natural frequency of system, as the length of cable in circuit is increased, because I do not see readily what combination of cable and apparatus is taken to be oscillating. The natural frequency, of course, is determined by a combination of inductance and capacity, and it seems to me that the inductance would be more or less fixed by generators and transformers, while the capacity would increase as the number of miles of cable increased. This would tend to leave the inductance a constant figure with variable capacity, which would tend to increase the frequency rather than lower it as more cables are connected in.

Are not these men magnifying the dangers of operating an alternating-current system? Is an oscillogram of charging current with prominent thirteenth harmonic any evidence of narrow escape from a dangerous condition? The finest sine-wave found on any generator will pass to a condenser a current which is far from a sine-wave. If the thirteenth harmonic were a constant-potential affair; if the generators were constructed to give the thirteenth harmonic, and maintain it at constant potential irrespective of current drawn at that frequency, the matter might be serious, although resistance will always damp, and variable inductance of apparatus containing iron will always prevent, perfect resonance.

I have said before in discussing papers, that harmonics in alternating-current systems are interesting, but very seldom are they found to be the bugbear that some of us are inclined to think they are.

Ralph D. Mershon: Am I to understand that Fig. 23 is intended to show a voltage wave of the generator on open circuit? I am surprised to see such a ragged wave. I did not know that any modern generators had such a marked effect from the teeth.

E. E. F. Creighton: It is not a modern generator.

Ralph D. Mershon: That explains it. I should greatly appreciate it, and doubtless other members present would also, if one of the authors would give us some data relating to the latest form of the electrolytic condenser for this or other uses. How durable it is when continuously subjected to voltage? How durable it is if it is intermittently subjected to voltage of any sort? What are the details of construction so far as they are willing or able to give them, both from a mechanical and a chemical standpoint?

Charles P. Steinmetz: I believe I can answer Mr. Taylor's question, as to why the frequency decreases with increase of number of cables. The oscillating circuit is shown in Fig, 3, and consists of a system of from one to twelve feeders, each feeder with its potential regulator, and all connected in multiple through a single potential regulator to the ground; that is, the grounding arc, over which the oscillating current passes, contains in series first a single potential regulator, and then all the cables with their regulators. All these cables which their regulators in multiple would keep the same frequency, no matter how many cables, because the ratio of inductance and capacity remains the same, but as they are all in series with a constant inductance, the frequency increases with the decrease of number of cables, and the resultant frequency can be calculated from the number of cables, and the inductance and capacity, and checks well.

E. E. F. Creighton: Dr. Steinmetz has already answered the question relating to the variation in natural frequency. I might simply add that we gave no calculations at all on that subject. The results are all measurements. The matter which Mr. Taylor brings up, regarding the thirteenth harmonic disappearing, is worthy of still further comment. In Fig. 23 the oscillogram is shown first on open circuit, but the fact that a load is placed on that machine does not destroy the harmonic. There is always a possibility of getting the harmonic any time under the proper conditions, even though there be a great deal of power taken from the generator at the same time. The thirteenth harmonic may be brought out by the proper capacity and inductance relation, or by the proper length of arc connecting it to ground.

There have been a number of tests made of the effect of the length of arc on the frequency, and one laboratory experiment brought it out very clearly, without the aid of oscillograms. By placing an electrolytic condenser in series with the primary of the transformer, the amount of energy and voltage could be limited, Then, putting on the secondary side—the high-potential side—a spark-gap that could be varied, it was possible to open the spark-gap and get different musical notes at different lengths of arc, showing that the frequency—the artificial harmonic—actually does change with the length of gap.

In regard to the construction of the different aluminum protectors, there are three types at the present time, one that has been in use for some time, known as the gap-aluminum arrester consisting of nested plates. In that case there is always a gap in series, set at a voltage slightly above the line voltage, the minimum being, say, about 25 per cent above the line voltage. The length of time that any one of these arresters will operate depends entirely on the construction. The normal construction gives an operation of about 30 min. without any damage to the arrester. The lower voltage arresters, having a greater radiating surface, will operate for a long time without overheating.

A test was made on a 100,000-volt arrester, that being the maximum voltage in use, and the discharge was allowed to play for 40 minutes. The temperature rise at the top of the coil was about 18 deg. That type of arrester has been thoroughly tried out at the present time, and aside from slight changes, which will not affect the arrester in general, it is presumed at the present time that it is in a finished condition.

The second type of aluminum arrester is that used on direct current; that is, used without any series-gap. Where direct currents are employed the loss of energy in the film is very slight, and consequently it becomes a very easy matter to connect the cells directly to the circuit without a series-gap. In that case a single cell, operating on a potential of 300 volts, will have a loss of energy, internally, of very much less than one watt, the exact amount being 300 times 0.001, or about 0.3 watt for normal operation.

The other type of protector is illustrated in the paper, and consists of a number of cells connected in series and directly connected to the line, using alternating current. That corresponds to the direct-current arrester just described. In this case it is necessary to give a great deal more area of radiation in order to get rid of the extra amount of heat which is caused by the alternating current, the latter destroying and reforming the film every half cycle, and in that way giving a considerably greater loss of voltage as compared with the direct-current cell. It is also necessary in that case to place across each one of the cells a potential regulator, which is nothing more or less than an auto-transformer. The discharge rate of these cells at double voltage, is somewhere between 200 and 400 amperes, and can be measured by an ordinary ammeter, the cells being able to carry the current during that period. The discharge current at normal voltage is a fraction, say about 0.2 of an ampere.

Ralph D. Mershon: What is the voltage to which each cell is continuously subjected ?

E. E. F. Creighton: 220 volts in the latter case.

Ralph D. Mershon: What would be the magnitude of the loss in a case like that?

E. E. F. Creighton: It would be a few watts per cell.

Ralph D. Mershon: Are the cells quite small?

E. E. F. Creighton: Yes; fairly small, about a quart size.

Ralph D. Mershon: What area of plate would that correspond to?

E. E. F. Creighton: That varies in the different cases where we made our tests. We have used large plates and small plates, and it all depends upon the general design. By giving more cooling area a larger plate may be used. Of course the idea is to use as small a plate as one consistently can and have the protection.

Ralph D. Mershon: Is there not some relation between the size of the plate and the amount of discharge the arrester will take care of?

E. E. F. Creighton: Yes; there is a direct proportion. For instance, the larger the plate area the more discharge is obtained at double potential, which really gives the capacity of the surge protector expressed in kilowatts, in the same way as with a transformer. The service the surge protector will be called upon to give is one of the objects we had in making these tests.

Ralph D. Mershon: What happens when the surge protector is too small?

E. E. F. Creighton: It takes energy from the surge proportional to the abnormal voltage and it must necessarily lower every surge that comes on the system.

Ralph D. Mershon: If your plate is not large enough, what results—does it blow the electrolyte out?

E. E. F. Creighton: We have not found anything of the kind so far. The cells will stand a great abnormal voltage, just how much cannot be stated simply—we have had three or four or five times normal voltage for a brief time on them without causing any trouble. It has to be brief in that case, because the size is small, and the current that flows, due to the abnormal voltage, is power current, and therefore an energy loss.

Ralph D. Mershon: I should think that if a heavy discharge took place there would be enough steam formed to make trouble.

E. E. F. Creighton: The one case given here, where a cell was placed across a regulator and the regulator then grounded, gave a very large rush of current through the cell. The cells were exceedingly luminescent, and it was apparently a case of severe arc over the entire area of the plate, and still no change resulted from it. Of course, in that case the voltage was somewhat limited. Furthermore it was quite possible that the frequency was very high, somewhere in the neighborhood of 20,000 cycles, being the natural frequency of the cable without the regulator in series.

Ralph D. Mershon: Is this regulator across each set of cells a transformer with the taps brought out?

E. E. F. Creighton: It is an auto-transformer.

Ralph D. Mershon: Will not the cells divide the voltage properly?

E. E. F. Creighton: They divide the voltage fairly well, but better results are obtained by using the transformer.

Ralph D. Mershon: Why will not they divide the voltages; because the capacities are not the same?

E. E. F. Creighton: Because slight differences between the cells, and little impurities in the plate cause a difference in the capacity current, or energy current, and consequently a variation in voltage resulting from it.

Ralph D. Mershon: Things other than the density of the electrolyte, size of plate itself, etc.?

E. E. F. Creighton: Yes; each has an effect entirely aside from them.

Ralph D. Mershon: Will you explain the matter of destruction and re-formation of the film?

E. E. F. Creighton: The film seems to consist of two parts: there is a skeleton part that requires a long time in forming and seems to be very little affected. Then, apparently, inside of that skeleton, is formed a gas or a liquid of some kind that can be dissolved out. This is dissolved out in every case of every electrolyte that we know of at the present time.

Ralph D. Mershon: That is, if you let the cells stand?

E. E. F. Creighton: Yes, if the cells stand without any current. That same dissolution takes place if the current is reversed, or something similar to that dissolution takes place. That is what causes a loss of energy, we presume, in a cell when the alternating current passes through it; whereas the loss of energy is only a fraction of a watt on direct current, it is several watts on alternating current.

Ralph D. Mershon: On the alternating current, though, is there enough change to alter the color of the film?

E. E. F. Creighton: Yes; this skeleton, when the cells are first formed, has an iridescent color on the outside of the plates. After the cells have operated for a long time, the skeleton becomes thicker, although the film, apparently, does not change; that is, the film thickness is of about the same capacity as before. As it ages it becomes frosty in appearance.

Ralph D. Mershon: What means do you have for cooling?

E. E. F. Creighton: That is obtained by immersion in oil.

Ralph D. Mershon: By the immersion of the cell itself?

E. E. F. Creighton: By the immersion of the cell itself, in the case of the gap aluminum arresters, where a stack of cones is immersed in a tank of oil. In the case of the surge protector, which is the aluminum arrester without the gap, each separate cell is immersed in a horizontal tank or trough of oil.

Ralph D. Mershon: Can you get enough convection in the oil to keep it cool?

E. E. F. Creighton: Yes.

Ralph D. Mershon: In the case of the arrester with a gap in series, is the gap closed at intervals to keep the arrester in operative condition?

E. E. F. Creighton: The normal method is to have a switching arrangement. The gap itself is a switch which can be closed, but it seems that once a day is the best time to do it. It may stand for a long time, especially in cold weather, but charging it every day keeps down that first initial rush of current which must invariably take place in every aluminum cell. Each day that it stands the dissolution increases, and the initial current rush is greater; so if it stands for some time the initial current rush may easily be as great as 300 amperes. That will vary somewhat with the nature of the electrolyte.

Ralph D. Mershon: How many cycles does it take for the film to get back into proper condition?

E. E. F. Creighton: The oscillograms show that it requires just a few cycles for the film to re-form. It is only a momentary rush, which might be compared to the rush in the transformer when it is first thrown on the circuit, it unbalances magnetic conditions.

Ralph D. Mershon: Is that found in the case of a perfectly new cell, or in the case of a cell which has been formed once?

E. E. F. Creighton: In every case, where it has stood in the electrolyte.

Ralph D. Mershon: Whether it has had current or not?

E. E. F. Creighton: Whether it has had current or not, if it has stood any length of time.

Ralph D. Mershon: If you put the raw plates in the electrolyte?

E. E. F. Creighton: I misunderstood your question. It is usually impossible in that case to form the plates. They must go through a preliminary process before that is possible.

Ralph D. Mershon: As to the forming process, and the electrolyte, is that a secret at the present time?

E. E. F. Creighton: Yes; at the present time; these things are still in the patent department.

Charles P. Steinmetz: I think I can answer the remaining question, as to the destruction and re-formation of the film. The oscillograms taken of the voltage and current of the aluminum cell in good operating condition show that at the reversal of electromotive force a slight re-forming of the film is necessary.

An extensive investigation of the operation of the aluminum cell, under normal and under abnormal conditions, on alternating voltages and oscillating discharges, has been made in my laboratory by my assistant Mr. J. L. R. Hayden, by means of the oscillograph. As the interest shown in the subject by the discussion seems to warrant it, we shall present the results in a paper before the Institute at an early date.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

THE APPLICATION OF STORAGE BATTERIES TO THE REGULATION OF THE ALTERNATING-CURRENT LOAD AT THE PLANT OF THE INDIANA STEEL COMPANY, GARY, INDIANA

BY J. LESTER WOODBRIDGE

Inasmuch as the paper presented by B. R. Shover before the Institute at the meeting in New York on March 12, 1909, gave a general description of the power plant at Gary, including a brief outline of the storage-battery and regulating apparatus, and the paper presented by the writer at the twenty-fifth annual convention of the Institute in 1908, set forth the general theory of the operation of this storage-battery regulating apparatus, it has seemed advisable in this paper, after a brief description of the battery plant and accessories, to dwell more particularly upon a few of the features which have not as yet been fully described, and then to give an account of the actual commercial operation.

The battery proper consists of two series of cells, each series comprising 125 cells. Each cell contains 73 plates measuring 18⅝ in. by 18⅝ in. The capacity of each cell is 4320 amperes at the hour rate, or 8640 amperes at the usual regulating rate. It will be understood of course that this latter rate is more or less arbitrary, and the cells are capable of discharging momentarily at much higher rates under emergency conditions if the service should require. The two series, operating in parallel, are therefore designed to give a momentary output of 17,280 amperes at double the 1-hr. rate at a voltage which may vary from 225 down to 200, depending upon the duration of the discharge, the state of the battery, etc. Discharges as high as 25,000 amperes have already been taken from the battery.

The batteries are installed in a two-story building, one series of cells being located on each floor. Each battery room measures 46 ft. 3.5 in. by 80 ft. 1.5 in. inside. A view of the upper floor is shown in Fig. 1. Ventilation of the battery rooms is provided by forced circulation of air, the air being taken from outside the building and filtered through wet coke to remove all dirt and particles of iron and then forced into the battery rooms under pressure by means of a centrifugal blower.

In order to provide for the automatic transfer of energy in either direction between the battery and the alternating-current circuit, two split-pole converters have been installed, each having a continuous rating of 6800 amperes, direct current, in either direction with a voltage range from 225 to 275 at the direct-current brushes The momentary overload ratings are for 10,000 amperes output as a true converter at 300 volts, or 14,000 amperes input as an inverted converter at 200 volts, the alternating voltage at the collector rings remaining constant throughout these ranges of direct voltage. The converters are six-phase machines arranged for double-delta connection to the secondaries

FIG. 1.—Battery room second floor diagonal view, Indiana Steel Co., Gary, Ind.

of the static transformers. Only one of these converters was included in the original installation, the second having been ordered soon after the first was completed and tested. One of these machines is illustrated in Fig. 2.

The direct-current terminals of these converters are connected directly across the battery without the interposition of any booster, and the variation of direct voltage required to cause the battery to charge and discharge is brought about by varying the distribution of field flux over the pole face. The general theory of the operation of this type of machine was discussed quite fully at the last annual convention of this Institute, and it is therefore unnecessary to take it up at length in this paper.

FIG. 2

The converters for the Gary installation were originally designed to operate as three-part-pole machines, each pole being divided into three sections, each section being provided with separate shunt-field windings. In this type of machine, in order to reduce the direct voltage without changing the alternating voltage, the field strength of the outer sections of each pole is reduced while the field strength of the middle section is increased, this change in the distribution of the field flux producing a variation in the voltage ratio of conversion. While the first Gary converter was being built along these lines, the two-part-pole converter was developed. The results of a number of tests on the latter type of machine indicated certain advantages over the three-part-pole type, and finally led to a change in the original plan. It was decided to operate the Gary converter as a two-part-pole machine, two of the pole sections being combined and excited as one, with constant excitation, this constituting the main pole, the third section being used as an auxiliary or regulating section, its excitation being controlled automatically to produce the desired variation of direct voltage. The second machine, being designed to operate in parallel with the first, was made identical with it throughout. The excitation for the two main-pole sections is obtained from the 250-volt exciter bus-bar while the winding on the auxiliary-pole section receives current from a specially designed synchronous exciter.

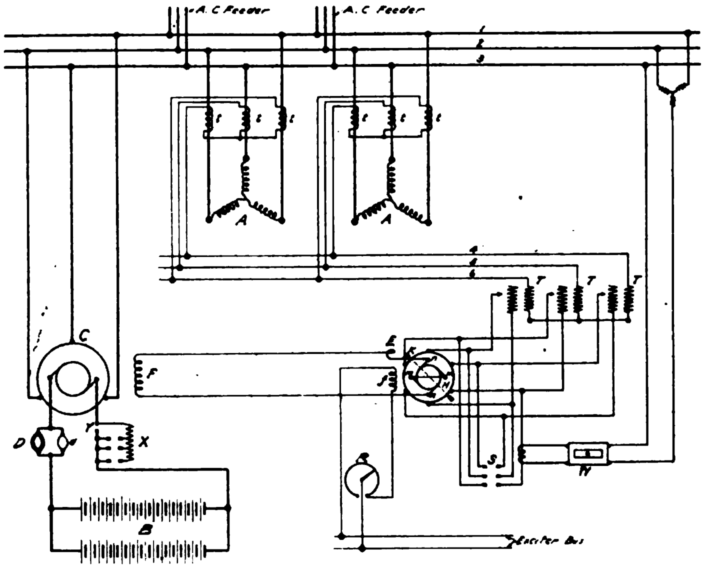


FIG. 3

The theory of this exciter was given in the paper presented by the writer at the 25th annual convention of the Institute in 1908, but it may be well to present a brief review of this theory here. In Fig. 3, which is a simplified diagram of connections of the alternating-current regulating apparatus at Gary, this exciter is shown at *E*. The armature *H* is provided with six collector rings connected to its winding at equidistant points. These collector rings are connected to three current transformers in the alternating-current circuit whose load is to be regulated. The alternating currents thus transmitted through the armature winding will set up a revolving field proportional to these currents. A synchronous motor connected to the alternating-current circuit revolves the armature in a direction opposite to that of the field rotation, thus holding this field stationary in space. The machines are so designed that at unity power-factor this field will take the direction indicated by the arrow *K*. To the armature winding is connected a commutator upon which bear two pairs of brushes. One pair of brushes, *m m* called the auxiliary brushes, is located at points of maximum potential difference due to the field *K*. The other pair of brushes, *n n*, is connected to the regulating field coil *F* of the split-pole converter.

The fields of the exciter are provided with two field windings. One of these is a shunt winding energized from the exciter busbars and controlled by the rheostat *R*. The current in this field winding may be adjusted to neutralize the field *K* set up by the alternating current at some particular load on the alternating-current circuit. Under these conditions there will be no potential across the brushes *m m* and they may be short-circuited, as shown in the diagram. This being done, any change in the alternating-current load above or below the value for which the shunt field of the exciter has been adjusted will produce a difference of potential between the brushes *m m*. A small change in the alternating-current load will be sufficient to cause a very considerable flow of current through the short-circuit connection between these brushes, and this flow of current will set up a second field at right angles to the field *K* and of considerable magnitude. This second field produces a potential across the brushes *n n*, and a corresponding flow of current in the regulating field *F*.

If the alternating-current load has increased, the direction of flow of current in the field coil *F* will be such as to cause the battery to discharge, while if the alternating-current load has decreased, the current in *F* will be in the opposite direction, causing the battery to charge. The second field winding on the exciter is connected in series with the field coil *F* and serves to neutralize the armature reaction due to the current output from the brushes *n n*, and thus makes the machine more sensitive. If the power-factor is not unity the alternating current transmitted from the current transformers through the armature winding may be divided into two components; one of these, the energy component, will produce the field *K*, while the other, being at right angles to this, will pass directly through the short-circuit between the brushes *m m* and have no appreciable effect on the regulation. It will be seen, therefore, that this machine is responsive to the energy component of the alternating current.

In the Gary installation this exciter is an eight-pole machine, the armature being provided with a four-pole winding, and is driven by a four-pole synchronous motor. There are eight brushes bearing upon the commutator, four of these being the auxiliary brushes, which are short-circuited, while the other four are connected in pairs and constitute the main terminals of the machine. This exciter set is shown in Fig. 4.

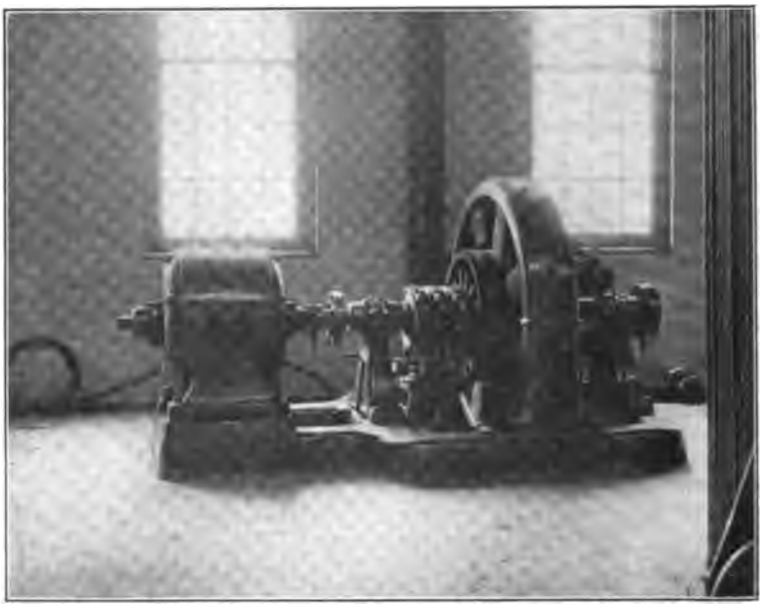


FIG. 4.—Converter auxiliary field exciter, Indiana Steel Co., Gary, Ind.

For supplying alternating current to the exciter, a current transformer is connected into each phase of each of the main generators. These current transformers are connected to a set of common totalizing bus-bars, which in turn are connected to the primaries of three totalizing current transformers. The secondary windings of the latter are connected to the collector rings of the exciter. This arrangement was made necessary owing to the fact that there is no point in the main alternating-current bus-bars of the station through which the entire output of the plant passes, the outgoing alternating-current feeders being connected at various intermediate points between the points of connection of the main generators so that there is no point in the bus-bars where a single set of current transformers could be connected for regulating the total load.

Inasmuch as the main bus-bars of the station are installed in duplicate, it was found necessary to duplicate the totalizing bus-bars for the current transformers. The switching arrangements are such that any number of the main generators may be connected to one set of bus-bars, while others may be connected to the other set. The feeders may also be divided between the two sets. The split-pole converter may be connected to either set of bus-bars for regulating. The oil switches which connect the generators and the converters to the bus-bars are installed in duplicate, one set for each set of bus-bars. The oil switches are provided with pallet switches interlocked in such a way that when the converter is connected to one set of main bus-bars the totalizing current transformers are connected to the corresponding totalizing current-transformer bus-bars. When any generator is connected to either set of bus-bars its current transformers are connected to the corresponding totalizing current-transformer bus-bars. The exciter therefore responds to the fluctuations of load on only those generators which are connected to the bus-bars to which the split-pole converter is connected. The totalizing current transformer bus-bars which are not in use for regulating at any time are automatically short-circuited.

One special feature of the regulating apparatus in this installation is the short-circuiting switch across the secondaries of the totalizing current transformers. When this switch is closed all the current transformers are short-circuited through the totalizing current transformers, and at the same time the exciter is short-circuited on the alternating-current side. This reduces the exciter direct voltage to zero and instantly kills the regulation, but owing to the high armature reaction of the exciter only a small flow of current is set up through the short-circuit switch. In fact, at times when the total load on the plant is just equal to the average load which is being maintained on the generators, so that the battery is neither charging nor discharging, the exciter voltage will be zero under normal operating conditions. The short-circuit switch may therefore be closed without producing any effect whatever. Any variation of load from this point will produce a flow of current through the short-circuit switch proportional to the increase or decrease of load, but will not affect the voltage of the exciter. In one of the leads to this short-circuit switch is connected the current coil of a wattmeter, its voltage coil being suitably connected to indicate the energy component of the current passing through the short-circuiting switch. This wattmeter provides a means for adjusting the shunt field of the exciter to any predetermined average load on the generators before opening the short-circuiting switch. In this way the process of putting the regulating apparatus into service is much simplified.

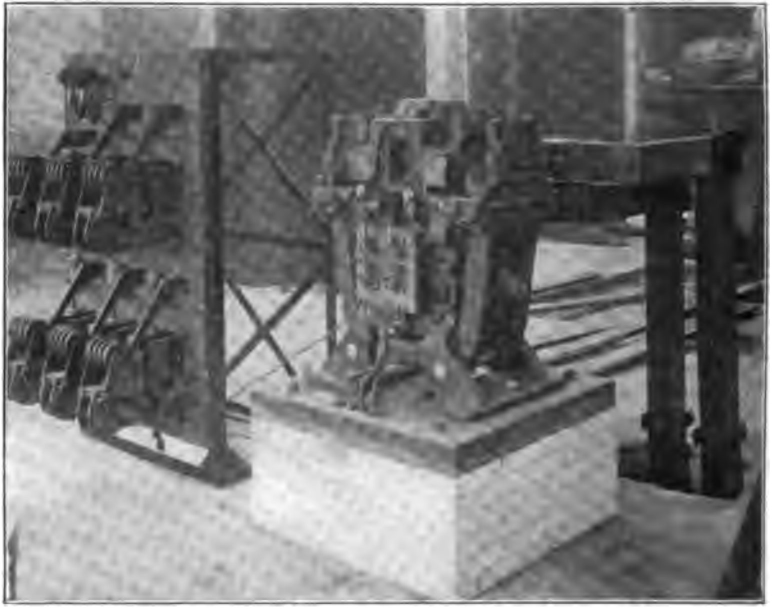


Fig. 5

Fig. 3, as already stated, shows a simplified diagram of connections which will serve to explain more clearly the operation of this regulating apparatus. In order to avoid confusion, most of the switches, circuit-breakers, and duplicate bus-bars have been omitted from this diagram. Two of the main alternators *A A* are shown connected to the main alternating-current bus-bars 1, 2, 3. The static transformers and oil switches which are interposed between the generators and the bus-bars are omitted. Current transformers, *t*, are shown in the generator leads connected to the totalizing bus-bars 4, 5, 6, which in turn lead to the primary windings of the totalizing current transformers *T*. The secondary windings of the latter transformers are connected to the exciter *E*. It will be observed that the ratio of transformation of the totalizing transformers may be varied by cutting in or out coils in their secondary windings.

FIG. 6.—Booster and exciter, Indiana Steel Co., Gary, Ind.

This is shown conventionally on the diagram and is accomplished actually by three dial switches connected to a common shaft and operated by a single hand-wheel on the bench-board.

The short-circuiting switch is shown at *S* and the wattmeter connected to one phase of the short-circuit connection is shown at *W*. The rheostat *R* controls the field *f* of the exciter. The main brushes of the exciter are connected to the regulating field *F* of the converter *C*. This converter is shown connected on the alternating-current side to the main alternating-current bus-bars 1, 2, 3 and on the direct-current side to the battery *B*. The alternating-current connections of this converter are shown three-phase conventionally, the static transformers and oil-switches being omitted. Actually this is a six-phase machine with double-delta connections to the secondary windings of the static transformers. The multiple-contact resistance for starting the converter from the battery is shown at X, the final contact at Y being that illustrated in Fig. 5. The two circuit-breakers, D, and d, are connected in parallel between the battery and the converter, the one of small capacity being used in starting, the other for normal operation.

The method of putting this apparatus into service is comparatively simple. The converter is started by closing its main field circuit and supplying current to its armature from the battery through the automatic starting resistance X and the circuit-breaker d. The machine is then synchronized with the alternating-current bus-bars and the oil-switch is closed. The closing of this switch automatically trips the starting circuit-breaker, d, cutting the converter free from the battery. The direct voltage of the converter is then adjusted by its main field rheostat and the running circuit-breaker D is closed. The

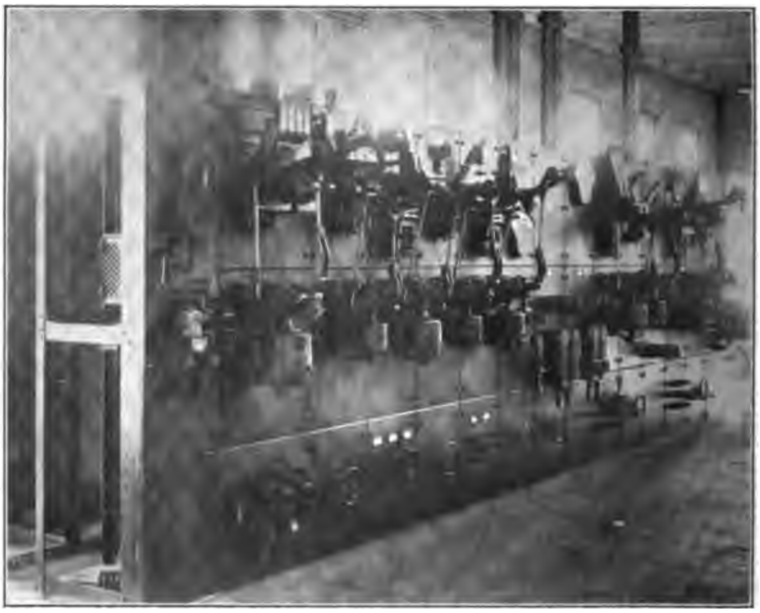


Fig. 7.—Front booster and converter panel (positive side), Indiana Steel Co., Gary, Ind.

battery and converter are then floating on the alternating-current bus-bars. The exciter E is then started up and connected to the field F of the converter, the switch S being closed so that no

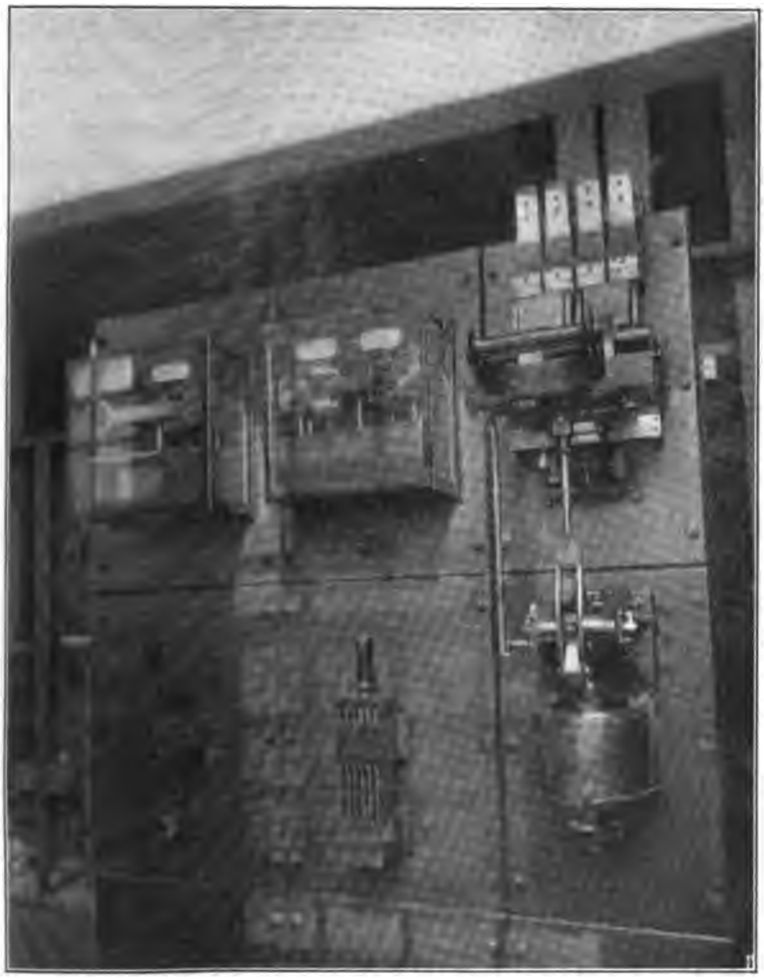


FIG. 8.—Battery switchboard, negative side, Indiana Steel Co., Gary, Ind.

voltage is developed in the exciter. The rheostat R is now adjusted until the wattmeter W reads zero. If there is a fluctuating load on the alternators the wattmeter needle will be swinging on either side of zero, but the adjustment may be made so that when the load on the alternators is at the desired average value, the wattmeter *W* will read zero. When this adjustment is effected the switch *S* may be opened and the regulating apparatus will be in operation.

The battery is also arranged to control fluctuations of load on the direct-current bus-bars, to which it is connected by means of two direct-current boosters which may be operated either singly or in parallel. These boosters are provided with carbon-regulator control in the usual manner, the carbon regulator being actuated by a soft-iron horse-shoe magnet suspended over a portion of the direct-current bus-bar. The operation of these boosters in conjunction with the battery is like any other direct-current regulating plant and need not be further described here. One of the boosters with its exciter is shown in Fig. 6.

FIG. 9.—Bench-board Indiana Steel Co., Gary, Ind.

The main switchboard for this regulating apparatus is located on the ground floor of the power house and is shown in Fig. 7. With the exception of the second panel from the left, which contains switching apparatus for one of the direct-current generators, the apparatus shown on this switchboard is employed for controlling the batteries, split-pole converters, direct-current boosters and exciters. All the operating switches are of the remote-control type and are operated from the bench-board in the gallery overhead.

A single 25,000-ampere, remote-control circuit-breaker is interposed between the negative bus-bar and the two series of batteries. This circuit-breaker, with the two battery wattmeters, is shown in Fig. 8. The wattmeters are of the double-dial type registering the input and the output of each series of cells separately. The bench-board, from which all of the switches and controlling apparatus are operated, is shown in Fig. 9.

The results of operation of the battery and converter and the regulation obtained on the alternating-current circuit are shown in Fig. 10. In this diagram the heavy line represents the total load on the alternators whose load is being regulated, while the light line is the sum of this generator load and the battery output expressed in kilowatts. These curves were plotted from readings taken at 5-sec. intervals. The total alternator load was read on a wattmeter connected into the circuit of the totalizing current transformers and suitably calibrated, while the readings of battery output were taken from the battery ammeter and voltmeter.

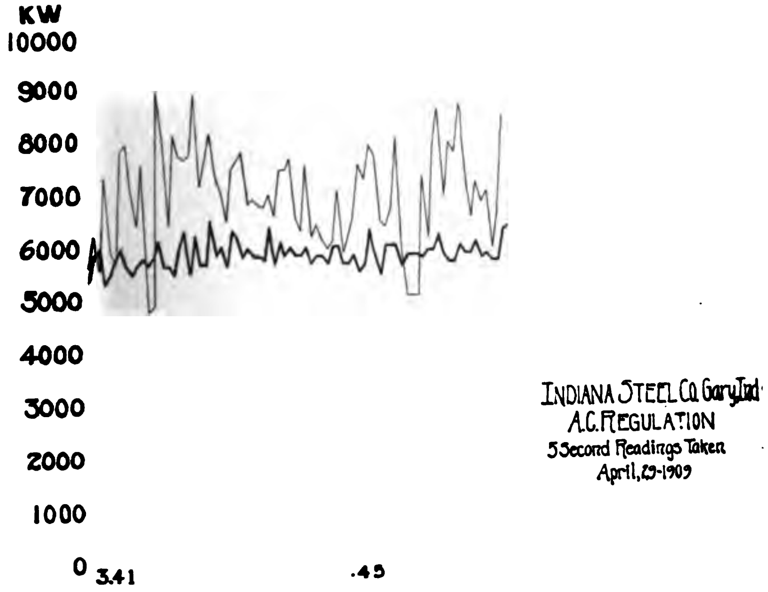


FIG. 10

The effect of the battery regulation on the operation of the entire plant is very marked. In the first place the battery permits the shutting down of one 2000-kw. gas-engine unit, which would be required if the battery were not in service. Even with this additional unit in service, the operation of the plant without the battery involves constant attention by the switchboard attendants and a continual adjustment of generator field rheostats and engine governors. Notwithstanding this constant attention, it is impossible without the battery in service to maintain satisfactory voltage regulation, and the speed of the engines is continually varying over a wide range, whereas with the battery in service the regulation of speed and voltage is all that could be desired.

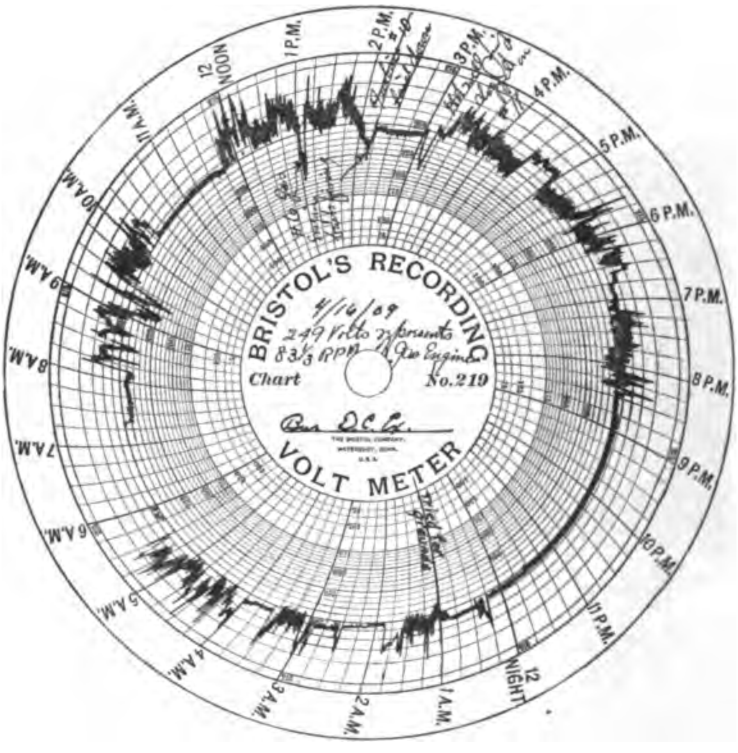


FIG. 11

These effects are clearly shown on the recording voltmeter charts taken from the main exciter bus-bars at the station. Two of these charts are reproduced in Figs. 11 and 12. In explanation of these charts it should be stated that the Gary power house is connected to another gas-engine station in South

Chicago by a three-phase tie-line, so that at times the two power houses are operating in parallel. The chart shown in Fig. 11 was taken with the battery out of service, the tie-line to South Chicago being disconnected. The variations of voltage on the exciter bus-bar as shown on this chart are almost directly proportional to variations of speed of the gas engines, since the exciters are driven by synchronous motors. The chart shown in Fig. 12 was taken with the battery in service. From 7 a.m.

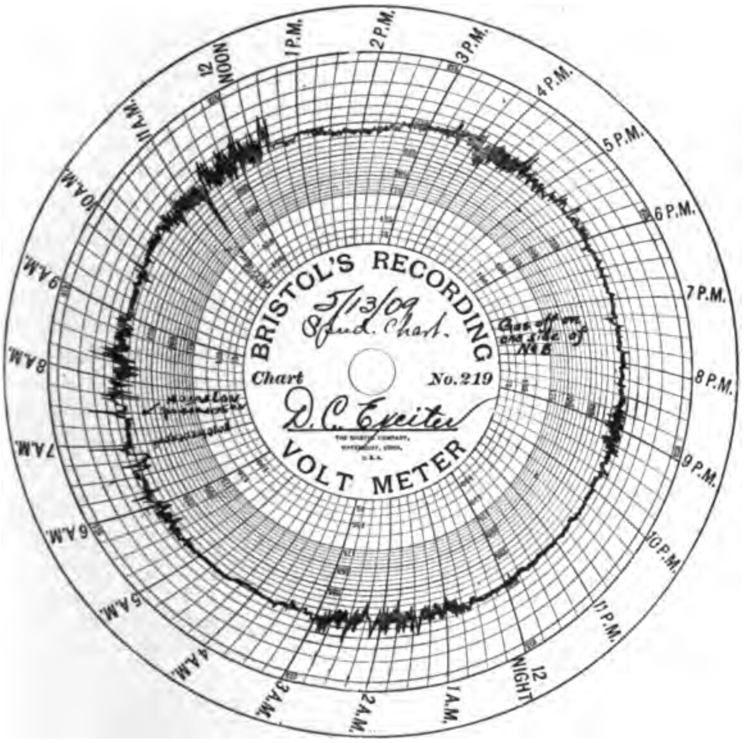


FIG. 12

to 5.35 p.m. the South Chicago tie-line was disconnected, while during the balance of the 24 hours the Gary plant was operating in parallel with South Chicago. The momentary fluctuation of voltage on the exciter bus-bar occurring at 7 a.m. was due to disconnecting the South Chicago feeder , while a similar fluctuation at 7.30 a.m. was caused by shutting down one gas-engine unit and putting another in service. The severe drop in voltage at 11.15 a.m. was due to the opening of the battery overload circuit-breaker. It should be borne in mind that changes of frequency which are not accompanied by changes of load would not be controlled in any way by the battery regulation and their full effects would appear on these charts

One of the most obvious of the practical commercial results of the battery regulation is the increased speed at which the rolling mill may be operated. When the battery is not in service a very appreciable reduction in the daily output is observed, due to irregularity of speed and voltage.

In addition to this regulating effect, the battery is an ever present source of energy to supply power in case of some emergency such as the sudden shutting down of one of the prime movers or any other partial interruption of the power supply. The vital necessity of continuous power supply to a steel rolling mill is well understood, and the effect of the battery in eliminating costly delays in the operation of the mill would undoubtedly warrant the fixed charges against the battery investment, even if these were not largely offset by the saving in investment for additional generating capacity which the battery replaces.

DISCUSSION ON "THE APPLICATION OF STORAGE BATTERIES TO THE REGULATION OF THE ALTERNATING-CURRENT LOAD AT THE PLANT OF THE INDIANA STEEL COMPANY, GARY, INDIANA." FRONTENAC, N. Y., JUNE 29, 1909

Edward Van Wagenen: As described in the paper, the potential across the regulating brushes *n-n* at unity power-factor is caused by the current from the armature through the auxiliary brushes *m-m*, this current reversing as the energy from the series transformer rises above or falls below the value of the opposing field. At other than unity power-factor the armature will be fed with alternating current, causing a displaced field which may be divided into two components; an energy component desired for regulation, and a so-called non-energy component at right angles to it and therefore causing a potential across the regulating brushes *n-n*. This direct action could easily be made small where plants are designed for coarse regulation, but as the strength of the field energy is multiplied by the factor of regulation, I believe this action would be considerable in plants operating on close regulation such as that required where power is taken from a transmission line or close voltage regulation is required on a plant supplying a variable inductive load. With a plant designed for 5 per cent regulation, for example, the strength of the alternating-current field (energy component) must be twenty times that required to give full current through the brushes *m-m*, and at 70 per cent power-factor the energy and non-energy components are approximately equal.

It seems to me that any variation in potential of the source supplying the opposing field would cause variation in the average load, and that the effect of changing the power-factor will be produced when the load on the driving synchronous motor changes, for the reason that the regulation depends on the space-relation between current in the series transformers and the motor armature. This armature displacement takes place whenever there is a flow of current from the brushes *n-n*, as at least part of the energy is derived from the motor and not entirely from the series transformer, as in the case of the converter used in the previous alternating-current plants operating with true energy regulation.

I think that the above outlined factors would cause considerable deviation from the true energy regulation, thus causing fluctuations on the generating equipment.

J. L. Woodbridge: When I undertook to prepare this paper I expected to have an opportunity to make a good many more tests and observations on the plant at Gary than I have been able to make. The delay in the installation of the second converter, which is only just now being put in service, and the necessity of keeping the first one in commercial operation, have prevented the making of tests which I hope to make later, when there is one spare machine on which I can work.

In regard to Mr. Van Wagenen's point, I think he has failed to distinguish between current out of phase and field out of phase in the exciter. If the power-factor is not unity, there will be a component of current transmitted to the armature at right angles to the energy component, but that component will pass directly through the short-circuit across the auxiliary brushes, and not through the armature winding, inasmuch as the former is a path of very low resistance. That component will not produce a field at all, and consequently will not affect the regulation.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

FUNCTION OF FLY-WHEELS IN CONNECTION WITH ELECTRICALLY OPERATED ROLLING MILLS

BY H. C. SPECHT

For all kinds of motor drive and particularly for rolling-mill service, where the load conditions are very unstable, the use of a suitable fly-wheel is of great importance. As is well known, the function of a fly-wheel is to take up the sudden shocks and equalize the unsteady loads as much as practicable in order to produce the cheapest installation and obtain the most satisfactory and economical operation. The smallest size of motor and the minimum capacity of the generating plant are obtained when the action of the fly-wheel is such that the load on the motor is constant and equal to the average of all the loads. To a certain extent this will be impossible in rolling mills, and it will be the problem for the engineer to determine the most suitable size of fly-wheel, motor, and generating plant with the auxiliary equipments.

In reviewing the characteristics of the load curve of a fly-wheel in connection with an induction motor, attention is called to Fig. 1, in which the area $A\ B\ C\ D$ represents a peak load, the ordinates giving the torque in pounds at 1 ft. radius on the shaft of the motor or the mill and the abscissas giving the time of rolling in seconds.

Assume that a constant resistance is inserted in the secondary circuit of the motor and that the motor is carrying all the load until the peak is reached. We will then obtain the torque curve $A\ E$, the section below the line $A\ E$ representing the torque developed by the motor and that above $A\ E$ the torque delivered by the fly-wheel. During this time the speed of the motor has decreased somewhat, thus making it possible for the fly-wheel to deliver part of its stored energy to the driven shaft.

At the end of the peak load, the motor begins to speed up, giving energy back to the fly-wheel, as shown by the torque curve $E F$. The energy indicated by the area $E D F$ must be equal to the energy indicated by the area $A B C E$, the energy delivered by the fly-wheel.

Since the torque of an induction motor with a constant resistance in the secondary circuit varies almost directly as the slip, an equation for the torque curve $A E F$ may be determined as follows:

Let T_1 = the torque at 1 ft. radius developed by the fly-wheel at the start of the peak load.

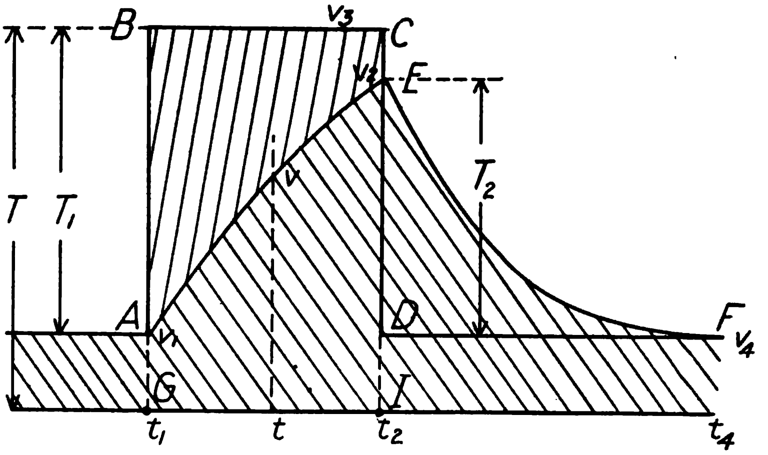


Fig.1. Showing the relation of the torque of Motor and Flywheel.

T_2 = The accelerative torque developed by the motor at the end of the peak load.

v_1 = the velocity of the motor in feet per second at 1 ft. radius at the start of the peak load.

v_2 = The velocity at the end of the peak load.

v_3 = The velocity if the motor were developing all the torque without the assistance of the fly-wheel.

v_0 = The velocity at synchronism or no-load.

v_4 = The velocity at the beginning of the succeeding peak.

v = The velocity at any time.

t = Time in seconds.

W = Fly-wheel effect; that is, the total weight of the rotating parts multiplied by the square of the radius of gyration.

g = Acceleration due to gravity = 32.2

The equation for the torque curve $A\ E$ during the period of retardation is, then,

$$T_1 - \frac{v_1 - v}{v_1 - v_3}\ T_1 + \frac{W}{g} \cdot \frac{d\,v}{d\,t} = 0$$

or,

$$d\,t = -\frac{W\ (v_1 - v_3)}{T_1\,g} \cdot \frac{d\,v}{v - v_3}$$

integrating.

$$t = -\frac{W\ (v_1 - v_3)}{T_1\,g} \cdot \log \text{nat} \left(\frac{v - v_3}{v_1 - v_3}\right) \qquad (1a)$$

or,

$$v = \frac{v_1 - v_3}{e^{\frac{t\,T_1\,g}{W\,(v_1 - v_3)}}} + v_3 \qquad (1b)$$

The equation for the torque curve $E\ F$ of the period of acceleration is

$$\frac{v_4 - v}{v_4 - v_2} \cdot T_2 - \frac{W}{g}\ \frac{d\,v}{d\,t} = 0$$

or,

$$d\,t = \frac{W\ (v_4 - v_2)}{T_2\,g} \cdot \frac{d\,v}{v_4 - v}$$

integrating

$$t = -\frac{W\ (v_4 - v_2)}{T_2\,g} \cdot \log \text{nat} \left(\frac{v_4 - v}{v_4 - v_2}\right) \qquad (2a)$$

or,

$$v = v_4 - \frac{v_4 - v_2}{e^{\frac{t\,T_2\,g}{W\,(v_4 - v_2)}}} \qquad (2b)$$

As examples of the above, Fig. 2 shows several torque curves for different fly-wheel effects and speed-torque characteristics. For simplicity, a continuous cycle of constant peaks of 100,000 lb. has been selected, with half-second periods of duration and half-second intervals.

The fly-wheel effect and the slip for a torque of 100,000 lb. at 1 ft. radius, from which these curves are derived, are as follows:

Curve I—W = 150000, slip at 100000 lb-ft. torque = 10%
" II—W = 300000, slip at 100000 lb-ft. torque = 10%
" III—W = 150000, slip at 100000 lb-ft. torque = 5%
" IV—W = 300000, slip at 100000 lb-ft. torque = 5%
" V—W = 900000, slip at 100000 lb-ft. torque = 10%

It will be noted that curves I and IV are identical; that is, in curve IV, with half the secondary losses or slip and double the fly-wheel effect, the same results are obtained as in curve I with double slip and half the fly-wheel effect. From these curves it can clearly be seen that the greater the fly-wheel effect and the greater the slip for a given torque, the better will be the equalization of loads. When the resistance in the secondary circuit is not kept constant, the foregoing method of determining the torque can be used if the load diagram is divided into sections for which the secondary resistance may be considered constant.

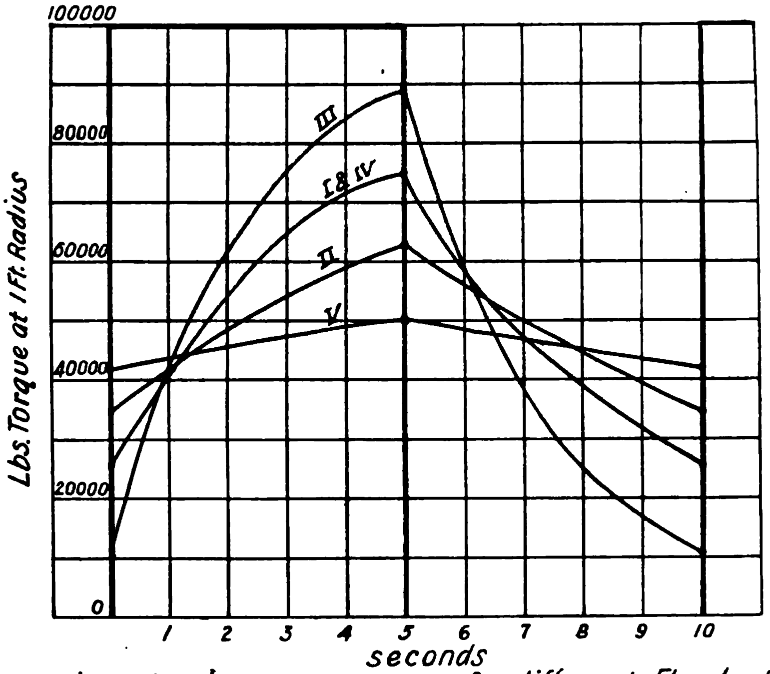


Fig. 2. Showing torque curves for different Flywheel effect and slip

Since the motor must always slow down in speed during the peak loads in order that the fly-wheel may assist it in carrying the load, and since the peaks in all kinds of rolling-mill service vary from pass to pass, it appears that an automatic method of cutting resistance in and out of the secondary circuit of the motor at the proper time would be most desirable. In such a way we could obtain the best equalizing effect and the highest combined efficiency and power-factor.

However, the load conditions in rolling mills are usually such that an automatic control cannot follow the changes of load. For example, in a sheet or a merchant mill where the peaks are quite variable in size as well as in duration and are generally very short, the automatic control cannot be used to advantage. Owing to the time-constant of the automatic controlling devices, the additional resistance may not be inserted at the proper time. This results in the motor at first carrying an excessive load until the resistance in circuit has been increased, when the fly-wheel will assist by delivering part of its stored energy to the shaft. After the peak is over the same sluggishness of the control may prevent the motor from restoring to the fly-wheel all the energy delivered by the latter during the peaks, resulting in a slowing down during succeeding passes. In such a case the automatic control will do more harm than good. Therefore, with such load characteristics the best results would be obtained by having a permanent resistance of the proper amount in the secondary circuit.

In but few rolling mills the periods of peak loads are such that an automatic control can be used to advantage. The duration of all the maximum peak loads must be long enough to allow the controlling devices to act. On the other hand, if the peak loads exceed a certain length of time, an equalization of loads may not be practicable. In this case, the most economical operation would be obtained by running the motor with a small slip and a fly-wheel of sufficient capacity.

In view of the foregoing, it appears that as a general rule for peaks of very short duration (approximately 2 seconds or less), of very long duration (approximately 8 seconds or more), and for extremely variable loads, a permanent resistance in the secondary circuit or a control operated by hand is most desirable. An accurate rule as to the proper kind of control and the size of the fly-wheel can scarcely be given. In each individual case all the possible load conditions should be taken into consideration in order to obtain the best equalization of loads, the highest efficiency, power-factor, etc.

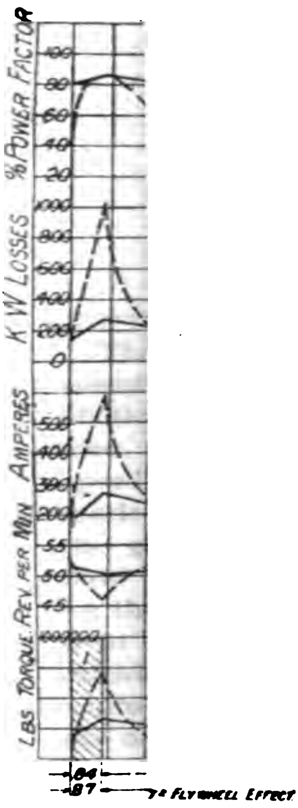
As a rule, the electric manufacturers are forced to submit the lowest-priced outfit with the highest power-factor and efficiency; that is, with secondary directly short-circuited, disregarding the actual working conditions as to the efficiency, power-factor, safety of operation, simplicity of control, etc. What does the efficiency with the secondary directly short-circuited mean to the customer if the motor is not to be run under such conditions?

The cost of operation is dependent upon the combined efficiency of the complete cycle. The highest combined efficiency will require, in most cases, a great fly-wheel effect, and it may be necessary to build a separate fly-wheel in addition to the motor. Considering the fact that the fly-wheel masses of the motor are generally moving at very low velocity and that the fly-wheel effect increases with the square of the velocity or the radius of gyration, it is apparent that a greater fly-wheel effect might be obtained without increasing the weight of the complete outfit by the use of a separate fly-wheel. This might also allow a cheaper and mechanically better construction.

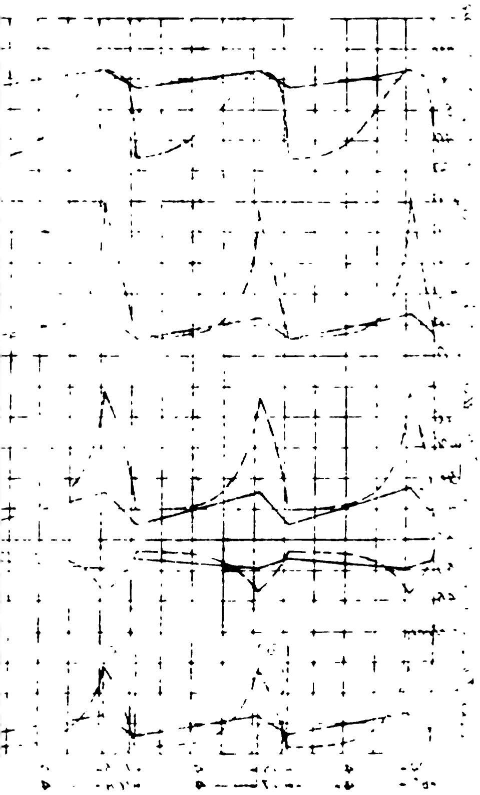
On the other hand, when a very great fly-wheel effect is desired in order to equalize the load, it should also be noted that a greater fly-wheel effect will require more time to stop or start or to change over from one speed to another. Therefore, in a case where this is of great importance, a compromise has to be made between the questions of equalization and time. It should also be borne in mind that the total time of a complete cycle of rolling differs with the different speed controls.

The conclusion from the foregoing is that the cheapest outfit is not always the most desirable, nor does it always give the lowest operating cost. Even if it requires considerable time to work out the best arrangement in all the details, the entailed expenses will be saved many times in the installation and operation. It is somewhat surprising that in the past no more time has been spent in the careful study of the subject, since the future of the electrification of rolling mills depends so much on the first installations.

As an illustration of how to arrive at the most economical result the writer has selected an example with load characteristics similar to those of a universal plate or rail mill. For the sake of simplicity the example has been limited to the first nine


% POWER FACTOR
100
80
60
40
20
K W LOSSES
1000
800
600
400
200
0
AMPERES
500
400
300
200
REV PER MIN
55
50
45
LBS TORQUE
100000
84
87
% FLYWHEEL EFFECT

(Specht)



passes and to two different fly-wheel effects. The data given for this example are as follows:

Pass	Pounds torque at 1 ft radius	Time in seconds
1	1,000,000	0.82
2	900,000	0.93
3	880,000	1.03
4	840,000	1.24
5	800,000	1.55
6	700,000	1.85
7	720,000	2.17
8	700,000	2.58
9	650,000	3.3

The intervals between passes are four seconds each. The speed is 52 rev. per min. and the supply circuit three-phase, at 6600 volts and 25 cycles. The motor for this speed would, therefore, have 56 poles, which would correspond to a synchronous speed of 53.6 rev. per min. With these data the calculation was made as follows: the average torque and the horse-power for the given load diagram were found to be 261,000 lb-ft. and 2640 h.p., respectively. In arriving at an approximate size for the motor required if the equalizing of loads by the fly-wheel is to be small, the square root of the mean square of the loads is calculated, the torque being 418,000 lb-ft. and the horse power approximately 4100 for normal rating. The design for this size of motor gave a fly-wheel effect of approximately 20,000,000 lb. at 1 ft. radius.

Since the peak loads are of short duration, a speed control having a constant resistance in the secondary circuit was selected. The size of the resistance was made such that a 1,000,000 lb-ft. torque on the motor shaft would correspond to 20 per cent slip.

On this basis, the torque curves were drawn in Fig. 3 by means of formulas *1b* and *2b*. For these torque curves the corresponding values for speed, amperes per terminal, kw. losses, and power-factor were obtained from the curves shown in Fig. 4, and plotted in the dotted lines shown in Fig.3.

These curves show that the fly-wheel is very much too small to give a satisfactory equalization of loads and that a much larger fly-wheel is required. Since the fly-wheel masses of the rotor are moving with a very low velocity—not over 3000 ft. per minute—and since it will be almost impossible to add sufficient weight to the rotor without making rather a poor design, it is desirable to build a separate fly-wheel with much greater

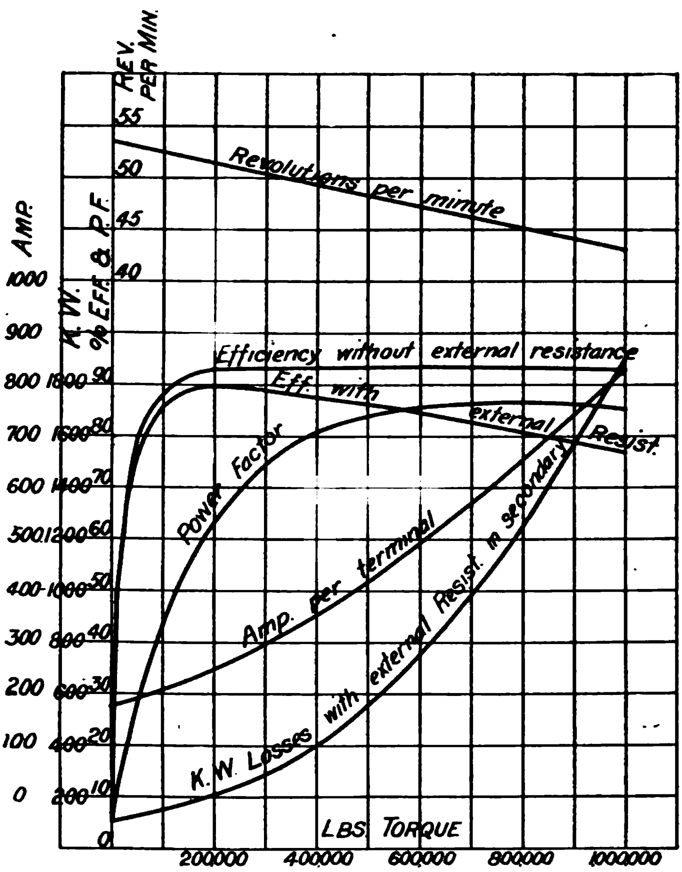


FIG. 4. SHOWING PERFORMANCE CURVES FOR MOTOR WITH 20 MILL. LBS. FT.^{2} FLYWHEEL EFFECT.

fly-wheel effect. One of 120,000,000 lb-ft.^{2} fly-wheel effect was selected. Curves for this value and for a motor with the same slip as the foregoing are shown in Fig. 5 and in full lines in Fig. 3.

Comparing the curves of the smaller and the greater fly-wheel effect shown in Fig. 3, it can easily be seen that the results with the greater fly-wheel effect are very much better in every respect. The power-factor remains nearly constant in comparison with the power-factor for the smaller fly-wheel with which a variation of 28 to 86 per cent occurs during every pass. Comparing further the torques and current values and obtaining from them the square root of the mean squares, we will find

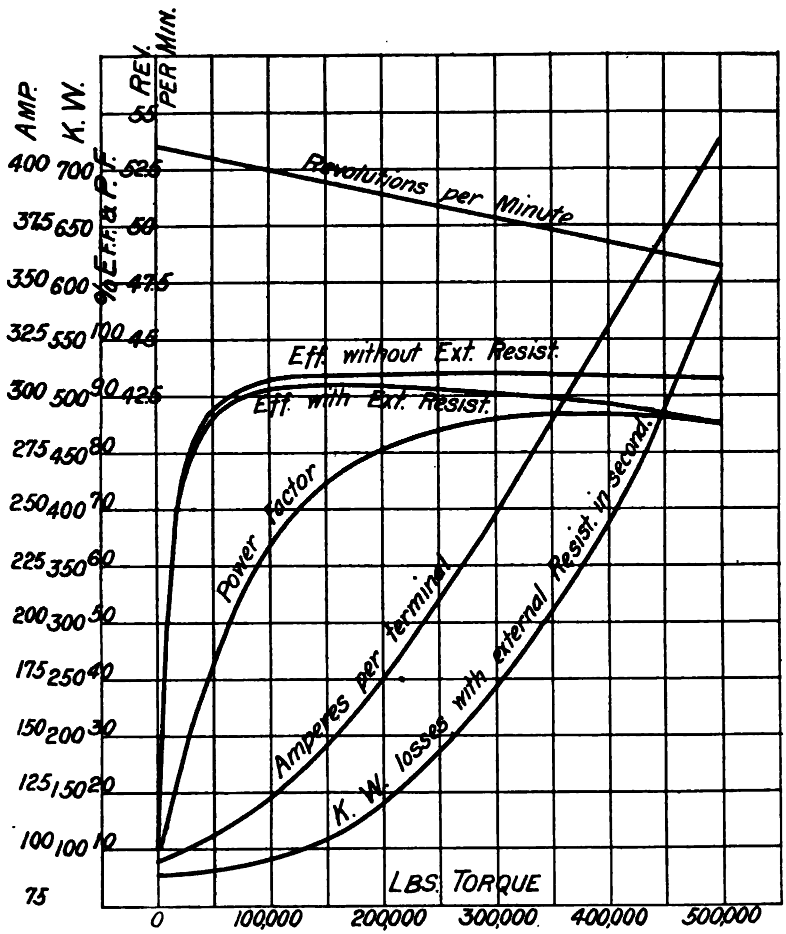


FIG. 5. SHOWING PERFORMANCE CURVES FOR MOTOR WITH 120 MILL. LBS. FT.² FLYWHEEL EFFECT.

that a motor with a normal rating of approximately 2800 h.p. and a pull-out torque of approximately 700,000 lb-ft. would be large enough, whereas, for the smaller fly-wheel, a motor of normal rating of approximately 3700 h.p. and a pull-out torque of at least 1,200,000 lb-ft. would be required.

Further, by integrating the time losses in Fig. 3 and taking their average value per second, we obtain 212 kw. for the set with the larger fly-wheel and 352 kw. for the set with the smaller. The combined efficiency of the motors, including the losses in the external resistances, would then be equal to 90.3 per cent against 84.6 per cent with the small fly-wheel effect.

The total time for one complete cycle of rolling is 51.9 sec. for the large fly-wheel and 52.7 sec. for the small one. However, the time required to accelerate the motor with the greater fly-wheel effect from 0 to 52 rev. per min. or to retard it from 52 to 0, is 58 seconds for a constant torque of 350,000 lb-ft. The time for the motor with the small fly-wheel effect is only one-sixth of this.

With the exception of the foregoing disadvantage, there should be no doubt that the installation with the greater fly-wheel effect is more economical than the other. The motor can be made much smaller, and even with the heavy additional fly-wheel the total cost for the complete motor outfit might be lower than for the larger motor without the separate fly-wheel. Further, the higher efficiency, the nearly uniform high power-factor and the lower average current make it possible to reduce the capacity of the generating plant and the transmission system, thus increasing the saving. Finally, the higher combined efficiency means also a lower operating cost. It might also be mentioned that with the use of a large fly-wheel to take up the heavy shocks, the motor might be built with a smaller air gap and for higher speed and geared, belted, or roped to the mill shaft carrying the fly-wheel, thereby obtaining a still cheaper motor outfit.

It is not the intention to say that the set with the 120 million lb-ft.^{2} fly-wheel effect in the foregoing example is the final solution. It is simply to show how to design a motor equipment for rolling-mill drive and what results can be obtained with a large fly-wheel. In order to obtain the best result it would be necessary to try other fly-wheel effects, slips, efficiencies, etc.

If rolling-mill propositions are treated in a manner similar to the above, and further, if advantage is taken of more reliable test data, which may be obtained from installations both here and abroad, there can scarcely be any doubt that the electric drive in rolling mills will be a success.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

ROLLING MILL MOTORS

BY E. W. YEARSLEY

Protection is extremely important in the steel mill where conditions are necessarily uncleanly, and electrical apparatus must work in the midst of dust, moisture, and gases. Large motors should be enclosed in solidly built tight compartments, ventilated by clean air if necessary, or should be of the totally enclosed type.

Considered economically, the writer believes main motor drives to be superior to engine drives, even when power must be derived from a steam-engine-driven generator plant fed by coal-fired boilers. Steam losses due to condensation and leaky valves and rings are surprisingly large, but usually escape definite measurement. Then in the usual rolling-mill engine very little expansion is utilized, and it is not likely that attempts to refine such machines are satisfactory. Where water power or waste gas is available there is no question of the greater economy of electric drive.

The controlling apparatus for mill service is usually the weak part of the system; it is much less satisfactory than the motors. Mechanical strength and simplicity are the main points to be observed in designing this apparatus. Heavier and more mechanical switches and circuit-breakers, better protected and more durable rheostats, and more dependable automatic controlling devices requiring less attention, are badly needed. This is a problem more difficult of solution than improvement of the motor, but no less necessary.

For large main-drive motors the advantage of continuous running at constant speed is so great that it would appear advisable to make the design of the mill suit the characteristics of the motor, and avoid the extra expense and complication of devices like the reversing drive. The tendency has been to build a machine and then to couple on a motor somewhere to drive it. This mistake, while not so frequent as formerly, is still made.

There seems to be no great difficulty in designing mills for continuous-running motors. By combining such motors with a suitable fly-wheel, it should be possible to keep the line load sufficiently uniform. This combination has not, in the writer's opinion, received sufficient attention, possibly because of lack of knowledge of power and speed regulations of the rolling operation.

Tests of these characteristics will be comparatively easy on electric mills, so that data will rapidly become available for supplying the system with the proper inertia. In some installations the writer has seen the fly-wheel so badly proportioned as to be detrimental to the operation of the motor. Initial speeds should be carefully selected, especially when the drive is direct; and if possible a considerable speed regulation should be provided, so that the speed may be increased with increase in proficiency of the operators.

The importance of low armature inertia for reversing motors is now well recognized, but designs could be improved by still further reduction in speed. The writer is decidedly against the use of high-speed motors for any kind of mill service, and believes the extra cost of slow-speed machines well warranted.

Electric motors subject to excessive vibration communicated from the gearing and other parts of the machine should be protected by a flexible coupling.

For mill apparatus which must be handled directly, especially for direct-current apparatus, the writer favors a maximum of 250 volts Safety of employes requires that with higher voltages special guards be provided to isolate the apparatus.

Both alternating-current and direct-current apparatus have their advantages for steel-mill installations. Local conditions must determine which is superior. Unless transmissions are too long, the writer favors a direct-current installation, especially if the plant has many machine tools. With an alternating-current system as few direct-current motors as possible should be used.

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ELECTRIC-DRIVEN ROLLING MILLS

BY E. FRIEDLANDER

The first electric-driven steel rolling mill in the United States was installed about four years ago by the Carnegie Steel Company at its Edgar Thomson works. Since then a number of other electric mill drives have been installed and run with entire success, a noteworthy example being found at the steel plant at Gary, Indiana.

The introduction of the electric drive has made it possible to clear up many points in regard to the power required for rolling different shapes of steel, and moreover, the roller, or operator, is able to see at a glance the work done by each pass. The electric roll drive has also taught us how to get the best relation among rotating masses, speed, time, and horse power. It has helped the roll designer to calibrate rolls in such a manner that the power characteristic for all the passes is uniform, thereby avoiding high power peaks, decreasing the size of the prime-mover, and reducing first cost and fuel consumption.

The watt-hour meter warns the roller that bearings or rolls are becoming tight and hot, or that steel is causing excessive friction in the passes, often due to overfilling, cold steel or faulty calibration, thereby guarding against damage to the rolls and bearings. The meter indicates that lower heat, greater elongation, and especially change of profile in different directions, increase the power required at the rolls much more rapidly than do chemical hardness, high tensile strength, or larger draughts. The meter also shows that it is not the higher percentage of carbon in steel which requires more power in rolling but the lower temperatures at which this steel has to be rolled, and also that an increase in width of the steel shape requires more power than a decrease in height. By means of the meter too, it can readily be seen that rolling " squares " and " rounds " takes per square inch displacement much less power than that of shapes with large peripheries and many flanges, as the latter cool off quickly and cause much friction in the rolls.

Tests on rail-mills have shown that the foot-pounds per square inch of displacement gradually increase the nearer the rail is to the finishing pass. A 75-lb. rail required 1100 ft-lb. at the first pass on the first " rougher. On the same stand in the seventh pass it required 3000 ft-lb., in the first pass on the second roughing rolls 4800 ft-lb., in the fifth pass 8150 ft-lb.; 9500 ft-lb. were required for the last or finishing pass. The large increase in foot-pounds is partly due to the greater density and rapid cooling of the steel, especially at the thinner flanges near the finishing pass. For this reason, the flanges are rolled out as late as possible. Whenever required, exact power consumption can be given for each phase of rolling.

The ideal motive power for rolls should drive them slowly when the steel enters and should drive them faster as the piece lengthens. The reciprocating engine will do just the reverse; namely, run very fast without load and slow down as the load increases, finally stopping if the load becomes too great.

The maximum torque of reciprocating engines is fixed by the size of the cylinders and the pressure; it cannot be increased no matter how much steam or gas is available. For this reason most mill engines are made very large and often run with only half load, causing high steam consumption per horse power, their most economical cut-off being at full load.

For this work the characteristics of the electric motor are much better. Even with double its full torque, the efficiency is good and the motor will not stop, but will take more and more current, finally becoming overheated and burning unless properly protected. If desirable, its speed changes from no load to full load can be made small. The current can also be limited to a certain maximum, without stopping the motor. in this manner preventing excessive strains and probably serious breakdowns.

Where high speeds are necessary, motors can be direct connected to rolls, increasing the energy of the rotating parts and at the same time decreasing the size of motor, the power required and the fuel consumption. Heavy reciprocating engines cannot run at such high speeds, and must be connected to the rolls by means of gears, ropes or belts.

To obtain accurate information as to the exact power requirements for rolling steel, indicator diagrams were taken on reciprocating engines doing similar work, but these in many instances were misleading. The work of rolling steel is very changeable and intermittent. Engines often run with light loads, but at short intervals have their valves wide open. This, together with the work done due to the energy of the rotating parts, should be carefully observed. Although it probably is not difficult to get the maximum torque required to decide on the normal capacity of the motor, the above-mentioned points must be considered, together with the length and number of pieces in the rolls, and also time-intervals between passes. To be on the safe side it is advisable to follow standard mill practice and make motors of ample size and strength, in order to stand the severe service and overloads without injury.

In mentioning fly-wheels, the writer had only three high non-reversible mills in mind. As the weight of rotating parts is much greater in large motors than in reciprocating engines, and the energy of the rotating parts increases as the square of the speed, it is obvious that even a small change in speed is of great importance. As tests have shown that rotating masses are sometimes not only of no use but that they often prove a drag on the motor, careful study of this feature has to be made in each case.

While the steel is being rolled, both the motor and the fly-wheel should furnish the power, but as soon as the steel leaves the rolls the motor should accelerate the rotating masses to the same speed before rolling. The time available and the number of revolutions will determine the size of the motor more than anything else.

It has been observed that on blooming and roughing mills, where the pieces are very short and the intervals long, rotating masses supply the largest part of energy during the rolling period and should therefore be large. The reverse takes place at the finishing passes, where pieces are long and follow each other rapidly. Heavy rotating masses would in this case be useless, and would even require larger motors for their quick acceleration.

Where one motor drives roughing and finishing rolls, curves should be plotted showing the number of pieces in the rolls at the same time, the length of passes and intervals, the power required for each pass, etc. With the help of such curves, the best relation between the sizes and speed of the motor and fly-wheel, radius of gyration, and slip of motor can be easily determined.

The total motive power required in a steel plant is changeable and fluctuates continuously, the average in many plants being often below one-fourth of the total horse power installed in motors. The electric-driven rolling mills will, however, demand considerably larger power-stations to take care of the large currents, especially when all the motors happen to be overloaded at one time, as for instance when rolling cold steel. It is very important to find out beforehand how much of this fluctuating load the power house may have to supply, assuming the worst conditions, as the shut-down of the electric power station for even a very short time, will stop the operation of a large number of machines and cause enormous losses. This is the one very objectionable feature of making such a great number of prime movers entirely dependent on one power station, and, therefore, some means should be taken to prevent this disturbance.

With steam engines and boilers the liability of a complete shutdown is not so great, but the delays and annnoyances caused by low steam-pressure are of daily occurrence in many plants. In such cases not only will all the steam-driven prime movers be unable to develop the required power, but also in trying to develop this power, they will use more and more steam, thus making it difficult to raise the steam pressure without increasing the number of boilers, or decreasing for a while the load and consequently the production.

The short, high-peaked current demands should be kept off the power station as much as possible and only the average current be supplied. The least number of units can then be kept running under nearly full load with the most economical fuel consumption and the least wear and tear of moving parts. As before mentioned, the average current consumption in a steel plant is always small in comparison with motor capacity, on account of the intermittent work and large amount of inertia of the rotating parts. By means of storage-batteries or fly-wheel sub-stations the occasional large demands for current can be taken off the station and supplied from these two sources, where it is stored up when the current demand is below the average.

The exchange of current from one motor to another, in connection with electric roll-drives, is often considerable and should not be overlooked.

With regard to the electric reversing mill, it is a fact that soon after its first appearance the use of reversing rolls became more general, especially in England and Germany. In those countries, small quantities of one kind and shape of material are rolled, and the cost of the large number of rolls required and the saving of time in changing rolls are probably the chief reasons for using the reversing mill, where many different sections can be worked with the same rolls. The absence of the heavy and troublesome lifting tables is also a welcome feature, especially when pieces rolled are very long.

The first installation in this country of an electric reversing mill, at the Illinois Steel Company's works at South Chicago, has given entire satisfaction from the start, and has demonstrated that the electric motor is much better adapted for this kind of work than the reciprocating engine. Although the first cost was high, its lower depreciation, better operation and lower cost of maintenance should justify its installation.

In a reversing mill the operator is able to draw steel slowly into the rolls and " speed up " while the piece lengthens, making a great advantage in rolling steel. In order to obtain perfect speed regulation, no use can be made of steam expansion, but admission continues during nearly full stroke. Even then much depends on the skill of the operator, who can subject the engine and the mill to very severe shocks and cause serious breakdowns if he is not careful. Reversing mills are therefore made heavy and strong.

If too much steam is admitted, it is difficult to prevent such large engines from racing without load. It is also wasteful, as both the time of actual rolling and the speed of the rolls are limited, most of the power being consumed in the rapid starting and stopping of the heavy rotating parts, without making any use of their fly-wheel energy.

With the use of electric motors in place of reciprocating engines, the problem of reversing rolls becomes much simpler and better, in regard to manipulation, fuel consumption, and cost of maintenance. Operation of electric-driven reversing mills is nearly automatic; no skilled operator is required and all danger to the motor and the mill is eliminated. The speed of acceleration is prearranged, and no matter how fast the operator moves his levers, the maximum current and the speed are limited.

Reversing is done with the least shocks in rolls and couplings and the danger of overstraining machinery is done away with. It is important to be able to reverse the motor just as rapidly as the engine. Special care should therefore be taken to have a motor-generator that will give large currents with very low excitation, and one that will be quickly magnetized and demagnetized.

It has been observed that only one-fourth of the power required at the reversing-roll motor is the average supplied from the power station. The large current demands are furnished by the motor-generator through the energy of the high-speed fly-wheel, and a considerable amount of current is sometimes sent back into the line.

As for all other mill work where power and speed variation are considerable, the direct-current motor, on account of its load and speed characteristics, is better adapted for driving rolls than the alternating-current motor. For reversible roll drives it is used exclusively.

There is no reason why the direct-current motor should give any more trouble than the direct-current generator at the power station. Four years' experience has shown that the wear of the commutator and the cost of maintenance amount to practically nothing. The transmission of large low-tension currents is much more serious, especially when tens of thousands of horsepower have to be supplied and the distance of the motors from the station is considerable.

The use of higher direct-current voltages in connection with large rolling mill motors should be satisfactory; but no doubt high-tension alternating-current transmission and induction motors direct on the line will be generally employed, especially in new installations. Where conditions demand it, the induction motor characteristics can now be made nearly similar to those of the compound-wound, direct-current motor. However, much of its simplicity and efficiency will be sacrificed in doing this.

Among some of the earlier disadvantages of the induction motor were: very large current required for starting under heavy load; one speed fixed by the number of poles and the tendency always to run at synchronous speed; low power-factor with light loads; small air gaps; impracticability of reversing large units; and inability to change speed to fly-wheel requirements.

In the design of the modern rolling-mill motor, most of these objectionable points have been remedied by different means such as wound rotors, the introduction of variable resistance, changing the number of poles, shifting the phases, slip-rings, etc.

Whether direct-current power stations and direct-current motors are used, or alternating-current stations are installed for high-tension transmission with alternating-current motors directly on the line or fed through transformers, or direct-current motors are supplied from an alternating-current station through converters, or motor-generators, batteries or fly-wheel substations, is a matter of detail. No doubt any one of these systems will give satisfaction if properly designed and installed.

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POWER REQUIREMENTS FOR ROLLING HIGH-CARBON STEEL OF SMALL SECTION

BY BRENT WILEY

The tests* in this paper were taken from a 9-in. merchant mill, a plan of which is shown in Fig. 1. The mill consists of seven stands of three-high rolls and one finishing stand of two-high rolls driven by a two-speed, two-phase, 60-cycle, 2200-volt induction motor of squirrel-cage rotor construction connected to the mill by means of a 42-in. three-ply belt. The ratings of the motor are 600 h. p. at 600 rev. per min. (synchronous speed) and 450 h. p. at 450 rev. per min. The pulley reduction gives a mill-speed of one-half these values.

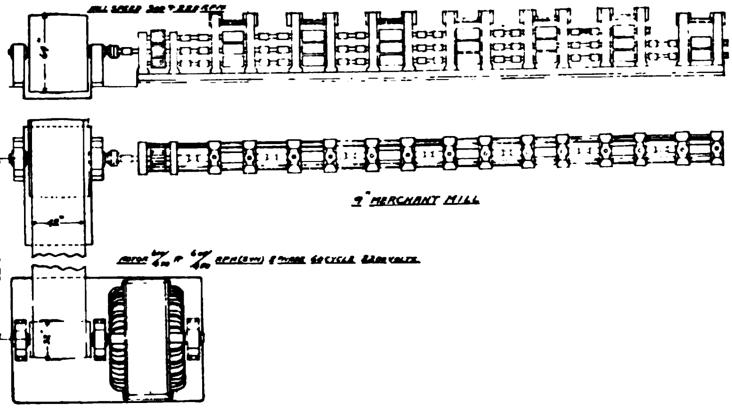

FIG. 1.—General arrangement of mill.

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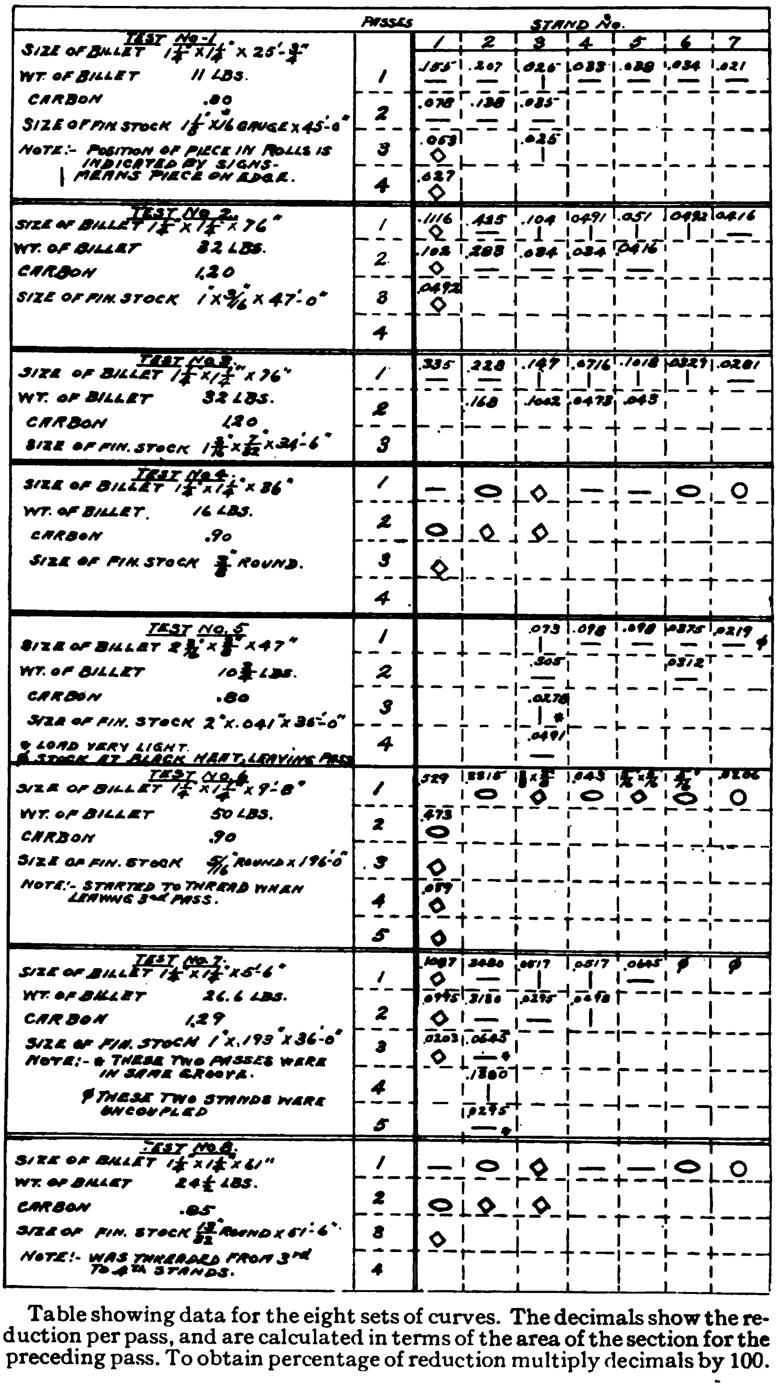
* The tests referred to in this paper were conducted under the supervision of C. J. Russell, through whose kindness they are presented in this form.



	PASSES	STAND No.						
		1	2	3	4	5	6	7
TEST No. 1 SIZE OF BILLET 1¼" x 1¼" x 25'-¾" WT. OF BILLET 11 LBS. CARBON .80 SIZE OF FIN. STOCK 1⅛" x 16 GAUGE x 45'-0" NOTE:- POSITION OF PIECE IN ROLLS IS INDICATED BY SIGNS- | MEANS PIECE ON EDGE.	1	.155 —	.207 —	.026 |	.033 —	.028 —	.034 —	.021 —
	2	.078 —	.138 —	.035 —				
	3	.053 ◇		.025 |				
	4	.027 ◇						
TEST No. 2. SIZE OF BILLET 1¼" x 1¼" x 76" WT. OF BILLET 32 LBS. CARBON 1.20 SIZE OF FIN. STOCK 1" x 3/16" x 47'-0"	1	.1116 ◇	.435 —	.104 |	.0491 |	.051 |	.0492 |	.0416 —
	2	.102 ◇	.283 —	.084 —	.034 —	.0416 —		
	3	.0492 ◇						
	4							
TEST No. 3. SIZE OF BILLET 1¼" x 1¼" x 76" WT. OF BILLET 32 LBS. CARBON 1.20 SIZE OF FIN. STOCK 1 3/16" x 7/32" x 34'-6"	1	.335 —	.228 —	.147 |	.0716 |	.1018 |	.0329 |	.0281 —
	2		.168	.1002	.0473	.045		
	3							
TEST No. 4. SIZE OF BILLET 1¼" x 1¼" x 36" WT. OF BILLET. 16 LBS. CARBON .90 SIZE OF FIN. STOCK ⅜" ROUND.	1	—	⬭	◇	—	—	⬭	○
	2	⬭	◇	◇				
	3	◇						
	4							
TEST NO. 5 SIZE OF BILLET 2 3/16" x ⅜" x 47" WT. OF BILLET 10⅜ LBS. CARBON .80 SIZE OF FIN. STOCK 2" x .041" x 36'-0" * LOAD VERY LIGHT. ∅ STOCK AT BLACK HEAT, LEAVING PASS	1			.073 |	.098 —	.098 —	.0375 —	.0219 — ∅
	2			.305 —			.0312 —	
	3			.0278 | *				
	4			.0491 —				
TEST NO. 6 SIZE OF BILLET 1¼" x 1¼" x 9'-8" WT. OF BILLET 50 LBS. CARBON .90 SIZE OF FIN. STOCK 5/16" ROUND x 196'-0" NOTE:- STARTED TO THREAD WHEN LEAVING 3rd PASS.	1	.529	.2816 ⬭	[illegible] x ⅝ ◇	.043 ⬭	5/16 x 5/16 ◇	5/16" ⬭	.3206 ○
	2	.473 ⬭						
	3	◇						
	4	.059 ◇						
	5	◇						
TEST No. 7. SIZE OF BILLET 1¼" x 1¼" x 5'-6" WT. OF BILLET 26.6 LBS. CARBON 1.29 SIZE OF FIN. STOCK 1" x .193" x 36'-0" NOTE:- * THESE TWO PASSES WERE IN SAME GROOVE. ∅ THESE TWO STANDS WERE UNCOUPLED	1	.1087 ◇	.3080 —	.0517 |	.0517 |	.0605 —	∅	∅
	2	.0995 ◇	.3186 —	.0295 —	.0478 |			
	3	.0203 ◇	.0643 — *					
	4	—	.1380 |					
	5		.0295 — *					
TEST No. 8. SIZE OF BILLET 1¼" x 1¼" x 61" WT. OF BILLET 24½ LBS. CARBON .85 SIZE OF FIN. STOCK 13/32" ROUND x 51'-6" NOTE:- WAS THREADED FROM 3rd TO 4th STANDS.	1	—	⬭	◇	—	—	⬭	○
	2	⬭	◇	◇				
	3	◇						
	4							

Table showing data for the eight sets of curves. The decimals show the reduction per pass, and are calculated in terms of the area of the section for the preceding pass. To obtain percentage of reduction multiply decimals by 100.

The product of this mill is high carbon steel of comparatively small section, test data being given for steel ranging from 0.80 to 1.29 carbon and of section ranging from $1\frac{3}{16}$ in. by $\frac{1}{32}$ in. to $\frac{5}{16}$ in. round. Originally the intention was to run the mill on the slow speed for the larger sections and on the high speed for the small rounds and very thin flats, but on testing the high-speed operation it was found that special provisions would have to be made for handling the stock as it was being rolled, including the use of repeaters for the finishing stands. It was also difficult to enter the material in the rolls at the high speed. These plans have not been fully developed and all material is being rolled on the slow speed. The results obtained under these conditions are most gratifying, as a comparison with a steam-engine-driven mill of the same general design but of five stands of rolls shows that the capacity of the latter mill is exceeded by that of the motor-driven mill by 35 per cent. This difference is

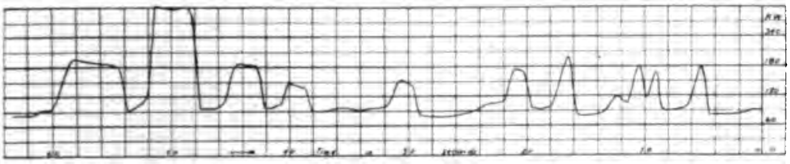


FIG. 2.—One piece in rolls, Test No. 1.

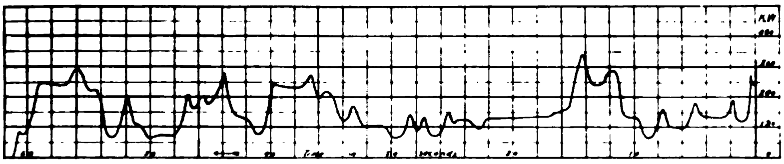


FIG. 3.—Rolling conditions, Test No. 1.

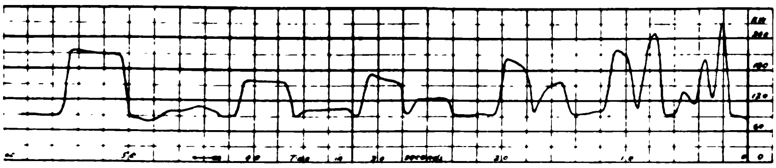


FIG. 4.—One piece in rolls, Test No. 2.

partly due to the two additional stands of rolls, but chiefly to the practically constant speed of the motor, as the average speed of the engine is appreciably reduced by the heavy load conditions.

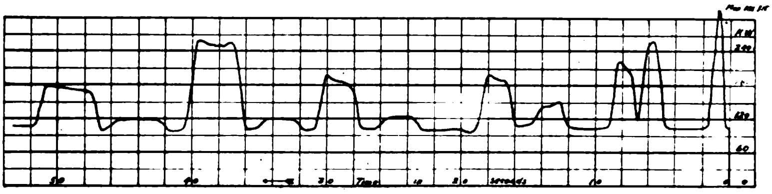


FIG. 5.—One piece in rolls, Test No. 3.

It will be seen that the areas of the sections at each pass are only approximate, but the relative values, which are of more importance, give a good idea of the operating conditions and work done.

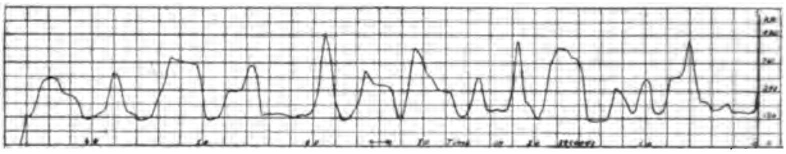


FIG. 6.—Rolling conditions, Test No. 3.

The recorded readings as shown by the series of curves were taken to obtain the power required per pass, the total power for one piece of stock, and the power requirements when the mill was in regular operation with several pieces of stock in the rolls at one time. These latter data were, however, not obtained for tests Nos. 2 and 6.

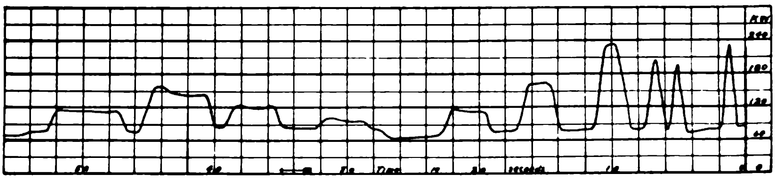


FIG. 7.—One piece in rolls, Test No. 4.

An all-day record was kept during test No. 7. The results give a good idea of the capacity and the average power requirements per ton of product.

Records observed from 6:55 a. m. to 3:49 p. m.

Size of stock rolled	1 in. by 0.193 in. by 36 ft-0 in.
Carbon	1.29
Size of billet	1.25 in. by 1.25 in. by 5 ft. 6 in.

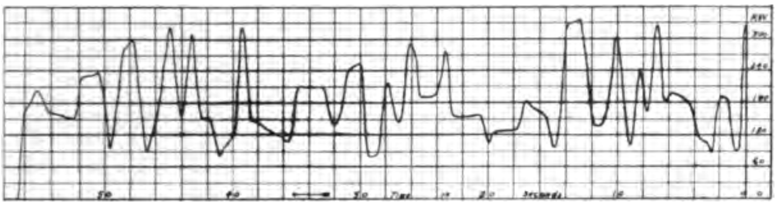


Fig. 8.—Rolling Conditions, Test No. 4.

Weight of billet	26.6 lb
Number of billets rolled	1121
Total weight of billets	29,818 lb.
Actual operating time	408 min.

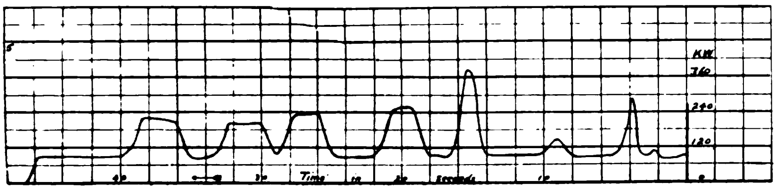


Fig. 9.—One piece in rolls, Test No. 5.

Time lost	126 min.
Total kilowatt-hours	1140
Kilowatt-hours friction load	408
Kilowatt-hours (including friction) per ton of metal rolled	71.2

Rate of rolling 22 tons in 12 hr.

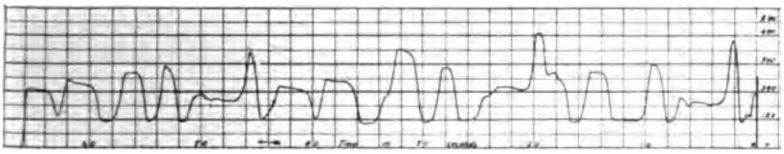


Fig. 10.—Rolling conditions, Test No. 5.

Recorded readings as shown in Figs. 12 and 13 were taken during the above run.

The fly-wheel effect of the system is practically limited to that of the rotor of the motor; this effect is comparatively small, as the slip of the motor is but 3 per cent. at full load. The efficiency of the motor is, therefore, kept as high as possible. By referring to Fig. 6 (test No. 3), it will be seen that the peak-load conditions have a duration of from 4 to 6 sec; to equalize this load to the average power would require an excessively large flywheel on the mill-shaft, and the slip of the motor would have to be increased approximately three times the present value, thereby lowering the efficiency of the motor.

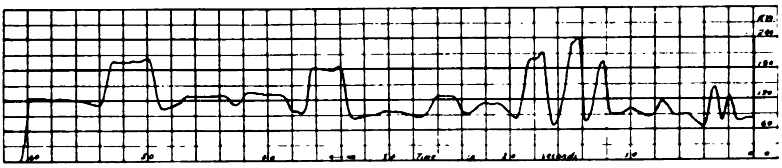


Fig. 11.—One piece in rolls, Test No. 6.

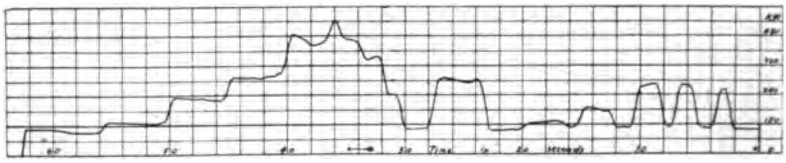


Fig. 12.—One piece in rolls, Test No. 7.

From the average working conditions as estimated from the various power curves for usual mill operation, it would require approximately a 15-ton fly-wheel 8 ft. in diameter, with a 10 per cent. drop in speed for 250 h. p. increase of load in order to lower appreciably the peak values of the load. In this case the fly-wheel is located on the mill-shaft and the peak loads are considered of 4 seconds duration. The time and efficiency costs of this equalization do not warrant the use of a fly-wheel in the system.

Fig. 13.—Rolling conditions, Test No. 7.

The friction load of the mill is somewhat high, this being due principally to the fact that it is necessary to keep the mill adjusted very closely. Every precaution is taken to keep the mill tight, which results in heavy pressures in the bearings.

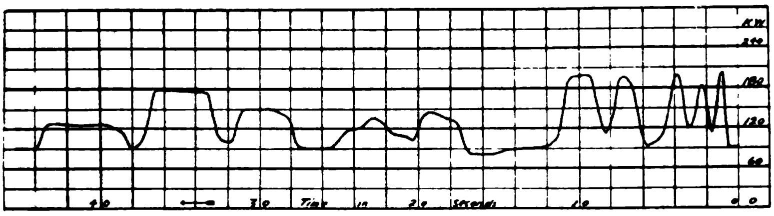


FIG. 14.—One piece in rolls, Test No. 8.

It is generally supposed that, owing to its hardness, more power is required to roll the high-carbon steel than the ordinary mill steel, but at the same temperatures the energy required is

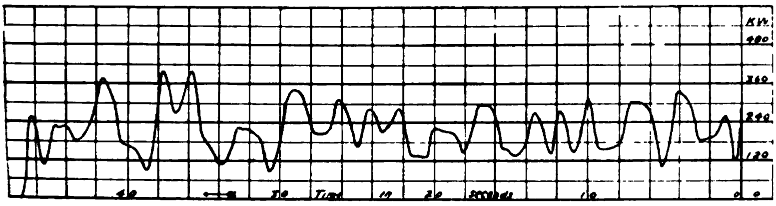


FIG. 15.—Rolling conditions, Test No. 8.

practically the same. Owing to the high percentage of carbon, the harder steel billet must not be heated as hot as the milder steel, and it is therefore rolled at a lower temperature, the lighter sections being finished at a black heat.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

ELECTRIC CONTROL FOR ROLLING-MILL MOTORS

BY C. T. HENDERSON

Much has been said regarding the remarkable electrical applications during the last few years in connection with the iron and steel industry, but only those directly interested in this work realize how much impetus has been given to it by the development of suitable controlling apparatus. When A. C. Dinkey, then chief electrician of the Carnegie Steel Homestead works, installed the first electric motor for roll-table service in 1893, he naturally used the standard apparatus of the day, and quite naturally it failed. He immediately sought for something better, especially in controlling apparatus. At that time the only service comparing in severity with that encountered in rolling mills was in electric railway practice; accordingly, the railway motor was rewound for 250 volts and placed in service. In controllers not even temporary satisfaction was found in the devices available, so Mr. Dinkey developed a simple rheostatic controller of the face-plate type. This controller, or one similar to it, together with the rewound railway motor, supplied the demands for about 12 years. Meantime, however, it was found that mill service was much more severe than railway service—more severe in the number of starts and stops per hour, in continuity of service, in lack of intelligent handling, and in the initial temperature of the surrounding atmosphere. It should be said, too, that the penalties of delay in the mill are much higher. If a car in a traction system is put out of service, it can, at the worst, wait and be taken to the car-barn by the following one, without causing essential money loss. But a steel works is unusual in being a manufacturing plant in which there is no reservoir: the material must pass through in an uninterrupted stream; for a delay at any point breaks up the process all along the line, resulting in the derangement of the entire system, much spoiled steel, and consequent loss.

Again a steel plant is unique in the relation of the initial cost of the installation to the value of the product. The Gary plant, with its large and costly electrical equipment, can roll a value in finished product equal to the entire cost of the plant in a couple of months. So it has come to pass that a steel concern figures that the loss of a blooming mill, for instance, in time of good business, costs somewhere between $300 and $1000 per hour, depending upon its capacity.

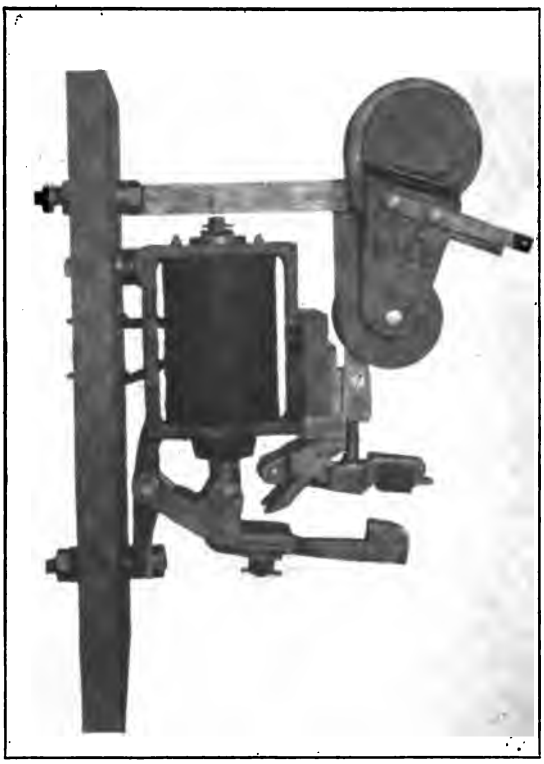


Fig. 1—Contactor type switch

Though in the light of present-day practice the first motors and controllers in steel works were unsuited to the work, they grew steadily in favor, and continued to supplant steam auxiliary apparatus. But as the number of motors increased the dissatisfaction with existing types of controller increased correspondingly. Series-wound motors with a torque almost directly proportional to the current were hardly satisfactory substitutes for steam engines (whose torque was limited by piston area and boiler pressure) when the controllers were operated by ignorant and often vicious persons. To remedy this defect in the operating conditions, about the year 1900 there appeared various devices for properly controlling the motors. Lack of ruggedness caused most of these devices to fail, and it was not until about 1903 that really serviceable apparatus of this nature came into use. From the start the necessity for current-limit control was recognized, and apparatus was designed to make the period of acceleration dependent on the current supply to the motor, the control system being an

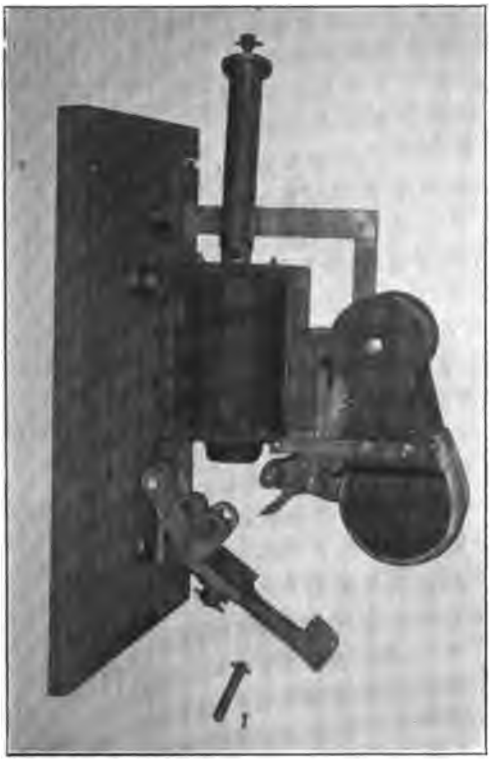


FIG. 2—Contactor type switch opened for repairs

organization of magnetically operated switches whose details left much to be desired on account of the steel mill practice of making repairs on Sunday. At first the demand was for a controller made up of switches rugged enough to operate continuously for 6 days; this was produced late in 1903. Soon there was a demand for a switch more rugged and more susceptible to quick repairs when such were needed.

The importance of minimizing delays in steel mill work has

Fig. 3—Contactor type switch after 60,000 operations

already been touched upon. Apparatus of this nature was produced in due time. Its design may be of interest. Fig. 1 shows a typical switch for this purpose. It consists of a cast-steel frame carrying a fixed contact on an insulated block, and having hinged in it a movable contact lever adapted to be moved by the solenoid plunger into and out of engagement with the fixed contact. The main or current carrying contact is of laminated copper, protected from arcing by auxiliary contacts of carbon and copper normally in the field of a powerful blowout. The poles are shown in Fig. 1, swung up, as they are in practice, to facilitate inspection and repairs. In designing this switch the strength of the materials used was determined by the destructive power of the average repair man. The arrangement of parts is laid out to minimize the probability of delay, should the parts break. For instance, the carbon auxiliary contact is so placed that it will be actuated by gravity should its spring be broken.

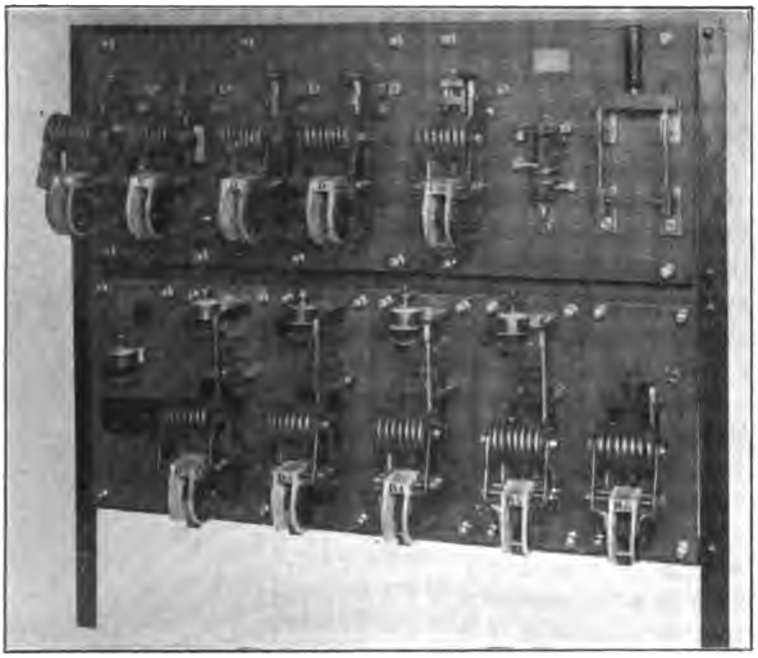


FIG. 4—Contactor type switchboard

Every effort has been made to minimize the time required for replacing defective parts; for example, new arcing contacts can be put in in 15 sec., a new arcing contact spring in 20 sec., a new magnetizing coil in 1 min. 40 sec. (Fig. 2). In case of serious trouble, the switch being self-contained, it can be removed from the board as a unit, replaced by another, and then taken to the shop to be repaired at leisure. This exchange has been made with a delay of 1 min. 30 sec. Numerous experiments and observations seem to indicate that the life of contacts on a switch of this kind varies inversely as the square of the number of operations per minute.

Fig. 3 shows a contactor after opening and closing a high inductive circuit carrying 120 per cent in excess of its normal rating 66,000 times at the rate of 30 operations per min. Both auxiliary contacts have about reached the end of their life, and hence require renewal. Reduced to 10 operations per min., which is about the average rate, this switch should operate about 600,000 times without requiring renewals, and longer under normal load conditions instead of 120 per cent overload. In service this type of switch has operated over 1,000,000 times without repairs.

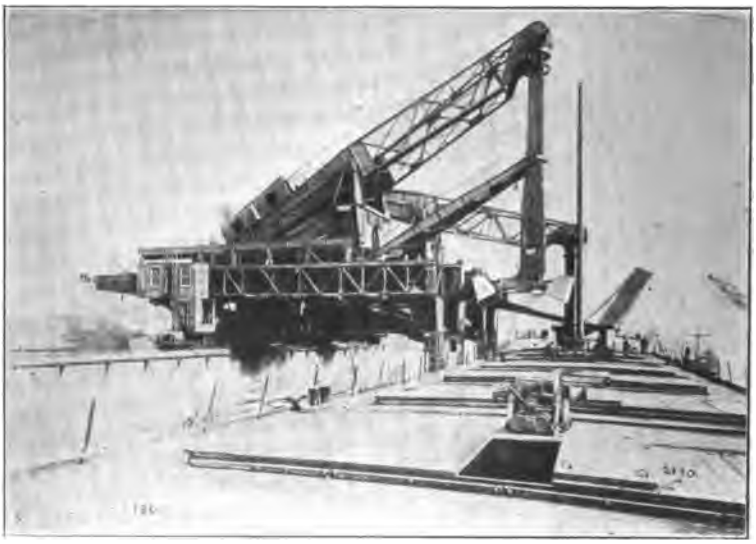


FIG. 5—Hulett unloader

It has been said that the necessity for current-limit control was recognized very early. The first systems employed were far too complicated. Further, they were adapted to maintain the accelerating current at an approximately constant value. In many instances this is undesirable; for instance, where motors are reversed while in rotation, the high armature reaction makes them incapable of commutating current that could be commutated safely when starting from rest. Again, as the motor comes up to speed its commutating limit falls off. This is taken care of in modern controller practice by having a multiplicity of current relays, one associated with each accelerating switch, so that the current can be adjusted independently at each point in the cycle. (Fig. 4.)

Starting at the docks where the ore is unloaded and shipped to various steel plants, we find one of the most spectacular machines in the steel industry, the Hulett unloader. Figs. 5, 6, 7, and 8. These machines were originally steam-hydraulic operated, and have been successfully electrified only during recent years. The operator rides in the bucket-leg and controls all motions of the unloader. The walking-beam carrying the bucket-leg must be started smoothly and quickly when the bucket has been filled, then slowed down and stopped automatically at the top. In lowering, the hoist motor must be transformed into a generator and serve as a retarding means.

FIG. 6—Hulett unloader

At the bottom, when the operator throws his master controller to the " off " position, the beam must be brought to rest quickly and smoothly. This is accomplished by the same current limiting devices used in acceleration. So perfect are the results obtained, that riding in the bucket-leg reminds one of a trip in a hydraulic elevator.

The bucket, which handles 10 tons per trip, can be rotated so as to pass between hatches, and automatic control of this motion serves to limit the rotation to seven-eighths turn either way from the normal position. The bucket having been rotated 90 degrees, it is easily seen that if it should get caught on a stanchion while closing, the enormous side strains would be thrown on the supporting beam. This distinctly calls for current-limit control of the highest order. Since such apparatus has become available, it is possible to reduce the weight of the machine 15 per cent by reason of the elimination of these extraordinary strains.

During the present season four such machines of 15 tons capacity per trip are being installed. Aside from their huge size they have many interesting features. They are made to span five railroad tracks, and carry a weighing larry that runs across these tracks. The bucket conveys ore from the hold of a vessel into a hopper, from which it is drawn into the larry and weighed. From the larry it is dumped into railroad cars, being weighed by subtraction on especially constructed scales during the process. Thus the cars are loaded and weighed without the necessity of first weighing the empties. Furthermore, each car is loaded to its capacity, a feature of great importance to docks whose daily tonnage is limited by the cars available.

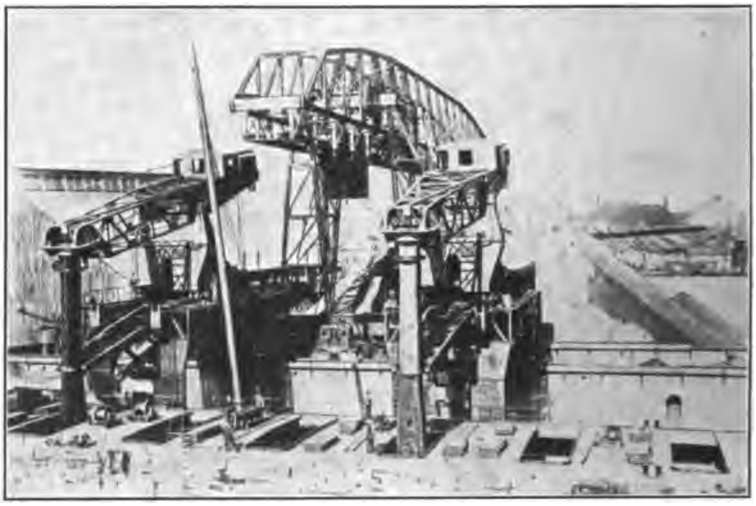


FIG. 7—Hulett unloader

In ore-bridge practice the availability of proper controlling apparatus has brought about a change in design but little short of revolutionary. To-day in grab-bucket hoists in place of the single motor of 15 years ago, we have the double-motor system, in which the drums are driven by individual motors, thus eliminating the friction clutches, and, by making the operator's physical task easier, increasing the capacity of a given plant. These same motors, equipped with current-limiting, dynamic-braking controllers, can be made to act as generators during lowering, thus retarding the downward movement of the bucket, and transforming the kinetic energy stored therein into heat in a rheostat. Here its conversion is not attended by mechanical abrasion, and hence the necessity for continual adjustments is eliminated. During the lowering operation the braking of either of the two motors can be varied independently, and thus the bucket made to open gradually, close gradually, or remain with the jaws at a fixed opening, as desired.

In the steel plants themselves the complete electrification of auxiliary machinery was not attempted until some time after both controlling apparatus and motors had been brought to a condition closely approaching perfection. As late as 1905, steel plants were erected in which all auxiliary machinery (except the blooming-mill tables and elevating mechanism in the case of three-high mills) was electrically operated. Gradually the prejudice against electrically operated blooming-mill tables was overcome, but the elevating-table mechanism seemed destined to remain hydraulic. When the problem presented is considered carefully, the hesitancy on the part of the mill owners must be acknowledged to be justified. The elevating tables referred to consist of live rollers which must be elevated or lowered between passes, first to admit the steel to the lower pair of rolls, then return it to the upper pair. The rolls are very heavy, seldom weighing less than 100,000 lb., and must be operated in


FIG. 8—Hulett unloader

very short periods. At last a steel plant was found which was building a new 40 in. blooming mill; this plant was willing to put in the electrically operated table mechanism, if it could be shown to be feasible. A careful investigation of the speed in other plants showed that the shortest period required by hydraulic equipments to raise or lower was 3 sec. To insure the table being fast enough, the steel company's specifications required a complete cycle in 2.5 sec., apparently on the supposition that the equipment would not come up to specifications, and that by specifying a 2.5 sec. period they would insure operation in 3 sec. This table weighed 118,000 lb. and was required to rise a total distance of 40 in.

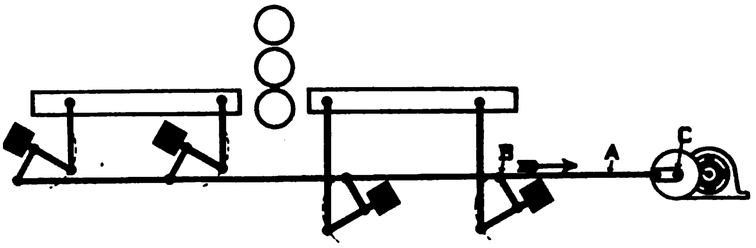


Fig. 9

The arrangement adopted is shown diagramatically in Fig. 9. The motor finally decided upon was 160 h.p. at 88 rev. per min., geared to a crank at a ratio of 1 : 5.8. This crank is connected to four bell-cranks carrying the table. The bell-cranks also carry counterweights aggregating 89,500 lb., giving a total mass of 207,500 lb. to be moved. The ingot to be rolled weighs 10 tons, and the counterweights are so disposed as to counterbalance the table and ingot. Thereafter the problem becomes merely one of starting and stopping, but with enormous masses and unusually short time-periods involved. If the connecting rod *A* were of infinite length, plotting the movement of point *B* in the direction of the arrow against

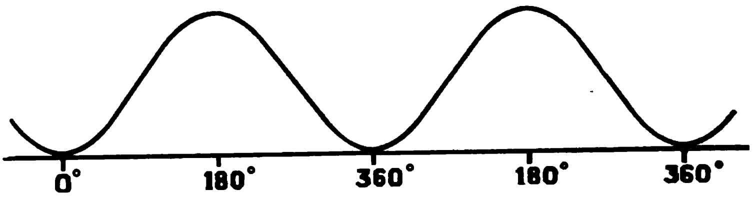


Fig. 10

the degrees of rotation of crank shaft *C* would result in a true sine curve, Fig. 10. Taking this curve as a basis, it is easily seen that during the first few degrees of rotation there is but little movement imparted to the connecting rod and hence to the table. This being true, almost the entire starting torque of the motor is available for accelerating its own armature; and if it is accelerated before the curve begins to rise abruptly the full torque will then be available for accelerating the table and counterweights. At the top the table is decelerated by virtue of the shape of the curve, the full torque of the motor being again available for retarding its own armature. While the connecting rod used in actual practice is so long as somewhat to distort the rotation-movement curve, Fig. 10, at the same time this curve is close enough to that obtained in practice for an understanding of the installation.

FIG. 11—Three-high blooming mill with motor-operated elevating table

The first installation worked out very well indeed. The table rose in 2.4 sec., 0.4 sec. of this period being required to accelerate and 0.4 sec. to stop, the motor operating at full speed 1.6 sec. Recording ammeter charts show that this is accomplished without the motor requiring more than full-load current at any time. The controlling mechanism is entirely automatic, a movement of the operator's master-switch causing the table to rise and automatically slow down, and stop, while a reverse movement causes it to lower automatically, slow down, and stop. Although there is a solenoid-operated brake on the equipment, its time-lag is such that it never acts until the table has been brought to rest by generative action. The shape of the rotation-movement curve is again of value in that a few degrees of error in the stopping point, top or bottom, does not influence the position of the table to any extent.

The objection to the installation just described is the necessity for accelerating and stopping the counterweights at either end of the cycle, which adds considerably to the power required to operate. Therefore when the table for the blooming mill at Gary, Fig. 11, was designed, hydraulic counterweights were employed. The bell-cranks carrying the table are connected to hydraulic cylinders piped to the compression tank partly filled with air. When the table is down the air pressure in the compression tank over-counterweights the table by 25 per cent. When the table is up it is under-counterweighted by 25 per cent. This is accomplished by a proper proportion of air and water in the system.

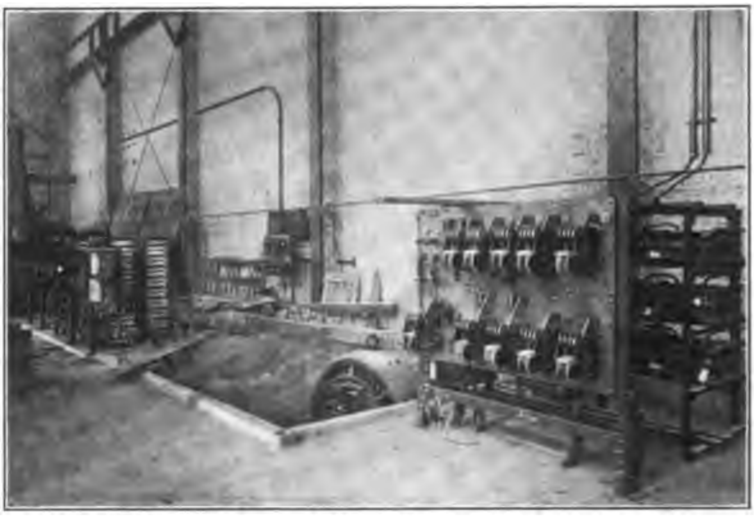


FIG 12—Contactor type controlling panel for 200-volt, 250-h.p. direct-current motor used to raise and lower blooming-mill table

The Gary table moves 43 in., weighs approximately 250,000 lb. and makes a cycle in 3 sec. It is operated by a 250-h.p. motor running at 100 rev. per min. Immediately after completion of the Gary table, an interesting test was made to determine how closely the acceleration curve followed a true sine wave. A board carrying a paper chart was placed on the side of the table, and an electric bell with clapper removed and a pencil substituted connected on a 25-cycle circuit and arranged to make dots on the chart. Connected on a circuit of this frequency, it would make 50 dots per second. The distance between dots served as a guide in the compiling of a curve which, considered with the recording ammeter chart, shows the motor to be up to speed when the table begins to rise with any rapidity. Unfortunately a copy of this accelerating curve is not available for presentation at this time.

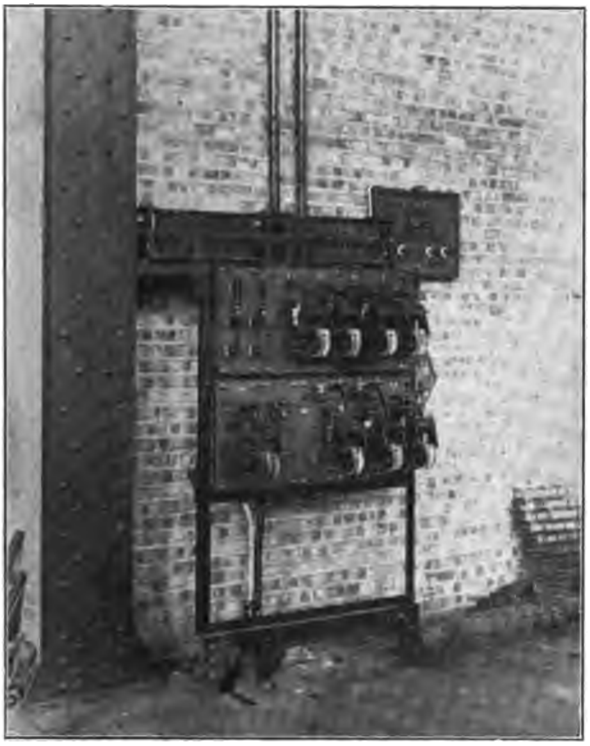


Fig. 13—Typical contactor type controller panel

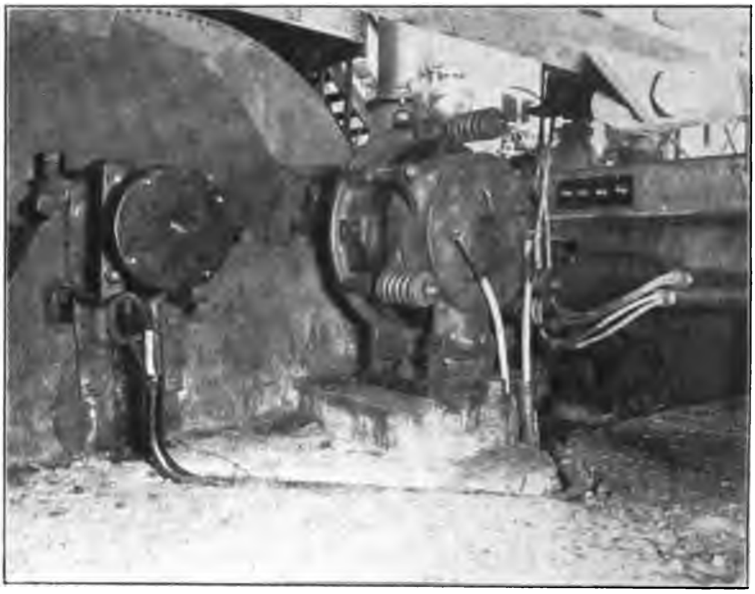


Fig. 14—View underneath tilting table of three-high roughing mill, showing automatic limit switch and disc brake

Fig. 15—Hot bed with pulpit containing master switches for rake-offs and drag-outs

The Gary plant is filled with interesting automatic controllers. The completeness and effectiveness of the installation can be appreciated when it is considered that eight operators are able to turn out 100,000 lb. of rails per month. One of the most unique features of the plant is the automatic coal skips. Coal is delivered to the gas producer houses in standard railroad gondolas, from which it is dumped into a hopper. From here it goes through a crusher, and thence to the coal skips, which are of the double-balanced type, and arranged to dump into the bins, from which the producers draw their supply.

Fig. 16—Hot saws for sawing steel rails

When at the bottom, the skip-car automatically opens the chute-gate and rests on one end of a counterweighted lever. If there is any coal coming through the crushers, t will feed into the skip; if not, the entire equipment will remain inoperative. As soon as a certain quantity of coal has been fed into the skip-car it overcomes the counterbalance. This action starts the motor driving the hoist. In leaving the bottom position the chute is closed, and when the first skip-car is dumped, a second is at the bottom and ready to take coal. This automatic action continues as long as there is coal to be hoisted, a counting device for registering the number of trips being a fairly accurate indicator of the total tonnage of coal handled.

While this electrification of auxiliary apparatus has been going on, there has also been great progress made in the electrification of the rolls themselves. No electrical engineer is over-optimistic in believing that another 10 years will see the complete elimination of all motive power other than electricity in steel plants. In fact the only question to-day seems to be whether auxiliary apparatus of a reversing character shall be operated by alternating current or by direct current. Experiments now being conducted at Gary, where both types will soon be installed, may lead to some definite conclusions on this subject.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

AUTOMATIC MOTOR CONTROL

BY H. E. WHITE

Of the various systems for controlling electric motors, none surpasses in interest and economic importance those which make use of electrically actuated switches controlled by automatic or semi-automatic means. A few years ago the drum controller was quite sufficient for any motor then in use. Since then the use of larger motors and the need for automatic features, unattainable in a simple manner with drum controllers, have resulted in the development of a great variety of magnetically controlled switches, and of various means for operating them in control systems.

At the present time, contactors may be obtained for handling the current required by the largest motors in use, and it can safely be predicted that in the future with even larger motors, air-break switches of the contactor type with magnetic blowouts will be used more and more for high-voltage current, hitherto thought controllable only by oil switches. Tests have in fact already been made showing that currents of 6600 volts can be successfully handled in this way.

Control by contactors is so universally adapted to service under special conditions, that the advantages which it offers over other devices are worthy of mention. Among these are:

a. The ability to control motors of any size with facility and with slight muscular effort.

b. The ability to control many motors from one conveniently chosen place.

c. The ability to control large motors from a distance with comparatively inexpensive connecting cables.

d. The ability, in conjunction with overload devices, to predetermine the current input to the motor, either during or after starting.

e. The ability to use sensitive devices, such as pressure gauges or thermostats to start motors operating machines such as pumps or blowers.

f. The ability to obtain " no-voltage release " and automatic re-starting features without additional complication.

g. The ability to secure interchangeability of parts to an extent not possible with any other type of control.

h. The ability to secure automatic stopping by limit switches to prevent overwinding or to stop the motor at predetermined places.

The methods by which these results are attained are best understood by examining the principles of operation with particular reference to which recent designs have been made.

The design of the contactor itself is the one thing on which too much stress cannot be laid, for the reason that on it falls the function of repeatedly opening and closing heavy currents in a reliable manner without frequent inspection or adjustment. Properly designed contactors have the inherent advantage of opening and closing quickly, thereby lessening the duration of the period during which the circuit-closing parts are making poor contact. This poor contact period results in a local fusion of metal with consequent wear. In fact, it is well known to those familiar with this type of apparatus, that the wear on the contacts is due almost entirely to local effects at the instant of making or breaking circuit and only slightly due to the vaporous arc formed. It is largely to this fact that the efficiency of motor control at high voltage is due, since the tendency to fuse the points of contact is proportional to the square of the current value, and not to the voltage. In case the currents are very high, recourse must be had to the use of refractory contacts for which the only commercially available substance is carbon. As to carrying capacity, there is a tendency in recent designs to secure it by forcing the contacts together at considerable pressure, but carefully made experiments show that the gain is greatest for the first increase in pressure on the contacts, so that it does not pay to attempt to carry the pressure too high.

Operation at high contact pressure results in the very important advantage that, when the recoil of the springs takes place at the time the contactor is de-energized, a much quicker opening results. In case the contactor is required to carry a very large current for a long time, an auxiliary laminated copper contact is used. The magnetic blow-out has been found equally effective for both direct and alternating current.

Voltage variation affects the operation of contactors in common with other devices operated by a solenoid. The pull of a solenoid varies approximately as the square of the voltage. As a consequence, any abnormal voltage conditions produce correspondingly increased effects on the contactors. This necessitates, in order that satisfactory operation may be assured, that the amount of copper used in the solenoid be sufficient to carry the current at full voltage without overheating, and to give at the same time pull enough at low voltage to ensure reliable mechanical action.

In the case of contactors operated by alternating current, laminated magnets are necessary to ensure operation without excessive heating. The action of solenoids on alternating current is quite different from their action on direct current. On alternating current, the tendency is towards constant pull independently of the position of the armature, with a corresponding reduction in magnetizing current as the solenoid closes. On direct current, the pull greatly increases as the solenoid operates. These peculiarities have a direct influence on the comparative action of the two types of contactor. The alternating-current contactor closes at a great speed, almost violently, while the direct-current contactor closes more leisurely, its self-induction tending to slow it down very noticeably. The heat generated in an alternating-current contactor is usually greatest in its iron magnetic circuit, due to the high densities required and to the alternating magnetic flux. In the direct-current contactor, the heat is generated entirely in the copper parts carrying current. One peculiarity of the alternating-current contactor is its tendency to hum. This can be reduced to an unobjectionable amount by the use of "pole-shading" devices, and contactors for operation on alternating current will consequently be more extensively used as they become better known.

In applying contactors to the control of motors a so-called *current-limit control* is usually employed. In all the simpler systems, the contactors are so arranged that as each one closes, it completes the actuating circuit for the next contactor, thereby causing the controlling resistance to be short-circuited step by step. One or more overload relays are so arranged that this progressive action will be interrupted without causing any contactors to be opened whenever the current exceeds a predetermined amount. As soon as the current decreases and the relays fall, the operation is renewed, until finally the motor is operating at full speed. In other cases, the contactors are arranged with their operating coils in multiple with the armature of the motor, so that as the motor starts, the increasing electromotive force across the armature will cause the contactors to operate one by one. This arrangement is known as the *counter-electromotive-force system*.

The last-named system is open to the objection that if the voltage of the supply system is not constant, the operation of the control is interfered with, the result being that if the voltage is low, the contactors may not close at all, while if the voltage is too high they will close too soon. This system is best suited for use with shunt motors and not so well suited to series motors, for the reason that the counter electromotive force of a series motor depends upon the current as well as upon the speed of the motor, so that there is a tendency to cut out all of the resistance in case a contactor closes prematurely.

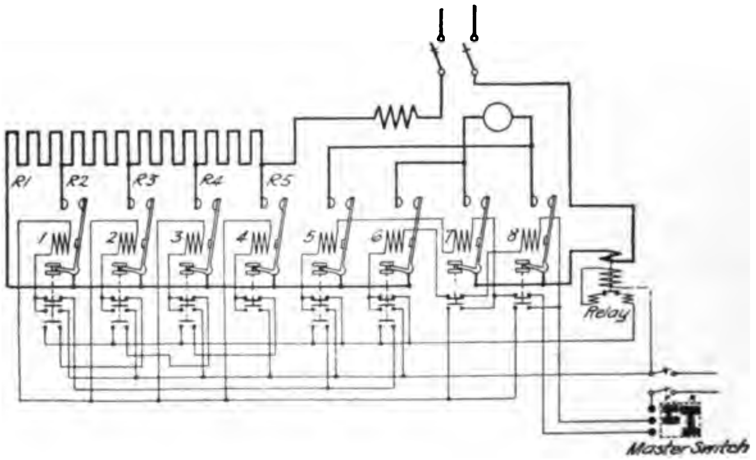


FIG. 1.—Current-limit control with single relay

A modification of this system, using potential relays in multiple with the starting resistance, is so arranged that as the current in the resistance decreases step by step, the relays will fall out and close actuating circuits for the contactors. This modified system is not open to the same objections as the counter-electromotive force system, and is substantially equivalent to current-limit control. In some cases, *time-limit control* is useful; that is, the contactors are arranged so that they will be energized in a given time regardless of other conditions. In this case an escapement or dash-pot is usually employed.

Still another type of control, which may for want of a better descriptive name be called *pilot-motor control*, uses some form of an electric motor to actuate a master switch. This motor can be controlled in any manner desired by overload relays or push-buttons. This system is the one generally used where the control is of a comparatively complicated nature, such as in printing-press work.

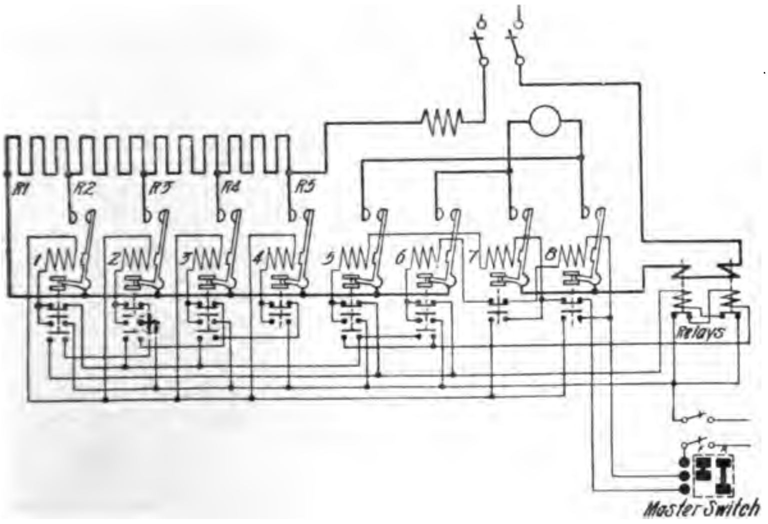


FIG. 2.—Current-limit control with double relay

It is interesting to note that the control of the 2000-h.p. and 6000-h.p. motors at Gary is of this type. In this place, it was used to avoid complicated interlocks on the contactors, which would otherwise have been required to secure the results desired.

The choice of control system to be used in a particular case will be determined by the special conditions governing each case. However, it can truthfully be said that while some of the other systems appear to be specially suitable in some respects, yet current-limit control is always better when all the conditions are considered.

Aside from the current-limit control obtained by the pilot-motor system, two comparatively distinct systems of current-limit control are now in common use. In one of these is used a single relay, with series and shunt coils. In this system as each contactor closes it completes a momentary actuating circuit for the next contactor, which then closes and establishes a holding circuit for itself independent of the momentary circuit above mentioned. The momentary actuating circuit passes through the contacts and shunt coil of the relay and causes the iron core of the relay to lift an iron core into the field of influence of the series coil, thereby interrupting the circuit at the relay just after the contactor has completed its holding circuit. When the contactor is fully closed, the interlocks establish a circuit to the next contactor through the relay, so that the above operation will be repeated for this contactor in the same manner, provided the current in the series coil of the relay does not delay the completion of the circuit by holding the iron core up. In other words, if the increase of motor current caused by the closing of the contactor is great enough, the core of the relay

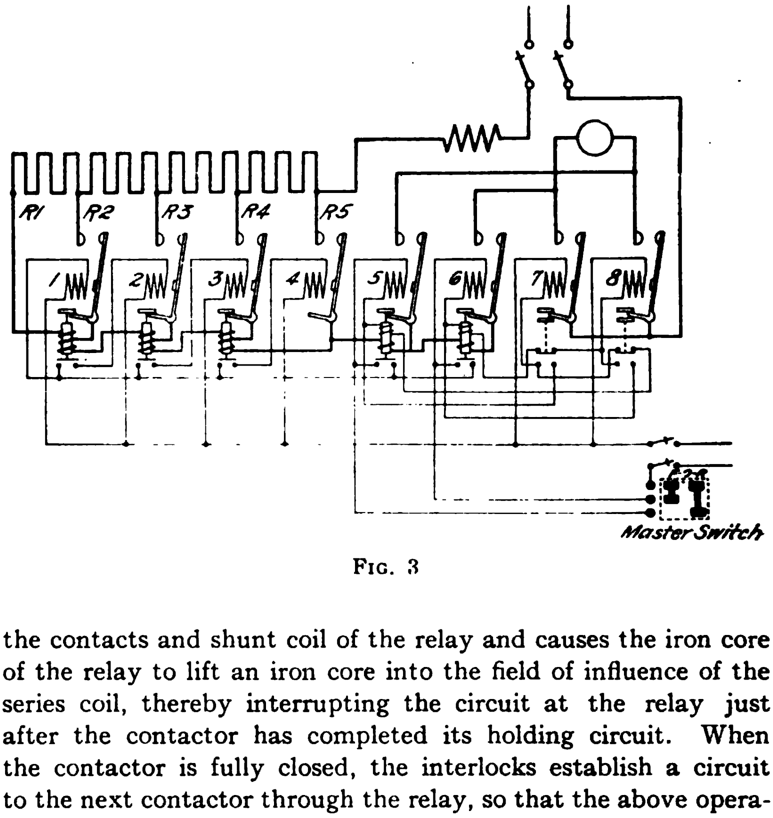


FIG. 3

will be held up and the " pickup " circuit for the next contactor will not be immediately completed. This system for reversible rheostatic control is shown in Fig. 1. The objection to this system is principally in the complicated interlocks necessary to perform the above operation. It has the advantage that the current-limit value for all of the contactors can be obtained by adjusting one relay. A further advantage lies in the considerable pressure with which the interlocks are held in contact. This advantage fits the system for use specially in transportation work and it is consequently most commonly used in railway service. A modification of this system using two relays and shown in Fig. 2, is an improvement in that less difficulty is met in adjusting the speed of the relays.

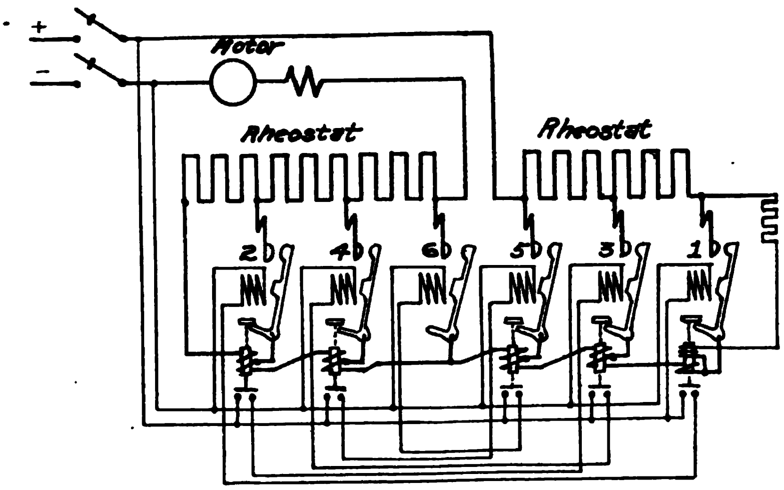


FIG. 4.—Current-limit control with separate relays arranged to introduce resistance into circuit step-by-step in case of overload

The second system makes use of a separate relay for each contactor. In its simplest form, each of the accelerating contactors includes as an integral part of itself an overload relay, which is held in the open position by a mechanical connection with the contactor until the contactor is closed, and is then allowed to drop and complete the circuit for the next contactor, only under the control of the current which passes through the contactor and the series coil of the relay. This arrangement is shown in Fig. 3, as used for a reversible control equipment.

A comparison of this system with the preceding ones will show its greater electrical simplicity. It will be seen that each series relay consists of two coils, and that these coils are so connected to the source of current and to the rheostats, that current flows through them both in series until the contactor is closed, after which current flows through only one coil. By this means, the relay is prevented from closing until the contactor has fully closed, and the increase of motor current resulting therefrom has become effective in the relay.

By using separate relays, acceleration can be secured at an increasing rate step by step or, if desired, at a decreasing rate. As ordinarily arranged, each relay is cut out of circuit as soon as the next contactor closes. In case, however, the circuits are so arranged that the relay is not cut out of circuit until the second next contactor closes, an equipment is obtained which has the interesting property of cutting resistance back into circuit step by step in case of an overload. The connections for accomplishing this result are shown in Fig. 4. Fig. 5 shows a motor starter with shunt type of relays in multiple with the starting resistance as described in the first part of this discussion.

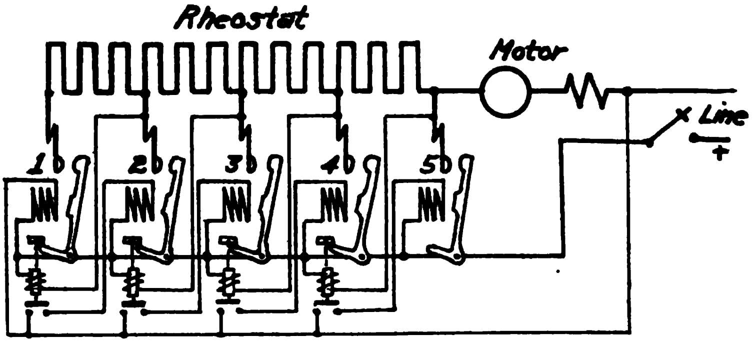


Fig. 5.—Automatic motor-starter with separate shunt-wound relays in multiple with starting resistance

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ELECTRIC POWER PROBLEMS IN STEEL PLANTS

BY R. TSCHENTSCHER

Prior to September 1904, the capacity of electric power plants in American steel mills varied locally from 200 to 3000 kw. The largest units were of approximately 1000 kw. capacity, and only direct current at a pressure of 250 volts was used. Plans in contemplation over a year before 1904 resulted in the construction of the first steel mill power plant of any magnitude at the south works of the Illinois Steel Company. This plant consisted of a 4000-kw. station composed of two 2000-kw. 25-cycle, three-phase, 2200-volt steam-engine-driven generators. It was put in operation during September 1904, and supplied two converter sub-stations, transformers for local alternating-current motors, and a 22,000-volt transmission line 10 miles long supplying alternating-current motors at a cement plant. Since 1904, many of the comparatively small electric power plants in steel mills have been increased to several times their original capacity.

Steel mills may be divided into four general classes; namely:

A. Finishing mills, or those that buy steel in the shape of blooms or billets and reduce them to a commercial form.

B. Steel-making mills, or those that buy iron and other materials needed in making steel. These mills are equipped with steel furnaces, and reduce their product to a commercial form.

C. Self-contained steel mills, or those that buy the raw materials necessary to make iron. These mills are equipped with blast furnaces, steel furnaces, and rolling mills for finishing the product.

D. Self-contained steel mills which also supply power to auxilliary plants, such as cement mills, or to other consumers.

A. The electrical problems differ somewhat in the mills as classified above. In finishing mills the electric plant usually consists of a direct-current, steam-driven station of from 200 to 1000 kw., supplying power for table motors, cranes, conveyors, lights, etc. No alternating-current power is used and the maintenance is a simple matter. The future problems of such a plant may result in the installation of motors to drive the mill rolls, replacing wasteful non-condensing engines and inefficient boiler equipment, and the installation of a modern efficient generating system, either steam-turbine or producer-gas-engine-driven (unless natural gas is available). The matter of installing storage-batteries and other refinements is a local one.

B. In existing steel-making mills the electric plant, though similar to that of plant *A*, is of somewhat larger capacity, ranging from 400 to 2000 kw. The power demand is also for a similar purpose, and a mixed alternating-current and direct-current system is not required. The future problems of such a plant are similar to those of plant *A*. The development of the electric steel furnace may, however, be such that a commercially feasible equipment might result and " cold metal " (pig iron, scrap, etc.) be converted into steel, thus doing away with cupolas or Bessemer converter installation. The electric power problem would then be materially altered, as described later.

C. In existing self-contained mills, the present problems are so diversified that a generalization is not as feasible as in the two preceeding classes. The electric plant problem is virtually a local one. A few general remarks may, however, be made. The electric power plants of such mills range from 500 to 10,000 kw. capacity, the larger capacity depending upon whether motor-driven rolling mills are in service, and other considerations of large power demand. In plants without motor-driven rolling mills a single direct-current system often exists, which, when properly arranged, makes for a decidedly simple and easily maintained equipment. The power demand consists of: 1. Ore-handling equipment, such as unloaders, conveyors, distributors, etc. 2. Sundry blast-furnace service, such as raw material supply cars, skip hoists, etc. 3. Steel-furnace application such as raw material, hot metal and scavenger cranes, charging machines, stripper cranes, etc. 4. And for the sundry rolling mill purposes as previously enumerated.

In mills without large concentrated power demand the problem of installing storage-batteries is a local one, and will depend frequently on the ore-handling equipment. If this be considerable, or if located some distance from the power plant, then questions of power-plant capacity or of voltage at the ore-handling plant may be solved advantageously by proper storage-battery installation instead of added direct-current generators in the former case and alternating-current generators and converters in the latter case. Where such ore-handling load does not exist, the station power fluctuations will in general not be over 10 or 20 per cent, and sufficient generating equipment only is needed. This equipment may be operated at a high load-factor, the necessary maintenance being attended to on Sunday when the rolling-mill load does not exist. The desirable arrangement of simplicity and uniformity of equipment which exists in every industry is most pronounced in mill work on account of the comparatively large repair expense, the inefficient operatives, and the costliness of delays. Therefore, a single generating system with simple distribution is desirable and feasible in plants of this kind.

In plants with motor-driven mills or other sources of considerable power demand, the problem becomes rather complicated. Again it is one of local treatment, though no doubt a few general principles may apply. The generating requirements will in most cases result in an alternating-current equipment. If the plant is an existing one and inefficient rolling-mill engine and boiler equipment is to be replaced by motors operated by means of efficient power generated in the vicinity of the blast furnaces so that blast-furnace gas may be utilized, then the commercial limitations will not usually admit of replacing the existing direct-current generating station. A second station must be built, either adjoining the direct-current station or at some more advantageous point. Proper electrical connecting apparatus between the two stations must be supplied. This will usually consist of a converter floating between the two station bus-bars. The advantage of this arrangement cannot be overestimated, as operating conditions will usually be such that at stated intervals (Sundays) either station may be shut down in whole or in part. The selection of proper alternating voltage may also be a local one, though the experience of the last 5 years shows that the increase of electrical application in steel mills is so rapid that a pressure of less than 6600 volts for local generation and distribution will no doubt result later in an unwieldy arrangement of switchboard and cable equipment and distributing feeders. The frequency of 25 cycles, now used almost exclusively, is most suitable, and nothing has yet appeared to indicate that a higher or a lower frequency would be more desirable.

D. It will no doubt be of some interest to discuss specifically a few of the electrical problems encountered in a large steel mill. For this purpose the plant of the Illinois Steel Company at South Chicago, Ill., will be outlined. This plant comes under classification *D*, previously referred to; namely, self-contained steel mills which also supply power to auxiliary plants such as cement mills, or to other consumers. Naturally enough, it is in such plants that the greater variety of electrical problems exists and where electrical application will be most extensive.

The South Chicago works of the Illinois Steel Co., is a good example of the self-contained steel mill. Its development during the last 5 years has been remarkable. Prior to September 1904, the electrical equipment of this plant consisted of a direct-current generating equipment of 2900 kw. at 250 volts pressure. Even at that time this was the largest electrical installation in an American steel plant. The electrical power demand consisted of that usually found in mills under classification *C*; namely, all classes of cranes, mill tables, and miscellaneous equipment, illumination etc. Since that time additional blast furnaces, ore-handling equipment, steel-making mills, finishing mills, and two cement plants have been added. Where steam engines had been used at blast-furnace skips, motors were installed and the cost of operating was reduced. Where steam engines had been used for ore handling and for all new ore-handling equipment, motors were installed, the output increased, and the cost reduced. Where new rolling mills were designed, motors on the main rolls were specified, with consequent increased tonnage at lower fuel and maintenance costs. Where new cement mills were installed, motor drive was employed throughout and power obtained by means of high-voltage transmission lines from an efficient power plant. Again the output was increased and the cost reduced.

Without going further into details, the electrical installations at this plant have during the last 5 years resulted in an equipment approximately as follows:

Number of motors, both alternating current and direct current	2,000	
Total motor horse power	75,000	
Total number of arc lamps	1,500	
Total alternating-current generating equipment installed	16,000	kw.
New alternating-current generating equipment being installed	9,000	"
Total direct-current generating equipment installed	3,000	"
Total generating equipment	28,000	"
Total synchronous converter (and transformers) and motor-generator equipment	6,500	"
Total storage-battery equipment	1,200	"
Total transformer equipment	31,000	"

The variety of the equipment may be judged from the various existing voltages; namely, 250-volt direct current; 110, 440, 1100, 2200, and 22,000-volt alternating current. This plant comes under the heading of " evolution plants "; that is, plants wherein steam and hydraulic equipment have been in process of replacement by electrical equipment. The solution of the various problems in such a plant does not result in the more desirable and simple systems which will be found in future new plants, for in the new plants the large variety of voltages mentioned above will surely be avoided.

One of the problems in steel mills now receiving considerable attention, and which in the future will be one of the real engineering problems, is the conservation of waste heat. The existing waste heat at open-hearth furnaces forms an enticing point of attack; this waste may be eliminated by replacing such furnaces by electric steel furnaces. These furnaces will be mentioned later. However, the waste heat at rolling mills does not as yet appear to be capable of satisfactory elimination. All steel before being rolled must be heated so that an even temperature, and hence even consistency throughout the piece, will result. Producer-gas furnaces are now used almost exclusively for this purpose. The stack temperatures are usually very high, being between 800 and 1200 degrees fahr. These temperatures may readily be reduced by passing the gases through suitable steam boilers to provide steam for turbine-generators. It is not at all improbable that instances exist where with proper installation of boilers, regenerators, turbine-generators, and roll motors, a rolling mill may be made a self-contained unit, obtaining from its present waste heat sufficient power to supply electrically the entire requirements of the mill, including the roll motor, table motors, crane equipment, lights etc.

The utilization of the energy remaining in the exhaust from non-condensing engines and from compound engines is now receiving serious consideration, the large amount of energy wasted in engine exhaust steam in non-condensing engines being roughly estimated at 50 per cent of the total available energy. The rolling-mill engine appears to offer a very desirable point of attack in this connection. However, the writer wishes to emphasize that there are many other places in most steel plants where this problem might better be attacked from the standpoint of permanent equipment. By attaching a low-pressure turbine equipment to the exhaust of a non-condensing rolling-mill engine, a premium is put on the retention of that engine in service. The superior operating and cost advantages of motor drive over reciprocating-engine drive (with accompanying boiler equipment) cannot be taken advantage of. The steam engine with a tail in the form of a turbine-generator will be much more difficult to get rid of. It would therefore appear that the other weak points about the mill should be first seriously investigated.

The steam-engine blowing equipment at many blast furnace plants consists of well built compound engines. The possibilities here for low-pressure turbine installation are very great. At a plant which recently came to the writer's attention, four blast furnaces receive blast from eight modern condensing blowing engines. Roughly, the amount of steam required by these engines is 300,000 lb. per hr. By the addition of less than 100,000 lb. these engines develop their required power with exhaust at 16 lb. absolute. These 400,000 lb. of steam would be sufficient to supply a low-pressure turbine-generator capacity of approximately 15,000 kw. The power station installation might consist of three 5000-kw. units. Sufficient power would be available to convert all the mills at this plant to electric drive.

One of the electrical problems at the plant of the Illinois Steel Company which may be of interest concerns the installation of additional generator capacity. A solution of the problem which contains many admirable points was an installation of a low-pressure turbine so designed that high-pressure steam up to full capacity will be economically utilized. Compound condensing reciprocating engines in the power station and in an adjoining blowing engine station will normally supply the steam for this turbine which will be of 9000 kw. capacity. Each compound engine will be so arranged that it may exhaust into the present condenser, or into the turbine main at slightly above atmospheric pressure. In case of insufficient low-pressure steam, the deficiency may be supplied from the high-pressure main, the turbine being so arranged that this high-pressure steam will be economically employed by means of a separate valve and nozzle chamber. Should no low-pressure steam be available, the full capacity at high-pressure steam may be obtained. The condensing equipment will be adequate, the yearly calculated vacuum averaging better than 1 in. absolute pressure. Reliability and economy are the predominating features in the installation. The operation will be watched with interest and it is expected that gratifying results will be derived.

Another problem at this plant which may be of interest was the improvement of the power-factor. The installation of alternating-current roll motors, miscellaneous small alternating-current motors, and the expansion of cement mills where the sole drive is by induction motors, have so affected the power-factor that at present the station power-factor is not over 70 per cent. The largest item in bringing about this condition is a load of approximately 7000 kw. of induction motors at a cement plant supplied by a 10-mile transmission line of 22,000 volts stepped down to 440 volts. Improvement of the station power-factor by corrective means at the cement plant at once suggested itself. This might originally have been accomplished either by the installation of direct-current equipment including motor-generators or synchronous converters or by the use of a considerable number of synchronous motors in place of induction motors. The operating conditions—character of service, cement dust, and inefficient operatives—make the former comparatively impracticable; the additional complication of miscellaneous operation of synchronous motors at proper power-factor by inefficient help makes the latter also undesirable. It is an ever present axiom in steel mill practice that the mill equipment should be simple, rugged, and easy of operation and repair. Whatever refinement and complication may be beneficial should be confined to engine rooms, power stations, sub-stations etc., where labor more skilled in maintaining the equipment may be employed. The foregoing therefore led to the decision that the cement-mill equipment should include the induction motor, the squirrel-cage type being used wherever possible, with simple starting apparatus such as step-down transformers with starting bus-bars, instead of local compensators and starters for each motor.

The question of power-factor correction resolved itself then into the installation of "synchronous condenser" equipment. In order to prove such an equipment commercially advisable, it is of course desirable to have the so-called condenser do mechanical work so that such proportion of its initial cost and operation and investment expense could be charged against it, making the charge for power-factor correction correspondingly less. However, mechanical work of sufficient magnitude did not exist at the cement plant, and the problem resolved itself into determining whether such a synchronous condenser equipment operating idle would prove a commercial proposition. A detailed study of this case was made; the following items give the points at which loss of energy would be reduced, a loss that could be expressed commercially, most of the factors being the components which tend toward combined efficiency;

a. At station generator fields, due to less excitation being required as the power-factor improved.

b. In station cables and switchboard equipment, on account of less current at improved power-factor.

c. In step-up transformers, due to improved power-factor.

d. In transmission line, due to less current and improved power-factor.

e. In step-down transformers for the same reason.

f. In step-down transformer wiring and switchboard equipment.

To offset the foregoing there is the energy required to operate the so-called synchronous condenser. With a delivered load of approximately 7000 kw. at 70 per cent power-factor, the over-all efficiency is approximately 83 per cent. The installation of two 1650 kilovolt-ampere synchronous condensers will raise this over-all efficiency to 87.5 per cent, the net gain of power being approximately 300 kw. which at 0.5 cent per kw-hr. represents a yearly saving of approximately $10,000. In addition to this, the power station capacity will be appreciably increased, due to the present engine capacity exceeding present generator capacity, and due in a small measure to decrease of excitation load. This gives the commercial aspect. The purely technical aspect of improved operation (regulation and control) due to improved power-factor needs but to be mentioned.

Where alternating-current motors are used to drive rolls, or for miscellaneous mill purposes such as for tables, cranes, etc., where now direct-current motors are used almost exclusively, the power-factor conditions will no doubt require power-factor correction; this may be accomplished by the installation of adequate synchronous condenser equipment. The commercial problem will here be rendered more simple, for considerable mechanical load in the nature of air-compressors, pumps, fans, etc., may be supplied to render the charge for power-factor correction materially less than that outlined above.

Before closing, it may be of interest to dwell upon another problem of considerable magnitude which is just becoming manifest. This refers to the manufacture of steel by means of electric power. The Illinois Steel Company has in operation a 15-ton electric furnace of the carbon-arc type. Three 750-kilovolt-ampere, 2200 to 100-volt, 25-cycle transformers are installed. That the making of steel by means of electricity will in the near future be an active commercial proposition in the manufacture of products where now crucible, open hearth, and Bessemer steel are used, is practically an established fact. This can easily be conceived to require power stations of a magnitude comparable with those of the largest lighting and railway plants. The writer believes the future will demonstrate that the country's largest power generating stations will be found within the confines of the steel plants. When one considers that a steel making furnace plant utilizing electric power to generate the necessary heat and having a capacity of 4000 tons per 24 hr. requires generating capacity of 20,000 to 30,000 kw., it is not difficult to conceive the magnitude toward which the future steel mill power plant will tend.

Let this thought be carried a little further to illustrate a plant wherein the application of electricity would be supreme. A 2,000,000-ton-per-year self-contained plant where coal, flux, ore, and other raw materials enter and where all classes of steel products, together with cement and the bi-products of coke ovens, leave the plant as finished salable products, might consist of a blast-furnace plant, a Bessemer converter plant, an electric steel-refining plant, a sufficient number of rolling mills, a cement plant, and a coke-oven plant. Such a plant would require electric generating capacity depending largely on the extent to which the finished product was carried. Consider the plant as finishing three-fifths its product as rails, one-fifth as plates, and one-fifth as structural shapes. The total electric power requirements for such a plant would be over 100,000 kw., and it is quite likely that such power could be generated without burning coal for power generation fuel purposes. The so-called waste gases of blast furnaces and coke plants and the utilization of other waste heat would supply more than the required fuel.

If now a plant be conceived wherein the product is further finished; for example, into tin plate, wire etc., a point may be reached where fuel must be obtained from sources other than the usually considered waste sources about the plant. The possible reduction of iron from ore by electrical application, or the manufacture of steel electrically direct from ore, are mentioned merely to show possibilities. The realization of such possibilities would be due to the designing and installation of power plants in comparison with which the foregoing mentioned equipment would be inconsiderable.

DISCUSSION ON "FUNCTION OF FLY-WHEELS IN CONNECTION WITH ELECTRICALLY OPERATED ROLLING MILLS." "ROLLING-MILL MOTORS." "ELECTRIC DRIVEN ROLLING MILLS." "POWER REQUIREMENTS FOR ROLLING HIGH CARBON STEEL OF SMALL SECTION." "ELECTRIC CONTROL FOR ROLLING-MILL MOTORS." "AUTOMATIC MOTOR CONTROL." "ELECTRIC POWER PROBLEMS IN STEEL PLANTS." FRONTENAC, N. Y., JUNE 30, 1909.

D. B. Rushmore: The subject of steel-mill work is certainly as important as anything at hand just now in the way of electrical development, and the most important requirement of steel-mill work is reliability. It is unfortunate that steel mills will to some extent buy on prices, but they are outgrowing that, because price always means a sacrifice of engineering features. The value of the output is so great in comparison with that of the machines which are used in its production that I think it is a wrong policy to make any very great difference in the equipment due to a difference in price, assuming that several alternative schemes are presented; that is, putting all the manufacturers on the same basis, the ordinary factors of competition, it seems to me, should in these cases give way. In reality, the man who is to control this situation should be the engineer of the steel mill and not the purchasing agent, because all manufacturers are to a large extent interested together in the success of electricity as applied to steel-mill work. At the present time there is no phase of the electrical development of steel-mill work more important than the control apparatus, for the steel mills must electrify generally if they are going to compete with those which have already done so and the controlling apparatus must be perfected so that the output of the mill will not be interfered with.

Mr. Tschentscher has touched the edge of the subject of getting power from the waste gas, but whether burning the gas directly under gas engines or burning it under the furnaces, or utilizing it in connection with steam turbines, is the best means of using it is still an unsolved problem. The design of gas engines for blast-furnace gas, for large powers, is by some considered somewhat of an open question; for while it is easy to figure out the supposed thermodynamic efficiency and the actual cost of the power which one will get, yet the development is not on such a basis that that is all which needs to be considered. What the steel-mill man wants is the net return on the gas from the operation of the steel mill; one of the factors is the output, and any interruption to service goes heavily against the cost of this, and has to be considered in estimating the cost of power. The proprietors of steel mills say they can handle electrically driven mills better than steam driven mills, for the reason that the piece always goes through the roll at approximately the same speed and it is in better shape to start the succeeding movement. The reciprocating apparatus is practically doomed, it seems, with the possible exception of the gas engine, and that has a threatening successor in the gas turbine. The use of gas turbines and the possible use of gas through the furnace and for steam turbine work, would practically remove all reciprocating apparatus from the steel mill.

Mr. Specht has picked out, perhaps, the most interesting problem in steel mill work, the fly-wheel capacity for special service. Unfortunately, this particular determination is not always left to the motor manufacturer. It seems that steel mill men, realizing that it is difficult to maintain normal conditions continuously on roll trains, often specify motor capacity and fly-wheel capacity much in excess of that needed for normal operation.

On the other side, there has been of late a carefully performed series of experiments to determine the power required for rolling steel, and some very interesting results have been obtained in regard to the variation of this power with the temperature of the piece. That is one case to illustrate the point that there is necessarily in all this class of work a very large margin, because the factors which enter into it cannot all be determined with precision, and are susceptible of considerable variation.

Brent Wiley: The following formula offers a convenient method of calculating the fly-wheel capacity of a system, and for an average case the run of the fly-wheel is figured as two-thirds of the total weight and the spokes and hub one-third of the total weight.

$$\text{Wt.} = \frac{Fs \times 2 \times 32.2}{B}$$

Wt. = weight in pounds.
Fs. = foot-pound-seconds = h.p. × 550 × sec.
B = difference of velocity squared at high and low speed in feet per second at radius of gyration.

I understand that originally the automatic features in the Indiana Steel Company's plant were incorporated in the motor-control apparatus and that later the system of control was changed somewhat; that is, to the extent of operating the controllers instead of automatically cutting in and out the resistances operating the motors with a permanent resistance.

K. A. Pauly: When the proposition for the rail-mill motors was being considered, the use of a small permanent resistance versus a variable resistance in the rotor circuit, to allow the fly-wheel to take the peaks, was discussed thoroughly; and it was finally decided that because of the ease of removing the automatic variable feature, it would be better to install the automatic control. Tests made after the apparatus was installed indicated clearly the use of a permanent resistance to be preferable. However, the direct-current contactor (because of the high inductance of its operating coils and the lack of opportunity of raising the impressed potential sufficiently above the operating potential by the insertion of resistance in series with the solenoids) is necessarily more sluggish than the alternating-current contactor. Possibly with the alternating-current contactor, recently developed, which operates more rapidly, there may still be something in the automatic acceleration and retardation over a small range. However, as the control with permanent resistance operates satisfactorily, and eliminates one of the possible troublesome parts of the control equipment, the automatic feature should be, at least for the present, omitted entirely.

With reference to Mr. Specht's paper, it must be borne in mind in determining the capacity of a fly-wheel to meet any given cycle, that the fly-wheel is employed as a means of reducing the operating cost of rolling. There are, therefore, many factors which must be taken into consideration in determining the most economical fly-wheel capacity. Among the important ones which are frequently overlooked are:

1. The cost of power, the first cost of the generating station and of the rolling-mill motor.

As pointed out in the paper, by the use of the fly-wheel we reduce the capacity of the rolling-mill motor necessary for performing the work, and of the generating station supplying the power, but at the expense of efficiency. When the cost per unit of power and the cost per kilowatt of generating capacity are high the economical size of fly-wheel is greater than when these costs are low.

2. The capacity of the fly-wheel is affected by the overload capacity of the generating units. For example, the most economical weight of the fly-wheel is greater where power for rolling is supplied from gas-engine-driven generators (which because of the better economy of the engines near the maximum load frequently have little overload capacity) than when the power is from a turbine station the momentary overload capacity of which is very large, due to the immense fly-wheel energy of its discs.

3. The capacity of the fly-wheel is affected by the number of mills or motors driven from the same generating station and, therefore, the number of intermittent cycles, which are combined to form the generator load curve. As the number of mills increases the peaks of the station load curve decrease. Beyond a certain point, depending on the overload capacity of the generating station, the advantages of the fly-wheel are confined to the rolling-mill motor. and the fly-wheel capacity may be reduced to a minimum

A fourth advantage of the fly-wheel that is difficult to capitalize at present, is the increase in reliability and life of the rolling-mill motor resulting from the reduction in mechanical and electrical strains in the windings.

A great many advantages have been put forth in favor of the steam turbine as a generating unit for supplying power for rolling mills. I think, however, little consideration has been given to the possibility of increasing the efficiency of the rolling by the use of turbine-driven generators.

M. O. Dellplain: There is a matter which might be brought up at this time and one regarding which steel-mill engineers would probably all appreciate information, as it has to do with the only portion of the mill in which electricity has not as yet been positively accepted. I refer to the use of motor-driven air compressors for operating the hammer shop. The successful application of air for use in the hammer shop would mean practically the complete solution of the problem of the electrification of the steel mill.

Clark S. Lankton (by letter): Mr. Specht says that in motor-driven sheet mills the automatic control can not be used to advantage, that it would do more harm than good. I wish to take the ground that a proper control for induction motors driving sheet mills is a very much desired feature. The advantages of control do not make themselves felt in the way it was first intended they should; that is, to smooth out the peaks. This is not practical because, as Mr. Specht says, the fluctuating load is too quick for the automatic feature to act. The control is practical, however, in that it affords a large amount of protection.

A sheet mill has from four to ten stands of rolls connected to the same shaft and each set of rolls is manned by a separate crew, each working independently of the other, hence the total load on the motor is made up of as many components as there are mills. Each unit requires power over and above its friction load but a relatively short period of the total time; that is, the actual time that iron is being passed through the rolls is short, say one-eighth of the total time, or 3 hours out of 24.

The different crews have no relation to one another, and, with several mills operating, combination loads of almost any magnitude might result. A motor of gigantic proportions would be required to meet every possible combination of peak loads which occur, although the square-root of the mean-square load would not require so large a motor. The advantage of a large fly-wheel reserve is apparent.

It has been suggested that a permanent amount of external resistance be inserted in the circuit of the motor secondary in order to obtain slip enough to allow the utilization of the fly-wheel energy. By this method the motor would run with lessened efficiency, not only at times of heavy load, but also at times of medium and light loads, which is by far the greater part of the time. The efficiency could be improved by installing a larger motor which would allow of less slip, but, on the other hand, it would have increased capacity and greater first cost.

It would not be so bad to sacrifice efficiency for a few seconds during a heavy jam, and, with proper control, it would be possible to hold the motor to the load until the load became excessive;

then to allow the motor to give way and receive aid from the wheel—thus the lower efficiency would be operative only occasionally and then for only a few seconds at a time. I have seen a sheet mill successfully operated in this way and no trouble apparent in control for some period of time.

Let us give up trying to smooth out every fluctuation, but do not discard the control feature. Set the control to operate at a high load, however, and use it as a protection against the unusual peak rather than to level all peaks. If the source of supply is a little larger than the capacity of the mill, these smaller fluctuations will not be troublesome, and because of their frequency with the added number of mills the resulting load approaches a continuous load.

H. C. Specht: The amount of fly-wheel effect of an induction motor, with wound rotor particularly, is fixed mainly by the design itself, and it is very difficult to add more fly-wheel effect unless the additional weight is placed on a smaller radius, where it is not as effective. Further, it is not often desirable for mechanical and other reasons to put all the fly-wheel effect in the motor. Assuming, for instance, that a motor has to drive certain machinery, and a specific fly-wheel effect is desirable, also that at some later date the machinery driven by the motor is to be changed or the motor has to be used otherwise; under these circumstances the fly-wheel effect first placed in the rotor may be no longer the right one. Then the motor would have to be changed, and in such a case it would be more desirable to make the motor of normal design in the first place without particular reference to the required fly-wheel effect. Any additional necessary fly-wheel effect is then secured by coupling to a separate fly-wheel. A further advantage of this arrangement is that the motor is relieved of any sudden shocks.

The equations which I give for the torque curve have also been worked out by Mr. I. E. Hanssen in a similar way, and agree exactly with mine.

Chas. F. Scott: The problem of power generation which has been presented, the peculiar conditions of power supply through gas at the steel mill, the severe conditions of fluctuating load—all these bring severe and peculiar conditions which must be taken into consideration and treated in a broad way by the engineer who is handling them. It was said by one of the speakers that the electrical engineer in the steel mill is only 40 per cent an electrical engineer and 60 per cent a business man. I am rather inclined to think that some of the things classed as business in that position are properly engineering, engineering in the broader sense, as the engineer must take into consideration not merely the formulas on which his apparatus is based, not merely the electrical phases of his apparatus, but that larger engineering consideration which applies means to the accomplishment of results. This larger view also includes the mechanical conditions in which the various elements are controlled by the electrical apparatus, and the various operations in which the electrical apparatus simply plays a part. There are other considerations. He must be human, and must be able to handle the rather obtuse mill operators who do not like to do anything differently from the way in which they have been accustomed to do it. All this emphasizes the fact that the steel mill engineer must be a pretty large and progressive man.

The matter of power-factor was referred to. Power-factor has a rather disagreeable reputation, and when one finds it attached to anything, it is usually regarded as quite discreditable. Mr. Tschentscher takes pride in telling that he has been able to save $10,000 a year in wiping out this power-factor, and I take it this is a case where auxiliary machines are fully justified. They are installed at the end of the transmission line, so they relieve the line of carrying an extra amount of current. But, after all, has he accomplished something which is large and fundamental? He saves $10,000 a year on 7000 h.p. of motors, or something less than $1.50 a year per motor horse power. That is equivalent to the saving of $1.50 a year in the power supplied to the motor for each horse power rating. I do not know what the power is estimated as costing; it is probably fairly high for the rated horse power of the motor, because motors in the cement mill are called upon to do fairly continuous duty. If the power costs $15 per year, the saving would be about ten per cent on the power; that is, the power would cost $15 instead of $16.50. If the cost were $30 a year, it would be a saving of about five per cent, so that in this case the power-factor of the motor is a matter which would increase the cost of power by five per cent or ten per cent. If direct-current motors were used, and the power-factor avoided by discarding the induction motor, there would be new objectionable features introduced, such as the loss in transmission apparatus, synchronous converter, or motor-generator, as well as a higher first cost and attendance.

In applying electricity to steel mills the first thing that is usually thought of, the thing that has been given large consideration here to-day, is the supply of power. The supply of power, considered in comparison with the total cost of production, is probably a relatively small factor, the larger matters being considerations of operation, of continuity of service, of applying the power effectively. If the motor can work more effectively—if, in conjunction with the mill which it operates, it can do better service, or produce a saving in labor, or more uniform or greater output—then these savings will far overbalance the saving in power, will far overbalance the fixed charges on the first cost of the motors. Consequently, effective operation is a point of far more value than the others I have mentioned.

I have been interested in Mr. Friedlander's paper in the description of the operation of certain mills by motors, and in the number of points which be brings out showing the indirect advantages of the motor, not simply because it does what the engines already do or could do, with possibly a saving in the power cost, but also is doing things which the engine did not do and could not do. In his second paragraph he tells us that the rolling mill drive has taught us how to get the best relation among rotating masses, speed, time, and horse power. It has helped the roll designer to calibrate rolls in such a manner that the power characteristic for all the passes is uniform, thereby avoiding high power peaks, decreasing the size of the prime-mover, and reducing first cost and fuel consumption. The watt-hour meter warns the roller that bearings or rolls are becoming tight and hot, or that steel is causing excessive friction in the passes, often due to overfilling, cold steel, or faulty calibration, thereby guarding against damage to the rolls and bearings. The meter indicates that lower heat, greater elongation, and especially change of profile in different directions, increase the power required at the rolls much more rapidly than do chemical hardness, high tensile strength, or large draughts.

After analyzing the conditions in reciprocating engines for this work, we find that the characteristics of the electric motor are much better. A little further on he says that heavy reciprocating engines cannot run at such high speed, and must be connected to the rolls by means of gears, ropes or bolts. Again:

> To obtain accurate information as to the exact power requirements for rolling steel, indicator diagrams were taken on reciprocating engines doing similar work, but these in many instances were misleading. * * *. With the use of electric motors in place of reciprocating engines, the problem of reversing rolls becomes much simpler and better, in regard to manipulation, fuel consumption, and cost of maintenance.

Now, these are all indirect things, points of inherent superiority of the electric drive over the steam drive, points which show a reaction or interrelation between the motor and the mill, which indicate that the motor is going to have a vital effect upon mill work because it does what the engine cannot do.

John C. Reed: Have controllers ever been designed for obtaining dynamic braking in connection with an induction motor?

H. E. White: So far as I am aware, there is no method of applying current to the induction motor that will bring it to rest, without a tendency to start it in the opposite direction. In some installations now being made, current is being applied with reversed phases, and some means is used to shut off the reverse current when the motor stops.

In reference to Mr. Wiley's question concerning the automatic features of the control of large induction motors, Mr. Pauly has given the principal points. From the controller designer's standpoint it appears to be very desirable that the arrangement of the control be chosen so that a permanent resistance can be left in the motor circuit. It is a simple matter to arrange it so that the permanent resistance can be changed by changing the position of the master controller.

If automatic overload features are used, and a number of excessively heavy loads occur at short intervals, the speed has a tendency to be greatly reduced; if, however, resistance is left in permanently without automatic overload features, the torque will increase to the limit of the motor and the work will be carried through. I think that with the use of alternating-current contactors instead of direct current we would not have very much difference in action in either case. If the motor is running synchronously with all resistance cut out, the current will increase very greatly with a slight change in speed, but it is difficult to get automatic overload devices that will operate before the current shows an undesirably great increase.

I should have said no method of applying alternating current. The large induction motors at Gary are now equipped to apply direct current to the stators of the motors, and this will stop these motors and fly-wheels in a few minutes, when they might run unretarded for as many hours. I understood the question to apply to alternating current only.

In my experience with contactors for alternating current, which has recently been extensively increased, I find that under all the conditions of design with which I am familiar they permit of very quick closing. While I have no doubt that an oscillogram of the operating current would show some very curious things, yet the contactors I am familiar with always close practically instantaneously; it is easy to see that this must be so, for even on 25-cycle current the time between the minimum and the maximum current value is only about one one-hundredth of a second.

A. M. Dudley: Mr. Parker asked about the relative desirability of having the entire amount of fly-wheel effect desired rotating at the same angular velocity as the motor, or connected to the motor by belting or gearing, and running at a higher speed. Mr. Specht, I believe, did not quite cover that point. Mr. Parker's statement is true, that there is no advantage in the one over the other, as far as the actual weight of the active material in the fly-wheel itself is concerned; that is to say, the same weight will have to be kept but disposed differently. It has been my experience, however, that when the extra weight is taken out of the motor structure and not carried on the motor spider, it is possible to build the entire motor somewhat lighter. It seems to me there might possibly be some advantage in that direction.

Mr. White said that he believed there was no method of employing dynamic braking in connection with the wound secondary motor and bringing it absolutely to rest. This holds good unless direct current is used in connection with the windings; that is, direct current is introduced into one member or the other, in which case the same effect is obtained as on a direct-current machine.

H. K. English (by letter): Mention is made of the fact that the time required to accelerate or decelerate a heavy fly-wheel must not be overlooked. This is especially true in plate-mill work, where it is often desirable to increase the rolling speed considerably after the first heavier passes are through. As an illustration, take the example used in the paper. Should it be decided to change at the end of the ninth pass, from 52 to 104 rev. per min. for the remaining 10 or 12 passes, the 120,000,000 lb-ft.^{2} fly-wheel would obviously be out of the question on account of the time and energy required to accelerate it to 104 rev. per min.

Again, it is an advantage, where possible, to have in the fly-wheel enough stored energy to clear the rolls should the power fail, or should the motor, for any reason, become momentarily inoperative. Referring once more to the data sheet, pass No. 9, Fig. 3 represents some 11,700,000 ft. lb., while a 20,000,000 lb-ft.^{2} fly-wheel running 52 rev. per min. has but 9,250,000 ft. lb. stored energy. Should the power fail just as the steel is entering for pass No. 9, the rolls would not be cleared, making it necessary to loosen the rolls, reverse the motor, and back out the steel. This consideration is of more importance in a rail mill with a number of motors in a train, and large quantities of steel, in different stages of completion, in the mill at one time.

I mention these two points to emphasize the fact that the choice of a fly-wheel for any given installation will be governed, more by an all-round practical consideration of the case in hand than by any mere efficiency calculations.

There has just been completed a series of tests on an electrically driven rail mill which has recently been put in operation, and it has been very gratifying to see how closely the test values check the original calculations both as to power required for the several passes, and as to motor performance. In view of this fact, and the successful record this mill is making, it would seem that Mr. Specht is scarcely justified in assuming that careful study has not been given these first installations.

Arthur C. Eastwood (by letter): I believe attention should be directed to the conditions under which controllers must operate in a steel mill. I refer to the controllers described by Mr. White and Mr. Henderson in which a separate series relay is associated with each contactor in a controller, the closure of each successive contactor being governed by the current flowing through the motor, and each series relay being susceptible of individual adjustment.

In steel mills I believe it is common practice when records are in view to doctor the controller relays with bolts, nuts, and wrenches. In other words, under mill conditions a controller designed automatically to limit the current input of a motor may, in a few seconds, lose all semblance of current-limit acceleration, the cutting out of the resistance being governed solely by the time element of the contactors or magnetic switches. Further, the larger the number of adjustments provided, the greater the chance for maladjustment where uneducated and electrically unskilled rollers, table men, shear men, millwrights, etc., have access to the controller, and where the adjustments are purely mechanical, consisting in weighting a plunger or tightening a spring. Even in the hands of a skilled electrician, to secure accurate adjustment of a controller having a relay on each switch, a recording ammeter is almost a necessity.

As to the advantage found by Mr. Henderson for the multiple relay system of acceleration; that is, the ability so to adjust the relays as to interpret the commutation curve of a motor—it is conceivable that this is an advantage under some conditions but not one which is likely to appear in a steel mill. A steel-mill engineer would hardly install a motor so near the limits of commutation that special provisions would be required to help it out, and if such a motor were inadvertantly installed it should be very promptly torn out and a motor installed better suited to conditions.

There is another system of automatic relay acceleration not described by either Mr. White or Mr. Henderson, which was specifically designed to meet conditions as they exist in steel-mill service, and it is extensively used in many of the largest steel works in the country. In this system only a single accelerating relay is employed. Hence there is but one adjustment; and accurate adjustment as to maximum accelerating current can be determined by the use of an ordinary indicating ammeter. The relay has a single winding of coarse wire, controls only a single pair of contacts, and in service is ordinarily enclosed in an iron box which can only be opened by a key in the form of a special horseshoe magnet with which only those properly qualified to make the adjustment are provided. This prevents tampering with the apparatus by those not properly equipped to adjust it.

Further, the adjustment for varying the maximum accelerating current is electrical and not mechanical. Consequently an unskilled worker who would not hesitate to hang a weight on the ordinary form of relay is very likely to keep hands off, since he will hesitate to tamper with electrical connections.

The adjustment is obtained by varying the portion of the total motor current which passes through the winding of the relay, and is accomplished by shunting the winding of the relay. The constants of the relay itself remain fixed. It will always lift its plunger when a certain definite current flows through its winding. Assuming this current to be 50 amperes and the desired maximum motor current to be 100 amperes, the relay will be so shunted that one-half of the motor current will pass through its windings. If the desired maximum motor current be 200 amperes, the shunt will be so adjusted that one-quarter of the total motor current will pass through the winding of the relay.

This method of shunting the winding of the relay not only provides means for adjusting the maximum accelerating current in case of a given motor and controller, but also permits of adapting a standard relay for use with motors varying widely in capacity. In an equipment installed in one of the large steel works of the country, embodying some 65 automatic magnetic controllers for motors varying in size from 25 to 250 h.p. duplicate relays were used in all the controllers, the adjustable shunt in each instance adapting the relay to operate at the required maximum motor current.

A diagram of connections of this system of automatic acceleration is shown in Fig. 1, in connection with a reversing controller for a series-wound motor.

A is the armature and *F* the field winding of the motor.

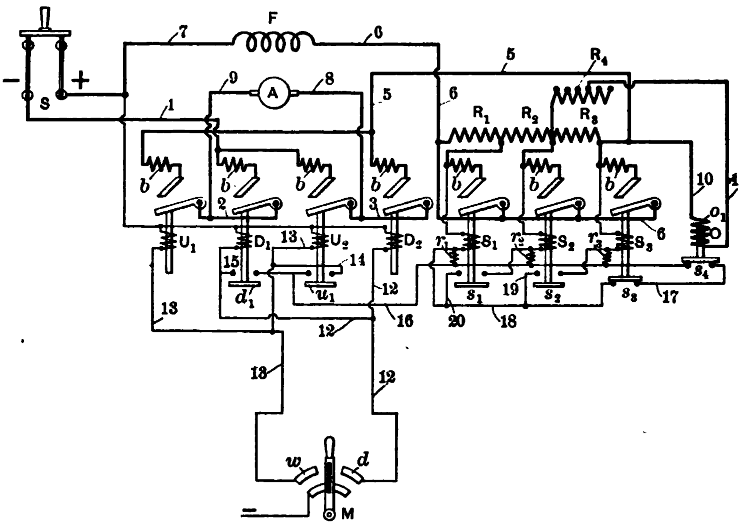
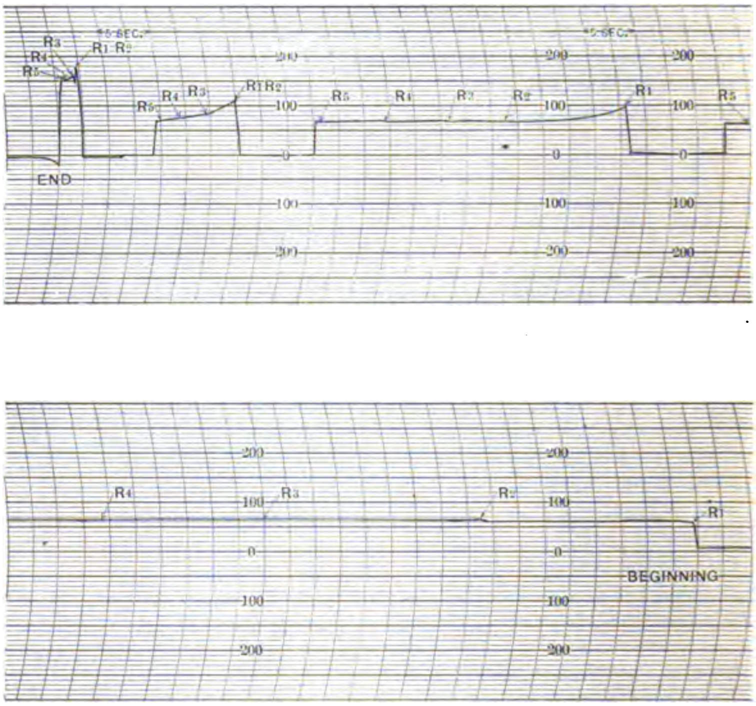


Fig. 1—Automatic accelerating controller

*R*1, *R*2, *R*3, and *R*4 are sections of resistance. *D*1 and *D*2 are reversing switches which give one direction of rotation, while switches *U*1 and *U*2 give the reverse direction of rotation. *S*1, *S*2, and *S*3 are magnetic switches controlling the sections ot resistance *R*1, *R*2 and *R*3. *M* is the master controller through the operation of which the motor is started, stopped, and reversed. *O* is the accelerating relay which governs the closure of the resistance controlling switches *S*1, *S*2, and *S*3. *R*3 is an adjustable resistance which shunts the winding of the relay *O*. It will be seen that the main current flows from positive through the field *F*, the resistances *R*1 and *R*2 where it divides, a part flowing through the resistance *R*3, the wire 5, the reversing switches, and armature of the motor to negative, and the remainder flowing through the adjustable resistance *R*4 and the winding of the relay *O* to the wire 5 where it joins the other path. Obviously, the portion of the motor current which flows through the winding of the relay may be adjusted by altering the relative resistance of the two paths. It will be noted that resistances *r*1, *r*2, and *r*3 are associated with the windings of the switches *S*1, *S*2, and *S*3. These resistances are so proportioned that when in circuit with the winding of a switch-operating magnet they will not permit sufficient current to flow to cause the switch to close, but will permit sufficient to flow to hold the switch closed after its plunger has been raised. The function of the contacts of the relay *O* is to control the resistances *r*1, *r*2, and *r*3. When the plunger of the relay is down, these resistances are short-circuited; when the plunger of the relay rises, these resistances are cut into circuit with the windings of the switch-operating magnet with which they are associated.



ACCELERATION CURVES OF 25 H.P. 220 VOLT SERIES MOTOR WITH AUTOMATIC CURRENT-LIMIT CONTROLLER.

FIG. 2

Assuming that the switch *S*-1 has closed, and in closing has produced a current value which causes the relay *O* to lift, the winding of switch *S*2 then receives current through the resistance *r*2 which, as previously mentioned, will not permit sufficient current to flow to cause the switch to close. It should be noted, however, that a small current flows through the winding of the switch which is about to close, thus partly building up the magnetism of its closing magnet and leaving the switch prepared to close promptly. This largely eliminates the time element of the successive switches in closing. When the motor has accelerated, thus reducing the current flowing through its windings to the proper point, the relay drops, thus short-circuiting the resistance *r*2 and permitting the switch *S*2 to close. Switch *S*3 is controlled in a similar manner.

The relay *O* is provided with but a single pair of contacts, and only a single electrical interlock is associated with the control circuit of each switch.

The curves shown in Fig. 2 were taken with a recording ammeter, and illustrate the acceleration of a 25-h.p. 220-volt series motor in which the maximum accelerating current, and hence the time of acceleration, has been varied by varying the resistance of the shunt round the accelerating relay, as above described. These curves illustrate the wide range of adjustment which may be secured in the total time of acceleration, showing as they do that the period of acceleration may be varied from 65 sec. to less than 2 sec. the accelerating current in the two cases being respectively 60 to 65 amperes and 160 to 165 amperes. These curves also illustrate the sensitiveness of the accelerating relay, showing that it will raise and drop its plunger with current variations of less than 5 amperes.

As to the Hulett unloader, which was described by Mr. Henderson as offering particular advantages for automatic control, the writer can speak with some authority as he designed and installed the controlling equipment for the first electrically operated Hulett unloaders in 1902 and 1903. On the first Hulett unloaders (installed at Conneaut, O.) the machines were driven throughout by steam and hydraulic power. The next machines (the first three installed on the Lackawanna Steel Company docks at Buffalo, N. Y.) were driven electrically with the exception of the bucket-closing and rotating mechanisms, which were operated by means of hydraulic cylinders. This necessitated mounting on each machine a motor-driven pressure pump operating at 1000 lb. pressure, a motor-driven air compressor, an air-hydraulic accumulator, and an elaborate system of high-pressure piping, swivels, valves, etc., which was a prolific source of trouble not only in itself but on account of damage to electrical apparatus which occurred through frequent leaks in the hydraulic system.

Hydraulic power was selected for the operation of the bucket because of the absolute necessity of limiting the torque or pull which occurred in closing and rotating the bucket. The bucket of the unloader is suspended from a structural leg some

40 ft. in length, as illustrated in Fig. 3, which shows the bucket of one of these machines in the hold of the steamer " Wolvin ". In scraping ore from between hatches, or in case the bucket should entrain more ore than it could hold, or if the bucket happened to foul a stanchion or other obstruction, obviously the torque or pull must be limited, as the bucket has a leverage of some 40 ft. on the frame of the machine, and a wreck would result if a definite maximum pull were exceeded. An electric motor, with its ability to increase its torque to perhaps ten times full-load value before stalling, appeared altogether unsuited to the purpose.

After experimenting with a number of other schemes, a form of controller was devised by the writer which gave to the operation of a motor substantially the characteristics of a hydraulic cylinder. In this controller a series relay was introduced, which weighed the load and when a given normal current was exceeded, automatically cut resistance into the motor circuit, thus limiting the current, and consequently the torque, to a safe maximum value. The arrangement was such that current would not be cut off from the motor when an overload occurred, but the current would be automatically limited and the current limiting resistance would be automatically cut out when the load was relieved. This arrangement successfully displaced the hydraulic

Fig. 3—Bucket leg of an ore unloader working in the hold of a steamer

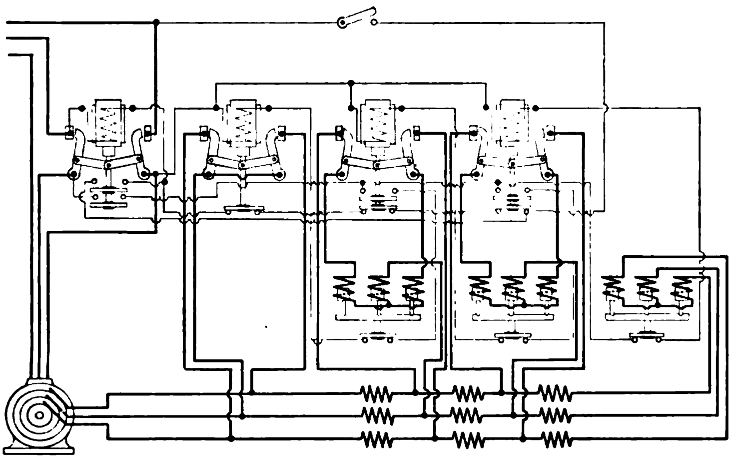


Fig. 1

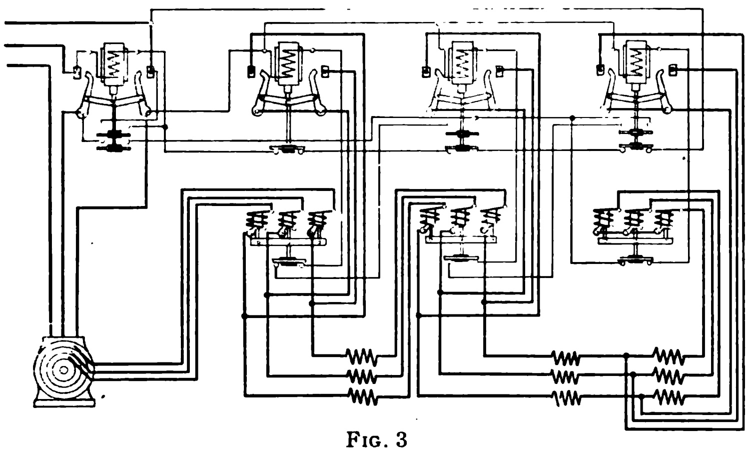


Fig. 3

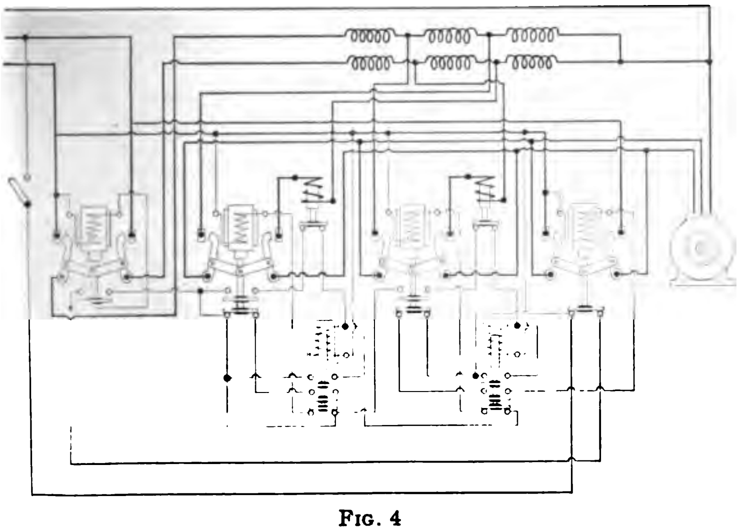


Fig. 4

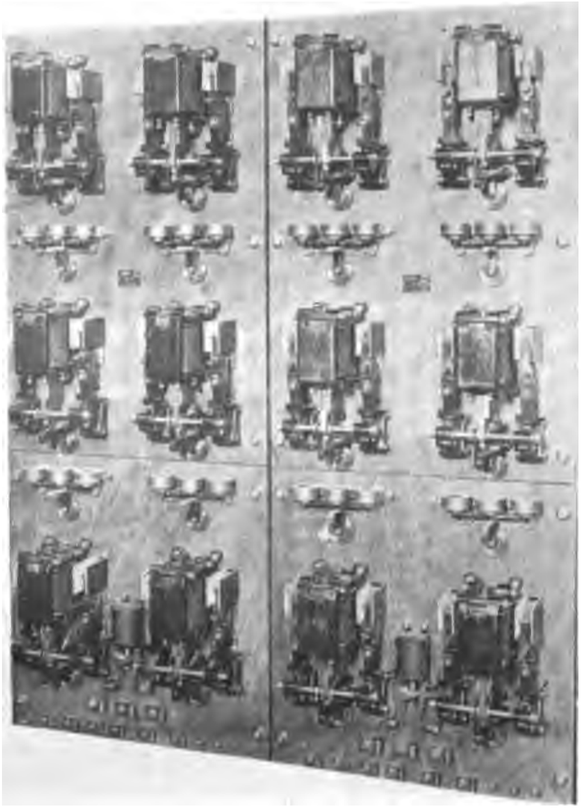


FIG. 2

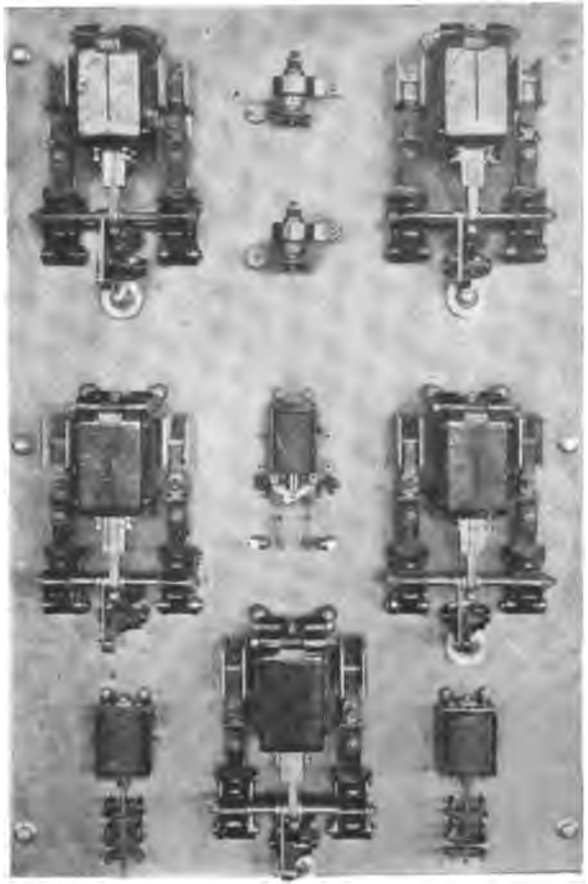


FIG. 5

cylinder and all subsequent Hulett unloaders have been similarly equipped. The Hulett unloaders on the docks of the Indian Steel Company at Gary are equipped in this way, and are also equipped throughout with the system of current-limit acceleration above described.

Arthur Simon (by letter): Mr. Specht states that the automatic regulation of resistance in the secondary circuit of the slip-ring type of motor is not desirable on account of the sluggishness of the controlling apparatus, and he therefore restricts himself to the calculations of a slip-ring type motor with a fixed resistance and a fly-wheel. This method of operation is undoubtedly the simplest, but by no means the most economical. Mr. Specht agrees that theoretically the variable resistance method with a lighter fly-wheel would be preferable, but the writer is not convinced that it will be impossible to produce a controller which will follow quickly the changes in load on the motor.

As far as the writer is aware, the controllers which were designed to accomplish the automatic regulation of the secondary resistance were all influenced primarily by a current relay connected in the primary circuit of the motor. Furthermore, most of these controllers, or all of them, were of the pilot-motor type. In other words, there were several elements, which, with regard to the cycle of operation, were connected in series. The ultimate result was obtained only after the successive operation of all parts, which necessarily must consume considerable time. The writer is satisfied that it would be possible to connect proper relays in the secondary circuit of the motor. As the secondary current is the first quantity which is influenced by a change in speed, that is, the change in load, it is only logical to accomplish the control by means of a relay in the secondary circuit. This relay should influence directly contactors which control secondary resistance, and this method will give entirely satisfactory results as far as the speed of response is concerned, and, furthermore, be still more desirable for other reasons, which will be discussed in the following:

Mr. White says that the 6000-h.p. motors at Gary are controlled by a pilot motor which is influenced by a current relay. A diagram of this control scheme was published in the "*General Electric Review*", and I note that the current relays are connected in the primary circuit. For the same reasons as stated above, these relays should be connected in the secondary circuit of the motor, and it is obvious that the scheme as shown in his Fig. 1 is preferable to the pilot-motor control. Fig. 2 shows a double panel of this type. With the pilot-motor control the entire operation of the motor, and with it the operation of the plant, depends upon the pilot motor and the current relays controlling it. The failure of any one part will shut down the motor entirely, while with the control scheme shown in the diagram all parts are interchangeable and the failure of one element does not necessitate the shutting down of the entire plant for repairs, but merely the short-circuiting of this element while the motor can then operate with a reduced number of accelerating speeds, and it is still possible to keep the mill running while repairs on the part which is in trouble are being made. This control scheme also reduces the time element necessary for the action of the automatic slip regulation. If such automatic slip regulation in connection with a flywheel is desired, it will of course be necessary to change the connections of the relays somewhat, for instance, as suggested by Fig. 3.

Mr. White further states that the current relay control is undesirable for squirrel-cage motors started with potential starters. The writer cannot share this opinion and submits, herewith, in Fig. 4 a connection diagram, and in Fig. 5 a self-starter for squirrel-cage motors controlled by current relays. The objection to the constant-time-element control is that the motor is switched from the starting to the running tap of the transformer at a variable speed, which causes considerable variation in the surges on the line. Suppose that the motor-speed at which same is connected to full line voltage was 10 per cent below normal and the normal slip of the motor was 4 per cent, in this case the momentary current inrush would be 250 per cent of normal. Such slight variations in the speed when switching over are entirely possible with the constant-time-element control, while it is possible to set current-relay controllers very closely, say, within at least 10 per cent, which will entirely avoid the danger of momentary overload on the line to which the motor is connected, or the tripping of the circuit-breaker during starting.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

SOME CONSIDERATIONS IN DESIGNING HEAVY CAPACITY FUSES

BY LOUIS W. DOWNES

The conditions governing the operation of the open link fuse and of the enclosed fuse are radically different. That such a difference exists is due largely to the presence in the latter of a confining case of relatively small dimensions and of a material, the porous filling, which acts in two capacities: first, to disintegrate the vaporized metal; second, to condense or cool it and render it non-conducting.

The filling, on account of its porosity, allows the expanding gases to escape in every direction and their continuity is thus broken up. Furthermore, the gases coming in contact with a substance, which is at a temperature many hundreds of degrees lower than that of the gases, are condensed and cooled and thereby lose their conducting power.

This feature is wholly absent in the open link fuse. The gases formed at the rupture simply expand in the atmosphere, and a continuous stratum of conducting vapor is formed between the two terminals of the cut-out in which the fuse is mounted. There is nothing present to disrupt, break up, or condense this vapor other than the air, which can act only in a slight degree and relatively slowly; and in this condition we find the explanation of the tendency shown by the open link fuses, whether multiple or single strip, to arc most violently when subjected to a short-circuit.

On the other hand, the gases so formed in the open link fuse are dissipated with greater or less rapidity into the surrounding atmosphere, and since there is no confining casing, no opportunity exists for the violent explosive action which will occur as a result of the expansion of the metal vapor in the enclosed fuse, if it is not properly designed.

The conditions to be met in the design of an enclosed fuse are therefore materially different from those imposed by the open link fuse. We not only have to suppress the arc but we have to handle the tremendous expansive force of the vaporized metal within a comparatively confined space.

Further, the radiation of the heat from the metal of the link takes place in an entirely different manner. With the open link the heat dissipation is directly from the surface of the metal. In the enclosed fuse, the heat dissipation must take place by conduction through the porous filling to the surface of the tube, so that in enclosing a fusible link and surrounding it with porous material we have modified practically all the conditions of operation.

The most serious difficulty that we have to contend with in the design of the larger capacity fuses is that of explosion, and this difficulty becomes greater as the capacity is increased. The problem is largely one of what we term " volume ratio and distribution;" that is to say, the relation which the volume of the fusible link bears to the volume of the enclosing tube and the distribution of the metal in the filling. Were it possible to carry out the same relationship in the large capacity fuses as that employed in the small capacity fuses, the problem would be too simple and would possess few features of technical interest. It is obviously impossible, however, to maintain this same ratio on account of both cost and dimensions; it is necessary, therefore, to devise other means which, while tending to reduce the volume of fusible metal to the lowest possible point, will so facilitate the ready escape and condensation of the hot metallic gases as to render the operation of the fuse quiet and reliable under all conditions.

Consider more in detail what actually takes place when an enclosed fuse is blown on short-circuit. As the rush of current occurs, the metal is raised through its melting point to its boiling point and the current continues to flow through the fuse for a brief interval on the conducting vapor path of the volatilized metal. It is extremely important that the temperature of these gases should be lowered with the greatest possible rapidity to a point where their conducting power ceases to exist, in order to bring about a reduction in the time of operation of the fuse, which is of tremendous importance in reducing the internal pressures developed and in preventing explosion.

To emphasize this characteristic more forcibly, consider that the maximum running temperature of the porous filling would be slightly less than the melting point of the metal of the fuse link, say approximately 315 degrees cent., were zinc employed and the fuse running at its full load capacity. When a short-circuit occurs, the metal of the link is suddenly raised to a temperature of at least 1000 degrees cent. and as the pressure in the tube becomes greater this temperature is increased. The relatively low temperature of the filling, however, immediately tends to cool these hot gases and convert them from a conducting medium into an actual insulator. Therefore, the sooner we can bring the hot gases into contact with the filling, or conversely, the sooner we can bring all the filling into action as a condenser, the more rapid will be the extinction of the arc within the fuse and the rupture of the circuit.

These considerations show that as little metal as possible must be used in the link and, further, its surface must be so extended as to provide every facility for the hot gases to escape and so distribute the metal within the mass of the filling that each particle of it shall be brought promptly into action.

All these conditions are effectively met by employing what is known as the " multiple link " or one of its modifications. It is quite a simple matter to obtain an increased link area of 100 per cent or more by this method, which will permit a reduction of at least 18 per cent in the total volume of the metal necessary for a given capacity, according to the design.

Reference to Chart 1, giving an end-section through three types of fusible links, will illustrate how readily this may be accomplished. In Fig. 1 we have an end-section of the widest practical single-strip link which could be used in a given tube. In Fig. 2 is shown how the surface may be readily extended 100 per cent without occupying a greater width, and with a further advantage that the metal is more widely distributed within the filling, rendering this far more effective and rapid in its action. At the same time the metal is brought closer to the radiating surface, which will also affect the total amount of metal necessary for a given capacity of a fuse. In Fig. 3 we have another arrangement of the same link which would also be effective. The mathematical consideration of the effect of a change in position of the conductors within the enclosing casing is interesting.

Applying the equation given in *Watson's Physics* on the transference of heat, and bearing in mind that this applies more strictly to transference between parallel surfaces and where the flow takes place in parallel lines, one can work out an equation which, with a proper value of the factor D, representing

Chart No. 1.

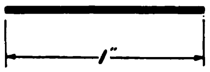


Fig. 1.

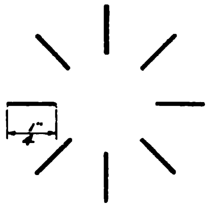


Fig. 2.

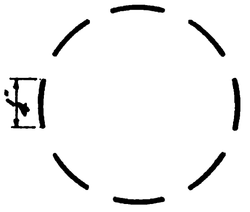


Fig. 3.

Length 3 inches
Area Fig. 1 = 6 sq. in.
Area Fig. 2 = 12 sq. in.
Area Fig. 3 = 12 sq. in.

the distance through which the heat is transmitted, bears out the author's hypothesis, thus :

$$Q = \frac{K\,A\,(T_2 - T_1)\,t}{d} \qquad (1)$$

Where Q = the quantity of heat in calories,

K = a constant for any one substance which is independent of the thickness, area, or the difference in temperature, but changes with the substance used. In this case it refers to the porous filling and the tube,

d = the distance through which the heat is transmitted,

t = the time in seconds in which a given number of heat units would pass from one surface to the other.

T_1 and T_2 are the temperatures respectively of the two surfaces between which occurs the transmission of heat, in this case the temperature of the fuse casing at the surface and the temperature of the fuse link,

A = the area or average cross-section through which the heat passes. Transposing, we get the equation:

$$\frac{Q}{t} = \frac{K\,A\,(T_2 - T_1)}{d} \tag{2}$$

and representing the calories per second, Q/T by Q', the equation becomes :

$$Q' = \frac{K\,A\,(T_2 - T_1)}{d}. \tag{3}$$

It is desirable to transform this equation into electrical units.

One calorie per sec. = 4.189×10^7 ergs per sec.

10^7 ergs per sec. = 1 watt.

Therefore, 1 cal. per sec. = 4.189 watts.

From this it follows that

$$Q' = \frac{I^2\,R}{4.189} \tag{4}$$

Substituting this equivalent in equation (3)

$$\frac{I^2R}{4.189} = \frac{K\,A\,(T_2 - T_1)}{d}, \tag{5}$$

in which I^2R = the total watt loss in the fuse.

Now, transposing and reducing to simpler form

$$I = 2.045 \sqrt{\frac{K}{R} \; \frac{A\,(T_2 - T_1)}{d}} \tag{6}$$

Since K and R are both constant for any given filling and fuse, we may represent $\sqrt{\frac{K}{R}}$ by K' and reduce the formula to a simpler form,

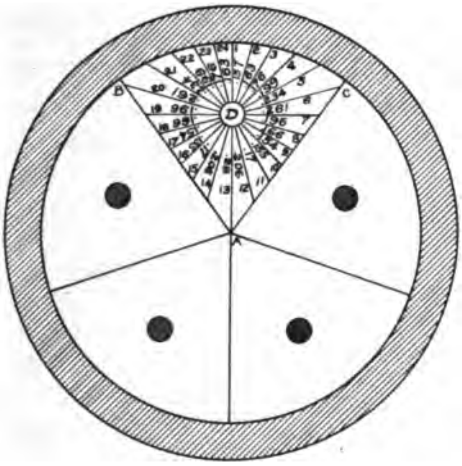
$$I = 2.045\,K' \sqrt{\frac{A\,(T_2 - T_1)}{d}} \tag{7}$$

As already pointed out, the value *d* must be determined in each case to meet the condition of divergent heat rays; but once determined, an examination of this equation shows that any variation in this factor, that is to say, any change in the position of the link, affects the current flow. This is further proved by tests of the fuses themselves which will be described later.

It will be apparent that in order to get the most satisfactory operation of an enclosed fuse, and one of the smallest possible dimensions for a given capacity, all the porous filling should be brought into service when the fuse is subjected to an excessive overload or short-circuit.

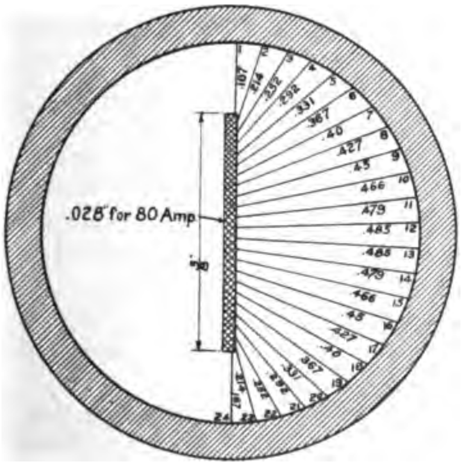
From this it is clear that the shorter the distance the gases have to pass in order to bring into action the maximum amount of filling, the greater will be the rapidity of condensation of the gases and the quicker will the arc be interrupted. To show what an important bearing a proper subdivision and distribution of the metal of the link has in accomplishing this result, consider the fuse sections shown in Chart 2, where in Fig. 1 we have a diagrammatic section through the center of a five-wire multiple fuse drawn three times larger than its actual dimensions. This is divided accurately into five segments, each segment, representing the space which must handle the gases evolved from one element of the link. The circle in the centre of each space represents accurately the proportionate diameter of the wire for a certain capacity of fuse and its relation to the enclosing space. The lines numbered from 1 to 24 represent the mean path or distance that the vapors have to travel in that specific direction in order to bring into action the total amount of filling. It will be understood that in actual practice the number of lines or paths would be materially greater, but for the present discussion any number which would divide the enclosing space into reasonably even proportions will be sufficient. The length of these lines has been accurately measured and their average length ascertained and found to be, as given in the diagram, 0.192 of an inch in the actual fuse, or in the diagram three times that length. In Chart 2, Fig. 2 we have a similar diagram of a flat-strip link of the same capacity. The space through which the gases will have to pass has been divided into an equal number with those of the multiple link and their average length determined. In this case the average length is found to be 0.363 of an inch, or with the flat

Chart No. 2.



Average length of vapor path=.192"

Fig. 1.



Average length of vapor path=.363"

Fig. 2.

link the gases have to pass through an average distance 89 per cent greater than in the five-wire multiple link. In other words, the time which must elapse before all the filling can be brought into action to condense the vapor is nearly double, with the result that a larger amount of energy is absorbed by the fuse, the current flows longer through it and the breaking or rupturing of the current becomes far more difficult. This furnishes another reason why an explosion will take place with a single-strip link and will not take place under similar conditions with a multiple link. With the single link in a given period of time a much smaller quantity of filling can be reached by the gases, with the result that the condenser or cooling action is not sufficiently rapid to prevent the pressure reaching a disruptive point, and the fuse explodes. With the multiple link, according to the above comparison, practically twice the mass of filling is brought into action in the same period, and the cooling rate is so rapid that explosive pressures are not developed. That this theory is correct is shown both by the oscillograph records referred to later, and by actual test of the fuses themselves.

To ascertain definitely the actual reduction in metal volume for any given capacity of fuse, obtained by proper subdivision of the link, an extended series of calibration tests were made on a set of fuses under identically the same conditions. These fuses were all made up in tubes of the same size and fitted with the same size of terminal, the lengths of the links being the same. Chart 3 gives tabulated data for the reduction in metal secured with both the round wire link and the flat strip link, showing clearly the effective reduction in metal volume obtained in this way. Chart 4 gives the tabulated results of another series of tests which show an interesting comparison of the gain in capacity brought about by the increase in surface of the links and the proper distribution of the metal. The areas referred to are the actual areas of the fusible portion of the link and do not include the copper terminals which, as previously stated, were identical in each fuse and consequently could be disregarded.

Having taken up the theoretical consideration of the subject and the calibration tests supporting some of the deductions, it is desirable now to consider the actual operation of the fuse under short-circuit. To permit of a full consideration of the phenomena shown at various intervals during the blowing of the

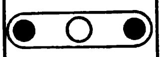
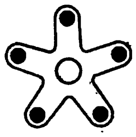
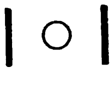
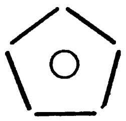
No. of Fuse	Style of Link.	Fuse Link Construction	Size of Link.	Volume Ratio	Amperes	Reduction in Metal Volume.
83	Single Wire		Diam. .164"	1.344%	80	Unit for Wire Links
106	2 Wire Multiple		Diam. .108" Each.	1.166%	80	13.22%
80	5 Wire Multiple		Diam. .063" Each.	.9919%	80	26.2%
88	Single Flat Strip		.063" x .3125"	1.253%	80	Unit for Strip Links.
86	Single Flat Strip		.028" x .625"	1.114%	80	11.1%
104	2 Strip Multiple		.0258" x .3125" Each	1.026%	80	18.1% Under No. 88. 7.8% Under No. 86.
105	5 Strip Multiple		.0095" x .3125" Each	.9447%	80	24.6% Under No. 88 15.2% Under No. 86.

Chart 3

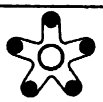
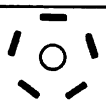
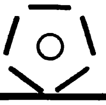
No. of Fuse.	Style of Link.	Fuse Link Construction	Size of Link.	Area	Ampere Capacity
81	Single Wire.		Diam. .141"	1.33	60
96	2 Wire Multiple		Diam. .10"	1.88	73
80	5 Wire Multiple.		Diam. .063"	2.96	80
91	Single Flat Strip.		.100" x .1562"	1.537	65
90	Single Flat Strip.		.075" x .208"	1.856	67
87	Single Flat Strip.		.050" x .3125"	2.175	70
85	Single Flat Strip.		.025" x .625"	3.90	75
89	Single Flat Strip.		.0215" x .728"	4.50	75
97	2 Strip Multiple		.025"Thick .3125"Wide.	4.05	78
84	5 Strip Multiple		.025"Thick .125"Wide.	4.50	80
98	5 Strip Multiple		.0125"Thick. .25" Wide.	7.875	83

Chart 4

fuse under those conditions, an oscillograph was used. The resultant curves are given in Figs. 5 to 16, and the actual records of the tests, together with a drawing of an end-section of the links used in each case, with other important data relating to the test, are given in Chart 5. The tests consisted in subjecting fuses, similar in every detail of construction, except as relates to the fusible portion of the link, to direct short-circuit across the bus-bars of a 6000-ampere-hour battery fed by one or more 500-kw. generators. The potential coil of the oscillograph was connected across the fuse rather than across the circuit, in order to show clearly the variations in the volts' drop at different intervals. An examination of these several curves gives a most interesting and instructive history of the complete cycle of events occurring within the fuse during its operation, all within a period of time considerably under 0.05 seconds.

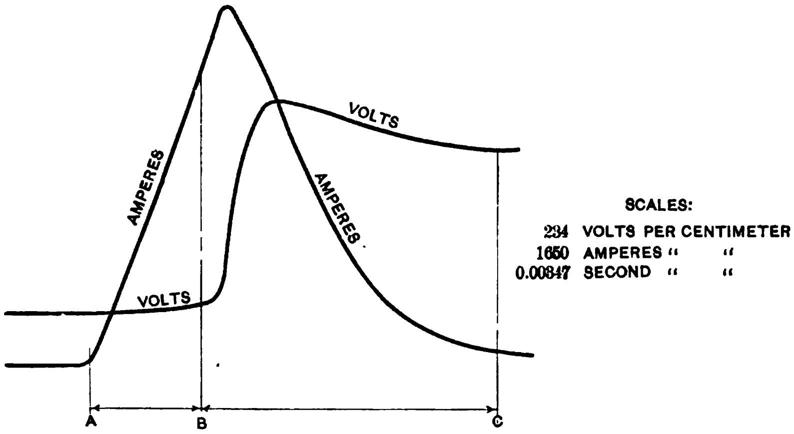


Fig. 5.—Five-wire multiple link 0.063 diam. capacity; 80 amperes. vol. ratio = 1 per cent

Referring to curve of Test IX, Fig. 12, as a good illustration, this may be analyzed as follows: This curve exhibits the operation of a five-strip multiple link fuse of 1 per cent volume ratio, 80 amperes capacity. Following the current curve, it will be seen that during the period *J A* the current is zero. At the instant *A*, the switch was closed and the current instantly rushed through the fuse, rapidly increasing in value until at *D* it had reached its maximum. It then begins to die away until at *C* it has become zero again, or in other words, the fuse has opened the circuit. Referring to the voltage curve from K to Y, the voltage as measured across the fuse is practically zero, that is to say, it was zero at K but at the beginning of the current flow, there was of course, a slight rise. This is, however, so small as not to be visible on the curve and for all practical purposes the voltage may be regarded during the interval $K\ Y$ as zero. At the instant Y, the voltage begins to go up with great rapidity until it practically reaches its maximum at I; it then continues at almost even value until just before the rupture of the current, occurring at C, a slight inductive kick is noticed at F, after which it sharply declines and becomes constant at M, $M\ O$ being the full voltage of the circuit across the fuse.

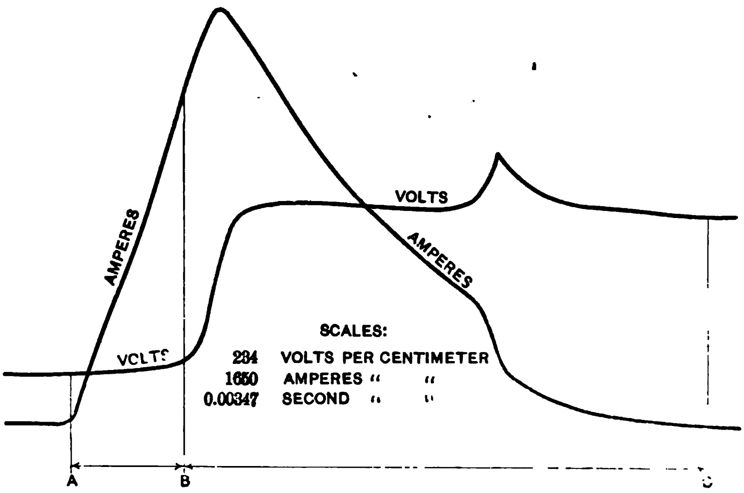


Fig. 6.—Single flat strip 0.028 x 0.625 wide. Capacity 80 amperes; vol. ratio = 1.12 per cent

Referring to the current curve, note the rapid rise of the current value from the point A to E. During that period, there was practically no voltage across the fuse. The actual time during which this rise in current was occurring, represented by the distance $A\ B$, is 0.0038 sec. It is during this interval that the fuse link is being raised to its melting point, the total energy impressed on the fuse being extremely small. From the point E on the current curve to its maximum value at D, the metal is being converted into vapor, and a corresponding rapid rise in voltage will be noted, showing the enormous increase in the resistance of the circuit. At *D*, the vapor begins to condense, or, in other words, lose its conductivity, and as the conductivity of the vapor path diminishes, the current falls. The voltage, however, continues to rise slightly, due to the same cause, but remains practically constant from the point *I* until just before reaching the point *F*. During this period the current is falling rapidly, and the total time or duration of fall is found to be 0.012 seconds. The maximum current which passes through the fuse is found to be 8415 amperes and the voltage at the same instant, found by measuring the height *H L*, was 304 volts, so that the power input into the fuse at the instant *G* is 2,558,160 watts, apparently an enormous amount of energy, but practically an instantaneous value. By integrating it is found that the average watts were 1,925,000 during the period that power was absorbed by the fuse. This period of energy input, is represented by the distance *B C*, and is found to be actually 0.0146 sec. from which is derived a value of 28,600 watt-sec. or a little over 27 B.t.u. The total period of operation, or the time *A C*, which elapsed after the switch was closed, until the circuit was opened, was but 0.0184 sec.

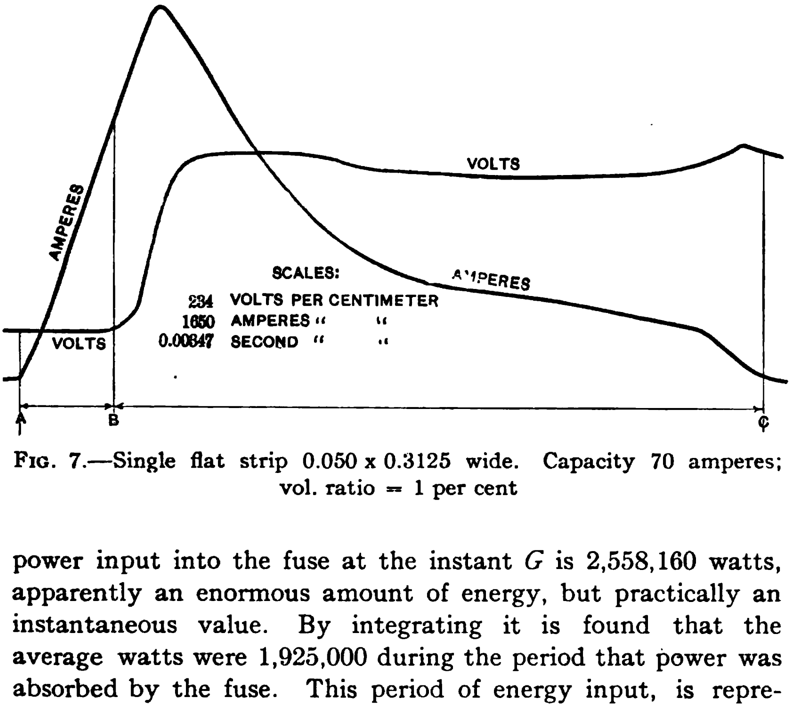


FIG. 7.—Single flat strip 0.050 x 0.3125 wide. Capacity 70 amperes; vol. ratio = 1 per cent

Referring to the curve, Test X, that of a single flat strip link fuse, it is noted that the time during which the link was being melted as represented by the distance *A B*, was practically the same as that of Curve IX of the previous test, but the significant feature lies in the relatively slow decline of the current value and the prolongation of the period during which energy was being absorbed by the fuse or the period *B C*. This time is actually 0.0246 sec. or an increase of 68 per cent in the period of operation of the fuse during which arcing was going on. By integrating the curve in precisely the same manner as that of Test IX, the average watts were found to be 2,360,000 and this value multiplied by the time, gives 58,000 watt-secs. or 57 B.t.u., an increase of the total energy input in excess of 102 per cent or more than double the total energy absorbed by the multiple strip fuse.

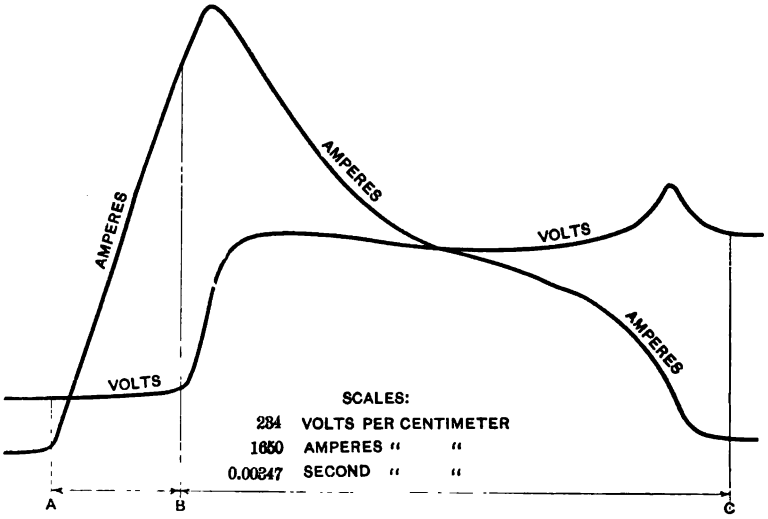


FIG. 8.—Single flat strip 0.030 x 0.625 wide. Capacity 83 amperes; vol. ratio = 1.19 per cent

A similar comparison of the other curves bears out in a most striking manner the important influence which the extension of the link surface and its proper distribution within the filling has in reducing to a large degree the total energy absorbed as well as the duration of the period of energy input. Comparing the results it will be found that the single link fuses invariably absorb more total energy.

The average energy input of the multiple link fuses tested was but 22,587 watt-secs. as compared with an average energy input of the single link fuses of 43,746 watt-secs.; that is to say, the single link fuses absorb practically double the energy. It should be further noted that even disregarding the fact that in several of the single link fuses, the explosion of the fuse materially shortened the period of power input, the average period of power input of the single link fuses was 72 per cent greater than the same period for the multiple link fuses.

Furthermore, in anything like equal ampere capacity the maximum current flow was greater with the single link fuses, the average excess being 15 per cent. This has an important bearing on the tendency to disrupt or burst the cartridge, since the greater the current, the more rapidly is the link raised to its boiling point and consequently the greater the rate of development of internal pressures. In all enclosed fuses provision is made for the escape of these gases. It will be apparent, therefore, that the rate of development of the gas must be considered, since in one case the rate of escape might be such as to prevent the ultimate bursting pressure being reached, whereas in another fuse of exactly the same metal volume, the rate of development of pressure might be so much more rapid than

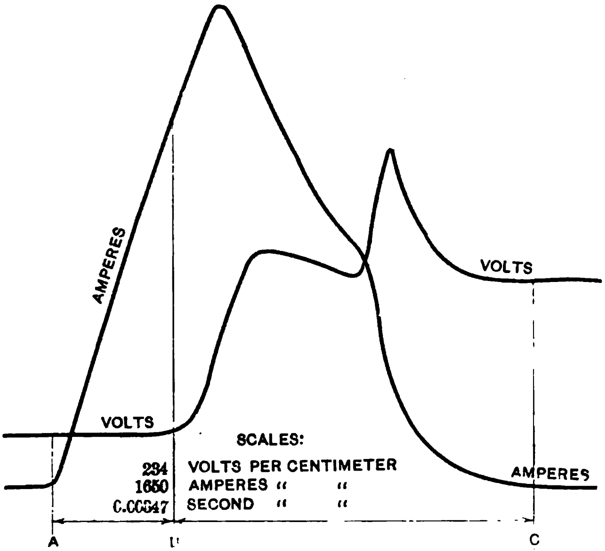


FIG. 9.—Single round wire 0.164 diam. Capacity 80 amperes. Vol. ratio = 1.35 per cent

its rate of escape that the bursting pressure would be rapidly reached.

I would briefly summarize the results of the other tests as shown in tabulated form in Chart 5 and the analyses of the other curves may be briefly summarized as follows:

Tests 1 and II (Figs. 5 and 6) compare the operation of a five-wire multiple link fuse and a single-strip flat link fuse of the same ampere capacity. By reference to Chart 5 it will be seen that the operation of the single flat link fuse was explosive and dangerous, whereas the multiple link fuse operated quietly. Comparison of these curves confirms this most forcibly. It will be noted that the period *A B*, during which the metal was being raised to its melting point, was practically the same for both fuses, but the period *B C*, during which energy was being absorbed by the fuse, was extended in a most pronounced manner in the single link and that the total energy absorbed was about 120 per cent greater.

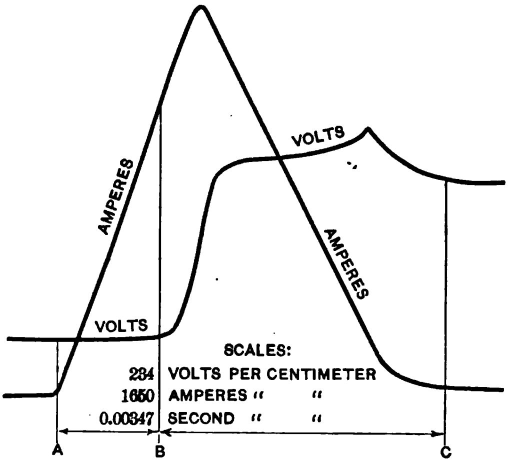


FIG. 10.—Five-strip, multiple link 0.0125 x 0.250 wide. Capacity 83 amperes. Vol. ratio = 1 per cent

Test III (Fig. 7) showing the operation of a single flat strip fuse of the same volume ratio as Test I but of a smaller ampere capacity, exhibits an extension of the period of energy input *B C* even in a more pronounced manner. The total energy absorbed in this fuse was nearly 140 per cent greater than with the multiple link.

In Tests IV and V (Fig. 8) we compare the operation of the five-strip multiple link fuse and the single-strip link of the same ampere capacity with the five-wire multiple link of the earlier test. Unfortunately the film record of Test IV was torn so that it was impossible to compare the curves. The record shows, however, that the multiple strip operated quietly, while the single strip exploded and one may judge of the characteristics of the curve of the multiple strip by reference to Test VII (Fig. 10) which was the curve made from a fuse of identically the same construction. The same characteristics are here presented as in Test I.

In Test VI (Fig. 9) is shown the operation of a single wire link fuse. This curve is particularly interesting as showing the effect of concentrating a mass of metal in as compact form as possible, thereby reducing to a minimum the avenues of escape of the gases within the filling. The rise of the current wave is more pronounced than in any of the other single link fuses, the current here reaching a maximum of 10,642 amperes; while the period of energy input, *B C*, is relatively short. This is due to the fact that this fuse exploded with greatest violence and the current was actually ruptured by the explosion. This is indicated by the very pronounced inductive kick shown on the curve, the rise in potential at the instant of rupture being about 450 volts.

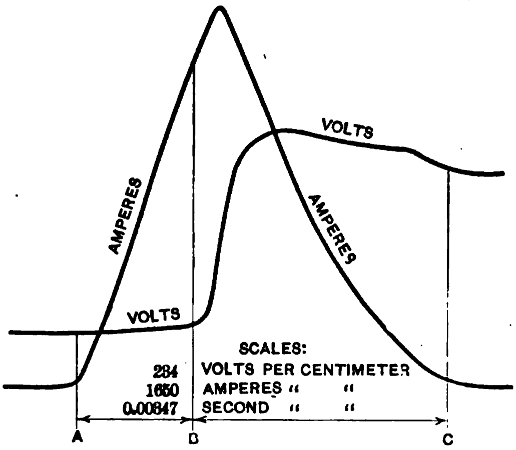


FIG. 11.—Two-strip multiple link 0.025 x 0.3125 wide. Capacity 78 amperes. Vol. ratio = 1 per cent

In Test VIII (Fig. 11) is shown the operation of a two-strip multiple link of slightly less capacity than that used in Test VII, its operation being most satisfactory in every way.

Tests IX, X and XI (Figs. 12, 13 and 14) give the comparative operation of two single-link fuses and a five-strip multiple link at 600 volts, as distinguished from 500 volts heretofore used. Again the multiple link operated quietly, whereas the two single-link fuses exploded.

Test XIII (Fig. 15) records the behavior of the curve of a fuse, where the explosion did not interrupt the current promptly but where the arc was maintained for a brief interval. The variations in the voltage during the period of arcing are here most pronounced.

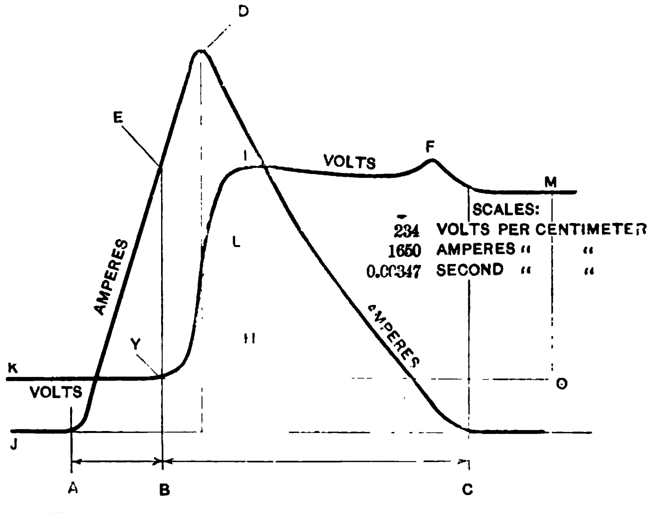


FIG. 12.—Five-strip multiple link 0.025 x 0.125 wide. Capacity 80 amperes. Vol. ratio = 1 per cent

In Test XV (Fig. 16) is shown the operation of a five-strip multiple link with a slight inductive resistance in the circuit. In comparison with other multiple link curves, the prolongation of the period *A B* is most marked with slower and less abrupt rise of the potential. The fuse operated perfectly although giving indications of the phenomena shown.

Another important consideration is the concentration of the energy at one point in a single-strip fuse as compared with its division in the multiple-link fuse. An interesting illustration of this particular feature is found in Tests I and II. The fuse of Test I was a five-wire multiple link, the total resistance of which was 0.0017 ohms or the resistance of each element was 0.0085 ohms. The maximum current flow through this fuse, the record shows was 7600 amperes, from which it is obvious that the energy required for raising the metal to the boiling point of each element was 19,650 watts or a total for the fuse of 98,250 watts. Compared with the single-strip link of Test II, the resistance of which was somewhat lower on account of its greater volume ratio, being 0.0015 ohms, the maximum current flow was seen to be 8910 amperes, giving a total power input of 123,700 watts. In other words, 25,000 more watts were absorbed by the single link fuse at the period of maximum current flow than by the multiple link, and further than that all of this energy was developed at one plane at the center of the fuse, whereas with the multiple link but 19,650 watts was developed in each element; that is to say, there was over six times as much energy developed at one point of the single link fuse as in the multiple link.

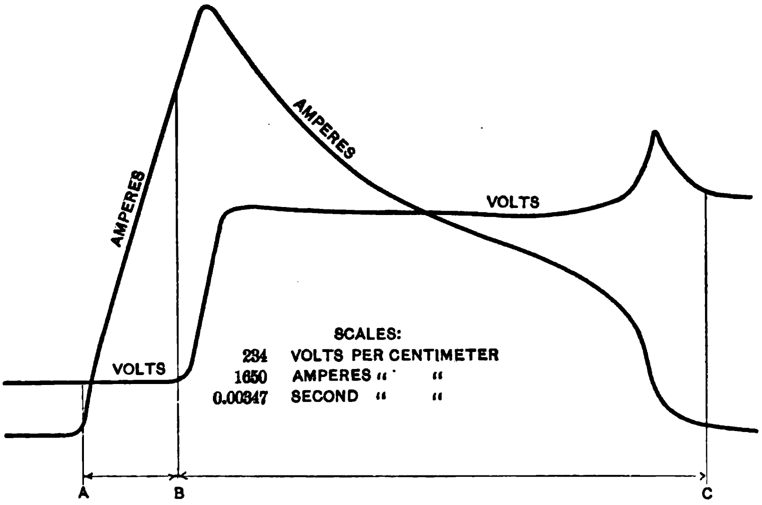


FIG. 13.—Single flat strip 0.028 x 0.625 wide. Capacity 80 amperes. Vol. ratio = 1.12 per cent

Now under such conditions it must be realized that there exists in the flat link fuse a hole or tunnel through the filling, being the space formerly occupied by the metal of the link, which is momentarily filled with a conducting vapor. The conductivity of this vapor is dependent very largely upon its density. In this concentration of a relatively large amount of vapor within an extremely confined space, and consequently of relatively great density, is found one explanation for the greater current flow seen in every instance in the single-strip link. With the multiple-link fuse we have five tunnels distributed at wide intervals within the tubing, the energy in each one being but one-sixth that in the single tunnel of the other fuse. More over, it has been shown that with the single link fuse, the vapor has to travel approximately twice the distance in order to bring all the filling into action as a condenser, and consequently requires more time than with the multiple fuse. Therefore, with the single link fuse, there is a rapid accumulation of pressure and a pronouncedly greater current flow, or an accumulative effect resulting in the disruptive action noted.

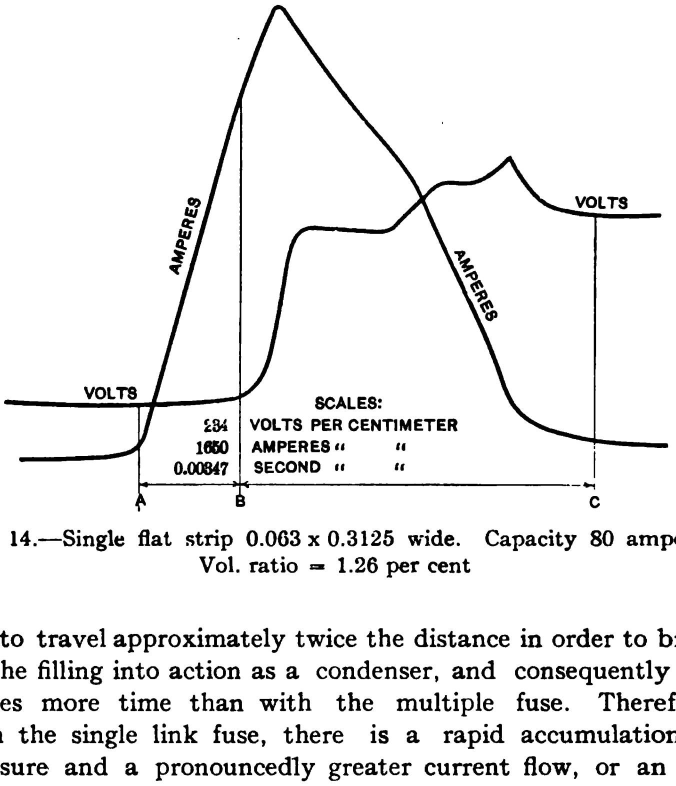


FIG. 14.—Single flat strip 0.063 x 0.3125 wide. Capacity 80 amperes. Vol. ratio = 1.26 per cent

The statement may be made that in making these comparative tests possibly the most efficient form of single link fuse is not used, and that the area might be extended by using a greater width and folding up the edges, etc. In this connection it should be pointed out that such modifications could hardly affect the results, since if such a peculiar form of single link fuse were employed, the same form could, of course, be used in the elements of the multiple strip for comparison, and the gain, both in area and distribution, would remain relatively the same. Further than that, it is difficult to conceive of any arrangement of the single link whereby all the mass of the filling could be so promptly and effectively brought into action.

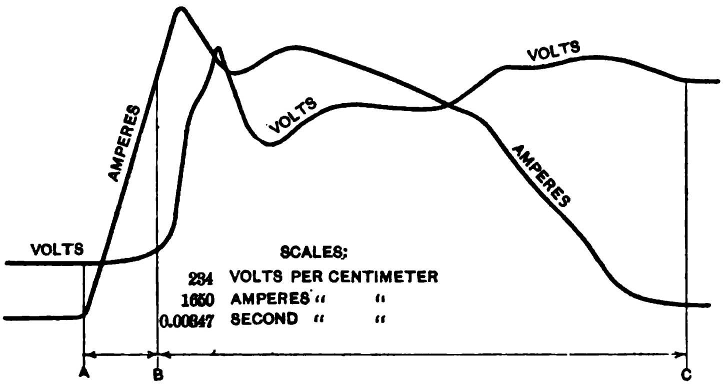


Fig. 15.—60 amperes, 600-volt. Single flat-strip link

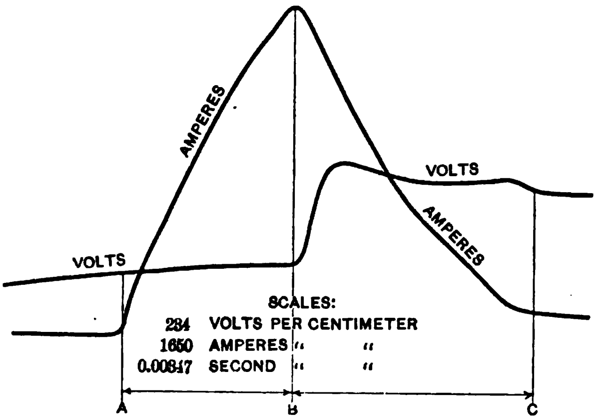


Fig. 16.—Five-strip multiple link 0.025 x 0.125 wide. Capacity 80 amperes. Vol. ratio = 1 per cent

Two other possible causes contributing towards the explosive action of a fuse have been suggested, one, the presence within the filling of a certain percentage of moisture and within the casing of a certain amount of air which, it was claimed, was

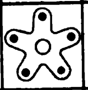
Test Number	Fuse Link Construction	Capacity Amps Volts	Volume Ratio of Fuse Link	Maximum Amperes	Time of Melting A. B.	Time of Arcing B. C.	British Thermal Units	Operation.
I		80 500	1%	7600	.0052	.0135	16.6	Quiet and satisfactory. Cartridge uninjured.
II		80 500	1.12%	8910	.0052	.0243	36.55	Explosive and dangerous Cartridge injured at one end
III		70 500	1%	8170	.0045	.0302	39.88	Explosive and unsatisfactory. Cartridge injured at one end.
IV		83 500	1%	—	—	—	—	Quiet and satisfactory. Photographic record lost. Cartridge uninjured
V		83 500	1.19%	9570	.0059	.0253	48.78	Explosive and dangerous. Cartridge injured at one end
VI		80 500	1.35%	10642	.0055	.0166	32.8	Explosive and very dangerous Cartridge burst.
VII		83 500	1%	8420	.0048	.0132	22.9	Quiet and satisfactory. Cartridge uninjured
VIII		78 500	1%	8170	.0052	.0118	18.9	Satisfactory. Cartridge uninjured
IX		80 600	1%	8420	.0034	.0146	27.0	Satisfactory. Cartridge uninjured.
X		80 600	1.12%	9390	.0042	.0246	54.94	Explosive and dangerous. Cartridge burst.
XI		80 600	1.26%	9650	.0048	.0163	35.8	Explosive and very dangerous. Cartridge burst
XIII		60 600	—	6520	.0035	.0243	44.42	Explosive and very dangerous. Cartridge burst Base broken
XV		80 600	1%	—	—	—	—	Quiet and satisfactory.

Chart 5.

suddenly and rapidly expanded by the heat of the arc. An examination of the filling of the ordinary fuse will show that there can be no material amount of air, the heating of which would occasion the violent explosions resulting from short-circuit, particularly when it is considered that the metal generally used for the link expands over 2400 times when converted from its metallic form to vapor. By actual measurement it is found that the total volume of air present in the average enclosed fuse is in the neighborhood of 19 per cent of the filling used. The presence of water might cause serious disturbance were there a sufficient amount of it converted into steam, but this would require the heating of the entire mass of filling to a high temperature; and to raise it to this temperature in the extremely short interval of time which is required to operate the fuse, would call for the application of a tremendous amount of heat energy. Of course if the arc should be maintained, the filling would rapidly reach such a temperature, but the condition under consideration is one where the fuse explodes when it is short-circuited, and as there can be no prolonged maintenance of the arc under this explosive action, which would affect the filling, it could not be heated in that manner and the only heat which could be applied for that particular purpose is that absorbed by the fuse in converting the metal of the link into its vapor. Actual measurement was made of the percentage of moisture present in the filling, both before and after a fuse had been subjected to a severe short-circuit which it had handled satisfactorily. Starting with an initial amount of 5 per cent, nearly 3 per cent remained, showing that but a little over 2 per cent of the total moisture had been driven off; namely, that portion of the moisture present in the filling which was quite close to the metal of the link.

While there are unquestionably various methods by which relatively the same effects may be produced as by the use of the multiple link, such, for example, as the well-known cigarette fuse or the cylinder link, it will be seen that these are but the amplification of the same principles; namely, extreme extension of surface and such an arrangement of the metal that the greatest possible contact with the filling is provided, to increase to the greatest degree the avenues of escape of the gases.

DISCUSSION ON "SOME CONSIDERATIONS IN DESIGNING HEAVY CAPACITY FUSES." FRONTENAC, N. Y., JUNE 30, 1909

Louis W. Downes: In making these investigations, the conditions on heavy overload and on short-circuits were principally considered. The analyses of the curves show to what a remarkably uniform degree they sustain the theory of proper fuse design, as I believe it is given in the paper. I would ask your special attention to the summary of the curves given in Fig. 8, and particularly to a comparison of tests 9 and 10, Figs. 12 and 13.

C. Francis Harding: In this and other papers presented before this convention, it is interesting to note the use of the oscillograph in studying electric phenomena under widely varying conditions. Several years ago when I made tests of enclosed fuses, the oscillograph had not been introduced for this purpose. It was attempted to determine the energy taken by the fuse under full-load, overload, and short-circuit conditions by measuring the resistance of the link and calculating the energy as I^2R loss. It was thought that a considerable discrepancy might exist in this method because the resistance was taken across the link alone, while there might also be a fairly high resistance in the joint between the link and the blade. There was, of course, resistance in the blade itself which caused heating. It was difficult, therefore, to determine just the amount of energy used in the fuse link itself—energy which must be carried by conduction to the tube and later radiated to the air.

Mr. Downes states that he has used and still uses that method in addition to the oscillograph method, and has calculated the energy taken by the fuse from the measurements of resistance as well as from the product of volts and amperes taken from the oscillograph. However, he has not compared these two methods of determining the energy. It would be interesting to determine how much of this heating comes from the soldered joint, how much from portions of the blades and how much from the link. As I understand it, the oscillograph product of volts by amperes would give the total energy expended in the fuse.

It is stated in the paper that the advantage of the multiple link over the single link is principally due to the shortening of the path through which the heated gases must be conducted to the tube, and also to the increase of surface area of the link. The fuses are identical as far as the blades are concerned, but I do not understand that the supports of the links are the same. I wish to ask how much of this difference between the action of the multiple link and that of the single link may be due to the conduction of heat away from the link, owing to the difference in the support, the multiple link having a much heavier support than the single link?

I would also like to know what effect a change in filling would have with the single link. I take it that the filling is the same in all cases. With the single link a larger amount of gas is generated in a small space than with the multiple link, and it would seem that if the voids in the filling were greater with the single link than with the multiple link there might be a freer path for the gases to reach the blow-holes, and possibly better operation of the single link in that case.

In the last paragraph of the paper the question of moisture in the filling is taken up, and it is also stated that the fuses were tested directly on short-circuit, without apparently anything being said about full-load or part-load operation. It seems to me that this condition is a bit different from that to which the fuses would be subjected in practice. Ordinarily the short-circuiting occurs with the circuit previously closed; that is, the fuses are under heavy load, three-quarters, or perhaps full load when the short-circuiting takes place. If the moisture—3 to 5 per cent in these fuses—be dissipated by the heat before this short-circuiting takes place, and held somewhere in the fuse ready to produce energy in the form of steam when the short-circuit occurs, this condition is different from that in the tests. As is well known, most of the fillers used in fuses are more or less hydroscopic, and the amount of the moisture in the filler will probably vary with the weather conditions and with the particular atmosphere in which the fuses are operated.

J. C. Lincoln: I wish to enquire as to the accuracy of these enclosed fuses. For instance, working at nearly full load, are the fuses accurate within 10 per cent or 20 per cent, or about what is the limit of accuracy which they may be expected to show? Secondly, is the fuse material itself of such a nature that when the fuse blows the gases will have the effect of blowing out the arc? I understand that some of the metals, in which zinc is one of the components, have this property to some extent. Is anything of this nature used in the fuse link itself?

W. S. Andrews: The paper shows the wonderful development of the art since the time, now nearly thirty years ago, when by mere chance I was called upon by Mr. Edison to make the first fusible links that were ever used for the protection of incandescent lamp circuits. Most of the fuses used in those early days were open, but a patent was allowed to Mr. Edison in 1880 for an enclosed fuse. It was customary to clamp the bare fuse wire under a screw-head, and this naturally made poor contact. To correct this, the late Luther Stieringer invented what he termed a " hard end fuse," which, as is well known, consisted of a fuse strip with copper ends. This improvement constituted the first important step toward the production of a reliable fuse link. A patent on this improved safety fuse was allowed to Mr. Stieringer in 1886.

A. E. Kennelly: The oscillograms in the paper are of great interest and value because they indicate the electrical actions that may occur when a large storage-battery is suddenly placed on a heavy short-circuit close to the switchboard, and also how severe are the duties of an enclosed fuse in such cases.

It will be seen that the current starts to increase at the rate of some 2,000,000 amperes per second. If the fuse does not suppress the enclosed arc in the first 0.01 sec. or so, the energy liberated within the fuse itself will be enormous.

Even when the fuse performs its functions promptly and satisfactorily, the quantity of energy liberated within it is about the same as in the cartridge of an ordinary shot-gun when fired.

Moreover, it is desirable that the rate of throttling of the current should be fairly uniform, otherwise there will be a considerable rise of voltage induced in the circuit by $L \frac{dI}{dt}$.

Louis W. Downes: In replying to Mr. Harding's questions in regard to the variation in construction between the different fuses used in these tests, I will say that he is mistaken in his inference that there was a difference in the construction between the multiple-link and the single-link fuses tested. They were all exactly the same, particularly the terminal wires; these were of the same length and of the same cross-section. The only difference in construction is that shown in the method of supporting the fusible portion of the link. That is shown in Chart 3 and Chart 4. In the five-wire multiple link there is a small star-shaped stamping of hard metal through the center of which the terminal wire, shown by the circle, is carried and to which it is soldered, the terminal wire being identically the same in all fuses.

The spacing in the filling, within certain limitations, has little to do with the case beyond a certain point; namely, it permits the escape of the gases, but if the spacings are too large, so that there is too great a flow of gas through any one section, then trouble will be experienced.

I believe the oscillograph tests clearly sustain the theory that the chief function of the filling in the enclosed fuses is to act in the capacity of a condenser; in other words. the volatilized metal of the fuse-link possesses a relatively high conductivity while hot. Below a certain temperature that conductivity ceases to exist and the condensed gas actually becomes an insulator, or at least possesses high insulating properties. Consequently, if a very coarse filling were used, having of necessity wide spaces among the particles, the volume of gas rushing through these spaces at one or more points might affect the cooling action of the filling to such an extent that the temperature of the gases would not be brought to a sufficiently low point to destroy their electrical conductivity; hence the arc would be maintained by the passage of the current through such a vapor path. It is desirable, therefore, to have the filling broken up into as fine particles as possible so as to present the greatest possible condensing surface to the hot gas, bearing in mind at the same time that the degree of fineness must not be such as to interfere with the ready passage of the gases through the mass of the filling. From this it will be seen that it is desirable to avoid too large spaces among the particles of the filling, and so to arrange the elements of the link that every particle of filling can be brought into action in the shortest possible time. In that way alone can we prevent the maintenance of an arc within the fuse. If the arc is not interrupted explosions or disruptions of the casing will soon result.

Mr. Harding further referred to the presence of moisture in the filling, and asked if it were not a fact that in fuses under load the moisture would be largely driven out by the high temperature of the fuse-link within the casing. We have found by rather an extensive investigation that it is extremely difficult to drive out all the moisture contained in the average porous filling. I wish to say, incidentally, that every enclosed-fuse manufacturer to-day is using for filling purposes practically the same material; namely, the different salts of calcium—calcium carbonate and calcium sulphate particularly.

We find that a filling as it comes from the mixers, ordinarily will contain from 16 to 18 per cent of moisture, and it is necessary to raise it to a temperature of between 600 and 700 deg. fahr. to drive this moisture off to any extent. After the moisture is down to about 4 or 5 per cent it will remain practically a constant factor and does not seem to be affected materially by atmospheric conditions, as we have exposed filling to the atmosphere in very foggy weather and have found no appreciable increase in the percentage of moisture, provided it has first been brought down to 5 per cent.

I do not think that Mr. Harding is correct in stating that an enclosed fuse at full load would have all the moisture driven out, because there is only a very small part of the fuse which approaches the high temperature necessary to drive the moisture off; that is, the part immediately in contact with the metal of the link, which if of zinc would run approximately between 500 and 600 deg. The exterior casing, however, runs at a very much lower temperature, about 160 deg. to 165 deg. being approximately the limit. This temperature limit is fixed by the fact that continued operation of the fuse at 175 to 180 deg. will rapidly destroy the fibre tubing, which will then become very brittle and would be likely to explode should the fuse be subjected to a heavy short-circuit.

Mr. Harding also asked where these tests were made—more particularly the short-circuiting—and if they actually represented a practically operative condition. As a matter of fact, the investigations were made with the idea of determining accurately the best method of avoiding the most serious difficulty of enclosed fuses; that is, explosion of the casing. Manufacturers had been troubled from time to time by the terrific explosions of the enclosed fuses, which were dangerous not only to property but to life if a man happened to be near the fuse when it exploded. Those explosions occured in the commercial operation of the fuse, so I do not feel it can be said that we have imposed impossible conditions upon the fuse in these tests.

A large amount of energy is available at the switchboard of stations all over the country, and a fuse is frequently called upon to withstand direct short-circuits under the most severe conditions. As an illustration, in New York City the fuses on the elevated railway and in the subway, with the enormous generating stations back of them, are carried on the truck and are there relied upon to sustain practically direct short-circuits between the third rail and the structure. A fuse that will not withstand that test is not only of no value, but is also a considerable menace to the company; for if one of them should explode as a train is drawing into a station, the result would be disastrous to the company financially from resultant damage suits.

In regard to Mr. Lincoln's inquiry concerning the accuracy of the fuse and the nature of the fuse metal, I would say that the accuracy of the fuse of course depends very largely upon the care with which it is designed, but it is not difficult to make a fuse which is within 10 per cent of its ratings. The great difficulty in the enclosed fuse is the difference in the overload blowing time when a fuse is first put into the circuit and after it has been in the circuit for some time, due to the fact that the heat conductivity of the porous material which is immediately in contact with the metal of the link of course rapidly decreases as the temperature rises. That to a certain extent does affect the accuracy of the fuse, but not to an extent which renders its use impracticable. There are several methods of overcoming this defect, the most common being the notching of the link to bring about a high current density at the center; and the other, the use of the air drum. By confining a small body of air immediately about the central part of the link, the heat is less rapidly absorbed by the filling at that point. That fuse possesses an astonishingly high degree of accuracy whether cool or hot. Its characteristic curve will be found to run uniform and the blowing time at any given overload is constant.

Mr. Lincoln's other inquiry as to whether any metal was employed which possesses a tendency to blow out the arc, I have already referred to by stating that the filling was what destroyed the arc by condensing the conducting medium; namely. the metallic vapor at the time of the operation of the fuse. As far as I know, there is not any practical difference in the arcing effect of any of the softer metals, such as zinc, aluminum, lead, tin alloys, lead-bismuth alloys, or in combinations of these—all of which I have tried very extensively and in a great many different mixtures. The harder metals, copper and silver, owing to their higher boiling point, are not well adapted for use in fuses, particularly enclosed fuses. The higher melting point affects them and the conversion of the metal into its vapor is accompanied by a more explosive action. I doubt very much if any effective results would be produced by what Mr. Linclon referred to; that is, the so-called tendency of the gases of some of the metals to extinguish an arc.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

COMPARATIVE COSTS OF 25-CYCLE AND 60-CYCLE ALTERNATORS

BY CARL J. FECHHEIMER

The statement is frequently made that 25-cycle alternators are more expensive than 60-cycle machines built for the same output, speed, voltage, and phase. A considerable difference of opinion exists at the present time as to how much more the low-frequency machine should cost than the corresponding high-frequency machine. When an attempt is made to analyze conditions, by examining the cost records of machines built by a large manufacturing company, one is confronted by a maze of figures which assist but little toward solving the problem. This is not at all surprising when one considers the many changes which have accompanied the rapid development of alternating-current generators. Some machines have a relatively great amount of iron, while others have a relatively great amount of copper; there is considerable difference in the results obtained from the various methods used for ventilating alternators; some are much more liberal as regards heating, or voltage margin, or regulation, than others; the excitation differs appreciably in machines for nearly the same rating; some were built when material and labor were high, etc. In this paper an attempt has been made to eliminate, as far as possible, some of these variables.

In a paper entitled "The Relative Proportions of Copper and Iron in Alternators," read by the writer before the Atlantic City Convention of the Institute in 1908, a method was worked out for determining the value of flux necessary to obtain the cheapest machine. In the appendix, which was subsequently added, the cost of the exciter is brought into the equations, with the view of reducing to a minimum the cost of the entire equipment, including alternator and exciter. In this paper the method employed has been to determine this value of flux for a machine of a given rating, and to use this value of flux for determining the capacity and cost of the exciter, the approximate diameter and length of machine, and the weights and costs of material in each of the principal parts of the alternator, in accordance with the method described in the paper referred to.

A sufficient number of points for plotting curves was worked out for two speeds common to 60-cycle and 25-cycle alternators; namely, 300 and 100 rev. per min. The former speed is intended to apply to water-wheel-driven alternators, and the latter to engine-type alternators. The curves are intended to apply to revolving-field alternators having rectangular poles.

They are further intended to apply to three-phase machines wound for approximately 2300 volts. The high-voltage machines require somewhat lower flux densities in the stator iron, and the necessity of using deeper slots in the stator causes the teeth to become a larger factor of the total stator iron than was allowed for. Moreover, the heating of the stator coils for the same copper loss is considerably greater than in the low-voltage machine. Furthermore, the insulation and the labor required for placing it on the coils become considerable factors in the cost of the alternator.

Allowances were made for each alternator to have an inherent regulation of about 8 and 19 per cent at normal load, and at unity and 85 per cent power-factor respectively; each will be capable of giving its normal voltage at 25 per cent overload in kilowatts at 85 per cent power-factor. The temperature rise of the stator coils will be about 35 degrees cent., when operated at full load for 24 hr., and 50 degrees when operated at 25 per cent overload for 2 hr. following the full-load run, these temperatures being based on 100 per cent power-factor conditions.

A curve was plotted with kilowatts per 100 rev. per min. against the cost of exciters; and from this curve the cost per kilowatt (*pe*) of the exciters could be determined. The exciters were considered to be belted units with a pulley ratio of 3 to 1. This represents about the average condition; for in a large number of plants the exciting current is taken directly from the direct-current bus-bars, in which case no exciter is furnished, while in others, an engine or motor-driven exciter is used.

In the following table, the values assumed for the various constants used are given.

TABLE I.

	100 rev. per min.		300 rev. per min.	
	25 cycles	60 cycles	25 cycles	60 cycles
B_a = Flux density in armature core in kilolines per sq. in.	65	40	68	40
$B_{f.\,r.}$ = Flux density in field ring in kilolines per sq. in.	38 (C.I.)	38 (C.I.)	70 (C.S.)	70 (C.S.)
B_p = Flux density in poles in kilolines per sq. in.	98	93	98	93
k = Distribution factor for stator coils	0.955	0.955	0.955	0.955
K = Ratio of net to gross iron in poles	0.91	0.91	0.91	0.91
K^{I} = Ratio of field ampere-turns per pole required for full field to the armature ampere conductors per pole with full load	1.7	1.8	1.7	1.8
K^{II} = Ratio of tangential dimension of pole to axial length of pole	0.5	0.34	0.65	0.45
K^{III} = Resistivity in micro-ohms, of an inch cube of copper at the temperature of the fields when hot	0.85	0.85	0.85	0.85
K^{IV} = Ratio of axial length of pole to pole pitch	1.	1.5	.75	1.
K^{VI} = Factor by which the product of amperes per sq. in. and ampere conductors per in. should be divided to give the temperature rise in degrees centigrade of armature coils	$3.\mathrm{x}10^4$	$3.5\mathrm{x}10^4$	$3.5\mathrm{x}10^4$	$4\mathrm{x}10^4$
K^{VII} = Ratio of length of armature end connection per coil to pole pitch	3.6	3.6	3.6	3.6
K^{IX} = Ratio of net iron in armature to axial length of pole	0.8	0.8	0.81	0.81
K^{XI} = Coefficient used for determining weight of yoke	1.9	1.9	2.2	1.9
K^{XIII} = Ratio of pole radial height to sq. root of pole tangential dimension	3.1	3.1	3.1	3.1
p_a = Price, in dollars per pound, of armature copper	0.2	0.2	0.2	0.2
p_{ai} = Price, in dollars per pound, of armature active iron	.0325	.0325	0.0325	.0325
p_f = Price, in dollars per pound, of field copper	0.2	0.2	0.2	0.2
$p_{f.\,r.}$ = Price, in dollars per pound, of field ring material	0.0225 to 0.025	0.0225 to 0.025	0.0325	0.0325
p_p = Price, in dollars per pound, of pole iron	0.0215	0.0215	0.0215	0.0215
p_y = Price, in dollars per pound, of yoke iron	0.0225 to 0.025	0.0225 to 0.025	0.0225 to 0.025	0.0225 to 0.025
T = Temperature rise in degrees centigrade, of armature coils	35	35	35	35
o = Pole leakage factor	1.2	1.2	1.2	1.2
o' = Field-ring leakage factor	1.25	1.25	1.25	1.25

The following additions were made for scrap material and parts not included in equations.

TABLE II.

	100 rev. per min.		300 rev. per min.	
	25 cycles	60 cycles	25 cycles	60 cycles
Field copper	2%	2%	2%	2%
Armature copper	10%	10%	10to12%	10to12%
Armature active iron	45%	50%	45to50%	50to60%
Yoke	15%	15%	15%	15%
Poles	25%	25%	25%	25%
Field ring	25%	25%	25%	25%

From an inspection of equation (21) in the paper previously referred to, it will be seen that if the same constants were employed, and the flux per pole varied inversely as the frequency, then the product of field copper weight and excitation would vary inversely as the frequency. The flux per pole is about three times as great in the 25-cycle as in the 60-cycle machine, and as there is a difference in the constants, the product is only about 44 per cent greater in the 25-cycle than in the 60-cycle machine. This is shown in Figs. 1 and 2.

As in the case of the field copper, if the constants were the same for the 25-cycle and 60-cycle alternators and if the flux per pole varied inversely with the frequency, the armature copper would vary inversely with the frequency. As will be seen from Fig. 2, however, the difference is but 63 per cent.

The necessity for using more active iron in the stator of the 25-cycle machine is evident, even though considerably higher densities are used, especially since the flux per pole is about three times as high in the 25-cycle as in the 60-cycle machine. The relative costs are shown in Fig. 3, where a difference of about 35 per cent appears.

The necessity for making the radial height of the pole greater in the 25-cycle than in the 60-cycle alternator, due to the greater number of ampere-turns, makes the weight of the poles for the former considerably greater than the latter. In Fig. 3 this difference will be seen to be about 70 per cent.

Since the internal diameter of the stator of the 25-cycle alternator is less than of the 60-cycle, the weight of the yoke will be very nearly the same, even though the axial length and radial depth of laminations are greater, and the greater depth of laminations necessitates a somewhat stiffer construction. This is shown in Fig. 4.

The field ring, while somewhat smaller in diameter for the 25-cycle machine, must be sufficiently greater in section to carry the greater flux per pole. For determining these curves, the assumption has been made that if the field ring is large enough to carry the flux, its cross-sectional area will be sufficient for mechanical purposes. The material used has been taken to be cast iron for the 100-rev. per min. machines, and cast steel for the 300-rev. per min. machines. From Fig. 4 it will be seen that the field ring is approximately twice as heavy for the 25-cycle as for the 60-cycle machine.

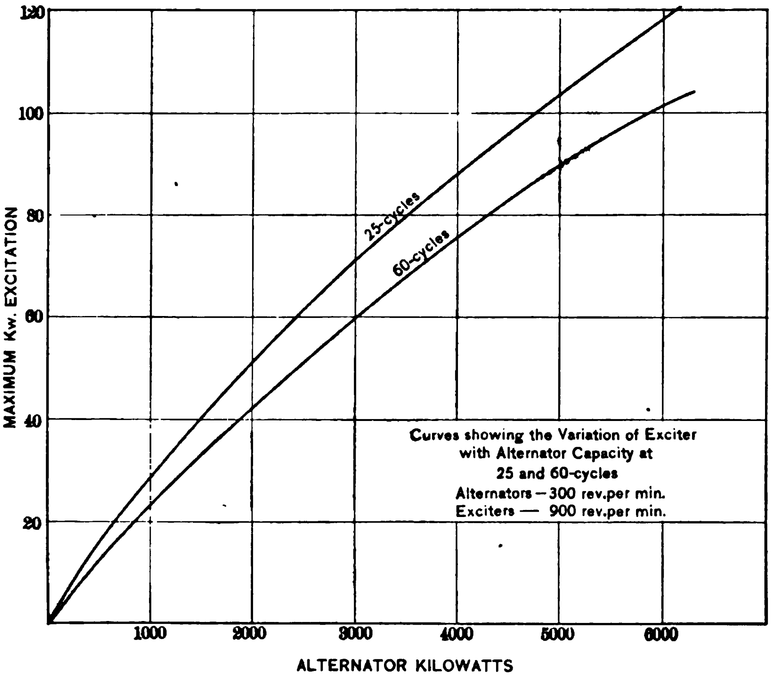
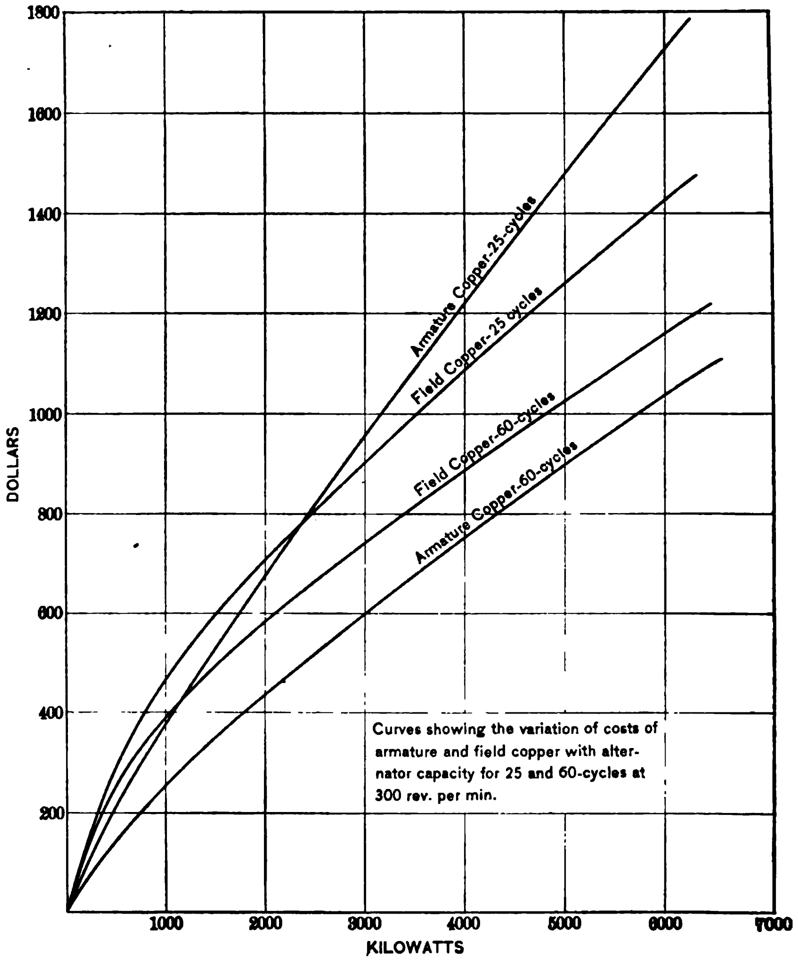


FIG. 1

Figs. 5, 6, and 7 show the comparative weights and costs of the copper and iron in the principal parts of the alternator. The principal parts include the armature and field copper, the armature active iron, the yoke, poles, and field ring.

With the exception of the curves shown in Fig. 7, the curves above described apply to alternators operating at 300 rev. per min. In Fig. 8, the relative costs of material in the principal parts are shown in the forms of curves for 25 and 60-cycle alternators operating at 100 and 300 rev. per min. It is interesting to note that the principal material in the 25-cycle machine at 300 rev. per min. will cost nearly as much



Curves showing the variation of costs of armature and field copper with alternator capacity for 25 and 60-cycles at 300 rev. per min.

Fig. 2

as the equivalent material in the 60-cycle at 100 rev. per min. Also the cost of the 25-cycle machine at 300 rev. per min. will be about 42 per cent more than of the 60-cycle machine, whereas the difference is but 33 per cent at 100 rev. per min. This condition exists, even though the "cubical contents" of the stator (represented by the product of the axial length of pole and the square of the internal diameter of the stator) is slightly less in the 25-cycle machine at 300 rev. per min., and slightly greater at 100 rev. per min., as shown in Fig. 9.

In order to determine the cost of the total material in the alternator, the cost of material in the principal parts was compared with the total cost of material in a number of alternators

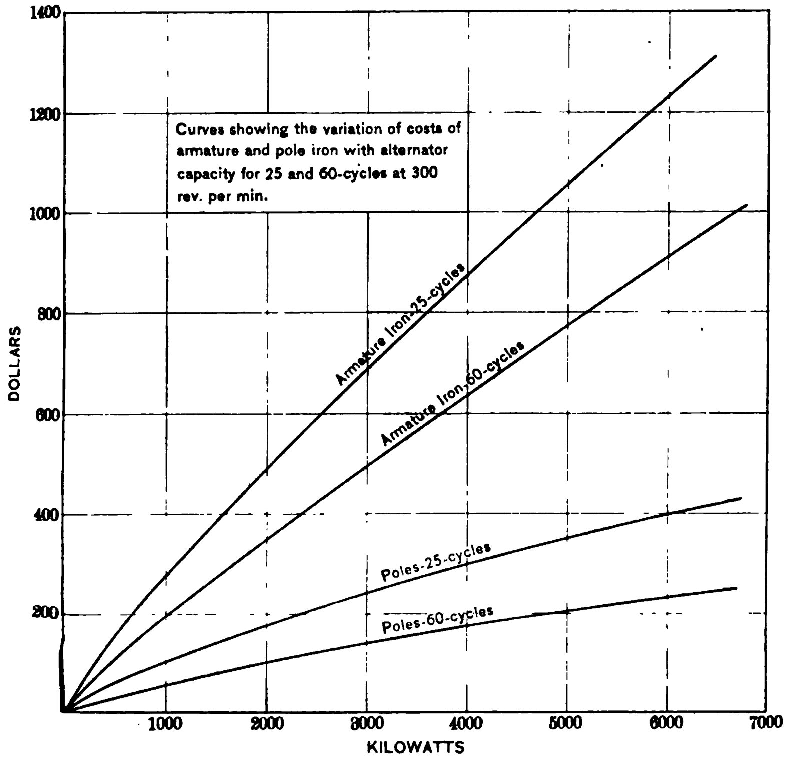


FIG. 3

which had previously been built. In estimating the cost of material in the principal parts of these machines, about the same allowances were made for unavoidable scrap material as those given in Table II, and the prices of the materials were taken to be the same as existed at the time at which the various alternators were built. The ratings of each of the alternators were nearly the same as those for which the estimated curves in this paper are given. None of them was made with heavy rotors with expensive material therein, necessitated by high over-speed requirements. The ratio of the cost of total material to material in the principal parts was found to lie between 1.4 and 2, the former applying as a lower limit to the engine type of

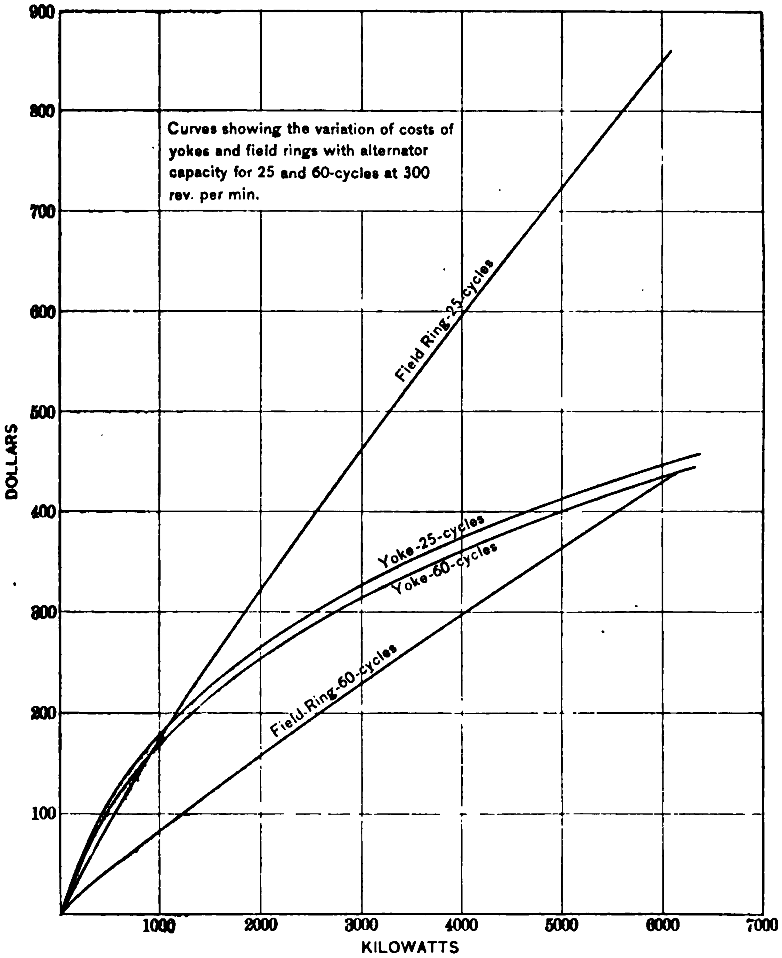
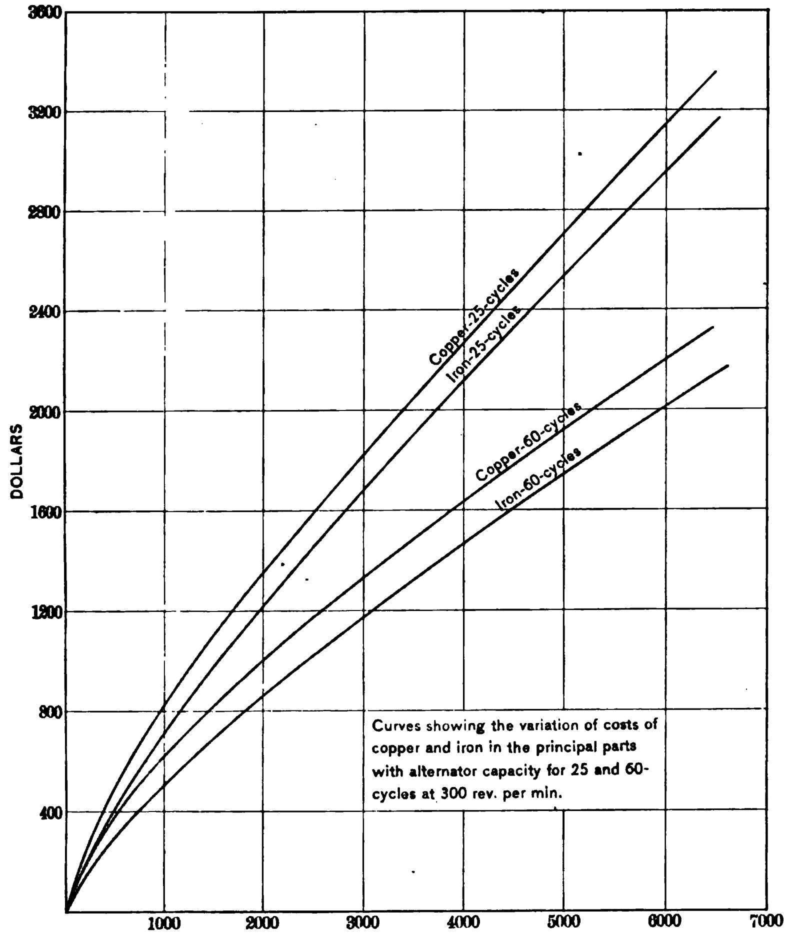


FIG. 4

alternator, and the latter as an upper limit to water-wheel type alternators.

For the purpose of determining the relation which the labor bears to material in the alternator, the ratio of labor to material was plotted against kilowatts per 100 rev. per min. for a large number of 60-cycle and 25-cycle engine and water-wheel-driven alternators which had previously been built. The burden has been omitted in allowing for the labor. Although this is contrary to the usual method of estimating costs, it has been taken to be nearly correct for an estimate of the character undertaken in this paper; for it is evident that the office expenses and other fixed charges usually included in the burden, are affected little, if any, by the frequency, or even by the size of machine which the factory undertakes to build.



Curves showing the variation of costs of copper and iron in the principal parts with alternator capacity for 25 and 60-cycles at 300 rev. per min.

Fig. 5

The costs of material previously considered, the material not included in the principal parts, the labor, rheostat, and exciter were added together, giving the actual factory cost of the entire equipment. In Fig. 10 these are plotted as " relative ", rather than " actual " costs, for the great difference in mechanical design of bases, bearings, etc., and the variation in labor, both as regards location and period, would influence the total cost of the equipment considerably; whereas the relative costs would not be greatly altered. This will be more evident when a com-

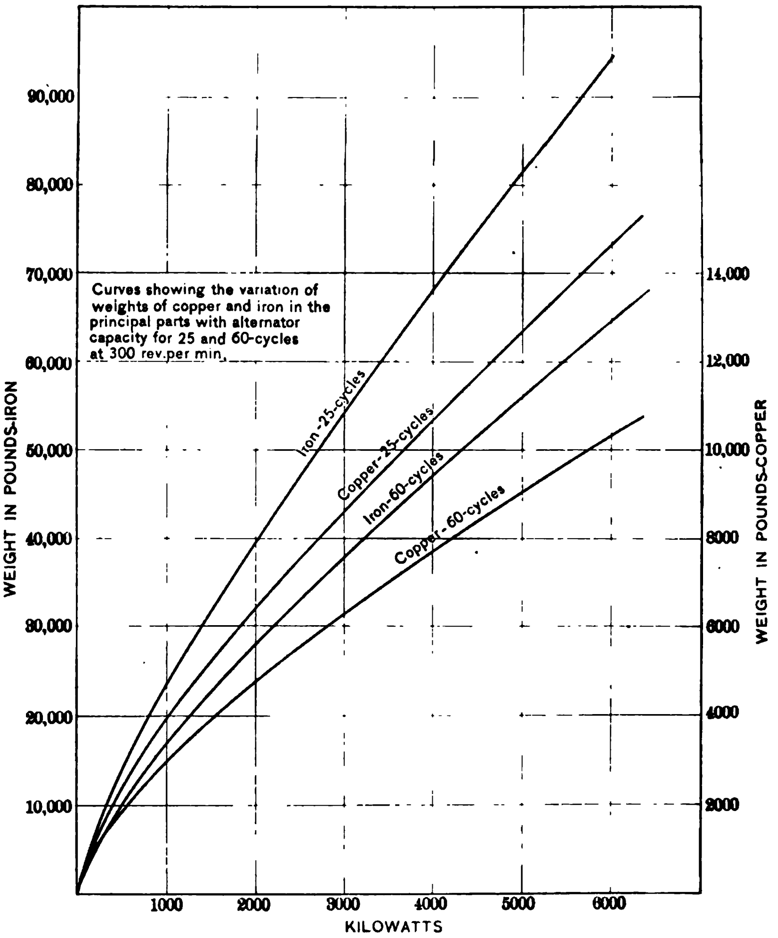
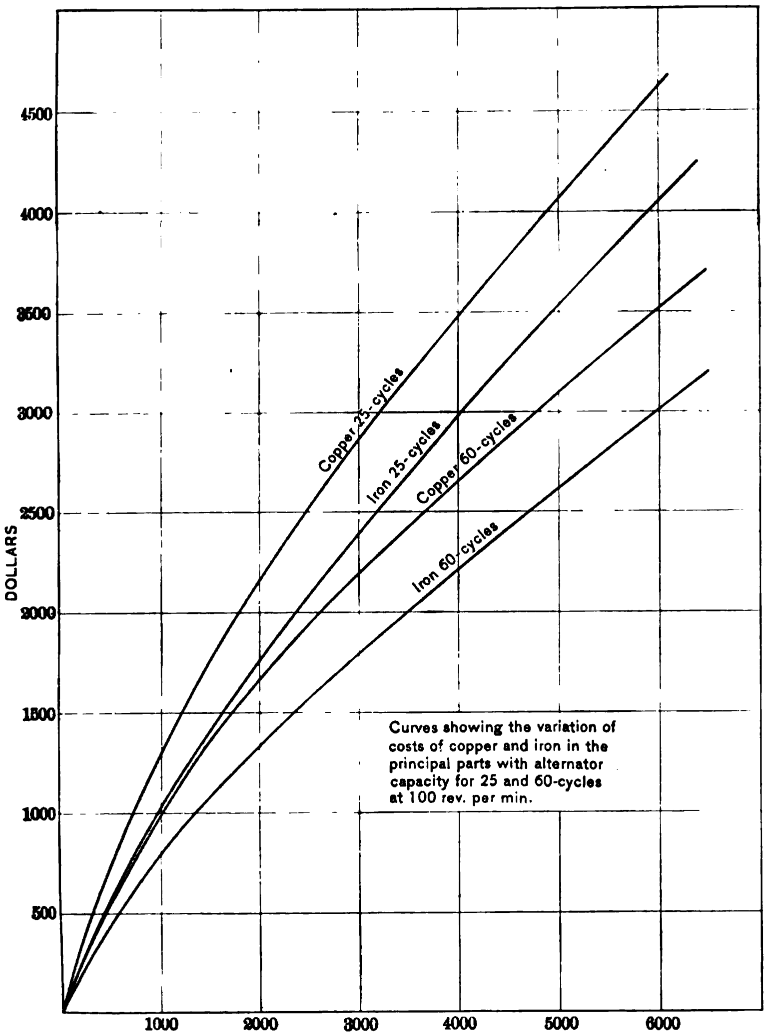


FIG. 6

parison of Figs. 8 and 10 is made; this comparison shows that the relative costs of the entire equipment and the material in the principal parts are nearly the same for the 25-cycle and 60-cycle machines operating at the same speed.



Curves showing the variation of costs of copper and iron in the principal parts with alternator capacity for 25 and 60-cycles at 100 rev. per min.

FIG. 7

Owing to the fact that bases, bearings, and shafts have been included in the total costs of machines operating at 300 rev. per min., and have been omitted for the 100 rev. per min.

machines, the 25-cycle equipment at 300 rev. per min. is more expensive than the 60-cycle at 100 rev. per min.; whereas the reverse is true when only the material in the principal parts is considered.

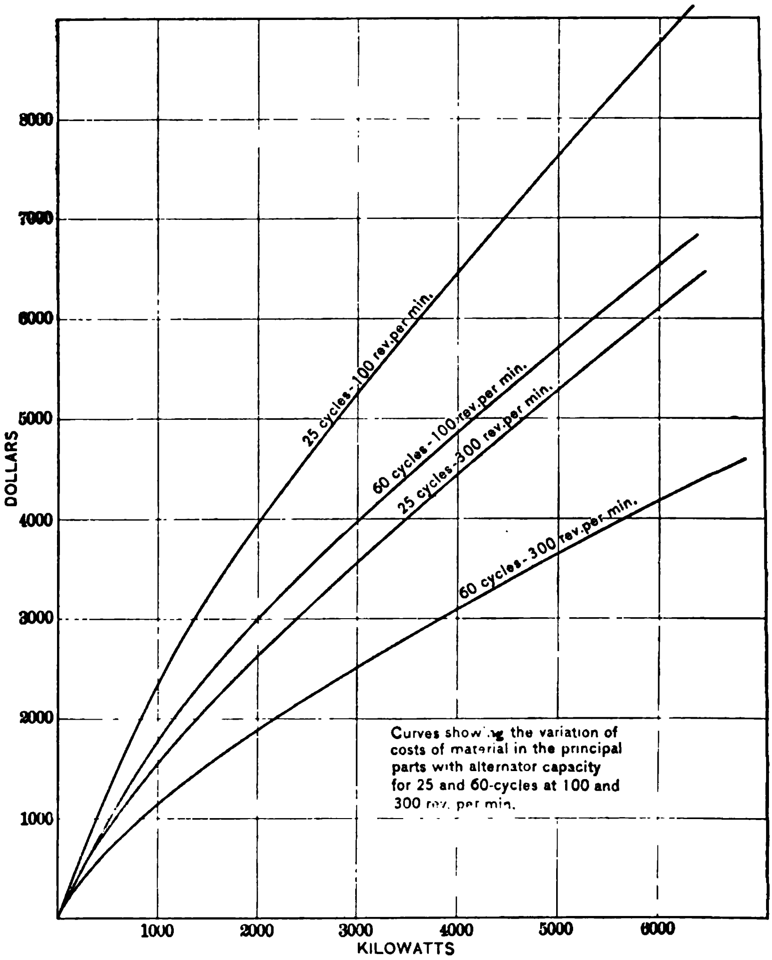


FIG. 8

It will be seen that the 25-cycle machine is about 42 per cent more expensive at 300 rev. per min., and 30 per cent more costly at 100 rev. per min., than the 60-cycle machine for the same output, voltage, and phase. This difference will be slightly greater in the high-speed machines for small outputs in which it is not possible with our present construction, when operating at low power-factors, to keep the temperature rise of the fields of the 25-cycle machines within reasonable limits, when that value of flux is employed to obtain the cheapest machine, unless a prohibitively large diameter be used. Moreover, the greater axial length and lower peripheral speed of the 25-cycle machines will cause the temperature rise of their stator coils to be greater for the same watts loss per square inch of radiating surface than in the equivalent 60-cycle machines,

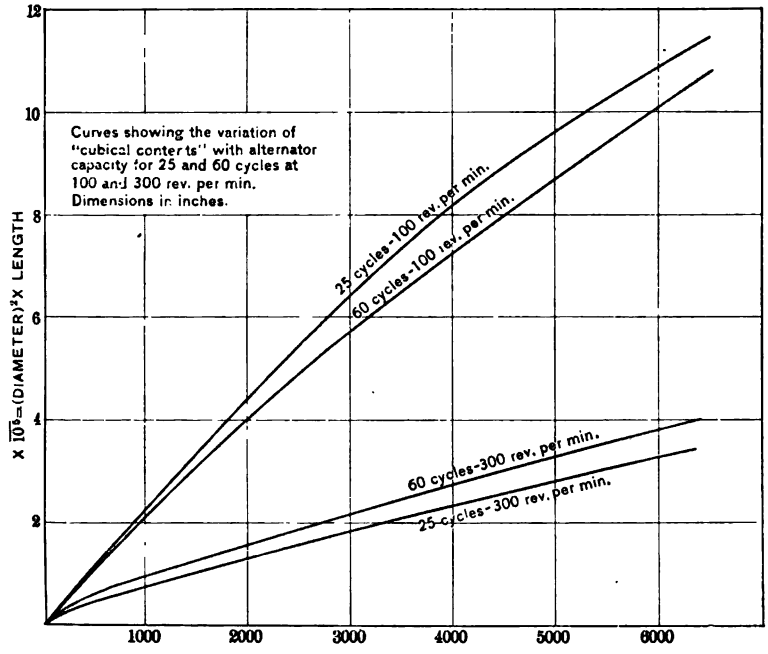
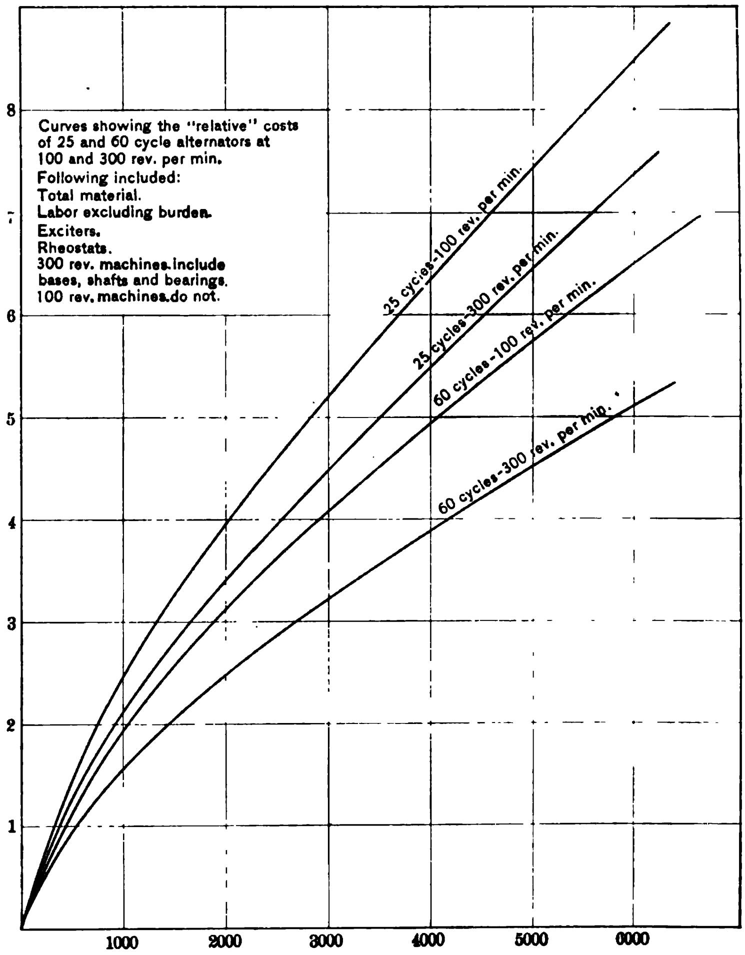


FIG. 9

for which due allowances were made in estimating the curves. On the other hand, somewhat more costly conductors must be used in the 60-cycle machines for large outputs, due to the greater eddy-current loss in them. The use of a larger number of stator slots causes the dies and windings to be somewhat more expensive in the slow-speed 60-cycle machine than in the 25-cycle machine for the same rating. This, combined with the fact that there are a greater number of poles in the slow-speed 60-cycle machines, will probably cause their cost to be somewhat more than was allowed for in estimating the curves in Fig. 10, thus causing the difference in cost between 25-cycle and 60-cycle machines at 100 rev. per min. to be slightly less than the curves indicate.



Curves showing the "relative" costs of 25 and 60 cycle alternators at 100 and 300 rev. per min.
Following included:
Total material.
Labor excluding burden.
Exciters.
Rheostats.
300 rev. machines include bases, shafts and bearings.
100 rev. machines do not.

Fig. 10

The great weight of the poles and field copper of the 25-cycle alternators makes the cost of the rotors of 25-cycle machines guaranteed to stand a large overspeed, considerably greater than for the 60-cycle machines for the same rating. The great length of the end-connections of the stator coils for 25-cycle alternators for large outputs at high speeds makes it essential to support them. This is unnecessary in most 60-cycle alternators (excluding turbine-generators), inasmuch as the end-connections are shorter and the reactance of the stator is higher, both of which will tend to prevent the rupture of the end-connections due to the great rush of current at the first instant, when the alternator is short-circuited. We thus see that the difference between the costs of the 25-cycle and 60-cycle machines at 300 rev. per min. will probably be slightly more than would appear from an inspection of Fig. 10.

The writer wishes to thank Mr. A. N. Brown for assistance in determining the costs of exciters and finding the relation which the labor bears to the material.

DISCUSSION ON "COMPARATIVE COSTS OF 25-CYCLE AND 60-CYCLE ALTERNATORS." FRONTENAC, N. Y., JUNE 30, 1909

J. C. Lincoln: In Fig. 2, the curves showing the costs of 25-cycle machines, the cost of the armature copper, and the cost of the field copper lines cross each other at 2500 kw., showing the costs to be approximately equal. I have always thought that in a large machine the cost of the field copper would be several times that of the armature copper. Ordinarily the air-gap is very long in these machines, and that requires a large amount of copper in the revolving field in order to keep down the temperature, also good regulation requires considerable flux. These considerations tend to increase the ratio of the field copper to the armature copper.

Is it not true that in increasing the output of the armature from a 600 to 900 ampere conductor per inch the excitation has to be raised in almost the same proportion?

M. G. Lloyd: Fig. 10 seems to me somewhat unfair in that in comparing the total cost the 300-revolution machine should include base, shafts and bearings, while the 100-revolution machine does not. Not being engaged in the manufacturing end of the business, I do not know what proportion that cost bears to the total, but it might make quite a difference in the relative value of the costs.

Has Mr. Fechheimer made any comparisons of the cost with regard to the use of silicon steel in the same way? I know that it is not very much used as yet, but it seems probable that it is going to be used in alternators and in motors.

C. J. Fechheimer: With regard to Mr. Lincoln's question, pertaining to the crossing of the field and armature copper cost curves for 25 cycles at about 2400 kw. in Fig. 2; the relationship of these curves depends to a great extent upon the relative proportions of copper and iron. Until recently it was customary to use 500- or 600-ampere conductors per inch in a large generator, with the result that the field copper would be considerably more expensive than the armature copper. It was shown in my previous paper* that the product of excitation and weight of field copper varies approximately as the number of conductors, whereas the armature copper varies as the square of the number of conductors. Hence it will readily be seen that if the ampere conductors per inch be increased from 550 in a 500-kw. alternator to 900 in a 5000-kw. alternator, the armature copper will increase more rapidly than the field copper as the size of the alternator is increased. These are the values of ampere conductors per inch which correspond approximately to the most economical machines. Sometimes we cannot build the most economical machine, as, for example, as Mr. Lincoln states, the field heating becomes the limiting factor, and we must use a smaller value of

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* TRANSACTIONS A. I. E. E. 1908, Vol. XXVII, p. 1429.

ampere conductors per inch than corresponds to the most economical machine in order to keep the field temperature within reasonable limits. In general, however. we can in large machines with well ventilated, single-layer, edge-wound fields, prevent their temperature-rise exceeding 45 degrees cent. with full load at 85 per cent power-factor, which should be satisfactory.

In regard to Dr. Lloyd's question as to including shafts, bearings, and bases, in Fig. 10; the 300-rev. per min. machines are intended to be water-wheel driven, in which cases the manufacturing companies are required to furnish these parts. Machines of 100 rev. per min. are usually engine-type machines, and with these the generator builder omits the shafts, bearings, and bases—the engine manufacturer supplies them.

As regards silicon steel, we have not made sufficient tests on the material for me to state definitely whether it would pay us to use it or not. I therefore omitted it in this comparison. We hope to make more complete tests in the future.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

CALCULATION OF IRON LOSSES IN DYNAMO ELECTRIC MACHINERY

BY I. E. HANSSEN

It is well known that the iron losses in all kinds of electric motors and generators are invariably much greater than those calculated from iron-loss curves, such as are obtained from tests of samples of iron, unless an allowance is made for additional losses.

The causes of this increase in the losses are many and varied. They have been dealt with in detail by various writers, but so far as the writer knows, a simple method for predetermining the total iron loss has never appeared in print. The losses in the different parts of the magnetic circuit will be considered in a general way and the causes of the additional losses will be pointed out. It is hoped that this paper will be of some use to designers in pointing out a method which has been found successful in actual practice after about one and a half years use.

Consider a smooth-core armature of a generator for either direct or alternating current. The paths of the flux are shown in Figs. 1, 2, and 3. It will be noticed that the distribution lacks uniformity more or less, due to the difference in the length of the paths. This lack of uniformity naturally leads to an increase of the losses above what they would be were the distribution uniform.

An allowance must further be made to take care of imperfect insulation between the discs, caused by filing, burrs, and crushing of the insulating material when subjected to pressure, and also for the hardening effect caused by the punching process if the discs are not again annealed.

To prevent the teeth from bulging out, a number of extra heavy discs are usually placed at the ends of the core and next to the ventilating ducts if such are provided. These heavy discs, being from two to three times thicker than the regular ones, will have from four to nine times greater eddy current losses. Sometimes these discs have a higher permeability than the thinner ones, and this will still further increase the losses due to the higher induction which will exist in the thicker discs.

Iron-loss curves of iron samples, as usually made, give the losses taking place when the iron is subjected to an alternating magnetic field. The field in an armature, however, is not an alternating one but is of a rotary nature, probably elliptical. Such a field is generally conceded to cause considerably higher iron losses than the alternating field, provided the density at which the iron is worked does not exceed a certain limit. This limit is reached at about 120,000 c. g. s. lines per square inch. If the density is increased above this value, the loss per unit of iron decreases rapidly. However, such high densities are hardly ever reached in armature cores, except in the teeth, so that there is generally a further allowance to be made, due to the field being a rotating one.

In a smooth-core armature, the foregoing probably covers all the additional iron losses in the machines, provided the armature and field structure are perfectly concentric. If they are not concentric, the gap reluctances will vary with different positions of the armature, the result being that the flux in the field poles and yoke will not have a constant value but will pulsate and thus produce eddy currents in the field structure. *Dr. W. M. Thornton, who first called attention to this fact, cites a case in which this loss amounted to 2300 watts for a 10-kw. generator.

Assuming that the armature and field structure are concentric, the actual iron loss, due to the above-mentioned causes, will be from 25 per cent to 35 per cent greater than calculated from the iron curves for smooth-core armatures.

Toothed armatures. What has just been said about smooth-core armatures applies equally well to the iron back of the slots of toothed armatures, the only difference being that in the latter

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*See Journal of the Institution of Electrical Engineers V-33, page 545.

Figures 1, 2, 3, 4, 5, and 6 are reproduced from the paper by Prof. W. M. Thornton, referred to previously. Figures 7, 8, and 9 are taken from a paper by Hele-Shaw, Hay & Powell, Journal of the Institution of Electrical Engineers, Vol. 37, No. 179.

FIG. 1

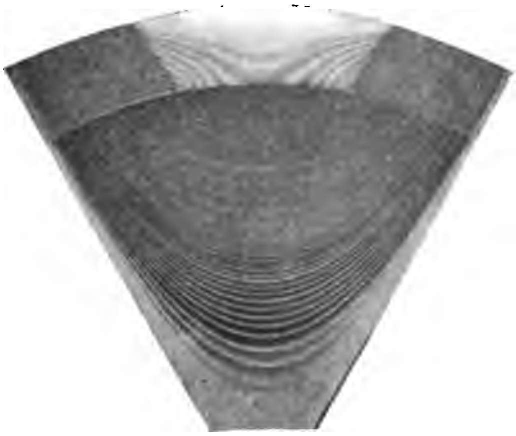

FIG. 2

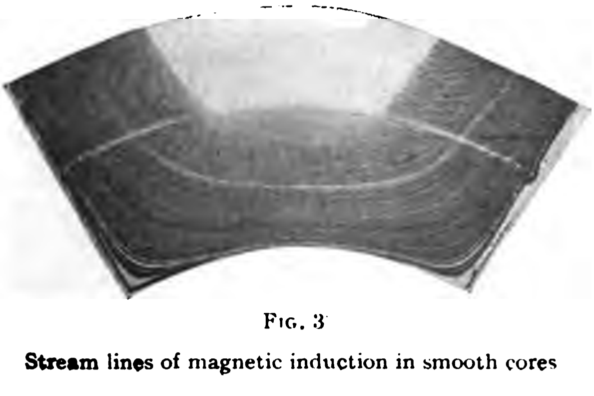

FIG. 3

Stream lines of magnetic induction in smooth cores

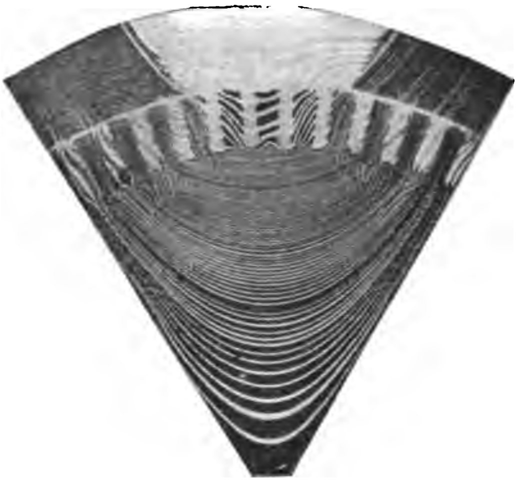

FIG. 4

FIG. 5

FIG. 6

Lines of magnetic induction in toothed cores the distribution is less uniform, as an inspection of Figs, 4, 5, and 6 will show. It will be seen that for some distance back of the teeth the density is higher than back of the slots, and of the same order as the density in the teeth. If the iron is nearly saturated, these streamers of higher density appear to continue all the way from pole to pole, as pointed out by Dr. Thornton. It is probable that this phenomenon nullifies somewhat the reduction of the iron loss which would otherwise occur when iron subjected to a rotating field is worked above 120,000 lines per square inch.

The writer has found that adding 30 per cent, 35 per cent, and 40 per cent for 25, 40, and 60 cycles, respectively, to the calculated loss in the iron back of the slots, gives very nearly correct results.

Losses in the teeth. In the teeth the percentage increase in the losses due to filing and burrs may become much greater than is the case for the part of the iron already discussed, particularly in high-frequency machines (50 and 60 cycles), in which the eddy currents in the burrs become very marked. Here also we have to allow for the thicker discs next to the ventilating ducts and at the core ends. Furthermore, due to the leakage field, the resultant field is elliptical instead of alternating. An addition of 30 per cent, 60 per cent, and 80 per cent, for 25, 40, and 60 cycles, respectively, has been found to give satisfactory results.

Losses due to slot openings. In addition to the losses already mentioned there are other losses, particularly in machines having wide-open slots, caused by variations in the gap density. In direct-current and synchronous machines these losses are produced by eddy currents in the pole-shoes, while in induction motors they are caused partly by eddy currents in the tooth-faces and partly by density variations extending throughout the depth of the teeth. Fig. 10 shows roughly the flux distribution in a portion of the gap of a direct-current machine or in a synchronous machine with projecting poles. As will be seen, the density opposite a slot is lower than that opposite a tooth, the result being that the pole-shoe is subjected to the influence of a high-frequency field.

The frequency of this field is $\frac{\text{rev. per min.} \times S}{60}$ cycles per second, S being the number of armature slots.

In an induction motor in which both the primary and second-

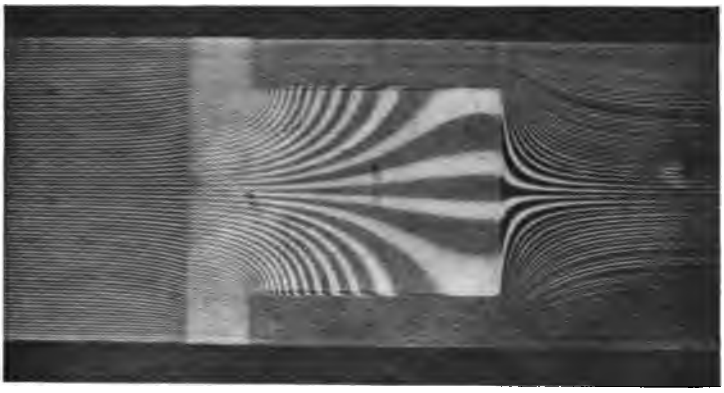

Fig. 9

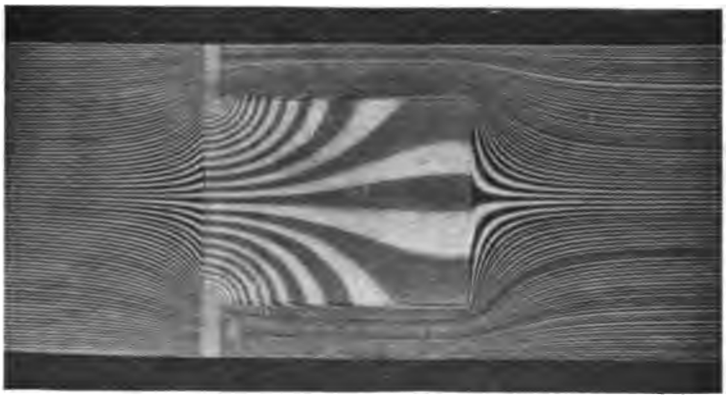

Fig. 8

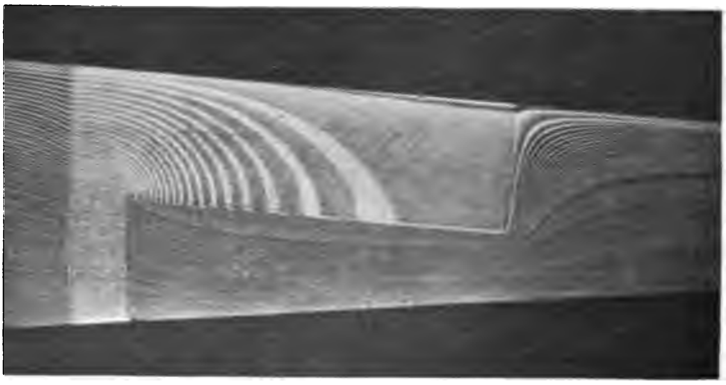

Fig 7

ary members are slotted, both members will be subjected to these pulsations. However, as the secondary slot openings are generally very small, the losses from this source in the primary iron will as a rule be of no great moment.

The frequency of the pulsations in the secondary member is $\frac{\text{rev. per min.} \times S\,p}{60}$ cycles per second, where $S\,p$ is the number of primary slots, while to obtain the frequency in the primary the number of secondary teeth is substituted for the number of primary teeth in this expression. The amount of variation in density can be calculated quite accurately, but this requires a considerable amount of time, and experience indicates that this refinement is not justified.

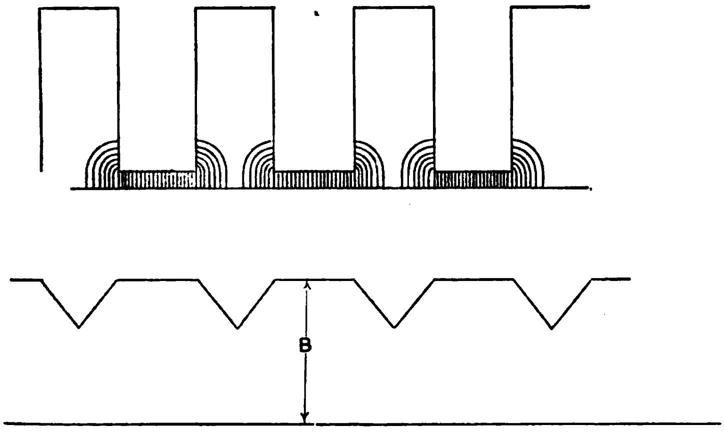

Fig. 10

Within practical limits of slot and gap dimensions, the variation can be said to be roughly proportional to the expression: k/δ

where δ = air-gap.
k = slot opening.

As the losses are caused mainly by eddy currents, while the hysteresis loss is much smaller, the total losses from this source will vary nearly as the square of the frequency and probably approximately as $\left(\frac{k}{\delta}\right)^2$. Therefore it should be possible to plot curves of the expression $\frac{B\,k\,s\ \text{rev. per min.}}{\delta}$ against watts loss per square inch of iron surface in the air-gap, B being the maximum density in kilolines per square inch of secondary tooth face, fringing being neglected.

In the case of alternating-current machines, in which only a few standard frequencies come into consideration, it is probably more accurate to plot the curves using the expression $\frac{B\,k\,s}{\delta\,p}$ making a curve for each frequency to be used. The necessary data can be obtained by determining the losses in the teeth and in the portion of the core back of the teeth in the manner already explained, deducting the value thus obtained from the iron loss observed on test.

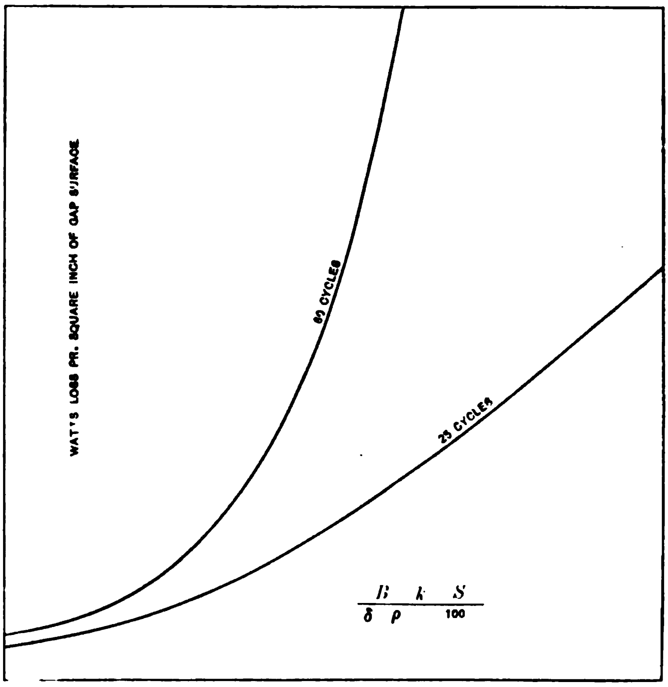

FIG. 11

In direct-current machines and in alternating-current machines having projecting poles, the result will represent the loss in the pole shoes, provided the rotating and stationary parts are concentric.

In machines with distributed field windings and in induction motors, part of the result represents losses in the primary and part in the secondary. It is possible in such a case to separate the two, but it is easier to obtain the necessary data from machines with projecting poles, and in the case of induction motors by choosing machines in which the secondary slot openings are small and the number of secondary slots less than that of the primary.

Curves obtained in this manner have been used by the writer and others with satisfactory results. The general form of such curves is shown by Fig. 11. In obtaining the data for these curves, it is necessary to distinguish between laminated surfaces which are not finished and such as are either ground or turned. A slight cut in the lathe will increase the surface losses about 50 per cent, while grinding may affect them more or less than this, the increase being greater for coarse wheels applied under considerable pressure.

In induction motors in which the air-gap necessarily is very short, wide-open slots are often objectionable, particularly in high-speed machines, as the iron loss due to the slot openings will often equal the losses due to the variations of the main field. This can be easily understood when it is known that for a 60-cycle machine, in which for the primary $\frac{B\,k\,s}{\delta\,P\;100} = 150$, this loss amounts to about 7 watts per square inch of secondary iron surface exposed to the gap.

Moreover, in comparing the running iron loss of an induction motor with the iron loss at standstill, it will in many cases be found that the former exceeds the iron loss at standstill although in the latter case the secondary iron is subjected to the full frequency of the line.

DISCUSSION ON "CALCULATION OF IRON LOSSES IN DYNAMO ELECTRIC MACHINERY." FRONTENAC, N. Y., JUNE 30, 1909.

R. E. Hellmund: Mr. Hanssen says that the teeth of dynamo electric machines are subject to a rotary magnetization by reason of leakage. Though some of the leakage fluxes actually pass the teeth crosswise, the leakages are so small compared with the main flux that the statement does not seem quite justified. This, of course, is not of great importance. In designing induction motors I have found Mr. Hanssen's method to be most useful. Other methods given for calculating surface losses are either too complicated to be of practical use or the results obtained by them are too inexact. Mr. Hanssen's method represents a very good compromise between exact theory and purely empirical formulas. It is, of course, not to be expected that any method for calculating core losses will always give correct results, it being well known that machines of the same type manufactured at the same time show core losses differing from each other as much as 20 per cent, sometimes even more. I have found, however, that the results obtained by Mr. Hanssen's method have always come close to the average value of the tests on a number of machines of the same type.

A. E. Averett: There are certain features of this paper which seems to me to be more of a specific than a general feature. In one part of the paper certain corrections should I think be applied to a specific type of machine. As soon as the type is changed, or the proportion of the iron in the teeth and in the yokes, the corrections will have to be changed.

Near the end of the paper it is said that a slight cut in the lathe will increase the core-loss about 50 per cent. I think that point is open to question. I have seen machines in which the rotors have been turned and in which the core-losses have not been increased appreciably; that is, with any commercial test the difference could not be detected. Again, I have seen machines where the core-loss has been nearly doubled. I think if the rotor is properly turned it will very seldom increase the core-loss appreciably.

In the high-frequency machines, silicon steel decreases the core-loss very much; for this reason I think it advisable to use it in spite of its increased cost.

V. Karapetoff: In estimating iron losses in revolving machinery it is not safe to rely upon the results obtained with stationary samples, because the distribution of the flux is far too irregular in space as well as in time. The safest procedure is to determine the actual iron loss from tests on a large number of actually built machines, at various densities and frequencies, and then use these data. In doing so, it will be found that the expression: total iron loss $= a\,B + b\,B^2 + c\,B^3$ comes much closer to the experimental curves than the formula $\eta\,B^n$. Here B is flux density, and a, b, c, are empirical coefficients.

In regard to Figs. 1 to 9 given in Mr. Hanssen's paper: These are not photographs of actual lines of force, but of some fluid flowing between two plates of glass. Into this fluid some coloring matter is injected, and then the apparatus is projected by means of a lantern or photographed. To my knowledge, the method was first used by Professor Hele-Shaw. The only difference between the assumed distribution of magnetism and the flow of the water between two parallel plates of glass is that water has inertia while the magnetic lines are devoid of inertia. By making the water flow very slowly the effect of inertia is practically eliminated, and in order to make the analogy complete paths are provided whose mechanical resistances to flow are in the same ratio as the magnetic reluctances of the air-gap and the iron teeth.

The streaks seen in Figs. 1 to 9 represent the actual directions of the streams of water. The light streaks between the poles are not assumed or anticipated, but show that, while the reluctance there is high, nevertheless some water prefers to flow into the narrow space between the poles, instead of going around through the armature. This illustrates magnetic leakage between the poles.

I. E. Hanssen (by letter): It is true, as stated by Mr. Hellmund, that the leakage flux is small compared with the main flux; for this reason the paper states that the teeth are subjected to an elliptical field, not to a rotary field as Mr. Hellmund says. However, as the path of the leakage flux is limited to a relatively small section the resulting density may become quite high, and consequently should be considered.

Mr. Averett states that as soon as the type of machine or the proportions of the iron in the teeth and yoke are changed the corrections will have to be changed. Such is the case when the older methods are used; however it is not so with the proposed method, as here the principal losses are estimated individually and it is equally good for all proportions of iron in teeth and iron in yoke. Mr. Averett has evidently misread the statement referring to the increase in the losses due to machining the air-gap surface. The paper says that a slight cut in the lathe increases the surface losses, (the losses due to the slot openings) some 50 per cent while Mr. Averett seems to think that reference is made to the total iron loss.

In a machine having narrow slot openings and relatively large air-gap the losses due to the slot openings are small; consequently, increasing them 50 per cent may not appreciably affect the total iron loss; if, on the other hand, the slot openings are large compared with the air-gap, then the increase in the total losses will be quite important, in most cases.

When comparing the losses before and after turning the rotor, it must be remembered that the turning process increases the length of the air-gap, which tends to reduce the surface losses; this must of course be taken into account, otherwise the results will be altogether misleading. If a heavy cut were made on the rotor of a machine, with say an air-gap of 0.020 in., we would probably find that the core loss would be decreased.

The writer cannot agree with Professor Karapetoff in what he says about the manner of estimating iron losses. The method outlined by the writer has been applied to several hundred machines with widely differing characteristics, and it has always given excellent results. Estimating core losses by comparison is, on the other hand, a very uncertain proposition particularly when, as is often the case, it becomes necessary to use very large slot openings or proportions out of the ordinary.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

ELECTRICAL MEASUREMENTS ON CIRCUITS REQUIRING CURRENT AND POTENTIAL TRANSFORMERS

BY L. T. ROBINSON

Modern requirements make it necessary to measure alternating current, volts, and watts on circuits where the magnitude of these quantities and the safety of the operator require that some means be provided so that the instruments used are not directly connected to the circuit. In certain special measurements it may be found accurate and convenient to use resistances to multiply the indications of the instrument, these resistances being used as shunts to the current coil or in the potential coils of voltmeters or wattmeters.

In a great majority of cases the most convenient arrangement is that of employing current and potential transformers. It is, therefore, necessary to be able to determine with exactness the ratio of these transformers under various conditions of frequency, voltage etc., to which they may be subjected in use. In connection with the measurement of watts it is also necessary to consider the phase displacement between the primary and the secondary current or voltage used on the transformers.

It is the purpose of the present paper to discuss, briefly, from a practical point of view, the causes which make certain corrections necessary either in the manufacture of the transformer or in their use; the most suitable methods for determining the variations in transformer ratio and phase-angle; the general order of magnitude of these errors or corrections and the most convenient way in which the known values can be made use of to correct the instrument readings which have been obtained. Before considering the question of transformers it may be well to discuss briefly certain points which relate to the instruments alone. In measuring amperes on alternating-current circuits, if ammeters are provided, having no correction factor due to frequency or wave-form, and which, therefore, measure directly the effective value of the current flowing, they may be tested on direct current. If without hysteresis as well, they may be used on alternating-current circuits without error.

Most ammeters which have been found useful for commercial purposes are not entirely free from one or more of these errors, and to obtain the most accurate results which they are capable of giving, they must be tested on an alternating-current circuit of the same order of frequency as that on which they are to be used. In some instruments the range of frequency, wave-form etc. over which they may safely be employed,. is greater than that found in any usual application, while others may be applicable to accurate measurements only within much closer limitations. However, it may be said that ammeters are readily obtainable both for switchboard and for portable use, the errors, due to any conditions under which the ammeters may be used, being so small that they may be neglected. If these meters are once calibrated on an alternating-current circuit of, say, 60 cycles, they may be used on any commercial frequency or wave-form without sensible error.

It is in general true that ammeters can be made having only a limited current-carrying capacity; and for measurements of current beyond this range, as well as for use on circuits where protection against high voltage is required, some arrangements are neccesary for causing a known part of the current to pass through the ammeter. The most satisfactory arrangement is the current transformer. For use with ammeters it is necessary to know the relation between the primary and the secondary currents under various conditions in which ammeters and other devices, having a different total resistance and reactance, are included in the secondary of the transformer.

In measuring volts somewhat similar considerations apply, with slight modifications, although in this case potential transformers of known ratio must be used.

In measuring watts, either current or potential transformers or both may be required. In addition to errors similar to those found in ammeters and voltmeters, but usually much less, in fact usually too small to be considered at all, wattmeters have an inherent error appearing as an effect equivalent to a displacement between the current in the moving coil—potential circuit—

and the electromotive force impressed upon the circuit to be tested.

It has been customary in theoretical discussions to compute this angle from the resistance and inductance of the potential circuit, but there are various other actions within a wattmeter that make it necessary to determine, by suitable means, this equivalent angle as it exists in the instrument. The discussion of the magnitude of this quantity, and of the most suitable means for determining it, is not the purpose of the present paper. It will be assumed that such an equivalent angle has either been determined or is too small appreciably to affect the results under the conditions in which the instrument is to be used. This angle is different for different frequencies and is also affected in somewhat imperfect instruments, due to other causes. Therefore, in speaking of this angle it must not be considered that it can be assigned a fixed value in all cases, but that a value for the angle is chosen which is suitable for the immediate conditions under which the instrument is used.

In using current or potential transformers with a wattmeter it is well known that the phase-angle between the primary and the secondary of the transformer must be taken into account, if the most accurate results are to be obtained. It may also be said that usually the effect of these transformer angles, especially when current transformers are used, is to cause errors in the indications of the wattmeters much geater than those caused by the equivalent angle of the instrument alone. Before proceeding to the consideration of ratio and phase-angle in current and potential transformers it is well to discuss the relation that these various angles have to the results obtained when wattmeters are used. The ratios of any transformers used have, of course, the same effect on a wattmeter as on an ammeter and voltmeter.

Before discussing the means which may be employed to determine the ratio and phase-angle in current and potential transformers it may be well to state briefly the effect which these angles will have on the indications of a wattmeter with which they are used. We will call the equivalent angle of phase displacement in the wattmeter α, the angle of phase displacement in the current transformer β, and the same quantity in the potential transformer γ. In an instrument in which the eddy currents have been quite completely eliminated, the angle represents a lag in the potential circuit, and when so existing will be given the positive sign, or $+\alpha$. In some instruments, however, due to causes which have been briefly referred to, this correction appears as an effect equivalent to leading current in the potential circuit, in which case the equivalent correction angle will be written as $-\alpha$.

Current transformers, as usually made, when carrying an instrument load give leading current in the secondary circuit. The effect of this is the same on the connected wattmeter as lagging current in its potential circuit, and, therefore, leading current in the secondary of the current transformer will be written $+\beta$.

Potential transformers, as usually made, give leading potential in the secondary, which affects the instrument in the same way as some cause within the instrument, which would make the current lead in the potential circuit; therefore, leading potential in the potential transformer will be written $-\gamma$.

It is useful to remember that in all cases correction angles tending to decrease the phase displacement between the current and the potential circuits in the instrument are to be considered as positive, and those tending to increase the phase displacement as negative; so that if the sum of the correction angles is positive, the wattmeter reading will, with lagging current, be greater than the true watts.

We will consider lagging current in the main circuit to be represented by a positive angle θ, and leading current by the same symbol with a negative sign $-\theta$. The reading on any wattmeter, divided by the volt-amperes, is equal to the apparent power-factor. Using $\cos\theta_2$ to represent the apparent power-factor of the circuit we can write

$$\text{Cos}\,\theta_2 = \frac{\text{wattmeter reading}}{\text{volt-amperes}} = \text{apparent power-factor} =$$

$$\cos(\theta \pm \alpha \pm \beta \pm \gamma) \text{ or } \cos\theta = \cos(\theta_2 \mp \alpha \mp \beta \mp \gamma)$$

where α, β, γ are the correction angles above referred to, which have been added with their proper sign to the angle of lag θ_2. If the angle θ_2 is leading it may be considered as a negative angle so that negative correction angles added to it will increase the total angle, or vice versa.

The ratio of the true power-factor to the apparent power-factor is naturally the correction to be applied to the indications of the instrument, as the instrument reading is due to the apparent power-factor. Therefore, the following relation holds.

$$\text{wattmeter reading} \times \frac{\cos\theta}{\cos\theta_2}$$

$$= \text{wattmeter reading} \times \frac{\text{true power-factor}}{\text{apparent power-factor}} = \text{true watts}$$

In some instances, when using wattmeters of small capacity it is necessary to correct the instrument reading for the losses in the instruments used. Usually the correct way to do this is to connect the voltmeter and the potential winding of the wattmeter in such a way that the energy consumed in them is measured by the wattmeter, as a part of the total watts. Sometimes this correction amounts to a considerable part of the total reading of the wattmeter. The instrument reading is then made up of two parts, one of which, the loss in the potential circuits of the instruments, is nearly or quite non-inductive, while the other may be inductive, and therefore require correction. It is still correct to use the total watts determined in this way in obtaining the apparent power-factor, and after the correction has been applied the measured or computed losses in the potential circuits may be deducted.

Perhaps the process can be best illustrated by examples. In the first case the correction is applied to an instrument used alone whose equivalent phase-angle is known, and in the second case current and potential transformers are used. In the first case also the watts lost in the potential circuit of the instrument itself have been subtracted, and in the second case this quantity is too small to be considered.

Example 1,

lagging load, 60 cycles, $P3$ wattmeter, volts 100, amperes 10.
resistance of wattmeter potential circuit 2500 ohms.
resistance of voltmeter potential circuit 2200 ohms.

$$\text{Watts consumed in instruments } \frac{100^2}{2500} + \frac{100^2}{2200} = 8.5 \text{ watts.}$$

Watts read corrected for scale error $= W = 100$
$\alpha = +3$ minutes

$$\frac{W}{V\,A} = \cos\theta_2 = \frac{100}{1000} = 0.1$$

Therefore, θ_2 = 84 degrees 16 min. (cos = 0.0999) and
$\theta = \theta_2 + \alpha$ = 84 degrees 19 min. (cos = 0.099).

True watts $= \dfrac{100 \times 0.099}{0.0999} = 99$. From this we subtract 8.5, the instrument losses, leaving 90.5, the required value.

Using the same values as above with leading load,

$\dfrac{W}{V\,A} = \cos\theta_2 = \dfrac{100}{1000} = 0.1$, therefore, $\theta_2 = -$ 84 degrees 16 min. (cos 0.0999)
and $\theta = -\theta_2 + \alpha = -(\theta_2 - \alpha) = -84$ degrees 13 min. (cos = 0.1008

true watts $= \dfrac{100 \times 0.1008}{0.0999} = 101$ nearly.

Subtracting instrument losses, 8.5 watts, we have 92.5 watts, the required value.

Example 2,

lagging load, 25 cycles,
current transformer, ratio 39.64:1, (99.1 × 40 from curve)
potential transformer, ratio 19.94:1,
volts 104.4 × 19.94 = 2082.
amperes 2.5 × 39.64 = 99.1
V A 206,360. Wattmeter reading 53.
apparent watts = 53 × 39.64 × 19.94. = 41893.

$$\text{Cos}\,\theta_2 = \frac{41{,}893}{206{,}360} = 0.20301,$$

therefore θ_2 = 78 degrees 17 min. 20 sec.

α at 25 cycles is negligible.

$\beta = +55$ min.; $\gamma = -38$ min.; θ = 78 degrees 17 min. 20 sec. +55 min. − 38 min. or 78 degrees 34 min. 20 sec.

Cos θ = 0.1981. Then the true watts $= 41893 \times \dfrac{0.1981}{0.203} = 40880$.

As in the first example, the instrument and potential transformer losses are to be subtracted, if appreciable and if the connection used requires it. In this example they are too small to be considered. If the load is leading, the sign of θ_2 is to be changed as in example 1.

To be useful in practical work some arrangement must be provided, whereby the necessary computations may be quickly made, and for this purpose Table I and Table II have been

TABLE I

$\frac{\cos \theta}{\cos \theta_2}$ LAGGING LOAD WITH $(\alpha+\beta+\gamma)$ POSITIVE

LEADING LOAD WITH $(\alpha+\beta+\gamma)$ NEGATIVE

Power factor $\cos \theta_2$

$\alpha+\beta+\gamma$	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90
5′	0.9855	0.9904	0.9928	0.9943	0.9953	0.9966	0.9974	0.9980	0.9985	0.9989	0.9993
10′	0.9710	0.9808	0.9857	0.9887	0.9907	0.9933	0.9949	0.9961	0.9970	0.9978	0.9985
15′	0.9565	0.9712	0.9786	0.9831	0.9860	0.9899	0.9924	0.9941	0.9955	0.9967	0.9978
20′	0.9420	0.9616	0.9714	0.9774	0.9814	0.9866	0.9898	0.9922	0.9940	0.9956	0.9971
25′	0.9276	0.9520	0.9643	0.9718	0.9768	0.9832	0.9873	0.9902	0.9925	0.9945	0.9964
30′	0.9131	0.9424	0.9571	0.9661	0.9722	0.9799	0.9848	0.9883	0.9910	0.9934	0.9956
40′	0.8841	0.9232	0.9429	0.9548	0.9629	0.9732	0.9797	0.9844	0.9880	0.9912	0.9942
50′	0.8552	0.9040	0.9286	0.9436	0.9537	0.9665	0.9747	0.9805	0.9850	0.9890	0.9928
1°	0.8262	0.8848	0.9143	0.9323	0.9444	0.9598	0.9696	0.9766	0.9820	0.9868	0.9914
10′	0.7971	0.8655	0.8999	0.9210	0.9350	0.9530	0.9645	0.9726	0.9789	0.9845	0.9399
20′	0.7681	0.8463	0.8857	0.9097	0.9257	0.9463	0.9594	0.9687	0.9759	0.9822	0.9884
30′	0.7391	0.8271	0.8713	0.8984	0.9164	0.9396	0.9543	0.9647	0.9729	0.9800	0.9869
40′	0.7101	0.8079	0.8570	0.8872	0.9071	0.9329	0.9491	0.9608	0.9699	0.9777	0.9854
50′	0.6811	0.7887	0.8427	0.8759	0.8978	0.9261	0.9440	0.9568	0.9668	0.9755	0.9839
2°	0.6521	0.7695	0.8284	0.8646	0.8885	0.9194	0.9389	0.9529	0.9638	0.9732	0.9824
10′	0.6230	0.7502	0.8140	0.8531	0.8791	0.9126	0.9337	0.9488	0.9607	0.9709	0.9808
20′	0.5940	0.7309	0.7996	0.8417	0.8697	0.9058	0.9286	0.9448	0.9576	0.9686	0.9793
30′	0.5649	0.7116	0.7853	0.8303	0.8604	0.8990	0.9234	0.9408	0.9545	0.9663	0.9778
40′	0.5359	0.6924	0.7709	0.8189	0.8510	0.8922	0.9183	0.9368	0.9514	0.9640	0.9763
50′	0.5068	0.6731	0.7566	0.8074	0.8417	0.8855	0.9131	0.9328	0.9483	0.9617	0.9748
3°	0.4778	0.6538	0.7422	0.7960	0.8323	0.8787	0.9080	0.9288	0.9452	0.9594	0.9733
10′	0.4487	0.6343	0.7277	0.7845	0.8228	0.8718	0.9028	0.9247	0.9420	0.9570	0.9717
20′	0.4196	0.6148	0.7133	0.7731	0.8134	0.8650	0.8976	0.9207	0.9389	0.9547	0.9701
30′	0.3906	0.5953	0.6989	0.7617	0.8040	0.8582	0.8924	0.9166	0.9358	0.9523	0.9685
40′	0.3615	0.5759	0.6845	0.7503	0.7946	0.8514	0.8871	0.9126	0.9327	0.9500	0.9670
50′	0.3325	0.5564	0.6701	0.7388	0.7852	0.8445	0.8819	0.9085	0.9295	0.9476	0.9654
4°	0.3034	0.5369	0.6557	0.7274	0.7758	0.8377	0.8767	0.9045	0.9264	0.9453	0.9638
10′	0.2743	0.5177	0.6412	0.7159	0.7663	0.8308	0.8714	0.9004	0.9232	0.9428	0.9621
20′	0.2452	0.4985	0.6268	0.7045	0.7569	0.8239	0.8662	0.8963	0.9200	0.9404	0.9605
30′	0.2161	0.4793	0.6124	0.6930	0.7474	0.8171	0.8609	0.8922	0.9168	0.9380	0.9590
40′	0.1871	0.4602	0.5980	0.6816	0.7380	0.8102	0.8557	0.8881	0.9136	0.9356	0.9573
50′	0.1580	0.4410	0.5836	0.6701	0.7285	0.8034	0.8504	0.8841	0.9104	0.9332	0.9557
5°	0.1289	0.4218	0.5692	0.6587	0.7191	0.7965	0.8452	0.8800	0.9072	0.9308	0.9540
10′	0.0998	0.4026	0.5548	0.6472	0.7096	0.7896	0.8399	0.8759	0.9040	0.9284	0.9524
20′	0.0707	0.3834	0.5404	0.6358	0.7002	0.7828	0.8347	0.8718	0.1008	0.9260	0.9507

any magnitude which would usually be met with in practice. The tables have been extended to well beyond such limits.

Where the algebraic sum of the correction angles is greater than 90 degrees minus θ, the multipliers are not given, as they would not often be used. Under such conditions it would naturally be impossible to know how the reading of the instrument would be used without making some test by inserting reactance or capacity in the potential circuit of the wattmeter. By varying this reactance or capacity it is possible to observe whether the reading is due to the influence of the phase displacement in the transformers overpowering the action of the energy flowing in the circuit or whether the two forces are acting in the same direction on the instrument. This aspect of the question is referred to only to make it clear that such a condition may arise and that it has been considered. On the other hand, it is quite evident that no such condition could arise unless the power-factor of the circuit to be measured was extremely low or unless the sum of the correction angles was comparatively very large. This would mean that the correction factor would be so large that a very small error in the correction angle would render the results worthless.

The intention is not to discuss the design of current and potential transformers, but rather to consider the best means which may be employed to determine their corrections, and to apply the results of these tests to any measurements that may be made, with reasonable accuracy, using any given combined apparatus. Under some circumstances it is necessary, especially with current transformers, to determine the ratio and phase-angle by indirect methods, and as these indirect methods involve a general understanding of the theoretical elements of current transformers, this part of the subject will be dealt with only to the extent which is necessary. The potential transformer may not need such consideration in this place as the theory of transformers operating at constant potential has been much more fully dealt with. The current transformer has of course, received the attention of several writers, but these articles have in general been theoretical and have not been expanded in sufficient detail to be useful to those who require quantitative results.

THE CURRENT TRANSFORMER

The current circulating in the primary of the current transformer may be considered as consisting of two components, the current appearing in the secondary and the current necessary to excite the core. These two components are not usually combined in a straight line. In order to consider the relation between the exciting current, the primary and the secondary current, reference may be made to the diagram in Fig. 1. The magnitude of the exciting current is very small in comparison with the primary and the secondary currents, and therefore is not drawn to scale in the diagram. On account of the small relative value of the magnetizing current it is usually much more convenient and accurate to compute the ratio and phase-angle from the exciting current or to compute the exciting current from careful ratio and phase-angle tests, than it is to attempt to scale the diagram, although the diagram is useful as an aid in obtaining a clear conception of the operation of the transformer. In the diagram i_e is the exciting current plotted as ampere-turns. I_s is the secondary current plotted as ampere-turns

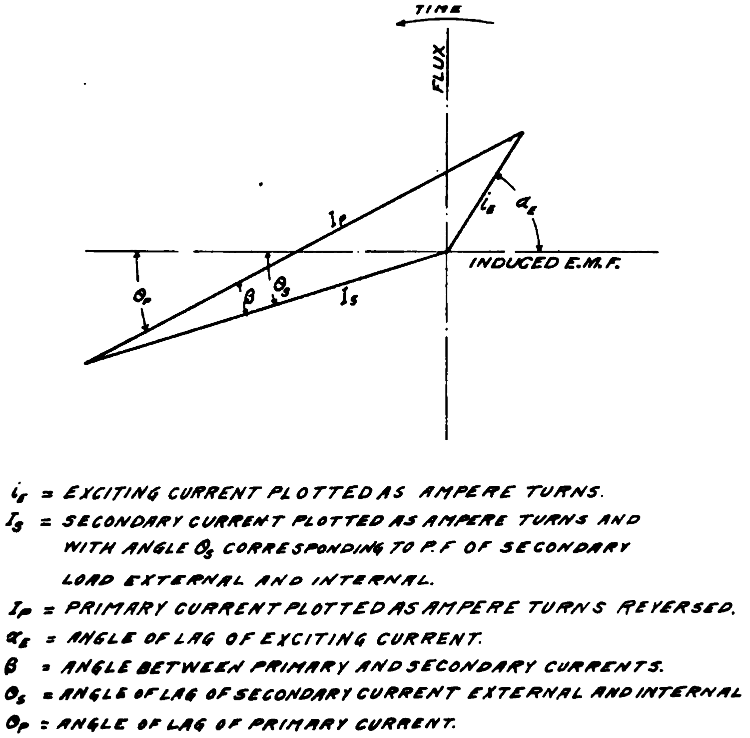

FIG. 1.—Diagram of current transformer

making an angle θ_s corresponding to the power-factor of the secondary load. This load consists of two parts: that external to the transformer, and that due to the resistance and reactance of the transformer secondary. The reactance of the secondary winding is inappreciable in any transformers that have been examined. I_p is the primary current plotted as ampere-turns reversed. α_e is the angle of lag of the exciting current; β is the angle between primary and secondary current; θ_s is the angle of lag in the secondary circuit considering both the external and internal portions combined; θ_p is the angle of lag of the primary current.

The diagram is drawn with counter clockwise rotation, with the core flux vertical and the induced electromotive force in the core horizontal. The exciting current is plotted as the ampere-turns necessary to produce voltage I_s Z_s where I_s is the secondary current, and Z_s is the total impedance ohms in the secondary circuit.

Examination of the diagram will show that the ratio and phase-angle between the primary and secondary currents depend on the impedance ohms in the secondary circuit, the power-factor of the secondary circuit, the power-factor of the exciting current and the ampere-turns for which the transformer is designed.

The secondary current may lead the primary current by an angle equal to $+\beta$ or it may lag behind the primary current with an angle equal to $-\beta$ depending on whether the secondary power-factor is higher or lower than that of the exciting current. If the power-factors are equal there will be no phase displacement. An examination of the diagram will show also that with non-inductive load on the secondary of the transformer the ratio is affected to a relatively small extent by the magnitude of the exciting current, whereas the phase-angle is greatly influenced under these conditions. On the other hand, when the power-factor in the secondary circuit is lower and approximately that of the core, the exciting current is fully effective in varying the ratio of the transformer but has little effect on the phase-angle. With the information which we now have at hand it is possible to outline the tests which should be made on a current transformer in order that its performance under conditions of use may be known.

It is useful to know how the ratio and phase-angle are affected by variations in the frequency, in the line current, in the impedance of the secondary circuit, in the power-factor of the secondary circuit, or in the wave-form of the primary current. Small changes of frequency have little effect on the ratio. Tests made at 60 and 25 cycles will give sufficient data from which ratios, for intermediate cycles, can be readily obtained by interpolation when required.

Variations in line current affect the ratio of the transformer because the exciting current necessary to produce the required potential to force the secondary current through its circuit is not proportional to the current flowing with a given connected secondary load. Much can be done with a suitable design to control this action, but any commercial transformer should be tested between the limits of 0.1 load and full load before it can be relied upon for accurate measurements, or if the transformer is one of a general type it may be satisfactory to make a short test to determine the quality of the core and rely on more general tests on the same type for complete information on the transformer.

Variations in the impedance of the secondary circuit affect the ratio and phase-angle of the transformer, and, as before stated, the power-factor of the connected secondary load has a bearing on the ratio and phase-angle resulting. It is therefore necessary in making a complete test on a transformer, to test it on various power-factors, and with each power-factor to increase the impedance from minimum to maximum value. Such a test, however, consumes almost too much time, even for a standard test on a few transformers to obtain the characteristics of a type.

In practice it is quite usual to find that the secondary loads of small impedance have a comparatively high power-factor, and that the larger loads are usually of higher relative reactance. For this reason it is satisfactory to make a general test of a transformer, using the two frequencies above referred to, 25 and 60 cycles, and 5 loads which cover practically a range from a single instrument and a few feet of wire to a trip coil for the direct operation of an oil switch. For very accurate work it is sometimes useful to tabulate or draw a curve for another load in which there is no sensible impedance in the secondary circuit other than that offered by the secondary winding of the transformer itself. This zero load may be determined by interpolation from the tests made on the other loads and is chiefly of value when the transformer is to be used in connection with a single induction meter. The characteristics of these loads, which have been used in tests referred to later, are as follows:

All of the loads were tested using 5 amperes and 60 cycles, and any other load which is to be used on a transformer may be tested or computed by addition of the separate items, after being tested on the same basis. It has been found more convenient perhaps without good reason, to designate a given transformer load as a certain number of volt-amperes rather than to reduce it to resistance-reactance components unless the power-factor is quite different from that of the standard load with which it is to be compared.

	Amperes	Volts	Watts	Volt-amperes	Power-factor	Resistance	Ractance X 60 cycles
Load No. 1..........	5	2.104	8.32	10.52	0.79	0.3325	0.1578
Load No. 2..........	5	3.72	15.34	18.6	0.829	0.6168	0.4167
Load No. 3..........	5	4.98	16.06	24.9	0.645	0.6423	0.7615
Load No. 4..........	5	9.36	22.9	46.8	0.489	0.9155	1.6325
Load No. 5..........	5	27.5	49.09	137.5	0.357	1.964	5.140

These loads may be represented, in commercial instruments, about as follows:

Load No. 1, portable ammeter, portable wattmeter, and 50-ft. leads of No. 10 wire, (100 ft. of wire) or two station instruments and 15-ft. leads, or one station instrument and 200-ft. leads.

Load No. 2, same as load 1, with the addition of one station instrument or two portable instruments.

Load No. 3, two station instruments, relay, and 50-ft. loads.

Load No. 4, the maximum number of station instruments, up to four or five in number, in combination with a relay and leads.

Load No. 5, one coil, for directly tripping an oil switch in combination with ammeters and leads.

All the information given, covering the way in which the loads are made up, is only very approximate, and to determine the performance of any given transformer which has been tested on the above loads, definite knowledge should be had of the particular load on which it is to be used before the desired information can be obtained for the test records. The foregoing loads are only for use in testing transformers which have been designed for general switchboard requirements. Of course, transformers of smaller capacity, built for some special or specific use, will require testing only on the loads with which they are to be used.

There are many methods which may be employed to determine the ratio of current transformers. The most obvious one, and that which may be employed successfully, if a high degree of accuracy is not required, is to measure the primary and secondary current by means of any alternating-current ammeters which may be available. Unless some special equipment is available for measuring the primary current, and if this current is beyond the capacity of the comparatively small range of commercial instruments, the test finally resolves itself into a comparison between two current transformers, as a second transformer must be made use of, in connection with the primary ammeter. If a good, carefully checked, variable-ratio current transformer is available for the purpose, in combination with two good ammeters, the results obtained are quite satisfactory. It is not possible by this means accurately to determine the ratio down to a small primary current, say 10 per cent of maximum, which is required in connection with wattmeters.

It is not advisable to attempt to obtain lower current values, by using a smaller capacity instrument in the secondary, because of the change which this brings about in the impedance of the secondary circuit. If the transformer is a very good one, this change may result in a comparatively small error, but in such a transformer the difference in the value obtained at 10 per cent and, say, 25 per cent of primary current would be rather small. In general it is believed that if anything at all is known of the characteristics of the transformer, a closer approximation to the true ratio value at 0.1 load may be obtained by exterpolating the lower part of the curve than by attempting a measurement with small capacity instruments on the secondary.

Ratio determinations made with small-capacity ammeters have been used in connection with 5-ampere-capacity wattmeters, resulting in considerable error where a high degree of accuracy is required. Wattmeters give a better indication lower down on the scale than ammeters usually do, so that the temptation to use these instruments of small current capacity is not as great as with ammeters. However, if this is done not only is the ratio affected but the error due to phase-angle is usually increased. To illustrate this point still further, a portable 5-ampere ammeter requires about one volt to force through it full-capacity current, or 5 volt-amperes. A two-ampere instrument, having the same number of ampere-turns, requires 2.5 volts at 2 amperes, or for comparison with the 5-ampere instrument, 6.25 volts at 5 amperes, and acts on the transformer as a load equivalent to a little more than 36 volt-amperes, a load about half way between the number 3 and 4 loads which have been used in the tests.

If the transformers are to be used with the same instruments with which they are tested, of course instruments of any capacity or impedance may be included in the secondary circuit. This error has been made many times.

Even before the manufacture of current transformers was undertaken commercially, it was apparent that accurate ratio determinations under widely varying conditions required some special arrangement to do the work with a high enough degree of accuracy so that determinations could be made on transformers independent of their being combined with any specific instruments. As soon as work was started the fact also became apparent that the current transformer was a very accurate and reliable device. The effect of the exciting current is comparatively small, and may be varied within wide limits without affecting, except to a small degree, the ratio and phase-angle. The current transformer is by no means a perfect device, because it cannot give a constant ratio or phase-angle with change of primary current or secondary load. However, these errors may be reduced by careful design to almost any size, and if they have once been accurately determined they cannot change in any sensible amount, by reason of any changes which may occur in the exciting current due to variations in the core. This is assuming, of course, that the magnetic material of the core has been suitably chosen, and has received proper treatment so that it may remain permanent.

The following schemes for determining ratio and phase-angle have been tried with more or less success; they have all been satisfactory as far as accuracy goes, but with some of them the time required is at present too long to make it possible to use the methods in practical work.

METHOD OF DETERMINING RATIO AND PHASE-ANGLE BY REFLECTING DYNAMOMETERS

Referring to Fig. 2, the fixed coil of the primary dynamometer is connected in series with a shunt to the source of supply. The moving coil of the dynamometer is applied to the drop terminals of the shunt, and included in this potential circuit is the resistance r_p. Choosing suitable values for r_p and for the shunt resistance R_p, the combinations can be arranged to give a good deflection at from 0.1 to full rated primary current. The secondary is provided with a similar arrangement, usually of 5 amperes maximum capacity. In this circuit the energy to operate the combination must be limited. As usually arranged the secondary requires about 2 volts with full-load current of about 5 amperes, and is the No. 1 load referred to in the test.

The primary and secondary dynamometers are first carefully checked on direct current by means of a potentiometer. The test is then made and the ratio determined by dividing the primary current by the secondary current. In actual testing the primary current is brought up to the calibrated point and the secondary current is read. The scale reading obtained in calibrating the secondary dynamometer at the current corresponding to the correct ratio, is then divided by the reading obtained with the correct primary current, and the square root of the result is the accuracy of ratio. The instruments used

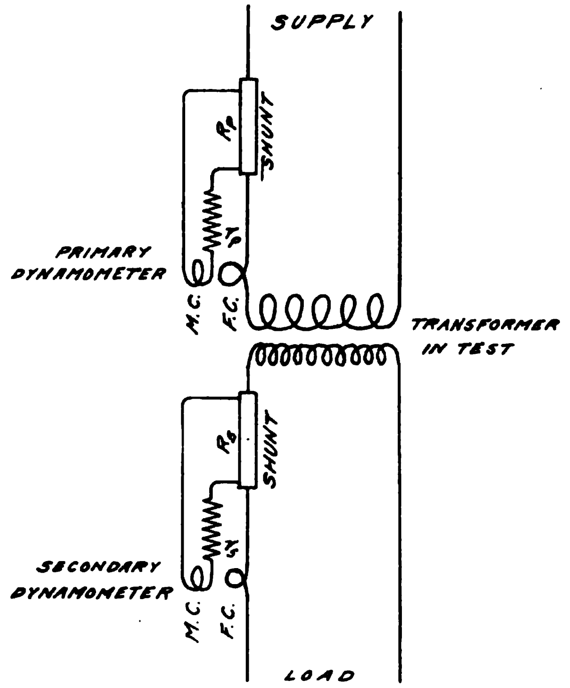

FIG. 2.—Connections for ratio test on current transformer by two dynamometer method

measure the watts lost in the shunt resistance, and, therefore, give a deflection proportional to the current squared. It has been found more convenient to express this ratio as that of a 1:1 transformer, or to write the true ratio divided by the marked ratio, than to use the actual ratio of transformation, as by this means transformers of the same type may be directly compared although their current capacity is quite different. In common with any other method in which the primary and secondary currents are actually measured and used to compute the ratio of the transformers, this method would not appear at first sight to be satisfactory from the standpoint of either accuracy or speed. It depends, of course, entirely on the accuracy which may be secured with the instruments used. The results obtained in this way have been more satisfactory, so far, than by any other method. In Fig. 3, connections are shown for determining the phase-angle between the primary and secondary

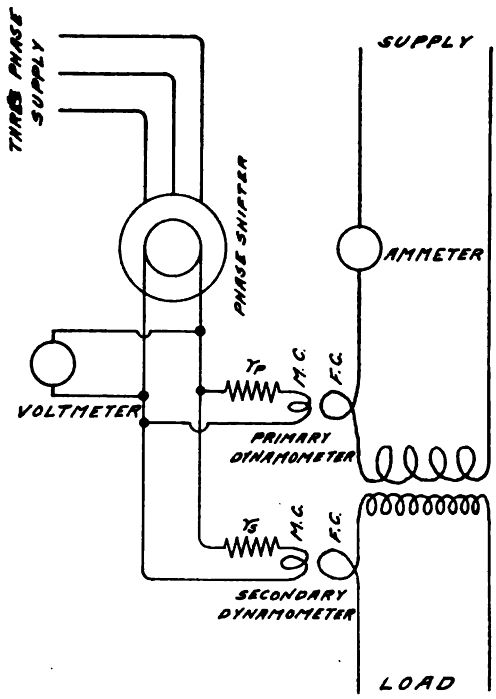

FIG. 3.—Connections for phase-angle test on current transformer by two-dynamometer method

currents. Dynamometers are the same as used for the ratio determination as in Fig. 2. The current windings are in the primary and secondary as before, but the current-carrying resistances are not necessary except to keep the secondary load unchanged. The potential coils of the instrument are connected to a phase-shifter, shown in the diagram, this phase-shifter being rotated until the primary dynamometer reads zero. The phase-angle then is,

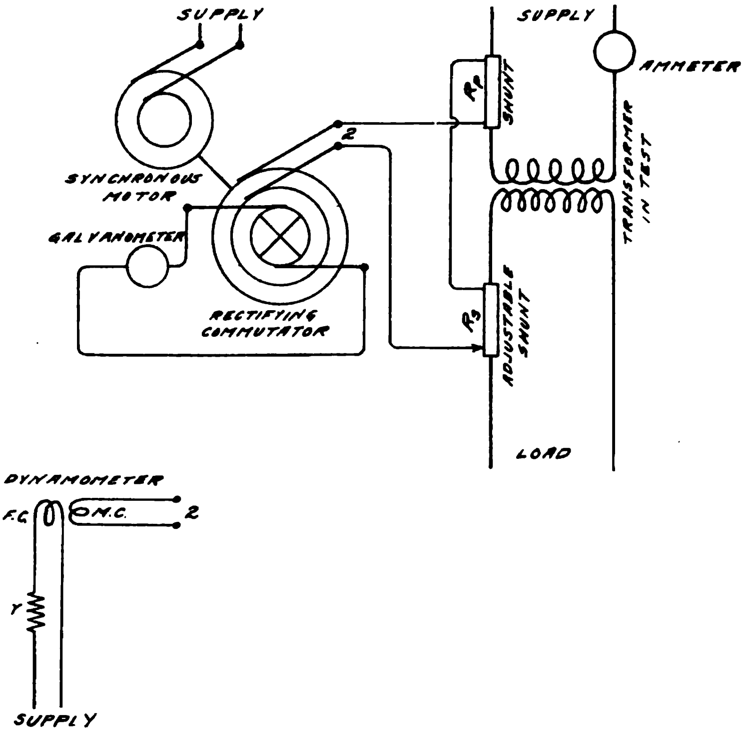

FIG. 4.—Connections for ratio test on current transformer by comparison of resistances, using dynamometer or rectifying commutator and galvanometer

$$\beta = \sin^{-1} \frac{W_s}{I_s \times E}$$

where I_s is the secondary current in the transformer, as before,

W_s is the watts read on the dynamometer and E is the voltage on the phase-shifter, at the point where the potential coil is attached. It is worth while mentioning here that to secure accurate results the resistances r_p and r_s must be practically perfect and without inductance or capacity, and if the moving coils have appreciable inductance the L/r of the circuits must be equal. In the actual tests referred to it has been found best to make the inductance of the moving coil practically zero.

FIG. 5.—Rectifying commutator

Referring to Fig. 4, suitable non-inductive resistances or shunts, one fixed and one adjustable, are included in the primary and secondary circuits. After connecting as shown in the figure, it is only necessary to make use of some form of sensitive alternating-current galvanometer to show when the potential drop on the two shunts balances. The secondary shunt is adjusted until this balance is secured, then the ratio equals $\frac{R_s}{R_p}$. The equality of potential can be shown by a rectifying commutator in combination with a direct-current galvanometer, or

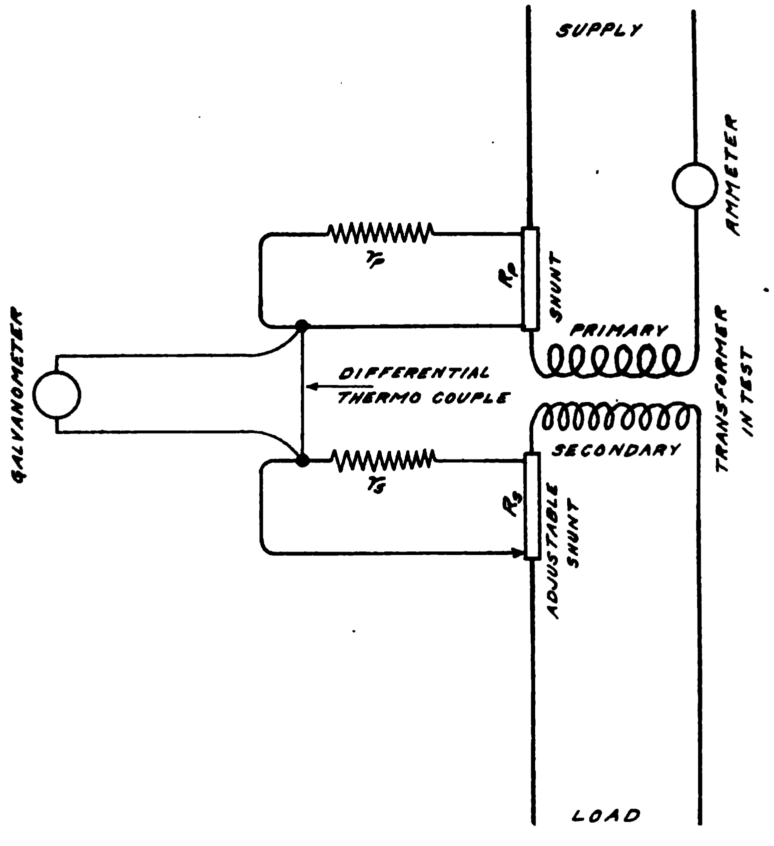

FIG. 6.—Connections for ratio test on current transformer by comparison of resistances, using differential thermo-couple and galvanometer

by using the moving coil of one of the reflecting dynamometers, the fixed coil of which is energized from any convenient point of the same circuit. Fig. 5 shows a rectifying commutator driven by a synchronous motor, which has been developed for this use.

Fig. 6 shows another way of determining the ratio by means of current-carrying resistances and an alternating-current comparator of any suitable type. The expansion comparator of Dr. Northrup has been used for this method, and also a thermo comparator, as shown in the figure. The experiment of using a differential dynamometer has also been tried, but without any very satisfactory results. It is hoped that one of the schemes illustrated for directly determining the ratio will ultimately be found more accurate and convenient than the two dynamometer methods now being used. But so far, owing to various minor difficulties, the time required to test in any of these direct ways is much longer, and the accuracy is no better than that obtained by using the first method in Fig. 2.

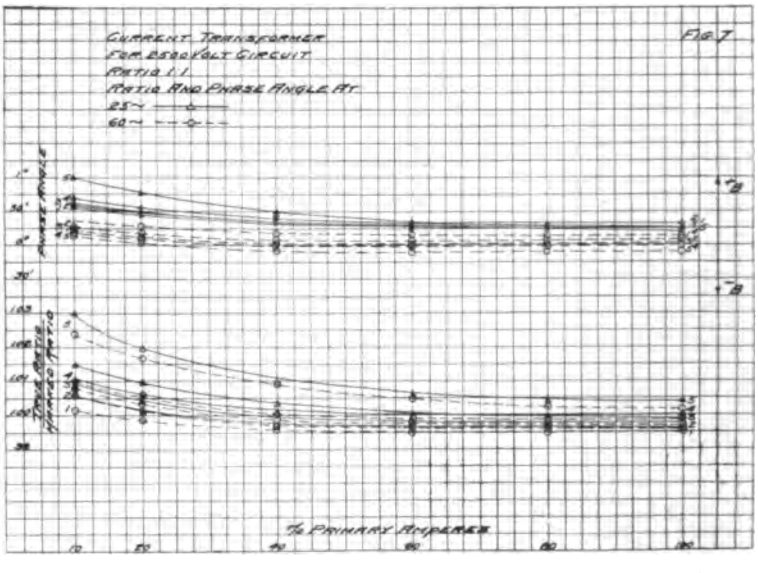

FIG. 7.—Full test (loads Nos. 1, 2, 3, 4 and 5) on current transformer for 2500 volt circuit

In order to show the general character of the tests as outlined, and to bring out clearly the fact that tests made by the method referred to in connection with Figs. 2 and 3 are satisfactory, as far as accuracy of results is concerned, two complete tests are shown in Figs. 7 and 8. It will be seen that the observed points lie very closely on the smooth curves. It can also be seen that the observations must be made with considerable precision, else the curves cannot be plotted with sufficient accuracy to be clearly read. This is especially true of the phase-angle tests.

It is possible to extend the capacity of the methods referred to up to any required current value; but with either the dynamometer or shunt methods great difficulties are encountered in producing instruments or shunts of very large capacities in which the eddy currents or other disturbing causes have been eliminated to the required extent. For this reason the expedient was tried of calculating the ratio and phase-angle of current transformers, from the exciting current determined by means of a sensitive reflecting dynamometer similar to those used for ratio determinations. Another instrument of the same class was used for determining the watts lost in the core. From the indications of these instruments may be plotted exciting current against volts produced on the secondary of the transformer and a second curve of volts and power-factor. From these the amount and apparent angle of the exciting current can be read for use in calculating the ratio and phase-angle. From the transformer diagram in Fig. 1, the following expressions for ratio and phase-angle can be obtained in terms of the exciting ampere-turns:

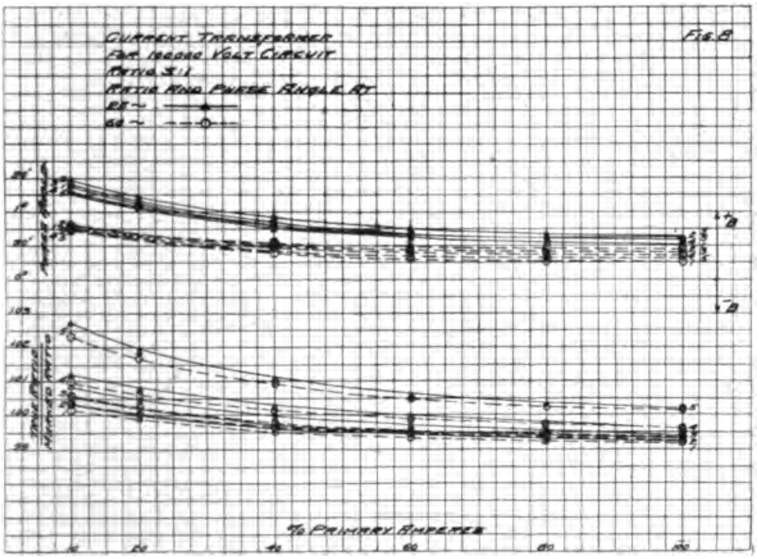

Fig. 8.—Full test (loads Nos. 1, 2, 3, 4 and 5) on current transformer for 100,000 volt circuit

Ratio =

$$\frac{I_p}{\sqrt{(I_p \cos \theta_p - i_e \cos \alpha_e)^2 + (I_p \sin \theta_p - i_e \sin \alpha_e)^2}}$$

where I_p = primary current in ampere-turns
θ_p = its angle of lag
i_e = exciting current in ampere-turns
α_e = its angle of lag.

As the calculations are usually made on the basis of given conditions in the secondary circuit we can write

$$\text{Ratio} = \sqrt{\frac{(I_s \cos \theta_s + i_e \cos \alpha_e)^2 + (I_s \sin \theta_s + i_e \sin \alpha_e)^2}{I_s}}$$

where I_s = secondary current
θ_s = its angle of lag
i_e = exciting current
α_e = its angle of lag

and for phase-angle

$$\beta = \tan^{-1} \frac{i_e \sin (\alpha_e - \theta_s)}{I_s + i_e \cos (\alpha_e - \theta_s)}$$

or

$$\beta = \sin^{-1} \frac{i_e \sin (\alpha_e - \theta_s)}{I_p}$$

In all the foregoing formulas the currents i_e and I_p and I_s are expressed in ampere-turns. As it is usual to compensate partly for the effect of exciting current on the ratio of the transformer by winding the secondary of a transformer with a few turns less than the primary turns times the marked ratio, this fact must not be overlooked in the calculations, and the actual number of secondary turns must be used. In certain cases it may be useful to work out, for comparison, exciting-current values from tests on ratio and phase-angle to compare tested points with those obtained by calculation. For this purpose we can write,

$$i_e = I_s \sqrt{R^2 - 2R \cos \beta + 1}$$

$$\sin (\alpha_e - \theta_s) = \frac{I_p \sin \beta}{i_e}$$

Of course, only a rough idea of the exciting current values can be obtained in this way, but when it is pointed out that an 0.1-per cent error in a ratio determination may easily cause 10 per cent error in the exciting current determined in this way, the explanation is sufficient.

The computer should not be misled by the fact that an exciting-current curve may frequently be computed back in this way, and pass evenly through all the points. This would simply indicate that a smooth curve had been drawn through the ratio determinations and accurately read before being introduced in the calculations.

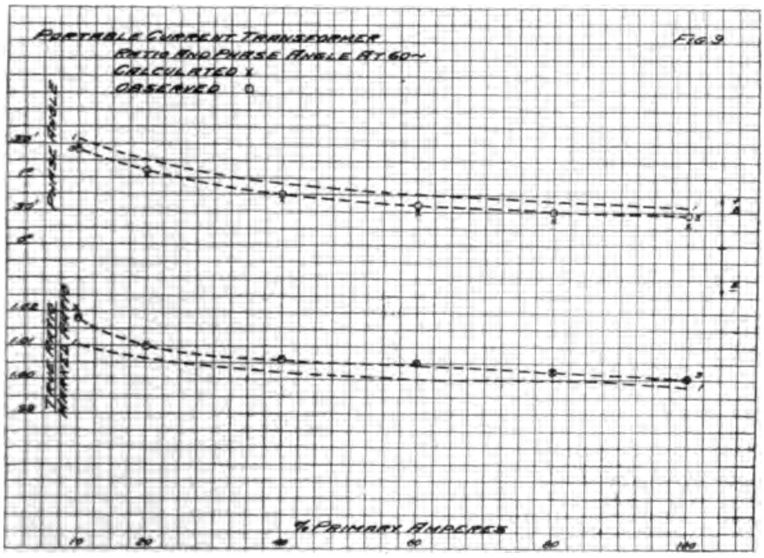

Fig. 9.—Comparison between observed and calculated ratio and phase angle on portable variable ratio current transformer

In Fig. 9 are shown ratio and phase-angle determinations on a portable transformer for variable ratio; in this transformer the primary winding is wound in by the user to meet the immediate requirements. This test was made on 60 cycles, using No. 3 load. The calculated and observed points have all been plotted. From this it can be seen that the calculated values agree with the observations well within the limits of accuracy expected. The phase-angle values have also been computed and are shown in the same way. The agreement here is also satisfactory and the method can be applied to transformers of any capacity. The reason for choosing the portable transformer of comparatively small ampere capacity in preference to a large bus-bar transformer, is the difficulty in determining the large primary current by methods that would be above suspicion.

The Potential Transformer

The same general considerations which apply to current transformers may be expanded to cover the potential transformers. As before stated this will not be done at the present time, both because the subject has received more general attention, and because the determinations of the ratio and phase-angle, even with comparatively high primary voltages, are much easier to make than similar tests on the current transformers. It is possible, using the apparatus about to be described and without a prohibitive expenditure of time, to test a potential transformer on any frequency with the secondary loaded from a single high-resistance instrument up to its maximum rated capacity. If convenient means are at hand it is also possible to determine quickly by test the ratio and phase-angle when the power-factor of the connected secondary load varies between any desired limits. Such a complete test is

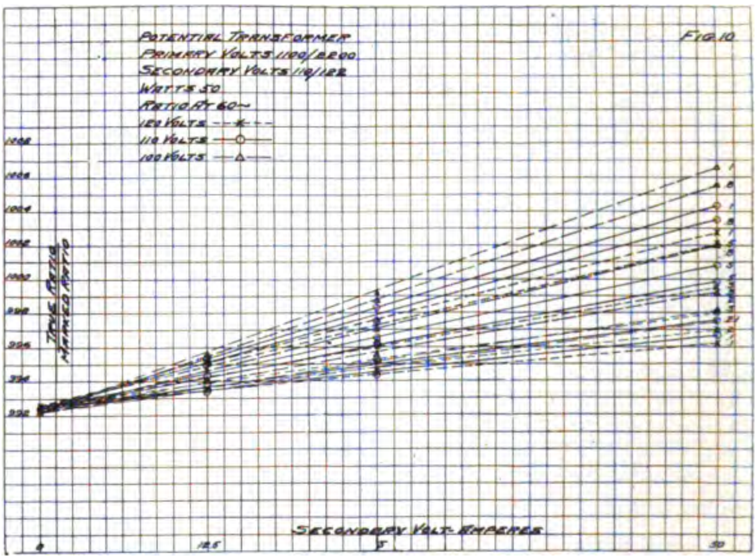

Fig. 10.—Full test of ratio on potential transformer

shown in Figs. 10 and 11. Various methods have been used for this work, as well as for current-transformer testing, but the one finally chosen has been found so convenient and accurate that no other special device will be referred to in connection with the testing of potential transformers.

Referring to Fig. 12, and to Figs. 13, 14 and 15, a complete equipment is shown there, especially constructed to produce transformer tests of the general kind shown in Figs. 10 and 11. This is suitable for use on any frequency and up to 33,000 volts. Additional resistance may be coupled to the standard arrangement, so that the range may be temporarily extended to any desired limit. The resistances r_1 and r_2 are connected across the primary circuit with taps for various voltages, so that about 10 ohms per volt may be used. The primary and secondary are connected together and to the ground as shown. The polarity is such that the potential rise from ground along the secondary of the transformer is in the same direction as that from ground along the main primary resistance. Then a point may be found in the primary resistance which is at the same potential as the high side of the secondary. We then have,

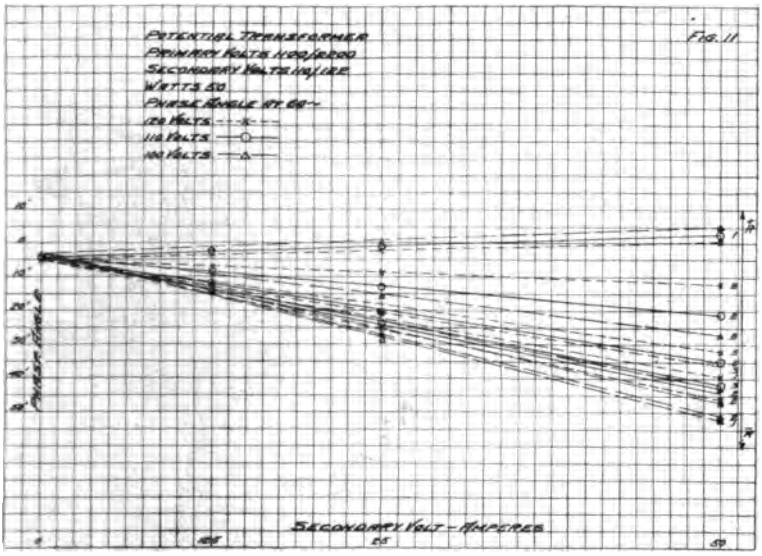

FIG. 11.—Full test of phase angle on potential transformer

$$\text{Ratio} = \frac{r_1 + r_2}{r_2}$$

The equality of potential is determined by a dynamometer, referred to in Fig. 4, or by a synchronous commutator, as shown in Fig. 13. The apparatus is made direct reading to within 0.1 per cent between the limits of 5 per cent below and 5 per cent above the marked ratio of any transformer, by employing the 100-point switch shown in Fig. 12. The movable contact, by which the potential coil of the dynamometer is moved along the primary high resistance, may be advanced by 1-ohm steps. Arranged in this way the ratio observations can be made as rapidly as they can be recorded, and values may be interpolated to 0.01 per cent if desired. The arrangements

FIG. 12.—Outfit for ratio and phase angle test on potential transformers referred to in Fig. 8

provided for loading the transformers are shown in Fig. 15. Reactances are provided taking about 0.12 ampere at 110 volts and 60 cycles, and having a power-factor of about 10 per cent, together with another set of reactances taking about 0.15 ampere at 25 cycles and having about the same power-factor. These may be combined in various ways so that the reactance load at low power-factor may be put on the transformers up to about 2 amperes. Resistance load, variable by much finer

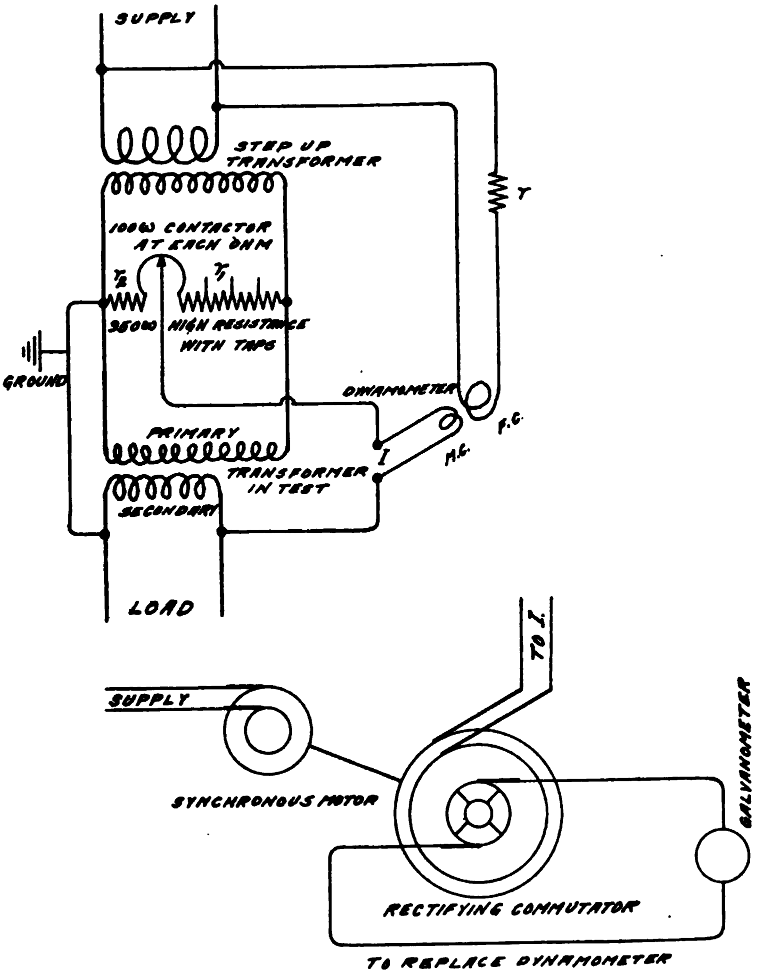

FIG. 13.—Connections for ratio test on potential transformer

steps, is also available up to the same ampere capacity. By combining these in suitable ways the desired load at any power-factor can be accurately obtained between the limits of 0.1 power-factor and unity. To avoid the time required to make adjustment of load, tables have been prepared by computations from instrument readings. By means of these tables approximately any ampere load at a definite power-factor can be arranged at once. It is not important to have the load in amperes very exact, as the lines connecting the observed points are practically straight, but the power-factor must be accurately adjusted to plot as shown in Figs. 10 and 11.

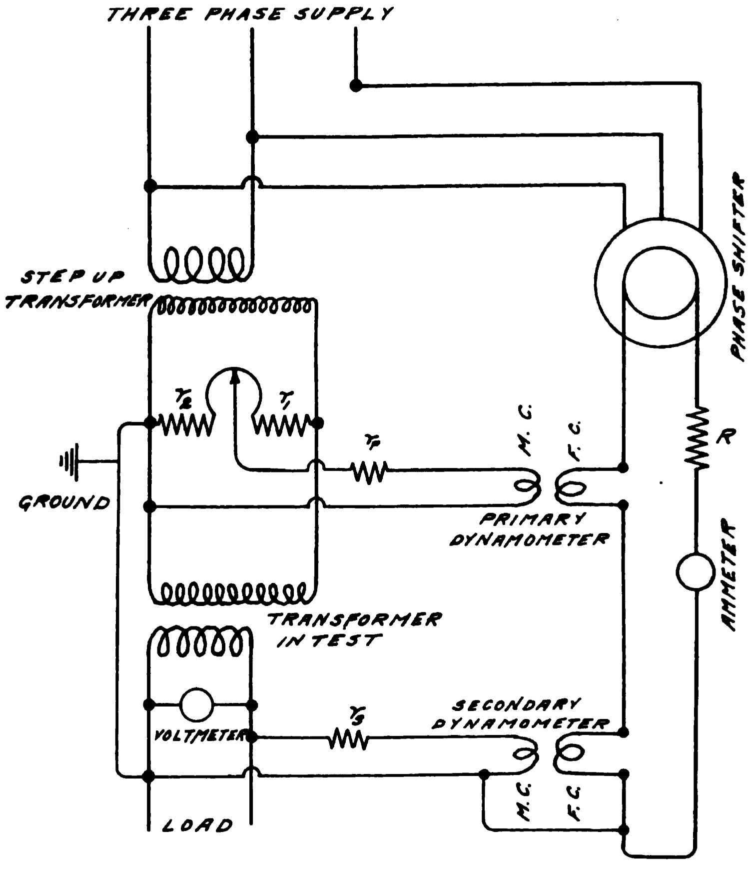

FIG. 14.—Connections for phase angle test on potential transformer

The phase-angle is determined on the potential transformers

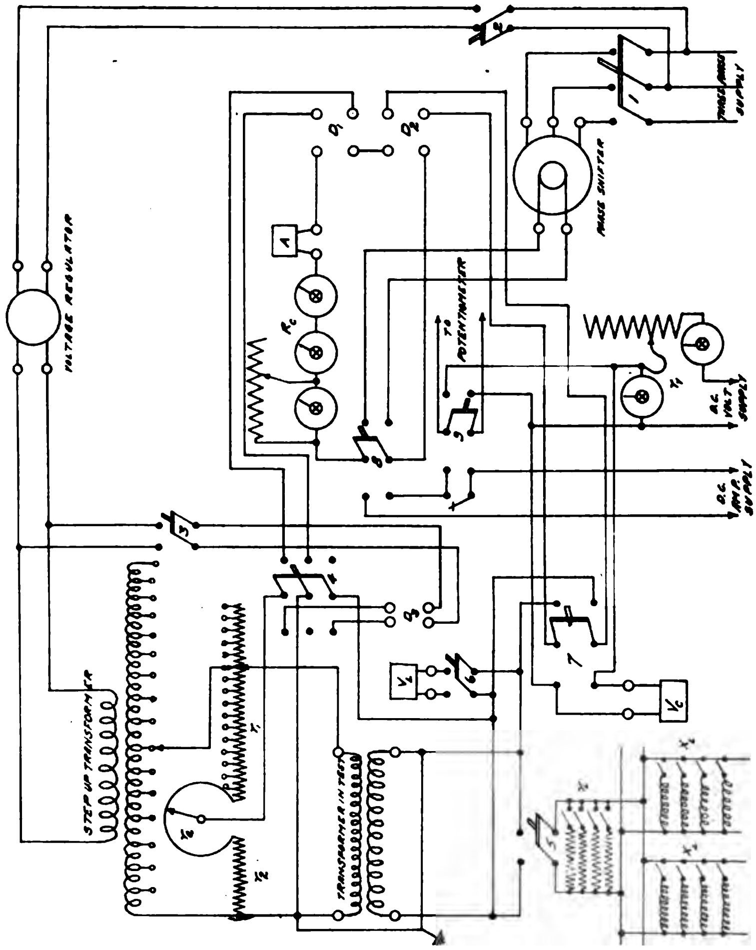

FIG. 15.—Diagram of connections of outfit for ratio and phase angle test on potential transformers. (1) Main switch on phase shifter. (2) Main switch on transformer supply. (3) Switch for exciting stationary coils of dynamometer for ratio test. (4) Main transfer switch; to left for ratio test, to right for phase angle test. (5) Main load switch. (6) Alternating-current voltmeter switch. (7) Secondary dynamometer potential coil switch. To right for phase angle test, to left for direct-current calibration, open for ratio test. (8) Dynamometer current switch. To right for phase angle, to left for direct-current calibration. (9) Potentiometer switch; to left to place potentiometer leads in series with direct-current for wattmeter calibration; to right to place potentiometer leads in multiple with direct-current voltmeter for calibration. r_1 high resistance with taps. r_2 950 ohms. r_a 100 ohms in 1 ohms steps for adjustment of moving contact. r_1 resistances to furnish load for secondary. x_1 reactance coils to furnish load for secondary. V_l alternating current voltmeter. V_c direct-current voltmeter for calibration. r_v resistances to regulate voltage applied in calibration. R_c resistances for control of current (alternating current or direct-current) applied to dynamometers. D_1, D_2 dynamometers with suitable resistances in series with potential circuits for determining phase angle. D_3 dynamometer with suitable resistances in series for ratio test.

in somewhat the same way as already described for current transformers. The connections used are shown in Fig. 14, and the complete connections as used in the device in Fig. 15.

The 3-phase or 2-phase line current is brought to a phase-shifter and to the low-voltage side of a step-up transformer. A duplicate of the transformer under test may frequently be used for stepping up the voltage. Current from the secondary of the phase-shifter is passed in series through the current coils of two dynamometers, usually of 5-ampere capacity, the amount being controlled by a suitable resistance *R* in series. By varying the current passing through *R* and the fixed coils, the sensibility of the arrangement may be made as desired. The same resistance used in the Fig. 13, ratio test, is connected in multiple with the primary of the transformer in test, and the drop across a considerable portion of it is used to excite the moving coil of the primary dynamometer. The resistances r_p, r_1, r_2, and r_s must be practically perfect, as in phase-angle testing of current transformers. The secondary voltage of the transformer under test is used to excite the potential coil of the secondary dynamometer through the resistance r_s. The current coil and the potential coil on the secondary dynamometer must be connected together, as shown. The load on the transformer under test is then adjusted to the proper current and power-factor, and the phase is shifted until the primary dynamometer reads zero. The phase-angle between the primary and secondary electromotive force is then,

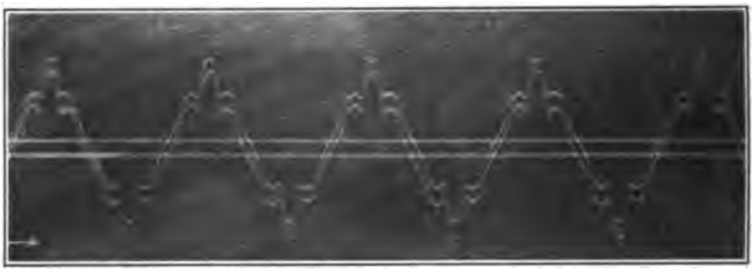

FIG. 16.—Primary and secondary current waves on portable current transformer with load No. 1, and 25 per cent of full primary amperes, 60 cycles

$$\gamma = \sin^{-1} \frac{W_s}{E \times A}$$

Where W_s, E and A have the same meaning as in the formula for phase-angle on the current transformer.

The voltmeter V, is used to regulate the test voltage on a transformer, and if it is left on during the test, it must be considered as part of the transformer load.

Before leaving the general subject of instrument transformers it may be well to refer to one point about which some uncertainty exists; namely, the effect of current transformers in causing a wave to appear in the secondary circuit, differing in form from that of the primary. As the shortest and most satisfactory way of disposing of this point, oscillograph records, Figs. 16, 17 and 18 have been taken, showing primary and secondary current waves in a current transformer. Examination of these figures will show that the primary wave is reproduced, practically unchanged, in the secondary. A much distorted wave was purposely chosen.

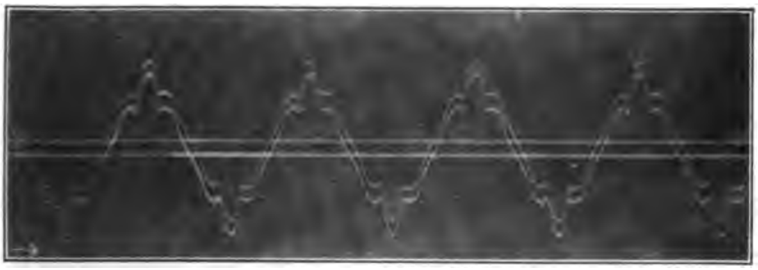

FIG. 17.—Primary and secondary current wave on portable current transformer with load No. 1 and 50 per cent of full primary amperes, 60 cycles

CONCLUSIONS

For measuring large alternating currents and voltages, current and potential transformers must usually be employed. If these are carefully designed they may be used with small errors resulting with various devices connected in the secondary circuit, and with primary current varying between the limits of the connected instrument scales, also with voltage and frequency variation usually met with in practice. If some care is not used in selecting suitable apparatus to meet conditions, errors as great as 5 or 10 per cent or more may occur. If the transformers are constructed with special reference to handling a given load, the errors may be limited to almost any required amount. To meet conditions of testing where low power-factor is present, or where a high degree of accuracy must be attained, carefully determined corrections for ratio and phase-angle must be applied. Such corrections, once determined for any given transformer, are permanent, and by their use the transformers may be considered precision instruments.

Wattmeters, when used without current or potential transformers, may be made to give indications correct within the limits of error of observation down to a power-factor as low as 10 or 15 per cent. Under certain conditions which may occur in practical work, it is well to know and apply corrections to the instruments themselves. If the conditions are such that the wattmeter must be corrected for phase-angle to insure suitable accuracy, current and potential transformers should not be used, unless the conditions are somewhat favorable and the corrections for the transformers are determined and applied with great care.

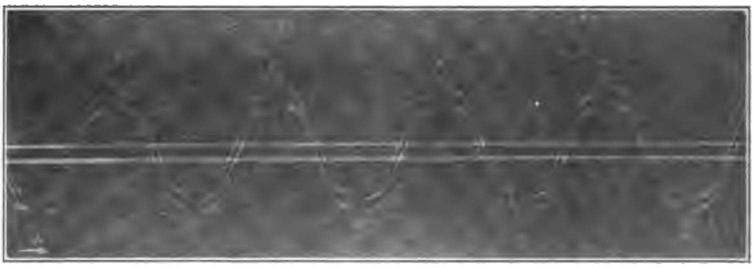

Fig. 18.—Primary and secondary current waves on portable current transformer with load No. 1 and 100 per cent primary amperes 60 cycles

In presenting the foregoing on the use of instruments in connection with current and potential transformers, it is perhaps proper to say that a considerable part of the subject matter contained therein has received more or less complete treatment in various publications. An incomplete list of such articles is here given. The paper should be considered as an attempt to describe, with enough detail to be of practical use, some specific methods of determining and applying corrections to the results obtained. The methods have been selected, after several years experience, as being best suited to the requirements that had to be met from time to time.

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DISCUSSION ON "ELECTRICAL MEASUREMENTS ON CIRCUITS REQUIRING CURRENT AND POTENTIAL TRANSFORMERS." FRONTENAC, N. Y., JUNE 30, 1909

C. H. Sharp: This important question of the measurement of ratio and phase-angle of transformers is beginning to receive the attention it deserves. I should like to call attention to similar work done at the Electrical Testing Laboratories under my direction by Wm. W. Crawford.

By the two-ammeter method of measuring the ratio of current transformers, it is possible to get quite accurate results, but their accuracy is limited by the steadiness of the available alternating-current supply. It is also desirable that the two instruments should have as nearly as possible the same natural frequency of oscillation.

Being dissatisfied with the results obtained by the two-ammeter method, we sought a method which would be free from its disadvantages, and two years ago worked out the two-shunt method outlined by Mr. Robinson. This is essentially a bridge or zero method in which the fluctuations of the supply do not go into the result directly, and which has also the great advantage of giving the result in terms of the ratio of two resistances. We have developed also the shortcomings of this method, which are described below, and have devised means whereby they might be overcome and also a scheme for measuring the phase-angle of the transformer at the same time that its ratio of transformation is obtained.

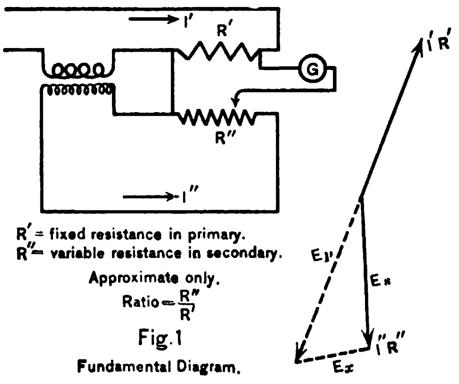


Fig. 1
Fundamental Diagram.

The simple connection shown in Fig. 4 of Mr. Robinson's paper does not give a wholly exact value for the ratio of the transformers, for the reason that the primary and secondary currents are not in phase with each other and their phase-angle increases with decreased load. Referring to Fig. 1, we have e_p the fall of potential on the primary shunt, e_s that on the secondary shunt, and e_x the reactive potential difference which is present even when $e_p = e_s$ numerically. Now, if the rotating commutator is adjusted so that its axis of commutation bisects the angle between e_p and e_s, the galvanometer measures the difference between the projection of e_p on the axis of commutation, and of e_s on the same axis. When the deflection of the galvanometer is reduced to zero by adjusting the secondary shunt, the ratio of shunt resistances gives very accurately the ratio of the transformer. The difficulty is to set the axis of commutation to approximately the right position. If this axis of commutation falls some distance outside the angle made by e_p and e_s, the ratio measured will be incorrect.

To obviate this difficulty, the reactive potential difference e_x must be nullified. The first method used for this purpose is illustrated in Fig. 2. In this method a fixed non-inductive resistance R'' is introduced into the secondary circuit, and this is shunted by a potentiometer arrangement R_s of 100 ohms, in series with which is a variable standard of self-induction L by means of which the current through R_s may be brought into phase with that through R'.

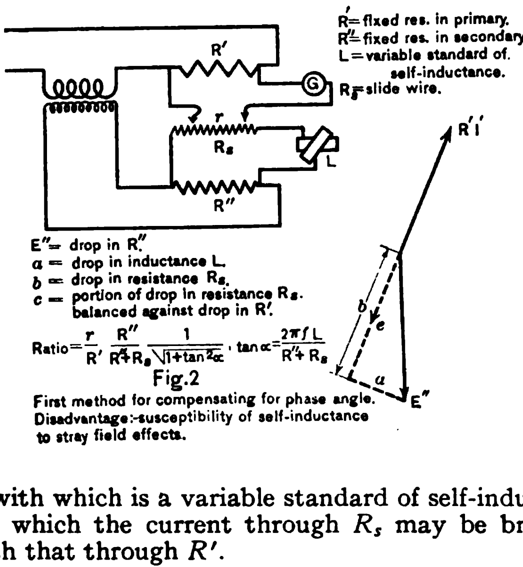


Fig. 2

First method for compensating for phase angle. Disadvantage:-susceptibility of self-inductance to stray field effects.

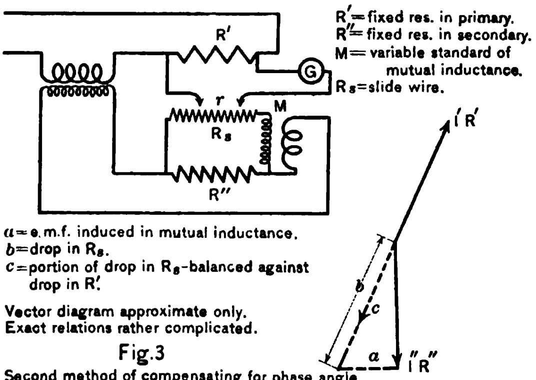
The procedure then is as follows: the axis of commutation is brought as nearly as possible into the general direction of the vectors of the fall of potential of primary and secondary shunts, by noticing the position of the commutator which gives the maximum sensibility to the arrangement; that is, the position in which a given change in the secondary shunt throws the apparatus farthest out of balance. Having determined this position, and having adjusted R_s so that the galvanometer deflection is zero, the line of commutation is rotated through an angle of 90 deg. At this point the sensitiveness of the arrangement in measuring the inductive difference e_x is the maximum, and the deflection here observed is brought to zero by adjusting the value of the self-induction L. This operates to bring the potential differences on the shunts substantially into phase with each other.

When this has been accomplished, the brush holder is rotated back into its original position and the adjustment of R_s is again made. The second value of R_s so found must be almost exactly correct since it is made when e_p and e_s are in phase with each other, and consequently the ratio of their projections upon any line gives the true ratio of the potential differences. The ratio of the transformer is then given by the expression:

$$\text{Ratio of transformation} = \frac{r}{R'} \cdot \frac{R''}{R''+R_s} \cdot \frac{1}{\sqrt{1+\tan^2\alpha}}$$

where α, the phase-angle of the transformer is given by the relation,

$$\tan\alpha = \frac{2\pi f L}{R''+R_s}\,.$$



R′=fixed res. in primary.
R″=fixed res. in secondary.
M=variable standard of mutual inductance.
R_s=slide wire.

a=e.m.f. induced in mutual inductance.
b=drop in R_s.
c=portion of drop in R_s-balanced against drop in R′.

Vector diagram approximate only.
Exact relations rather complicated.

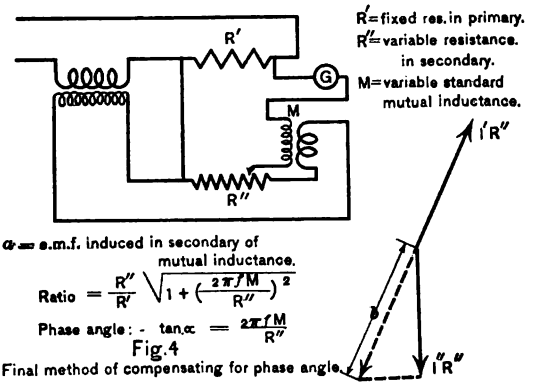
Fig.3

Second method of compensating for phase angle.
Disadvantage:- complicated formula.

The principal disadvantage of this method is that the ordinary Ayrton-Perry form of standard of self-induction is such that it is subject to influence by stray alternating fields, and a very feeble stray field would in the case of these measurements be sufficient to destroy the accuracy of the measurements. It is evident that in the foregoing work, not only has the ratio of the transformer been determined, but at the same time the phase-angle between primary and secondary currents has been measured.

Following this, a second method, shown in Fig. 3, was developed in which a variable standard mutual-induction was substituted for the variable standard of self-induction, and since a standard of mutual-induction can be made astatic so as not to be influenced by stray fields, this difficulty of the first method was overcome. The relations involved in applying this second method are rather complicated, and as a result the method has been abandoned for one illustrated in Fig. 4, in which the arrangement of circuits was suggested by Mr. F. K. Vreeland. As will be seen, the primary of the mutual-inductance is in series with the secondary of the transformer, while the secondary of this mutual-inductance is connected in series with the galvanometer. The operations are exactly as described in the first method but the formula is even more simple than in that method, while the trouble from stray field is avoided by using an astatic mutual-inductance.

The methods here given have the advantage over Mr. Robinson's method of not requiring two wattmeters which are accurate on low power-factors, together with a voltmeter and ammeter, three observers, and a steady current. By this method not only is the true ratio of the transformer obtained as a ratio of resistances, but the phase-angle is measured by actually nullifying the reactive potential difference which corresponds to it. With the exception of an ammeter to show approximately what the load is, no direct-reading instruments are required.



$$\text{Ratio} = \frac{R''}{R'}\sqrt{1+\left(\frac{2\pi fM}{R''}\right)^2}$$

$$\text{Phase angle:- } \tan\alpha = \frac{2\pi fM}{R''}$$

Fig. 4

Final method of compensating for phase angle.

Advantages: - Simple formula.

Less susceptibility to stray fields.

Greater sensitiveness.

Moreover, the arrangement is independent of sensitive suspended instruments. It is quite feasible to use a resistance of very small fall of potential for the primary and secondary shunts and still have sensitiveness enough even when a pivoted direct-current galvanometer is used. On account of the character of the apparatus employed, it is possible by one of these methods to measure the ratio of a transformer installed on a switchboard and to do it with a high degree of accuracy. This at once extends the range of possibilities of this sort of testing beyond the walls of the laboratory—a very important consideration in many instances.

We have found that the rectifying commutator in the form in which Mr. Robinson describes it is not a success. As soon as the current becomes very small the contact resistance of brush with commutator is very uncertain, sometimes reaching a high value. We have obviated this difficulty by substituting a vibrating rectifying device operated by a cam on the shaft of the motor. Straight pressure contact instead of rubbing contact is thereby obtained, and operates satisfactorily. The primary non-inductive shunts for this sort of work present very serious problems of construction as soon as heavy currents have to be dealt with. and they must be arranged to be cooled by some liquid.

A similar method can be used for the measurement of the ratio of potential transformers. As a current detector an alternating-current—direct-current voltmeter can be used, provided its connections are changed so that its field coils can be separately excited. For most purposes the sensitiveness of such an instrument is sufficient. The methods and apparatus for carrying them out as described in the foregoing have been developed in the Electrical Testing Laboratories quite independently of any similar work done elsewhere.

M. G. Lloyd: Mr. Robinson's table and diagrams will no doubt be useful as showing the general way in which those quantities change with the conditions of load.

I think it may be of interest to speak of some methods that have been developed at the Bureau of Standards and are now being used in this kind of work. Referring first to the current transformer and the diagrams in Figs. 2 and 3: we tried out the first method and found it objectionable, at least not quite as serviceable as the method indicated in Fig. 4, and similar to the one described by Dr. Sharp, in which only two shunts are necessary in the circuit of the transformer. In addition to the points raised by Dr. Sharp, one other is that while there is no trouble in getting accurate measurements with the arrangements shown in Fig. 2, since a dynamometer must be in the secondary circuit, it limits the load conditions which must be used; that is, the resistance and reactance cannot be cut down below the values necessary for the watt-dynamometer itself. Consequently, the secondary circuit cannot be made as small as it might be in practice, and therefore as small as it would be desirable to have the conditions in calibrating.

The alternative diagram in the lower left-hand corner of Fig. 4, is a method that we have found of more service. At the terminals 2, we connected one coil of the dynamometer; the other coil had current supplied to it in phase with the primary of the transformer. The result is that the potentials across the two resistances, R_p and R_s are opposite and not exactly in phase, their resultant being a small voltage in quadrature, and the dynamometer is made to read zero. In the case of any good transformer the ratio of resistances gives the ratio of the currents since the cosine of the small angle is a negligible factor.

We have found it simpler to obtain the phase-angle measurement almost simultaneously by using a somewhat different scheme. Instead of using a three-phase supply we have tried using a two-phase source of supply, and we have found that preferable. Using a two-phase supply we have a second dynamometer whose field is supplied with current in quadrature; we then apply the same electromotive force, which represents the difference in the drop in the two shunts, R_p and R_s, to the other coil of the dynamometer having its field in quadrature. The deflection, then, measures a small quantity which, in ratio to the primary potential drop, gives the phase-angle of the transformer; so that by a simple throwing of the switch the second measurement is obtained.

The method with the mutual inductance, mentioned by Dr. Sharp, I believe is the same as that used at the National Physical Laboratory, in England, and described in their last annual report.

In regard to potential transformers, our method is very similar to that used by Mr. Robinson; that is, we balance a fractional part of the potential of the primary against the potential of the secondary. I need not speak of that in detail; suffice it to say that here again in obtaining the phase-angle we use the quadrature current as the auxiliary instead of the phase-shifting transformer, with the result that by simply throwing the same difference of potential on the second dynamometer, that quantity is measured directly and gives the phase-angle. These methods which we have finally found the most preferable were given several months ago in a paper read before another society.*

As Mr. Robinson has pointed out, the transformer is an instrument of precision when used under proper conditions. There is one way, however, in which an error may be introduced even when the transformer has been calibrated and when it is not subject to such errors as aging. That is due to the fact that iron requires a different magnetizing current in some cases from what it needs in others. Such a case can be brought about by magnetizing highly in one direction and then subsequently breaking the magnetizing current. It will be then in a condition that is not neutral. If that operation is performed with the current transformer, and its ratio then measured, it will be found that the ratio will not be of the same value as when the iron is in a neutral condition.† That does not apply to a potential transformer, because there the magnetizing current comes in only as a second-order effect. In the current transformer, where the ratio is thrown off from the nominal value entirely by the exciting current, this effect comes in very strongly and may produce an appreciable error.

Hence when calibrating the current transformer and using it afterwards, one should be sure that a definite condition of the iron exists. That can be arranged by putting the core through a demagnetizing process before using it. Such an abnormal condition may easily result, because if the secondary happens to be open-circuited we have the condition spoken of. The magnetism of the core jumps to a high point and if the flux is suddenly cut down by closing the secondary, it is brought down without the demagnetizing process.

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* Agnew and Fitch, *Phys. Rev.* 28, p. 473; June, 1909.

† Attention was first called to this by Agnew and Fitch loc. cit.

In regard to which angle should be called positive and which negative, I wish to take issue with Mr. Robinson. The point mentioned earlier, depending upon whether we shall call a lagging angle positive or negative, I will not go into because that is a point which depends largely upon the way in which one has been trained. But coming to the specific case of designating these angles, it seems to me that the method used in this paper is inconsistent and undesirable. It will be noticed in the case of the current transformer that when the secondary leads, the angle is called positive, and in the case of the potential transformer it is called negative. There is an inconsistency between the two cases. The reason for doing this is to make it possible to take the sum of the two angles and determine the apparent power-factor. It seems to me that is confusing. Anyone understands that if the current and the potential are thrown off simultaneously in the same direction; that is, if each one is caused to lag by the same number of degrees, the reading of the wattmeter will not be altered. The first thing that naturally occurs to one is that the difference of the two phase-angles must be taken. So it would be more logical and less confusing to call the phase-angle positive in one definite direction, preferably when the secondary leads.

In the formula on the fourth page, I would suggest that having indicated which angles are positive and which negative, it would be better to omit the combined sign plus and minus and let it stand as plus.

In an early part of the paper, under the things to be investigated, Mr. Robinson has mentioned the effect of wave-form. I think he takes up all the other points, but he says nothing further about this. Over a year ago I published an article* giving some experiments on that point. The results showed that with any distortion that would be likely to be present on an ordinary circuit, the ratio is not affected. There is a small effect with very large distortion. In a book by Arnold,† this section of which was written by LaCour, there is a theoretical discussion on this subject, based on the assumption that harmonics can affect the result only by their value and regardless of their phase. In other words, if the same harmonics are in such phase as to produce a flat wave and a peak wave, the result should be the same. This is not in agreement with the experimental facts.

L. W. Chubb: I would like to ask if the transformers giving the curves shown in Figs. 7 and 8 were of special design for the test, or whether they were commercial transformers, and what were the load conditions 1, 2, 3, 4, and 5?

I would also like to ask Dr. Sharp if the extra circuit containing the resistance and inductance as shown in his diagram would take enough current to prohibit getting any desired conditions of instrument load during a test?

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* *Electrical World* 52, p. 845, 1908. *Bull. Bur. Stds.* 6. No. 1, 1909.

† Wechselstromtechnik, Vol. 1, p. 254.

Albert F. Ganz: I wish to ask Mr. Robinson whether he has any method to suggest for measuring the phase-angle α in the wattmeter itself, also whether in a properly designed transformer, β is not always positive and γ negative? Is there anything about the tests that will enable one to tell whether these angles are positive or negative?

C. H. Sharp: Answering Mr. Chubb's question: in this method of testing current transformers the high relative sensibility of direct-current galvanometers can be utilized. Consequently it is not necessary that the fall of potential in these shunts should be large. As a practical matter we work with one-quarter of an ohm in the secondary circuit of the transformer, but we could just as well use two-tenths or one-tenth. The inductance. is entirely negligible.

L. T. Robinson: In reply to Dr. Sharp, I would say that it is not necessary to take into account the small error due to the fact that the primary and secondary currents are not exactly in phase. I think that the somewhat elaborate arrangements which he has shown are an entirely unnecessary refinement. By reference to a table of cosines it will be seen that if the transformer is reasonably good; that is, if the angles are nearly as they should be, it will be entirely beyond the accuracy wanted in a commercial test. If the angle β is as much as 2 deg. the necessary correction ($\sec \beta - 1$) amounts to only about 0.05 per cent. If desired, correction can easily be made for this small angle, but if a transformer were brought to me for test, and I had to take this correction into account, I would not make a complete test. The transformer would evidently not be a good one.

I think that the method suggested for measuring the phase-angle is very ingenious. I have not had the time to try it but my opinion is that it would not allow a determination to be made with the same degree of precision that could be obtained by using the method given in the paper.

The question was raised as to the number of observers and the time required to complete the work. I would say frankly that I expected better results with the resistance methods that have been described, and the only reason I can give for not having adopted long ago for commercial work what will no doubt prove to be the final method is, that where one has so much to do it is difficult always to bring into daily use methods which promise to be better. I am quite willing to say. however. that from my point of view the length of time for these tests is quite satisfactory.

The commutator I myself do not like. We did try it and it will work, but I think I would prefer some other method.

Dr. Lloyd referred to Figs. 2 and 4. I prefer Fig. 4 unless some arrangement like that shown in Fig. 6 can be used. I believe this will be the ultimate outcome.

It is true that the secondary load conditions are limited by the dynamometers. From my own point of view this is no objection, because we can go to the limits of the smallest connected load that it would ever be necessary to use, and there is no use in going further. For precision work we would not use a transformer with less on it than one portable ammeter and one portable wattmeter, and the combined load of these two is just about equal to what we can easily get by the methods we have used.

As to the effect of the altered magnetizing current due to the previous state of the core affecting the ratio, I would say that this fact has been appreciated for some time. I thought it was so well known that I did not need to refer to it. All users of current transformers have for some time been cautioned against leaving the secondary circuit open.

M. G. Lloyd: The same effect is brought about if the dynamometer is calibrated with the secondary or primary in circuit with direct current.

L. T. Robinson: I know that, but we do not do it.

As to the angles and sines, I appreciate this fact, that it may not be logical and I do not offer it as such; but after one has carefully selected the best method and no one else is doing the same thing at that time, the only way is to proceed and afterward tell how it was done and what one's opinion of it is. I am perfectly willing to make a change if we can come to any satisfactory understanding about what it is best to do.

In reply to Mr. Chubb's question as to the loads used: I described their properties though perhaps not in sufficient detail. The loads are given in electrical terms and below is given a brief description of the actual loads used.

The tests of transformers were all made on commercial specimens. Professor Ganz asked how to determine the angle α. I would say that one cannot tell everything in a single paper. I shall be glad to tell him privately what we do.

J. Dalemont (by letter): I wish to call attention to the influence of the core-loss and magnetic leakage upon current transformers. I have recently made some measurements on two current transformers having iron cores of the same cross-section and nearly the same length, but of different form: one as in Fig. 1, the other as indicated in Fig. 2.

On one of the legs of the prismatic core, the following sets of coils were mounted in succession:

$$1 \begin{cases} \text{Primary;} & 5 \text{ turns.} \\ \text{Secondary;} & 460 \text{ turns.} \end{cases} \qquad 2 \begin{cases} \text{Primary;} & 41 \text{ turns.} \\ \text{Secondary;} & 460 \text{ turns.} \end{cases}$$

The transformer was supplied with an alternating current of almost sine shape and a frequency of 36 cycles. On the torus core, a secondary winding of 460 turns was wound uniformly. The primary wire carrying the current was placed in the direction of the axis of the torus, perpendicular to the plane of the paper and was supplied with the same current as before. The secondary circuits were closed on standard ammeters. Table I gives the values of the primary and secondary currents in each case.

It will be seen that in the first case (ratio of 5 to 460, prismatic core), the average of the primary and the secondary currents is 83.4, while the ratio of the number of turns is 92; with the other coils (ratio 41 to 460) on the same core, the average ratio of the currents is 12.2, while the ratio of the turns is only 11.2.

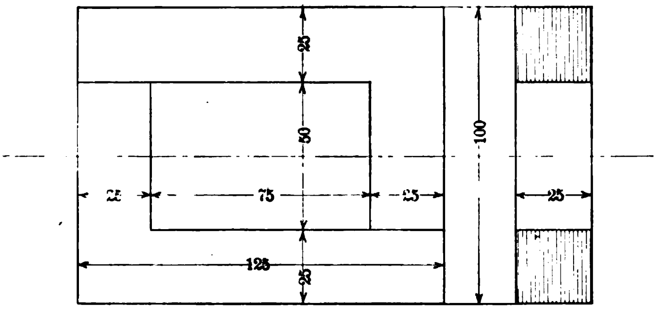

FIG. 1

Taking the relation between the ampere-turns, we have:

$$\frac{n_2 I_2}{n_1 I_1} = \frac{4 \pi n_2 p}{\sqrt{R^2 r_2^2 + (4 \pi n_2^2 + l_2 R)^2 p^2}}$$

where p is the frequency,

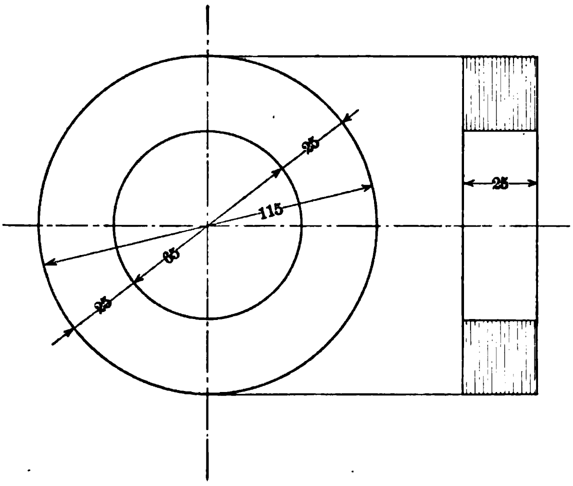

FIG. 2

R = the magnetic reluctance of the core.

r and $p\ l$, the resistance and the reactance of the secondary circuit.

It will be seen that this ratio is equal to 1 when the losses are negligible.

TABLE I

Ratio $\frac{5}{460}$		Ratio $\frac{41}{460}$		Ratio $\frac{1}{460}$	
Core 1		Core 1		Core 2	
I_1 ampere	I_2 ampere	I_1 ampere	I_2 ampere	I_1 ampere	I_2 ampere
93	1.09	15.5	1.23	567	1.15
116	1.37	19.8	1.58	755	1.58
135.2	1.61	23.4	1.89	936	2
150	1.79	27.7	2.23	1021	2.18
170	2.03	32.3	2.62	1098	2.32
184	2.19	35.8	2.91	1175	2.52
205	2.45	39.2	3.17	1265	2.68
233.3	2.77			1355	2.87
263	3.13			1495	3.17
275	3.25			1670	3.54
299	3.53			1772	3.77

TABLE II

Curve 1		Curve 2		Curve 3	
$n_2 I_2$	$\frac{n_1 I_1}{n_2 I_2} - 1$	$n_2 I_2$	$\frac{n_1 I_1}{n_2 I_2} - 1$	$n_2 I_2$	$\frac{n_1 I_1}{n_2 I_2} - 1$
502	-.073	565	.122	529	.048
632	-.082	727	.115	727	.036
742	-.088	870	.102	920	.020
825	-.092	1025	.098	1000	.024
936	-.093	1205	.100	1068	.032
1008	-.088	1339	.095	1160	.030
1130	-.092	1458	.095	1232	.028
1275	-.087			1320	.026
1440	-.086			1958	.025
1498	-.082			1628	.025
1625	-.080			1732	.022

The curves in Fig. 3 show the variation of the ratio

$$\frac{I_1 n_1 - I_2 n_2}{I_2 n_2}$$

plotted to $I_2 n_2$ as abscissas. The advantage of the torus form for the magnetic core is thus clearly demonstrated by these results. On the other hand, a rectangular section for the magnetic core is preferable to a square section, but with the low values of induction used in such apparatus (2750 c. g. s.), the difference is very small. For a comparison of the two cores from this point of view, the numerical values of the above expression are given in Table II.

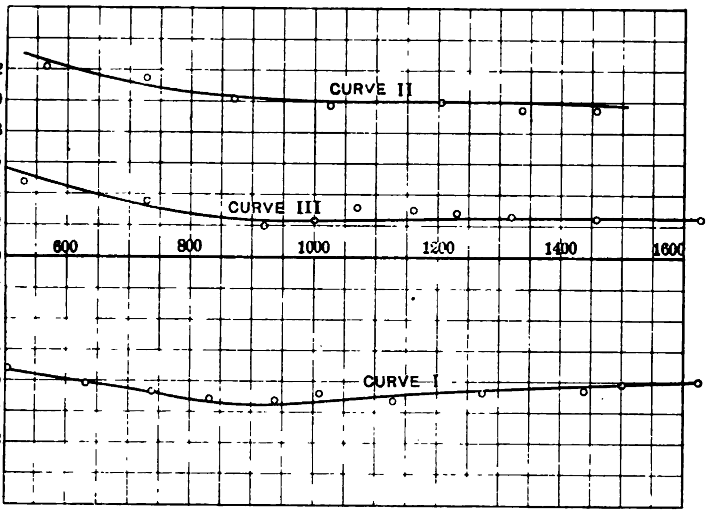

FIG. 3

Albert F. Ganz (by letter): Mr. Robinson shows that where a wattmeter is used with current and potential transformers, the wattmeter reading must be multiplied by the factor

$$\frac{\cos\theta}{\cos[\theta-(\alpha+\beta+\gamma)]}$$

in order to correct for the error due to phase displacement between current and voltage caused by the wattmeter itself, and by the transformers where

θ = phase angle between current and voltage in the main circuit assumed *positive* when the current is *lagging*.

α = equivalent angle of phase displacement between current in the potential coil and voltage across the potential terminals of the wattmeter, assumed *positive* when the current *lags* behind this voltage.

β = angle of phase difference between the primary and the secondary current in the current transformer, assumed *positive* when the secondary current *leads* the primary current reversed.

γ = angle of phase difference between the primary and the secondary voltage in the potential transformer, assumed *positive*, when the secondary voltage *lags* behind the primary voltage reversed.

Mr. Robinson has also given convenient tables of correction-factors for various power-factors of the load, and for phase displacements up to 5 degrees. The correction-factor as given by the above formula, and the tables as given by Mr. Robinson, are directly applicable to a single-phase circuit, in which case θ of the formula is the angle whose cosine is the power-factor of the load.

Where three-phase power is measured by two wattmeters, the indications of these wattmeters are proportional, not to $\cos\theta$, but to $\cos(30°+\theta)$ and $\cos(30°-\theta)$, respectively. Suppose the three-phase power to be delivered over three line wires, 1, 2 and 3, and let the two wattmeters be connected with their current coils in lines 1 and 3 and their potential coils across 1 and 2, and 3 and 2, respectively. Assuming the load to be balanced, and taking θ the angle whose cosine is the power-factor of the load, then the wattmeters will give indications equal to

$$P_1 = E\,I\cos(30° - \theta),$$

and

$$P_3 = E\,I\cos(30° + \theta).$$

Where current and potential transformers are used with two wattmeters, the displacement of phase in the transformers affects the angle $(30° - \theta)$ in wattmeter #1, and the angle $(30° + \theta)$ in wattmeter #3. With a lagging current in the load—that is, with θ positive—P_3 will be the smaller wattmeter reading and P_1 the larger wattmeter reading.

To correct for phase displacement, the reading of wattmeter #1 must be multiplied by

$$\frac{\cos(30° - \theta)}{\cos[30° - \theta + (\alpha+\beta+\gamma)]},$$

and that of wattmeter #3 must be multiplied by

$$\frac{\cos(30° + \theta)}{\cos[30° + \theta - (\alpha+\beta+\gamma)]}.$$

In applying Mr. Robinson's tables to three-phase power measured by two wattmeters, the θ used in the tables must be taken equal to 30 degrees minus the angle whose cosine is the power-factor of the load, for wattmeter reading #1; and equal to 30 degrees plus the angle whose cosine is the power-factor of the load, for wattmeter reading #3.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers. Frontenac, N. Y., June 30, 1909.

ELECTROMOTIVE FORCE WAVE-SHAPE IN ALTERNATORS

BY COMFORT A. ADAMS

The method of connecting the shape of the flux distribution curve of a synchronous converter with the shape of its induced electromotive force wave, developed by the writer in his Atlantic City paper,* is here applied more specifically to the alternator, with an illustration taken from Mr. Bache-Wiig's Atlantic City paper on the "Application of Fractional Pitch Windings to Alternating-Current Generators." Parts of the explanation of the *method* are reproduced in a somewhat modified and condensed form for the benefit of those who did not read the other paper.

The shape of the electromotive force wave of an alternator at no load is in general dependent upon the shape of the flux distribution curve and upon the arrangement of the armature conductors. But when the slots are large as compared with the air-gap, there is a pulsation of the flux in both magnitude and position,† which may materially alter the shape of the electromotive force wave. In the case of modern alternators with good inherent regulation, the air-gap is usually so long that these tooth pulsations are negligible; they will therefore not be considered here. The long gap and stiff field also tend to minimize the distortional effect of the armature magnetomotive force and to maintain a more nearly constant wave-shape at all loads.

With these reservations it will be assumed that a single con-

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* "Voltage Ratio in Synchronous Converters, with Special Reference to the Split Pole Converter." A. I. E. E. June, 1908.

† "Magnetic Pulsation in Alternators." Worrall. I. E. E. Jan. 1908.

ductor or a bundle of conductors placed in a single slot, will experience an electromotive force the wave-shape of which is the same as that of the flux distribution curve.

The electromotive force of one phase of an alternator is ordinarily made up of several of these slot electromotive forces added together in their proper phase relation, the electromotive forces of two adjacent slots being displaced by an angle corresponding to the slot pitch. If each slot electromotive force were sinusoidal the addition could be readily accomplished, but as this is not usually the case, the problem is not quite so simple. The method here employed is as follows:

Analyze the flux distribution curve into its fundamental and its various harmonics.

Make a vector addition of the fundamentals of the proper slot electromotive forces to obtain the fundamental of the phase electromotive force.

Make a vector addition of the *m*th harmonic of the proper slot electromotive forces to obtain the *m*th harmonic of the phase electromotive force.

Add the phase fundamental to the several phase harmonics to obtain the complete phase electromotive force.

Unless it is desired actually to plot the resultant wave, the last step is not necessary, since for all purposes of calculation the harmonics are treated separately.

TYPES OF ARMATURE WINDING

In order properly to carry out the above-mentioned vector additions, it will be necessary to consider the possible relative locations of the coil-sides which go to make up a given phase of the winding.

For the present purpose alternator armature windings may be classified as follows:

a. According to the angular span of a single phase belt. In the ordinary three-phase alternator this is 60 degrees, and as the three-phase machine is so nearly exclusively employed at the present time, the following discussion will refer thereto unless otherwise specified.

b. According to the number of slots per pole. Although this quantity can have almost any value, the more common values are small multiples of the number of phases, and these common values will be here considered unless otherwise specified.

c. According to the " pitch," " span " or " throw " of the coils.

The coil pitch is usually equal to or less than the pole pitch. Fig. 1 shows a simple two-layer winding with a full-pitch winding, six slots in six. Fig. 2 shows the same winding except that the coil pitch is reduced to four slots in six, or 66⅔ per cent. In this two-layer type of winding the pitch may be any whole number of slots, without destroying the mechanical symmetry.

d. According to the number of coil sides per slot. The two-layer winding shown in Figs. 1 and 2 has two coil-sides per slot, but a somewhat equivalent winding may be made with one coil-side per slot, see Fig. 3. With this one-layer winding, however, mechanical symmetry demands a coil pitch which, when measured in slots, is odd. In Fig. 4 is shown a similar one-layer winding, but with nine slots per pole; here there is a dissymmetry of coil connection, in that the alternate groups of coils in a given phase contain numbers of coils differing by one. This will be found to hold in this type of winding whenever the number of slots per pole is odd, 9, 15, 21, etc.

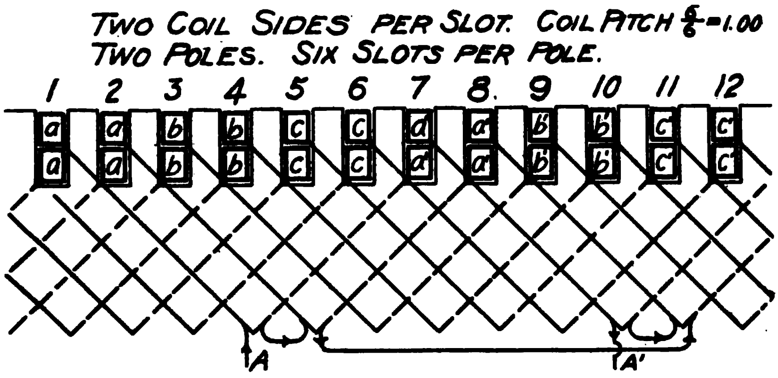

FIG. 1

There are other very common types of alternator armature windings, but for the purpose in hand they are for the most part equivalent to those already described.

In each type of winding shown there are two groups of coils per phase per pair of poles, and these are shown connected together between the terminals, A and A'. In each case except that of Fig. 4 the two groups thus connected are exactly similar. Each group of coils is in turn made up of two similar groups of coil-sides or phase *belts*. In Fig. 1 one of these belts comprises the two coil-sides in the tops of slots No. 1 and No. 2, and the other includes the two coil-sides in the bottoms of slots No. 7 and No. 8. These two belts make up one of the similar coil-groups above referred to, the electromotive force of which has the same shape as that of the whole phase. In Fig. 1 the two belts in question are displaced by six slots or 180 degrees (electrical), and as they are connected in circuit opposition their electromotive forces are exactly in phase. Thus the electromotive force of one of these belts is a sample of the whole phase electromotive force.

In Fig. 2, however, the second belt (in the bottom of slots No. 4 and No. 5) is displaced from the first by only three slots, or 90 degrees, and the two belt electromotive forces differ in phase by 180 degrees — 90 degrees = 90 degrees, which is the pitch deficiency of the coils, measured in electrical degrees. In this case the electromotive force of the coil-group has the same shape as that of the whole phase-circuit, but in general not the same shape as that of a single belt.

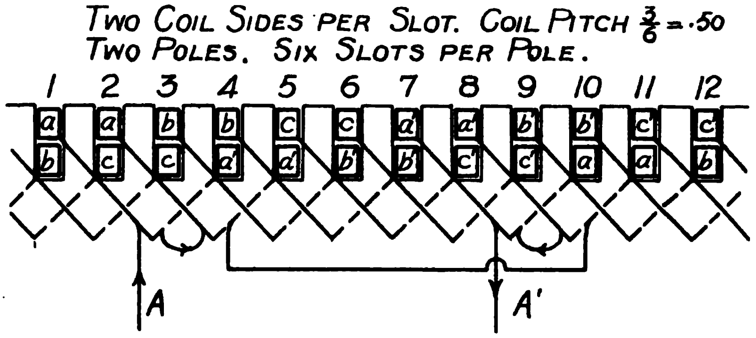

Fig. 2

In Fig. 3 the belt, which in Fig. 2 is distributed in the tops of slots No. 1 and No. 2, is all in slot No. 1. Had there been four slots per pole per phase, this belt would have been distributed in the tops of slots numbers 1, 2, 3 and 4 in the type of Fig. 2, but in the type of Figure 3 would be found concentrated in slots No. 1 and No. 3. There would be a similar change in the distribution of the other belts.

In Fig. 4 the two adjacent coil groups in a given phase are not similar since they contain different numbers of coils, and it takes both of these groups as connected between A and A' to make a sample unit as far as the electromotive force wave-shape is concerned. It will be observed in this connection that the phase of the electromotive force of the coil 11–16 is half way between that of coil 1-6 and that of coil 3-8. Thus the shape of the electromotive force wave is exactly the same as that of a two-layer winding with the same number (3) of slots per pole per phase. This relation obviously holds for the one-layer winding whenever the number of slots per pole per phase is odd.

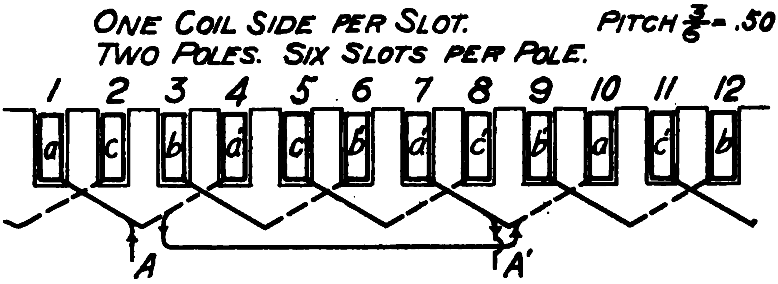

FIG. 3

DIFFERENTIAL FACTOR

In the vector additions of the fundamentals or of the *m*th harmonics of several slot electromotive forces, the vector sum will in general be less than the numerical sum, and the ratio of the former to the latter will be called the *differential-factor*. This name is employed since the real cause of the reduction from numerical to vector sum is the distribution of

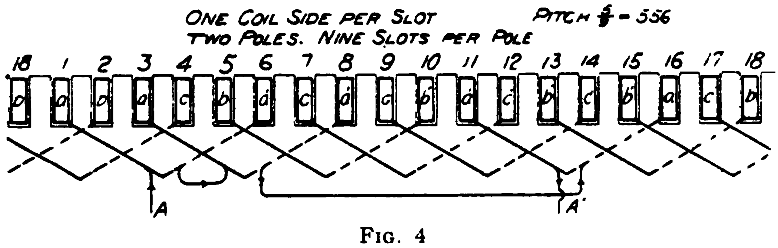

FIG. 4

the winding and the resulting *differential* cutting of flux by the conductors in the several slots of a given phase belt; that is, there are times when some of these slots are cutting positive flux while others in the same belt are cutting negative flux. This differential action is not considerable when the phase belt is narrow as compared with the half wave of flux distribution. For example, in an ordinary three-phase alternator with a belt

60 degrees wide the differential factor for the fundamental flux wave is about 0.96, depending somewhat upon the number of slots per pole; but when this 60-degree belt is considered as cutting the third harmonic flux distribution, the half wave of which spans only 60 degrees, it is obvious that the differential action is much greater. As the belt becomes relatively broader with respect to the length of the harmonic flux wave, the differential action increases and the differential factor decreases until the belt span equals the pitch of the harmonic flux wave. Beyond this point the differential factor becomes negative, again passes through zero and so on as the belt span passes through multiple values of the length of the harmonic flux wave, (see Fig. 7). For example the 120-degree belt of a three-phase converter, or the two adjacent 60-degree belts connected in series between the terminals of a star-connected alternator, would span 360 degrees of the third harmonic flux wave, 3×360 degrees of the ninth, 5×360 degrees of the fifteenth, and so on, the differential factor being zero in each case. That is, these harmonics disappear. Thus although the differential action reduces the fundamental electromotive force, it reduces most of the harmonics to a much greater extent, and tends to make the belt electromotive force more nearly sinusoidal than the slot electromotive force or flux distribution curve.

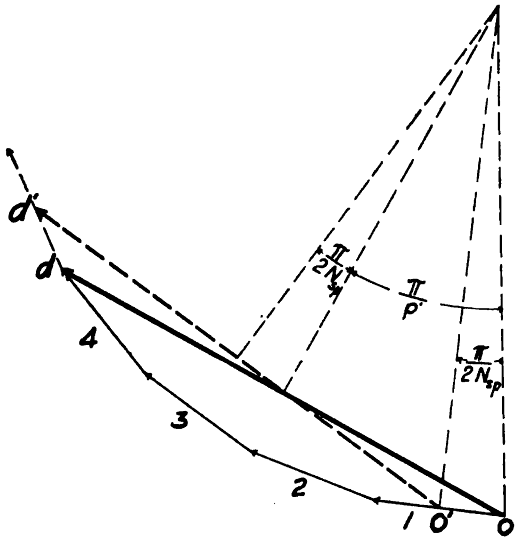

FIG. 5

The effect of a fractional pitch winding is to introduce still further differential action between the two belts which go to make up one coil group, the amount of which depends upon the coil pitch and the harmonic in question.

Belt Differential Factor. Consider first the differential action within a single belt for the case of a two-layer winding. Figs. 5 and 6 show the vector relations of the fundamentals, and the third and the fifth harmonics for a three-phase machine with 12 slots per pole.

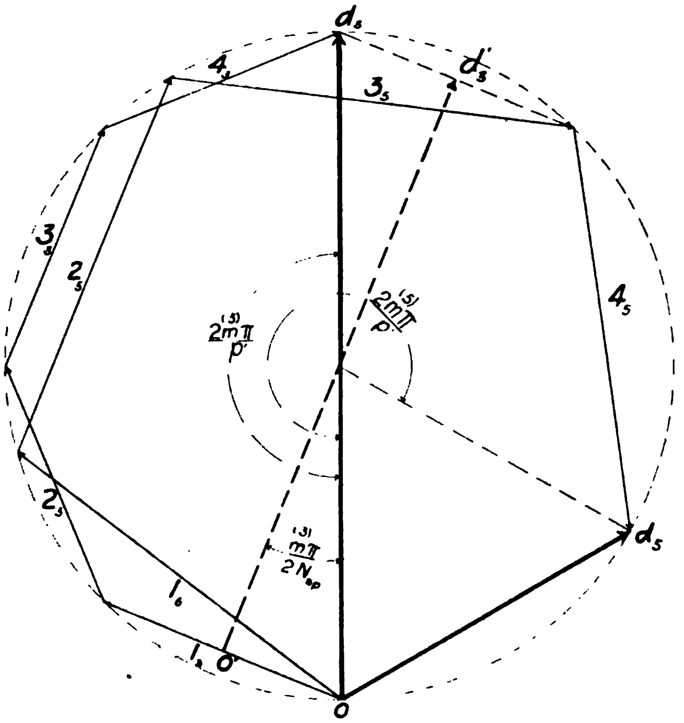

FIG. 6

In Fig. 5, the vectors 1, 2, 3 and 4 represent the four fundamental slot electromotive forces of one phase belt and $\overline{o\,d}$ their resultant. In Fig. 6 the vectors 1_3, 2_3, 3_3 and 4_3 represent the four third harmonic slot electromotive forces of one phase belt and $o\ d_3$ their resultant. Similarly 1_5, 2_5, 3_5 and 4_5 represent the corresponding fifth harmonic slot electromotive forces and $o\ d_5$ their resultant.

Let N_{sp} = slots per pole, and

p' = the number of belt spans per pair of poles, ($p' = 6$ for ordinary three phase).

Then $\frac{\pi}{N_{sp}}$ = the phase difference between the fundamental electromotive forces of two adjacent slots, $\frac{m\pi}{N_{sp}}$ = the phase difference (in *m*th harmonic radians) between the *m*th harmonic electromotive forces of two adjacent slots, $\frac{2N_{sp}}{p'}$ = slots per belt, and $\frac{2m\pi}{p'}$ = the total belt span in *m*th harmonic radians.

TABLE I

BELT DIFFERENTIAL FACTOR

N_{sp}	One coil side per slot	6	12	18	24	30	36	42	48
	Two coil sides per slot	3	6	9	12	15	18	21	24
	$m = 1$	1.00	+0.966	+0.960	+0.958	+0.957	+0.956	+0.956	+0.956
	$m = 3$	1.00	+0.707	+0.667	+0.653	+0.647	+0.644	+0.642	+0.641
	$m = 5$	1.00	+0.259	+0.218	+0.205	+0.200	+0.197	+0.196	+0.194
	$m = 7$	1.00	−0.259	−0.177	−0.157	−0.149	−0.145	−0.143	−0.141
	$m = 9$	1.00	−0.707	−0.333	−0.270	−0.248	−0.236	−0.229	−0.225
	$m = 11$	1.00	−0.966	−0.177	−0.128	−0.109	−0.102	−0.097	−0.095
	$m = 13$	1.00	−0.966	+0.218	+0.128	+0.102	+0.091	+0.086	+0.083
	$m = 15$	1.00	−0.707	+0.667	+0.270	+0.200	+0.173	+0.159	+0.149
	$m = 17$	1.00	−0.259	+0.960	+0.157	+0.102	+0.084	+0.075	+0.070
	$m = 19$	1.00	+0.259	+0.960	−0.205	−0.109	−0.084	−0.072	−0.066
	$m = 21$	1.00	+0.707	+0.667	−0.653	−0.248	−0.173	−0.147	−0.127
	$m = 23$	1.00	+0.966	+0.218	−0.958	−0.149	−0.091	−0.072	−0.063
	$m = 25$	1.00	+0.966	−0.177	−0.958	+0.200	+0.102	+0.075	+0.063
	$m = 27$	1.00	+0.707	−0.333	−0.653	+0.647	+0.236	+0.159	+0.127

If the diagram (Fig. 6) be reduced to unit radius, the resultant of the $\frac{2N_{sp}}{p'}$ *m*th harmonics will be $2 \sin \frac{m\pi}{p'}$. On the same basis the *m*th harmonic of the slot electromotive force is

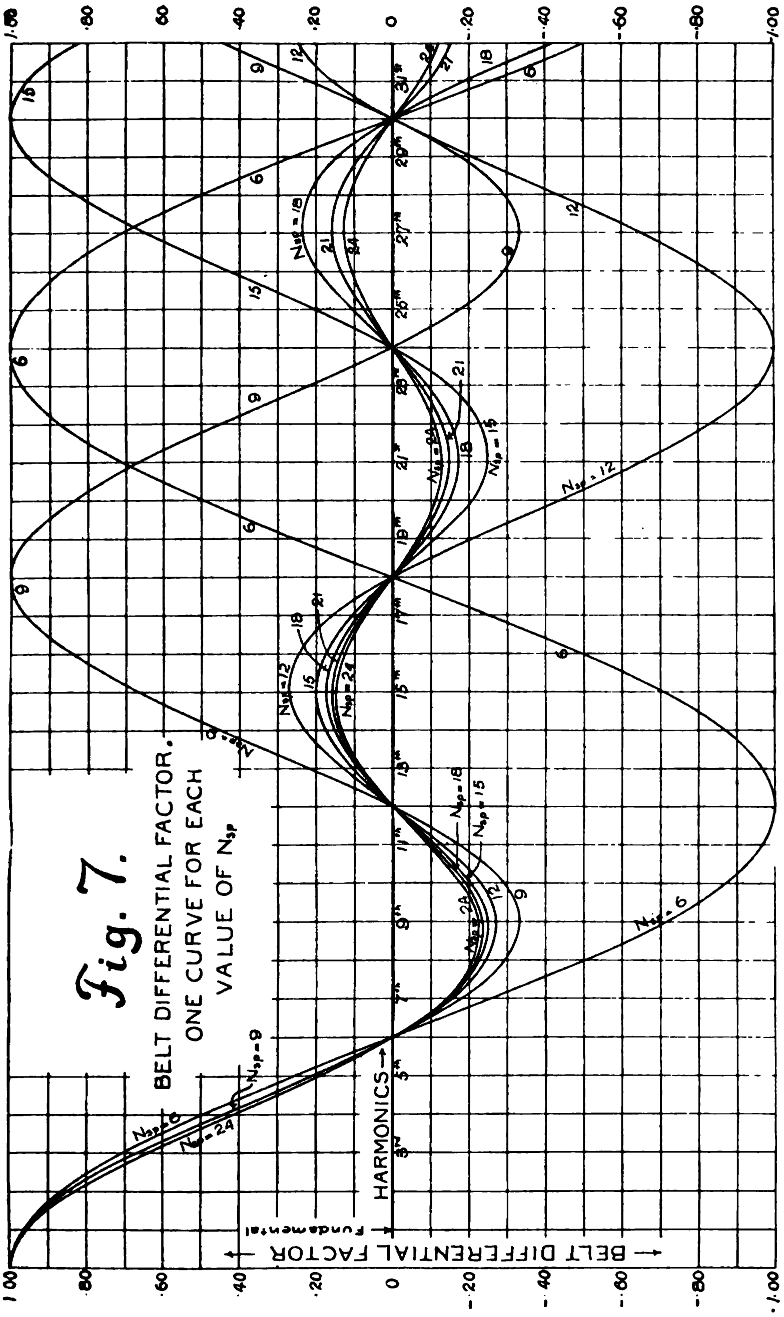

Fig. 7. BELT DIFFERENTIAL FACTOR, ONE CURVE FOR EACH VALUE OF N_{sp}

$2 \sin \frac{m \pi}{2 N_{sp}}$, and the arithmetical sum of the $\frac{2 N_{sp}}{p'}$ mth harmonics is $\frac{2 N_{sp}}{p'} \times 2 \sin \frac{m \pi}{2 N_{sp}}$.

Thus the belt differential factor for the mth harmonic of the belt electromotive force is:

$$k_{dm} = \frac{p'}{2 N_{sp}} \quad \frac{\sin \frac{m \pi}{p'}}{\sin \frac{m \pi}{2 N_{sp}}}$$

and that for the fundamental

$$k_{d_1} = \frac{p'}{2 N_{sp}} \quad \frac{\sin \frac{\pi}{p'}}{\sin \frac{\pi}{2 N_{sp}}}$$

Values of k_{dm} for a three-phase two-layer winding, for various values of N_{sp} and of m, are given in Table I, and are shown graphically in the curves of Fig. 7.

In the case of a one-layer winding (one coil-side per slot) and an even number of slots per pole, the belt differential-factor will obviously be the same as for a two-layer winding with half as many slots per pole, (see Fig. 3). But when the number of slots per pole is odd, (see Fig. 4), the two types of winding are exactly equivalent in this respect and have the same belt differential-factor.

The belt reduction-factor which is the ratio of k_{dm} to k_{d_1}, differs so little from k_{dm} in most cases that it is not given. It can be readily computed from the table.

Fractional pitch differential-factor. If a fractional pitch or chorded winding be employed, the two belt electromotive forces, though of the same shape and magnitude, will differ in phase by an amount depending upon the pitch deficiency, and their resultant will not have the same shape unless they are sinusoidal.

Let λ_c designate the coil pitch in terms of full pitch. Then $1 - \lambda_c$ is the pitch deficiency, and $(1 - \lambda_c) \pi_m$ is the phase difference between the mth harmonic electromotive forces of the two belts, in Fig. 8, where $O A$ and $\overline{A B}$ are the two equal mth harmonic electromotive forces and $\overline{O B}$ their resultant. The pitch differential-factor for the *m*th harmonic electromotive force is then:

$$k_{pdm} = \overline{OB} \div 2\,\overline{OA} = \cos \frac{m\pi}{2}(1-\lambda_c)$$

and that for the fundamental is,

$$k_{pd_1} = \cos \frac{\pi}{2}(1-\lambda_c)$$

Values of k_{pdm} for all values of the pitch above 50% are plotted in Fig. 9. *The pitch reduction factor* k_{pm}, which is the ratio of k_{pdm} to k_{pd_1} shows the degree in which the distortion or per cent harmonic is reduced by chording. It is shown in the broken curve of Fig. 9 for the eleventh harmonic only.

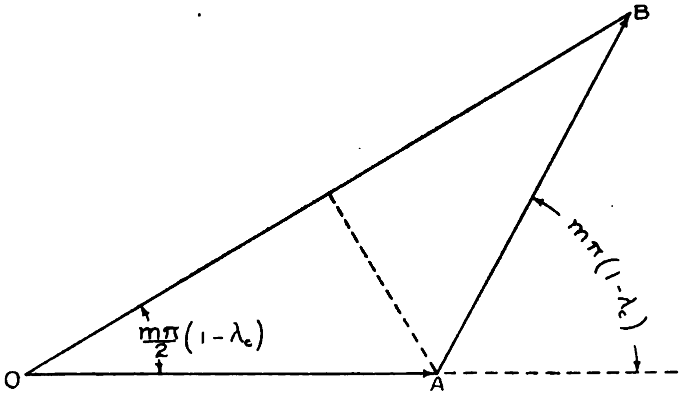

FIG. 8

It will be seen from Fig. 9 that any considerable change of pitch will usually reverse some of the harmonics, and that it is possible practically to eliminate any desired harmonic, or greatly to reduce several of the more important ones, by a proper choice of pitch. For example, a pitch of 0.833 (five slots in 6, 10 in 12, 15 in 18 or 20 in 24) would reduce the fifth, seventh, seventeenth and nineteenth to about one quarter of their full pitch values; then by connecting the phases in star, (which is equivalent to a pitch of 0.667), the third, ninth, fifteenth, twenty-first, etc., may be entirely eliminated. This would leave only the eleventh and thirteenth, which would ordinarily be reduced by the belt differential action to less than 10 per cent of their value in the flux distribution curve, see Table I and Fig. 7.

Mid-coil differential factor. If the phase winding begin and end in the center of a coil rather than at the junction of two coils, there will be two half-coil vectors, as shown in Fig. 5, where $\overline{o'\,d'}$ is drawn from the middle of No. 1 electromotive force to the middle of No. 5 electromotive force, and in Fig. 6 where $\overline{o_3'\,d_3'}$ is drawn from the middle of 1_3 to that of 5_3. The resultant is thus reduced in the ratio.

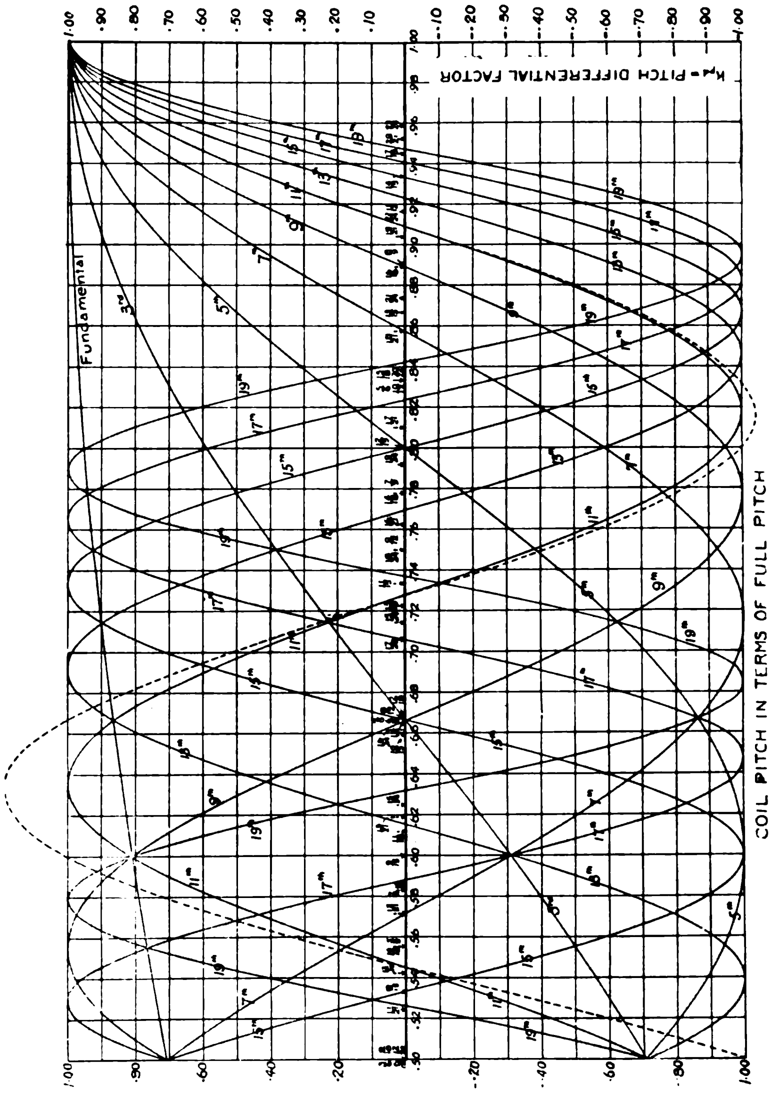

FIG. 9

$$k_{dcm} = \cos \frac{m\,\pi}{2\,N_{sp}}$$

which is the *mid-coil differential factor* for the *m*th harmonic.

For the fundamental this is

$$k_{dc_1} = \cos \frac{\pi}{2\,N_{sp}}$$

and the *mid-coil reduction factor* for the *m*th harmonic is

$$k_{cm} = \frac{k_{dcm}}{k_{dc_1}} = \cos \frac{m\,\pi}{2\,N_{sp}} \div \cos \frac{\pi}{2\,N_{sp}}$$

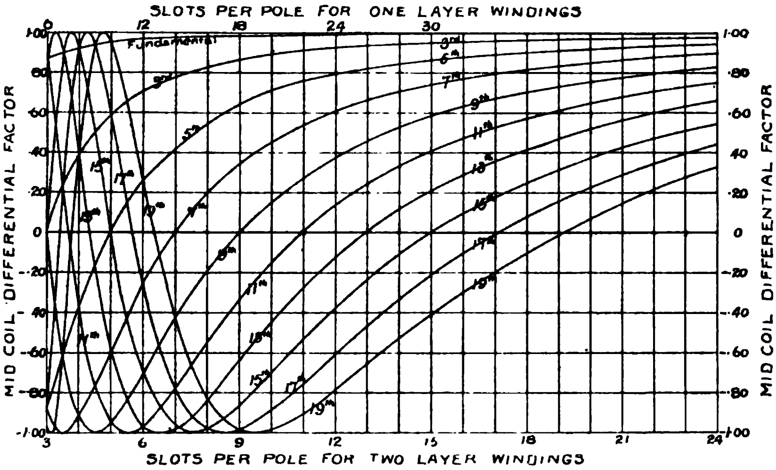

FIG. 10

Since k_{cm} is so nearly equal to k_{dcm}, the latter only is given in the curves of Fig. 10. The values given in Fig. 10 apply strictly only to the two-layer winding, but it has already been shown that in the case of an even number of slots per pole, the one-layer winding is equivalent to a two-layer winding with half as many slots per pole, and that in the case of an odd number of slots per pole, the one-layer winding is wholly equivalent to the two-layer winding.

With ordinary values of N_{sp} some of the higher harmonics are practically eliminated, and others are considerably reduced by the mid-coil connection.

Summary

There are thus several differential actions combining to reduce the electromotive force induced in the armature of an alternator, but they affect the fundamental and the various harmonics in different degrees, the amount of reduction of the fundamental being in general very small as compared with that of the harmonics. These differential actions may be classified as follows:

Belt differential action, between the several slots of each phase belt;

Pitch differential action, between the two belts of each coil group;

Mid-coil differential action, due to the mid-coil connection and the consequent equivalent widening of each belt;

Phase differential action, between two phases connected in series, as with three-phase star connection. This last may be looked upon either as a widening of the phase belt to 120 degrees in place of 60 degrees, or as equivalent to a fractional pitch of two-thirds; it reduces the fundamental and all the harmonics except the multiples of three in the same degree, (0.866), so that their reduction factors are unity. The multiples of three are reduced to zero, see Fig. 9.

By a proper combination of these various differential actions it is possible to reduce all the harmonics of an alternator electromotive force to very low values without seriously reducing the fundamental, even when the flux distribution is far from sinusoidal. For example, a star-connected three-phase alternator, with 12 slots per pole, a coil pitch of 10 in 12, and mid-coil connections, will have per cent harmonics in its electromotive force wave which bear to the per cent harmonics of the flux distribution curve the following ratios, labelled k_r, the *total reduction factor*.

$m =$	3	5	7	9	11	13	15	17	19	21
$k_r =$	0.0	0.045	0.023	0.	0.017	0.017	0.0	0.027	0.045	0.0

In this case the least reduction is to less than 5 per cent of the per cent value in the flux distribution curve, and if the largest harmonics in the flux distribution curve were not more than 10 per cent, the largest harmonics in the electromotive force wave would be less than one half of one per cent. But by a proper

TABLE II
TOTAL REDUCTION FACTOR FULL-COIL CONNECTION

		3rd	5th	7th	9th	11th	13th	15th	17th	19th
$N_{sp} = 6$	$\lambda_c = \frac{6}{6}$	+0.732	+0.268	−0.268	−0.732	−1.000	−1.000	−0.732	−0.268	+0.268
	$\lambda_c = \frac{5}{6}$	+0.536	+0.072	+0.072	+0.536	+1.000	+1.000	+0.536	+0.072	+0.072
	$\lambda_c = \frac{4}{6}$	0.000	−0.268	+0.268	0.000	−1.000	−1.000	0.000	+0.268	−0.268
$N_{sp} = 9$	$\lambda_c = \frac{9}{9}$	+0.695	+0.227	−0.185	−0.347	−0.185	+0.227	+0.695	+1.000	+1.000
	$\lambda_c = \frac{8}{9}$	+0.611	+0.148	−0.064	0.000	+0.064	−0.148	−0.611	−1.000	−1.000
	$\lambda_c = \frac{7}{9}$	+0.370	−0.042	+0.151	+0.415	+0.151	−0.042	+0.370	+1.000	+1.000
	$\lambda_c = \frac{6}{9}$	0.000	−0.227	+0.185	0.000	−0.185	+0.227	0.000	−1.000	−1.000
$N_{sp} = 12$	$\lambda_c = \frac{12}{12}$	+0.682	+0.214	−0.165	−0.283	−0.132	+0.132	+0.283	+0.165	−0.214
	$\lambda_c = \frac{11}{12}$	+0.636	+0.172	−0.101	−0.109	−0.017	−0.017	−0.109	−0.101	+0.172
	$\lambda_c = \frac{10}{12}$	+0.499	+0.058	+0.044	+0.207	+0.132	−0.132	−0.207	−0.044	−0.058
	$\lambda_c = \frac{9}{12}$	+0.283	−0.089	+0.165	+0.283	+0.055	+0.055	+0.283	+0.165	−0.089
	$\lambda_c = \frac{8}{12}$	0.000	−0.214	+0.165	0.000	−0.132	+0.132	0.000	−0.165	+0.214
$N_{sp} = 15$	$\lambda_c = \frac{15}{15}$	+0.677	+0.209	−0.156	−0.258	−0.114	+0.107	+0.209	+0.107	−0.114
	$\lambda_c = \frac{14}{15}$	+0.647	+0.182	−0.117	−0.153	−0.047	+0.022	0.000	−0.022	+0.047
	$\lambda_c = \frac{13}{15}$	+0.560	+0.107	−0.017	+0.082	+0.078	−0.998	−0.214	−0.998	+0.078
	$\lambda_c = \frac{12}{15}$	+0.418	0.000	+0.097	+0.258	+0.114	−0.066	0.000	+0.066	−0.114
	$\lambda_c = \frac{11}{15}$	+0.229	−0.114	+0.167	+0.229	+0.013	+0.078	+0.229	+0.078	+0.013
	$\lambda_c = \frac{10}{15}$	0.000	−0.209	+0.156	0.000	−0.114	+0.107	0.000	−0.107	+0.114
$N_{sp} = 18$	$\lambda_c = \frac{18}{18}$	+0.674	+0.206	−0.152	−0.247	−0.106	+0.096	+0.131	+0.088	−0.088
	$\lambda_c = \frac{17}{18}$	+0.653	+0.188	−0.125	−0.175	−0.061	+0.041	+0.047	+0.008	+0.008
	$\lambda_c = \frac{16}{18}$	+0.592	+0.135	−0.053	+0.000	+0.037	−0.063	−0.159	−0.088	+0.088
	$\lambda_c = \frac{15}{18}$	+0.493	+0.055	+0.041	+0.181	+0.106	−0.096	−0.132	−0.240	−0.240
	$\lambda_c = \frac{14}{18}$	+0.358	−0.038	+0.124	+0.294	+0.087	−0.018	+0.096	+0.088	−0.088
	$\lambda_c = \frac{13}{18}$	+0.192	−0.131	+0.167	+0.192	−0.010	+0.087	+0.052	+0.041	+0.041
	$\lambda_c = \frac{12}{18}$	0.000	−0.206	+0.152	0.000	−0.106	+0.096	0.000	−0.088	+0.088

TABLE III
TOTAL REDUCTION FACTOR MID-COIL CONNECTION

		3rd	5th	7th	9th	11th	13th	15th	17th	19th
$N_{sp} = 6$	$\lambda_c = \frac{6}{6}$	+0.536	+0.071	+0.071	+0.536	+1.000	+1.000	+0.536	+0.071	+0.071
	$\lambda_c = \frac{5}{6}$	+0.392	+0.020	-0.020	-0.392	-1.000	-1.000	-0.392	-0.020	+0.020
	$\lambda_c = \frac{4}{6}$	0.000	-0.071	-0.071	0.000	+1.000	+1.000	0.000	-0.071	-0.071
$N_{sp} = 9$	$\lambda_c = \frac{9}{9}$	+0.611	+0.148	-0.064	0.000	+0.064	-0.148	-0.611	-1.000	-1.000
	$\lambda_c = \frac{8}{9}$	+0.536	+0.096	-0.022	0.000	-0.022	+0.096	+0.536	+1.000	+1.000
	$\lambda_c = \frac{7}{9}$	+0.325	-0.027	+0.052	0.000	-0.052	+0.027	-0.325	-1.000	-1.000
	$\lambda_c = \frac{6}{9}$	0.000	-0.148	+0.064	0.000	+0.064	-0.148	0.000	+1.000	+1.000
$N_{sp} = 12$	$\lambda_c = \frac{12}{12}$	+0.636	+0.172	-0.101	-0.109	-0.017	-0.017	-0.109	-0.101	+0.172
	$\lambda_c = \frac{11}{12}$	+0.592	+0.137	-0.063	-0.042	-0.002	+0.002	+0.042	+0.063	-0.138
	$\lambda_c = \frac{10}{12}$	+0.263	+0.072	+0.101	+0.109	+0.007	+0.007	+0.109	+0.101	+0.072
	$\lambda_c = \frac{9}{12}$	+0.465	-0.046	+0.027	+0.080	+0.017	-0.017	-0.080	-0.027	+0.046
	$\lambda_c = \frac{8}{12}$	0.000	-0.172	+0.101	0.000	-0.017	-0.017	0.000	+0.101	-0.172
$N_{sp} = 15$	$\lambda_c = \frac{15}{15}$	+0.646	+0.182	-0.117	-0.153	-0.047	+0.022	0.000	-0.022	+0.047
	$\lambda_c = \frac{14}{15}$	+0.618	+0.159	-0.087	-0.090	-0.019	+0.005	0.000	+0.005	-0.019
	$\lambda_c = \frac{13}{15}$	+0.535	+0.093	-0.012	+0.048	+0.032	-0.021	0.000	+0.021	-0.032
	$\lambda_c = \frac{12}{15}$	+0.400	0.000	+0.072	+0.153	+0.047	-0.014	0.000	-0.014	+0.047
	$\lambda_c = \frac{11}{15}$	+0.219	-0.099	+0.125	+0.136	+0.005	+0.016	0.000	-0.016	-0.005
	$\lambda_c = \frac{10}{15}$	0.000	-0.181	+0.116	0.000	-0.047	+0.022	0.000	+0.022	-0.047
$N_{sp} = 18$	$\lambda_c = \frac{18}{18}$	+0.653	+0.188	-0.125	-0.175	-0.061	+0.040	+0.047	+0.008	+0.008
	$\lambda_c = \frac{17}{18}$	+0.634	+0.171	-0.102	-0.124	-0.035	+0.017	+0.012	+0.000	-0.000
	$\lambda_c = \frac{16}{18}$	+0.574	+0.122	-0.043	+0.000	+0.021	-0.027	-0.041	-0.008	-0.008
	$\lambda_c = \frac{15}{18}$	+0.478	+0.050	+0.033	+0.128	+0.061	-0.041	-0.034	-0.002	+0.002
	$\lambda_c = \frac{14}{18}$	+0.348	-0.034	+0.101	+0.209	+0.049	-0.007	+0.025	+0.008	+0.008
	$\lambda_c = \frac{13}{18}$	+0.187	-0.118	+0.138	+0.137	-0.006	+0.037	+0.013	+0.004	-0.004
	$\lambda_c = \frac{12}{18}$	0.000	-0.188	+0.124	0.000	-0.061	+0.041	0.000	-0.008	-0.008

choice of pole arc it is easy to reduce the fifth harmonic of the flux distribution curve to 5 per cent and since the nineteenth would never be as large as this, the maximum harmonic in the electromotive force wave would in this case be about two tenths of one per cent of the fundamental.

Tables II and III contain values of the *total reduction factor* k_r for a considerable range of values of N_{sp}, m and λ_c. The tables as they stand apply directly to the two-layer winding only, but it will be remembered that a one-layer winding with an odd number of slots per pole per phase is entirely equivalent to a two-layer winding with the same number of slots, and that a one-layer winding with an even number of slots per pole per phase is equivalent (for the present purpose) to a two-layer winding with half as many slots.

EXAMPLES

The curves of Mr. Bache-Wiig's Atlantic City paper provided such an excellent illustration of the value of the method above outlined that they are reproduced in Figs. 11, 12, 13 and 14.

Curve I of Fig. 11 is an assumed flux distribution curve or "field form" of a two-pole, three-phase, 60-cycle, 400-kw. turbo-alternator with 12 slots per pole. The other 16 curves were computed from the "field form" by the ordinary method for the various windings indicated on the curves.

The eight curves of Figs. 12 and 14 giving the phase voltage, and the flux distribution curve of Fig. 11, have been analyzed for the purposes of this paper. The results are given with the corresponding calculated values in Table IV.

In making comparisons it should be remembered that there were many opportunities for errors in the original computing, plotting, reproducing, transcribing, and analyzing. The method of analysis employed is that of Fischer Hinnen* and while it is very simple, it suffers from the fact that the correction made necessary in any lower harmonic by the presence of a multiple of that harmonic, is of the full magnitude of that multiple. This requires for reasonably accurate results that the analysis be carried to the higher multiples; but the probable error in the determination of these higher multiples is so great that it renders the lower harmonics less accurate than would otherwise be possible. The slice or strip† method in which areas

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* "Electrotechnische Zeitschrift", May 9, 1901; also "Electric Journal", 1908.

† Houston and Kennelly in "Electrical World", 1898.

are used instead of ordinates, is more accurate in this respect when carefully carried out, but the amount of labor involved for accurate results was too great for the task in hand.

After carrying the analysis of all the curves to the nineteenth harmonic, it was surmised that the correction due to still higher harmonics might have a considerable effect. This was found to be true by carrying the analysis of the flux distribution curve to the twenty-seventh harmonic, but time was not available for carrying the analysis of the other curves to the same point, so that some of the minor discrepancies are doubtless due to this omission.

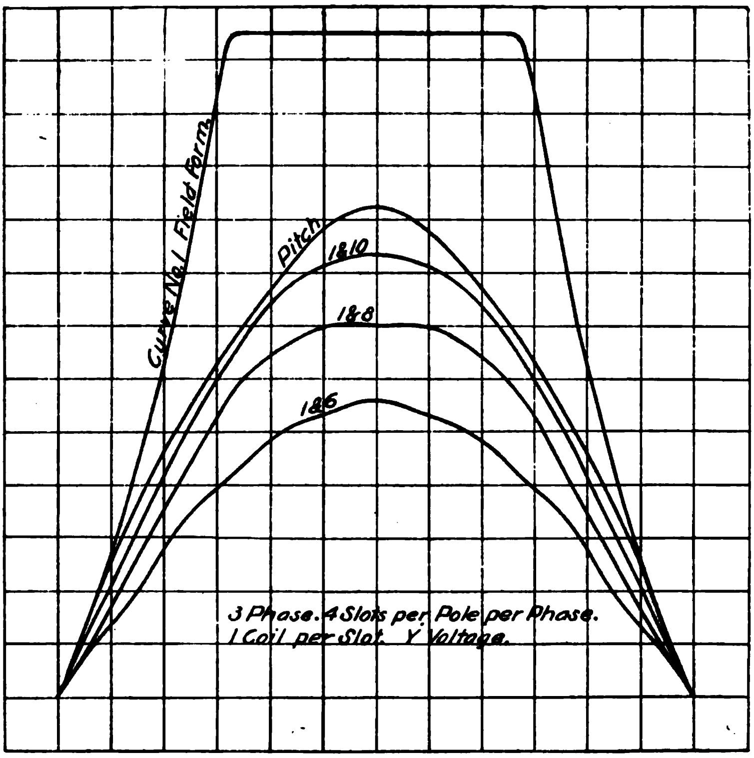


FIG. 11

Referring now to Table IV:

Under "*flux distribution curve*" are given the results of the analysis of that curve, (Fig. 11), the harmonics being given in per cent of the fundamental.

TABLE IV

ANALYSIS AND CALCULATIONS OF BACHE-WIIG'S CURVES

			Pitch curve $\lambda_c = 1$		" 1 & 10 " curve $\lambda_c = \frac{9}{12} = .75$			" 1 & 8 " curve $\lambda_c = \frac{7}{12} = .583$			" 1 & 6 " curve $i_c = \frac{5}{12} = .417$		
	Harmonics	Flux dist. curve	Analyzed from *B-W* pitch curve	Calc. from flux dist.	Anal. from *B-W* " 1 & 10 " curve	Calc. from pitch curve	Calc. from flux dist.	Anal. from *B-W* " 1 & 8 " curve	Calc. from pitch curve	Calc. from flux dist.	Anal. from *B-W* " 1 & 6 " curve	Calc. from pitch curve	Calc. from flux dist.
One-layer winding. One coil-side per slot. Fig. 12	Fundamental	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	3rd Harm.	+2.46	+1.78	+1.80	+0.86	+0.73	+0.74	0.10	-0.86	-0.87	-2.80	-2.70	-2.73
	5th "	-8.80	-1.91	-2.36	+0.94	+0.79	+0.97	+3.66	+2.39	+2.95	+0.43	+0.41	+0.50
	7th "	-1.32	+0.5	+0.35	-0.44	-0.50	-0.35	+1.11	-0.08	-0.06	+0.48	+0.81	+0.57
	9th "	+2.46	-0.6	-1.80	+1.75	+0.60	+1.80	-0.84	-0.70	-2.09	+0.9	+0.38	+1.13
	11th "	+0.09	+0.04	-0.09	+0.04	-0.02	+0.04	+0.78	+0.03	-0.07	0.0	-0.05	+0.12
	13th "	-1.42	+0.06	+1.42	+0.46	+0.02	+0.58	-0.02	-0.04	-1.09	+1.26	+0.08	+1.85
	15th "	-0.03	0.0	+0.02	0.00	0.00	+0.02	+0.02	0.0	-0.02	0.0	0.0	+0.01
	17th "	+0.81	+0.06	-0.22	0.0	+0.06	-0.22	0.0	+0.01	-0.03	-0.11	-0.10	+0.36
	19th "	-0.02	-0.05	0.0	+0.05	-0.02	-0.00	0.0	-0.06	-0.00	0.0	-0.01	0.0
Two-layer winding. Two coil-sides per slot. Fig. 14.	Fundamental	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	3 d Harm.	+2.46	+1.44	+1.66	+0.96	+0.59	+0.68	-0.41	-0.69	-0.80	-2.47	-2.18	-2.51
	5th "	-8.80	-1.88	-1.89	+0.29	+0.78	+0.78	+1.88	+2.35	+2.36	—	+0.40	+0.41
	7th "	-1.32	+0.22	+0.22	-0.35	-0.22	-0.22	+0.17	-0.04	-0.04	+0.54	+0.36	+0.36
	9th "	+2.46	-0.36	-0.69	+0.62	+0.36	+0.69	—	-0.42	-0.80	+1.07	+0.23	+0.44
	11th "	+0.09	-0.23	-0.01	-0.35	+0.09	—	—	-0.18	-0.01	—	+0.30	+0.01
	13th "	-1.42	-0.12	-0.20	-0.15	-0.05	-0.08	+0.12	+0.09	+0.15	-0.14	-0.16	-0.26
	15th "	-0.03	-0.12	-0.01	-0.2	-0.12	-0.01	-0.16	+0.14	+0.01	-0.24	-0.08	-0.01
	17th "	+0.81	-0.06	+0.13	-0.2	-0.06	+0.13	—	-0.01	+0.02	—	+0.10	-0.21
	19 "	-0.02	-0.04	0.00	—	-0.02	—	—	-0.05	—	—	-0.01	—

Under " *pitch curve* " are compared the analyzed harmonics of the full pitch curve with those obtained by calculation from the harmonics of the flux distribution curve by means of Table I.

Under " 1 *and* 10 *curve* " are compared the analyzed harmonics of the " 1 and 10 " curve with those obtained by calculation from both the pitch curve and the flux distribution curve.

The same explanation applies to the other fractional pitch curves.

Referring to the two columns under " pitch curve " in Table IV there are only two out of the eighteen comparisons where the computed harmonic differs by more than a reasonable error from that obtained by direct analysis.

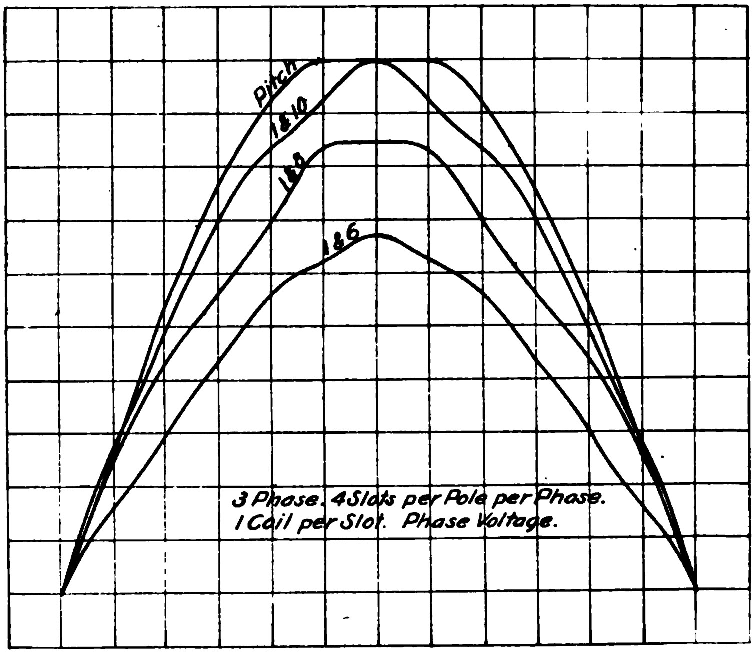


FIG. 12

Referring to the remainder of the table relating to the fractional pitch curves, the results calculated from the flux distribution curve are on the average closer to those obtained by direct analysis than those computed from the pitch curve, showing that some of the above-mentioned discrepancies under " Pitch Curve " were in the pitch curve itself or in its analysis, rather than in the flux distribution curve or in its analysis. This is reasonable since the flux curve harmonics, being larger, are determinable with a smaller percentage error.

The only considerable discrepancies in the fractional pitch results are those for the " 1 and 8 " curve and the one-layer winding, and it is altogether likely that there was some slip in the original computation or plotting of this curve, since the results for the same pitch in the two-layer winding, computed from the same flux harmonics, are much closer.

Referring again to Fig. 12 it is interesting to note the reversal of the harmonics in passing from one pitch to another as indicated by the curves of Fig. 9.

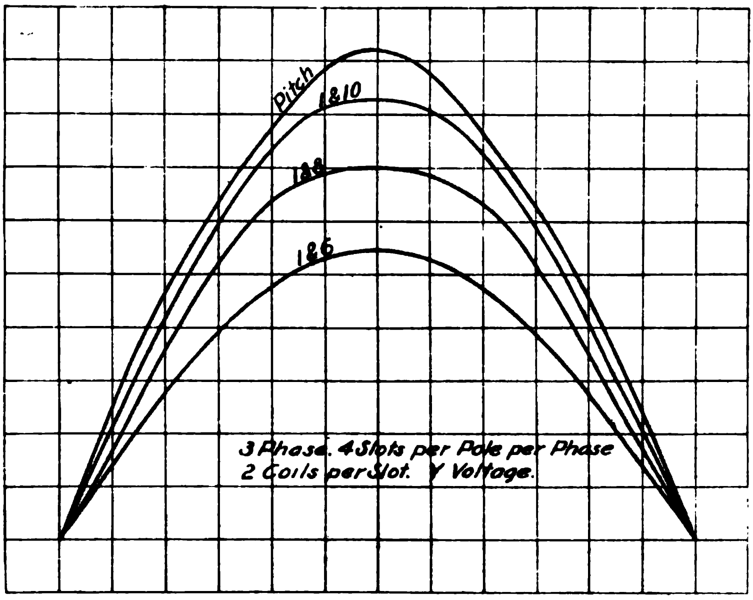


FIG. 13

Thus all the results shown in the curves of Figs. 11, 12, 13, and 14 can be obtained in a much more useful form and with greater accuracy than by the ordinary method and with the expenditure of a small fraction of the time.

As another example, Fig. 15 shows an observed flux distribution curve for a two-pole, 300-kw. turbo-alternator.

Table V gives the harmonic analysis of this curve together with the harmonics of the phase electromotive forces for all possible pitches down to 50 per cent (assuming $N_{sp} = 12$), from which it appears that with star connection to wipe out the third, ninth, and fifteenth harmonics, no one of these windings would give an electromotive force with any single harmonic larger than one per cent of the fundamental. This is not at all an extreme case since the pole arc is normal, being about 65 per cent of the pole pitch.

By employing the two-layer winding, star connection, and a pitch of ten slots or 83.3 per cent, the harmonics would assume the following values, in per cent of the fundamental, the largest being less than two tenths of one per cent, and the others less than five hundredths of one per cent.

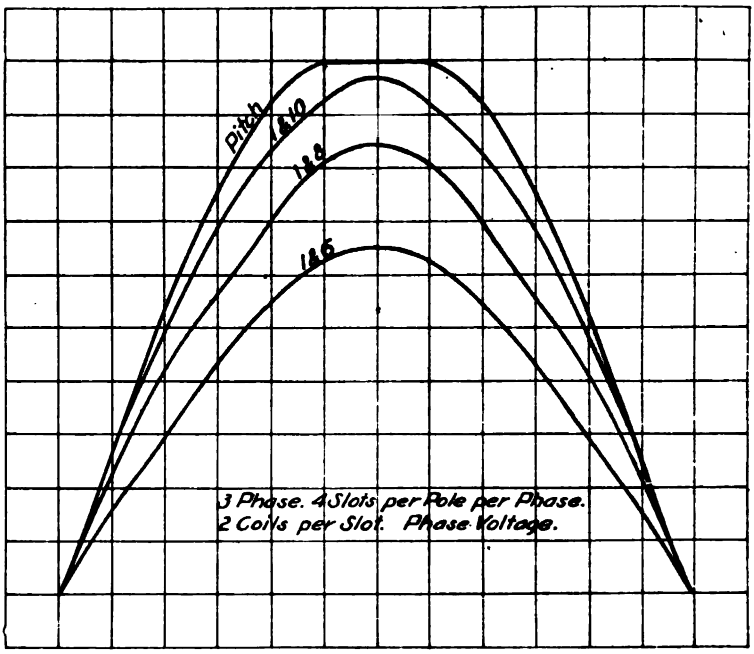


FIG. 14

m =	1	3	5	7	9	11	13	15	17	19
% =	100.0	0.0	0.043	0.003	0.0	0.15	0.0	0.0	0.0	0.002

Conclusion. It is fully realized that there are several considerations beside that of wave-shape which affect the choice of winding type in an alternator, but there are certainly some

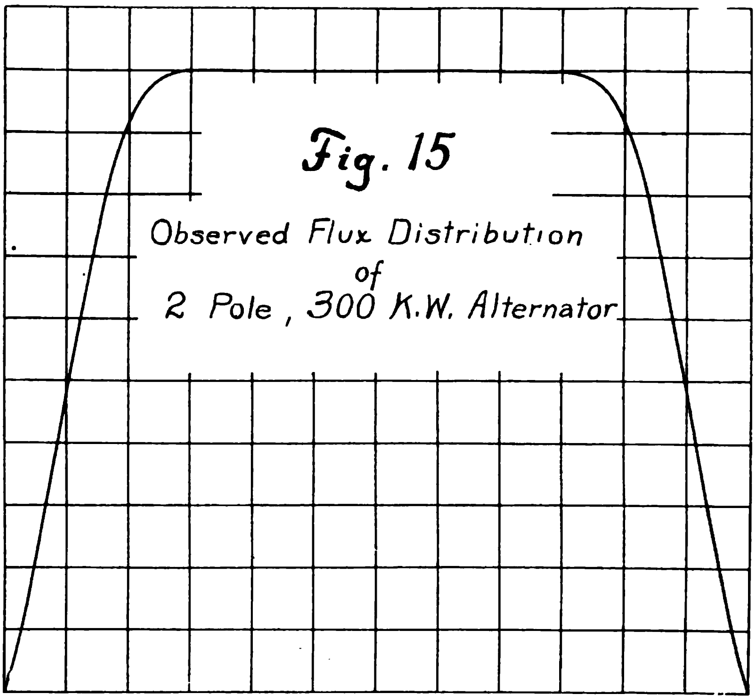
TABLE V

	Harmonics	Flux distribution curve	Pitch curve $\lambda_c = 1$	" 1 & 10 " curve $\lambda_c = \frac{9}{12} = 0.75$	" 1 & 8 " curve $\lambda_c = \frac{7}{12} = 0.583$	" 1 & 6 " curve $\lambda_c = \frac{5}{12} = 0.417$
One-layer winding. One coil side per slot.	Fundamental	100%	100%	100%	100%	100%
	3rd Harm.	20.6	15.1	6.21	-7.27	-22.8
	5th "	2.83	0.76	-0.31	-0.95	-0.16
	7th "	-0.30	0.08	-0.08	-0.013	0.13
	9th "	-1.90	1.39	-1.39	+1.62	0.87
	11th "	-0.80	.80	-0.33	+0.61	1.04
	13th "	0	0	0	0	0
	15th "	0	0	0	0	0
	17th "	0	0	0	0	0
	19th "	-0.12	-0.032	-0.013	-0.04	+0.007

	Harmonics	Flux distribution curve	Pitch curve $\lambda_c = 1$	" 1 & 12 " curve $\lambda_c = .916$	" 1 & 11 " curve $\lambda_c = 0.833$	" 1 & 10 " curve $\lambda_c = 0.75$	" 1 & 9 " curve $\lambda_c = 0.667$	" 1 & 8 " curve $\lambda_c = 0.583$	" 1 & 7 " curve $\lambda_c = 0.50$
Two-layer winding Two coil sides per slot.	Fundamental	100%	100%	100%	100%	100%	100%	100%	100%
	3rd Harm.	20.6	14.05	13.1	10.5	5.79	0	-6.77	-14.05
	5th "	2.83	0.61	0.49	0.16	-0.25	-0.61	-0.76	-0.61
	7th "	-0.30	0.05	0.03	-0.013	-0.05	-0.05	-0.01	+0.05
	9th "	-1.90	0.54	0.21	-0.39	-0.54	0	+0.62	+0.54
	11th "	-0.80	0.152	0.02	-0.15	-0.06	+0.15	+0.12	-0.15
	13th "	0	0	0	0	0	0	0	0
	15th "	0	0	0	0	0	0	0	0
	17th "	0	0	0	0	0	0	0	0
	19th "	-0.12	0.026	-0.022	+0.007	+0.01	-0.026	+0.012	-0.026

instances where an accurate knowledge of the relation of winding type to wave-shape would materially influence the choice of the former much to the advantage of the latter. Also, even when certain harmonics are practically absent from the flux distribution curve at no load, they may be present under full-load distortion, so that the choice of a winding with low reduction factors (see Tables II and III) is in general desirable, other things being equal.

Finally the knowledge as to which harmonics can be practically eliminated by a possible choice of winding makes it possible to choose the pole arc, or shape the pole face, so as to eliminate the principal remaining harmonics. A good example of this is given above, and illustrated in Fig. 15.



The writer wishes to take this opportunity of thanking Mr. Bache-Wiig for the use of the curves of Figures 11, 12, 13, 14 and 15, and Mr. Julian Tynz for his careful analysis of these curves.

DISCUSSION ON "ELECTROMOTIVE FORCE WAVE-SHAPE IN ALTERNATORS." FRONTENAC, N. Y., JUNE 30, 1909

J. C. Lincoln: I would ask Professor Adams if he has any particular pitch winding to recommend in order to give the best results in eliminating these higher harmonics?

C. A. Adams: The curves of Fig. 9 show the reduction of the various harmonics for all pitches above 50 per cent. The pitch that reduces the larger harmonics most effectively is a pitch of 10 slots in 12; it reduces the 5th, 7th, 17th, and 19th harmonics to about one-quarter of their value in the full-pitch winding. The 3rd, 9th, and 15th can be entirely cut out by star connection. This leaves only the 11th and 13th harmonics with their full pitch magnitudes, and these are usually small.

J. C. Lincoln: A pitch of about 84 per cent then?

C. A. Adams: Yes; approximately.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., July 1, 1909.

THE MODERN TELEPHONE CABLE

BY FRANK B. JEWETT

To those not closely in touch with the telephone situation to-day, the importance of the modern telephone cable may be indicated by stating that of the 8,000,000 miles of wire in the exchange plants of the associated Bell telephone companies, more than 6,800,000 miles are in the form of underground, aerial, or submarine cable. These figures refer solely to the wire used for outside construction and do not include the thousands of miles of wire in cable form employed in central offices or in the wiring of large buildings.

At the present time the bulk of the cable in any telephone plant is used in connection with exchange construction in urban districts. For a large part of such work the concentration of hundreds of circuits in the form of cables is the only available method of providing the facilities necessary to meet present-day service demands, which in many of the larger cities exceed one telephone for each 20 inhabitants, and in a few cities more than one for each 10 inhabitants.

It should be clearly recognized, however, that even the best cable circuit is much less efficient than an open-wire circuit; for example, one mile of the No. 19 B. & S. gauge cable circuit ordinarily employed in exchange construction results in as much current attenuation as 35 miles of No. 8 B. W. G. open-wire copper toll circuit, or 3.5 miles of the smallest size open-wire iron circuit used in rural exchange work. From these figures it is apparent that the extensive use of cable necessarily results in a material reduction of the radius within which satisfactory commercial transmission can be given, and as the most advanced telephone art to-day is only with difficulty meeting the increasing demands for long-distance service, cables can be substituted for open wires only when the further maintenance of open-wire circuits becomes impracticable. It is on account of this decrease in efficiency that the telephone company expends such large sums to retain open-wire circuits for its toll lines as close as possible to the central office, but even in this portion of the plant increasing numbers of circuits have forced the abandonment of pole lines in certain situations.

In another direction also the necessity for cable construction has developed to a certain extent; namely, providing the necessary circuit facilities between very large cities separated by moderate distances and between which there is a great deal of terminating telephone business; thus at the present time the business between New York and Philadelphia, New York and New Haven, and Chicago and Milwaukee, is handled over all-cable circuits.

The extensive application of cable construction in the modern telephone plant just outlined has been made possible only through the development of a form of cable exceedingly efficient as compared with the earlier forms. It is the purpose of this paper to consider a few of the essential requirements which have had to be met in the production of such a cable. While certain features of the manufacturing processes are described in order to explain the method of obtaining certain characteristics, the paper is in no sense an exposition of the technique of cable manufacture. In order to show how the telephone engineer ensures the production of a cable having the desired characteristics, clauses covering the points discussed have been taken from the standard form of cable specifications employed by the associated Bell companies.

THE ESSENTIAL REQUIREMENTS OF THE MODERN TELEPHONE CABLE

The essential requirements for an efficient and satisfactory telephone cable, while primarily electrical, are of course unavoidably connected with mechanical and cost restrictions. These requirements, which must be fulfilled by the cable and which form the basis of present-day cable specifications, are briefly as follows:

1. That the cable shall provide the maximum number of independent and non-interfering circuits within the minimum space.

2. That these circuits shall have the maximum transmission efficiency for currents of telephonic frequency, compatible with the other electrical and mechanical requirements.

3. That the dielectric strength of the cable shall be such as to insure against failure from any of the potentials normally employed and to make possible its protection against damage from lightning and from foreign circuits operating at potentials in excess of those employed on telephone lines.

4. That the mechanical arrangement adopted to obtain the necessary electrical properties shall be such as to insure a continued maintenance of these properties after the cable has been installed. This assumes a construction which will withstand the hard usage unavoidably connected with cable installation.

5. That this mechanical construction shall be made at a cost which will render the cable circuits economically available in comparison with other known means of circuit provision.

In addition to the foregoing, certain subsidiary requirements dealing with the general size of the cable desired; that is, the size of wire and number of pairs required; the method of circuit identification (color scheme); the length of cable sections to be furnished; the method of preparation for shipment and some form of guarantee which will insure high-grade material and workmanship in the manufacture of the cable, are ordinarily covered in the cable specification,

Standard cable construction. While differing somewhat in details, the essential features of all modern telephone cables, known as dry-core paper-insulated, are the same whether the wires are in the little five-pair or ten-pair subscribers' cables ordinarily strung on pole lines or in the largest sizes employed underground. Cables of this type are in one respect fundamentally different from cables which employ rubber or gutta-percha insulation. In the latter construction the dielectric which surrounds the wire serves not only to keep the wires in proper position, but being itself impervious to moisture, the dielectric serves to maintain the efficiency of the circuit, whether exposed to moisture or not. The telephone cable, on the other hand, belongs to that class of cable in which any solid dielectric employed is used primarily as a mechanical separator or to give the requisite dielectric strength. In this class of cable the deleterious effects of moisture are guarded against by surrounding the conductors with a water-tight metallic sheath.

For making up telephone cables, wires of the proper size are first insulated by wrapping them individually with dry paper ribbon. This ribbon, which is usually about ⅜ in. wide and of a thickness varying from 0.002 in. upward, depending on the size of the wire, and colored in some distinctive fashion, is spirally applied, but not with such a tension as to cause it to adhere closely to the wire. For the ordinary underground or aerial cable a single wrapping of paper suffices; in some forms of submarine cable two wrappings of paper, laid on in reversed directions, are used. In any event, the ribbon is so well overlapped that the wire is completely covered. Thus insulated, the wires are twisted together in pairs, the two wires of a pair being insulated with different colored papers and the length of twist depending upon the size of the conductors and the use to which the cable is to be put. The maximum length of twist, however, rarely exceeds 6 in. and for the smaller size of wires is ordinarily under 4 in. This twisting of the individual circuits is for the purpose of neutralizing inductive and capacity effects, which would occasion "crosstalk" between the various circuits if the wires of the core were laid up parallel to one another.

The core of the cables is made up in cylindrical form by assembling the requisite number of twisted pairs in concentric layers one or more pairs thick, the pairs in each layer being arranged spirally about the axis of the core and the direction of rotation in the alternate layers being reversed. As explained below, this use of a concentric layer construction is adopted to insure the necessary mechanical stability for the completed cable. The number of pairs in each layer is dependent upon the size and capacity of the cable required and is varied by changing the size of the central strand.

When the cylindrical core has been completed, it is wrapped with one or more thicknesses of paper tape to bind the conductors firmly in place, present a smooth exterior surface, and prevent the lead of the sheath from coming in contact with the insulation of the outer layer of conductors. This wrapping also gives the higher dielectric strength needed in the pairs of the outer layer. During the process up to this point the paper, being hygroscopic, has unavoidably taken on more or less moisture which must be removed before the sheath is applied. To this end the core, suitably reeled, is placed in a drying oven in which air at a high temperature is circulated for a considerable period, after which the core is taken immediately to the lead press and the final sheath is applied. This completes the process except for the testing, sealing of the ends and reeling for shipment.

While the individual wires forming the core of the cable just described are wrapped with paper, the cable is essentially different from the ordinary paper-insulated power cable, in that it is in effect an air-core construction. The paper, which is loosely applied and fills only a part of the total space not occupied by the conductors, is deformed in the process of cabling and serves merely as a mechanical separator to keep the wires apart and not as a dielectric *per se*, or as the carrier for a dielectric compound. In cable of this type the real dielectric is the dry air between the wires.

To show how nearly the present dry-core cable meets the essential requirements of the telephone industry, it may be interesting to examine some of these requirements and their actual fulfilment in detail and also the evolutionary process by which the present form of construction has been arrived at.

Choice of the dielectric.

Specification requirement: Each conductor shall be insulated with a single wrap of paper spirally applied.

In designing a cable for high-frequency current transmission work the principal requirement, as previously noted, is that it shall combine the maximum number of independent non-interfering circuits having a maximum of transmission efficiency within the minimum space and at a minimum cost. It is essential, therefore, that the dielectric selected for maintaining the proper separation of the wires and providing the necessary mechanical properties required of the cable should have both a low dielectric capacity and small dielectric hysteresis. These features, which in power cables designed for transmitting large amounts of low-frequency, high-potential current may be of secondary importance compared with high insulation and high dielectric strength, become paramount when the question is one of securing an efficient cable for the transmission of small currents having frequencies ranging up into the thousands of periods per second, and in which high dielectric strength is a matter of secondary consideration. The importance of these characteristics of the dielectric is readily apparent when we come to examine the mathematical expressions for the propagation of high-frequency currents such as those met with in telephony.

For a uniform metallic circuit containing resistance, inductance, capacity and leakage uniformly distributed, the formula for the attenuation constant is

$$a = \sqrt{\tfrac{1}{2}\sqrt{(R^2+L^2\,\omega^2)\;(S^2+C^2\omega^2)} + \tfrac{1}{2}\,(R\,S - L\,C\,\omega^2)}$$

In this formula R, L, and C have the ordinary significance, being respectively the resistance, inductance, and shunt capacity expressed in ohms, henrys and farads, while ω has the ordinary significance, being $2\,\pi$ times the frequency, and S, which represents the shunt leakage in parallel with the shunt capacity, expressed in mhos, is a measure of the combined direct-current conductance as determined from the insulation of the cable and also of the apparent conductance which results from the energy loss due to dielectric hysteresis.

For telephone cables where the wires are close together the inductance is negligibly small and the formula reduces to

$$a = \sqrt{\frac{R}{2}\left(\sqrt{S^2 + C^2\,\omega^2} + S\right)}$$

or when the leakage component is small in comparison with the capacity component, to approximately

$$a = \sqrt{\frac{R\,C\,\omega}{2}}\left(1+\frac{S}{2\,C\,\omega}\right)$$

This is the formula which ordinarily applies to cable circuits employed for telephonic transmission, and it will be noted that where S is zero; that is, for cables having high insulation and no dielectric dissipation, the expression for the attenuation constant is merely that of the so-called "$K\,R$ law." The quantity $\frac{S}{2\,C}$ in the above formula, known as the "damping constant," is dependent on the dielectric of the cable and is independent of the capacity of the cable, provided the dielectric is unchanged in character by changing the separation of the wires. In order, therefore, that the transmission efficiency of any cable shall be high for some particular frequency or range of frequencies, it is necessary that in addition to low capacity, the dielectric shall have the smallest possible ratio of shunt conductance to shunt capacity for these frequencies.

In the following table are given the constants at one thousand periods per second for No. 19 B. & S. gauge cables made up with rubber insulation, braided-cotton insulation impregnated with paraffin, and dry-core paper insulation. In each case the cables have the constants normal to the particular kind of construction. From this table it will be noted that for rubber-insulated and cotton-impregnated-insulated cables both the capacity and conductance are materially higher than in the dry-core, paper-insulated cable.

CONSTANTS OF NO. 19 B. & S. GAUGE TELEPHONE CABLES

Insulation	Mutual capacity mf. per mile 1000 p.p.s.	Mutual conductance m. mhos per mile 1000 p.p.s.	Damping constant $S/2C$ 1000 p.p.s.
Rubber................	0.15	40	133
Braided cotton filled with paraffin...........	0.12	16	67
Dry-core paper.........	0.08	2	12.5

Taking the constants of the foregoing table and applying them in the approximate formula, it will be seen that the attenuation constant of the impregnated cable is 24 per cent, and that of the rubber 40 per cent higher than that of the dry-core paper cable; also that while the dissipation of the dielectric increases the attenuation in the latter cable by less than 0.2 per cent at 1000 periods per second, that in the impregnated cable increases it by 1.05 per cent and in the rubber insulated cable by 2.10 per cent. In addition to the effect of dielectric dissipation increasing the attenuation of the cable, the fact that this increase is not constant for all frequencies but it is greater the higher the frequency, results in a cable with high dielectric dissipation having more distortion than one in which the dissipation is low over the range of frequencies involved in speech transmission.

From the above table it is also evident from the small value of the dissipation constant for the dry-core cable that with this type of construction conditions have been attained approximating very close to those in which nothing but air would intervene between the wires. In addition to the numerous mechanical, electrical, and economic defects which obtained in impregnated and rubber-cored cables, the fact that they were materially inferior in efficiency to the present type of dry-core construction was one of the principal factors leading to the adoption of the latter.

While the standard telephone cable of to-day is essentially an air-core cable, the amount of solid dielectric necessary for mechanical reasons is appreciable, and in specifying a wrapping of high-grade dry-rope paper ribbon the aim has been to utilize a material which will have the lowest possible dielectric capacity and dissipation, and at the same time possess the necessary mechanical properties to permit of its use in comparatively small quantities. That the paper should be spirally applied to the wires rather than put on in some other fashion, is the result of actual experience with other types of construction. In the early days of dry-rope paper insulation, numerous schemes for applying the paper were suggested and tried, with the result that spiral application was found to afford the greatest immunity from accidental crosses during installation while at the same time requiring a minimum amount of solid material in the core.

Insulation resistance.

Specification requirement: In every length of cable each conductor shall show an insulation resistance of not less than 500 megohms per mile of cable at 68 degrees fahr., each conductor being measured against all the rest and the sheath.

For telephone cables made in the United States the foregoing requirement is the one ordinarily specified. In Europe the insulation requirements are frequently very much more severe than this, and sometimes necessitate drying the cable after it is laid and spliced.

It is extremely doubtful, however, whether a high insulation specification can be justified in view of the extra expense incident to meeting it and the exceedingly small improvement in transmission resulting therefrom. The results of American practice have indicated that the specification of an insulation resistance which will insure honest manufacturing processes, a reasonable amount of drying and a permanent product, is all that is warranted. As a matter of fact the regular drying processes adopted ordinarily give an insulation resistance materially above 500 megohms, although under the exceptionally humid conditions frequently prevailing in the summer months, the insulation at times approaches the specification figure.

An inspection of the foregoing attenuation formula and the constants for different dielectrics will show at once that high insulation is not in itself necessarily an indication that the cable will be efficient. Thus rubber-insulated cables which have an insulation resistance of thousands of megohms per mile are decidedly less efficient than dry-core cables of the same capacity whose insulation is 500 megohms per mile. Since the principal dielectric loss in a dry-core cable results from dielectric hysteresis, rather than from direct conduction the specification of an insulation resistance requirement must, as previously stated, be looked upon primarily as one to insure an efficient process of manufacture and provide for a cable core which will not be subject to deterioration. The effect of this drying on the insulation and dielectric constant of the cable is shown in the following table of measurements made on a cable core before and after immersion in the regular drying tank. It will be seen that while the insulation has been improved materially by the removal of moisture the great improvement so far as efficiency is concerned has come from the reduction of the dielectric capacity and dielectric hysteresis in the cable.

EFFECT OF DRYING PAPER CABLE
300 pair No. 19 B. & S. Gauge.

Insulation megohms per mile		Mutual capacity mf. per mile		Damping constant $S/2C$ (1000 p.p.s.)	
Green core	Finished cable	Green core	Finished cable	Green core	Finished cable
300	1550	0.082	0.071	19	12

Thus while the transmission efficiency has been increased 7.1 per cent by the process of drying, the improvement due directly to the increased insulation resistance is less than 0.001 per cent, that due to the reduced capacity being 7.0 per cent and that to the reduced damping constant 0.1 per cent. As to whether further drying would not result in still further improvement it can be said that beyond the period of drying ordinarily employed, the dielectric capacity and damping constant of paper show but little further reduction even with the most elaborate drying by chemical processes. Such processes, on account of their expense, could probably never be justified in any but exceptional cases.

Dielectric strength.

Specification requirement. The insulation of each conductor shall be capable of withstanding a potential of 500 volts without rupture.

All dry-core paper-insulated cables used by the associated Bell telephone companies are required to withstand a direct-current potential of 500 volts between any wire and its mate, or between any wire and all the remaining wires and the sheath of the cable. As noted previously, this requirement is incorporated not only to guard against the danger from failure due to the normal potentials met with in telephone operation, but chiefly that the cable circuits may be efficiently protected from lightning or when they come in contact with light or power circuits. Past experience has shown that efficient protection without unduly great maintenance charges can be obtained only by providing open space cut-outs which will operate at potentials lower than the break-down potential of the cable. As it is not feasible to maintain open space cut-outs with operating potentials much below 500 volts, this figure marks the minimum dielectric strength which admits of suitable protectors. For certain classes of cable, where the exposure conditions either to power circuits or to lightning are exceptionally severe, or where, as at submarine cables crossing in the center of long toll lines, the inability quickly to clear trouble or repair damage would involve serious interruptions of service, special high dielectric requirements are frequently specified.

Electrostatic capacity.

> Specification requirements: In every length of cable the average mutual electrostatic capacity of all the pairs and the mutual electrostatic capacity of any pair per mile of cable at a temperature of 68 degrees fahr. shall not exceed the values given in the following table, the capacity shall be measured between one wire of a pair and its mate, the remainder of the conductors being connected to the sheath.

For cables used in exchange construction, such for instance as No. 19 gauge of 300 pairs or less, the mutual capacity referred to in the above quotation ordinarily averages slightly below 0.080 mf. Thus for a 300 pair No. 19 B. & S. gauge cable the specification average is 0.077 mf. and the maximum 0.084 mf. per mile for each length, while for cables of 240 pairs or less the corresponding figures are 0.070 mf. and 0.079 mf. respectively.

In the foregoing specification requirement the capacity is that measured by the ordinary charge or discharge method. While this constant is not that directly applicable to the computation of transmission efficiency for high frequencies, it is justified in manufacturing specifications on account of the difficulty of making accurate high-frequency determinations. It is also justified by the fact that in a thoroughly dried cable the capacity determined by the discharge method is not greatly in excess of the high-frequency capacity. This is indicated by the following table which gives the capacities of a small condenser having a cable paper dielectric 0.0085 in. thick, before and after the latter had been subjected to the ordinary drying process. It will be noted that in the undried state the difference between the discharge and high-frequency capacities is large. In a properly drawn specification the capacity requirement is a check on the insulation requirement as a guarantee of proper drying, it being impossible to provide the requisite number of pairs having the proper capacity in the specified sheath with an insufficiently dried core and still maintain the requisite dielectric strength.

EFFECT OF DRYING CABLE INSULATING PAPER.

Condition of paper	Thickness of paper	Capacity of condenser micro-microfarads		
		Discharge	1000 p.p.s.	2000 p.p.s.
Undried.......	0.0085 in.	11000	7020	6953
Dried.........	"	5793	5780	5779

With dry-core paper construction by a proper cabling of the pairs, the capacity of the cables can be varied at will within a moderate range to meet different transmission conditions, while at the same time retaining the necessary mechanical and electrical properties. Owing to irregularities in manufacture and differences in location within the core, not all the pairs have exactly the same capacity. For this reason, it is customary to specify both an average mutual capacity limit for all the pairs in each length and also the maximum mutual capacity limit of any one pair. This insures the proper efficiency for the completed cable run without putting such a stringent limitation on the uniformity of the product as to render the cost excessive.

It is now customary to specify mutual rather than grounded capacity, as the former is a constant of the cable directly indicative of its transmission efficiency. So far, however, as insuring efficient construction and good workmanship is concerned, either mutual or grounded capacity would suffice, since within the range of capacities ordinarily met with in telephone cables the relation between the mutual capacity of a pair and the grounded capacity of its component wires is fairly constant, the mutual capacity being approximately 60 per cent of the grounded capacity.

If an attempt is made to secure too low a capacity by separating the wires and employing too small an amount of paper, the core becomes so soft that the completed cable is easily deformed, and consequently extremely hard to handle; on the other hand, any attempt to secure an extremely high capacity by putting an excessive number of pairs in the core renders the cable stiff and unwieldy, or if the amount of paper is sacrificed the dielectric strength will be unduly low. Experience has shown that an average mutual capacity of about 0.050 mf. per mile marks the lower limit for single-wrap paper cable which can be readily handled without undue deformation, while approximately 0.09 mf. per mile marks the upper limit. Between these two limits practically any desired capacity can be obtained, although on account of having to conform to a limited number of cabling schemes it is not always possible to secure a uniform gradation of capacity with a specified sheath diameter and number of pairs.

Sheath.

Specification Requirement: The core shall be enclosed in a sheath composed of an alloy of lead and tin, the amount of tin by weight to be not less than 3 per cent. The sheath shall be free from holes or other defects and shall be of uniform composition and thickness. The thickness and outside diameter shall be for any size of cable as called for in the table given below.

For the mechanical protection of the core wires during and after installation and for preventing the ingress of moisture at all times, a continuous sheath composed of an alloy of lead and tin is moulded firmly about the finished and dried core. This sheath, which varies in thickness from $\frac{1}{12}$ in. to $\frac{1}{8}$ in. for aerial and underground cables, depending upon the size of the core, is molded in a continuous section over each individual length of core immediately on the removal of the latter from the drying oven.

To insure uniformity of practice in the cable plant it is necessary to set some limit on the maximum diameter of the sheath. At the present time the standard for a full size cable is $2\frac{5}{8}$ in. outside diameter, this being the limiting size that can be satisfactorily drawn into a standard 3 in. duct. A cable of this size will contain 300 pairs of No. 19 B. & S. conductors having the capacity noted above.

No single problem connected with the development of the modern telephone cable has probably been so difficult of solution as deciding upon the proper type of sheath, and the brief specification clause quoted above embodies the results of years of experience. Unlike most of the other features of the cable, the proper requirements for the sheath could not be forecast to a large extent and many indeed have resulted from conditions developed since the use of cable was first begun.

At the time when impregnated-cotton-insulated cable was the standard construction, the sheath was formed up separately and the core drawn in. This necessitated a considerable amount of clearance between the sheath and the core and although the entire inner space was ultimately filled with paraffin or resin oil, the cable had a decided tendency to buckle and crack if bent on any except a long radius. For this reason and because it was frequently necessary to relocate cables in the plant, early specifications usually contained a clause stating that the completed cable must be capable of being wound and unwound a certain number of times on a drum of specified diameter without buckling or cracking. This requirement was to insure that the cable would be serviceable when withdrawn from the duct.

The process also limited the length of sheath which could be continuous, so that where long pieces of large cable were needed to fit suitable manhole spacings, factory joints in the sheath had to be resorted to. The care in making these so as to withstand the rough treatment incident to pulling into the duct was such as to greatly increase the difficulties and expense of manufacture. As a result of the defects in the earlier forms the present process was developed of moulding the sheath directly on to the dried core so as to closely fit it, eliminating at once the necessity for factory joints and the need for clearance between the core and sheath.

The specification of a 3-per cent tin alloy for the sheath is likewise a result of experience gained in the early days of cable development. Added primarily for the purpose of hardening the sheath so as to better withstand rough usage during manufacture and installation, the amount of tin used was long a matter of individual preference. The present standard requirement was only arrived at when a careful investigation was made to determine the proper remedy for the cracking of aerial cable sheaths, which developed when the sheath was subjected to continued vibration. At the time there was a very strong sentiment in favor of a pure lead sheath for such cables, a sentiment based largely on the poor showing made by alloy sheaths in a number of instances and the feeling that a softer sheath would be less likely to crystallize. It was only when exhaustive laboratory experiments had shown the great superiority of a proper alloy over pure lead that the final solution was reached.

The following table gives some results of a series of experiments on the ability of different materials to withstand rupture when subjected to continued vibration under stress. In each case the test samples were strips 4 in. long, narrowed for 2 in. in the center to a section measuring $\frac{1}{2}$ in. by $\frac{3}{64}$ in. One end was fastened to a metal tongue pressing lightly against a toothed wheel and the noted weight suspended from the lower end. The tongue was given approximately 108 complete vibrations per second. Where two weights are noted the larger was added to hasten rupture.

VIBRATION STRAIN FOR CABLE SHEATH MATERIALS

Material	Weight suspended	Time of stress
1. Lead Pure..............	13 lb. 2 oz.	55 m.
2. " "	6 lb.	10 hr. 15 min.
3. Lead 99.5%, tin 0.5%....	13 lb. 2 oz.	32 hr.
4. Lead 99.0%, tin 1.0%....	*a*—13 lb. 2 oz. *b*—23 lb. 2 oz.	74 hr. with "*a*" and 1 hr. " "*b*"
5. Lead 97.0%, tin 3.0%....	*a*—13 lb. 2 oz. *b*—23 lb. 2 oz.	48 hr. with "*a*" and 9 hr. " "*b*"

With the advent of creosoted wooden conduit a great deal of trouble from the chemical corrosion of the sheaths was experienced. In these earlier ducts, wood creosote was the preservative agent employed but owing to the presence of considerable acetic acid, this had a ruinous action on sheath materials. Elaborate experiments at the time proved that while not wholly free from such corrosion, the 3-per cent tin alloy sheath was corroded much less than one of pure lead or one with but a small proportion of tin. While improvements in the process of creosoting by the substitution of dead oil of coal tar for wood creosote, thereby eliminating the acetic acid, and the advent of vitrified clay ducts, have practically eliminated chemical corrosion from the field of cable trouble, it was one of the factors which at the time led to the adoption of the present standard sheath material. Although an excess of tin renders the alloy too hard and brittle, only the minimum limit needs to be specified, the high price of tin automatically keeping the amount used as small as possible.

Cable specifications. In conclusion, a word might be said about the standard cable specifications to which reference has already been made. These specifications aim primarily to secure a certain standard for the finished product without unduly restricting the manufacturer as to the exact processes he shall employ to attain the desired end. While certain of the mechanical characteristics are incorporated, such as the use of a particular alloy for the sheath, and the employment of paper insulation to the exclusion of other materials, it is on account of experience having shown them to be the best available.

As a result of this aim, the specifications, though brief, have the clauses so drawn as to insure the equivalent of a process known to be satisfactory. In the matter of brevity the present-day specification is analogous to the earliest specifications, which also aimed at a suitable finished product without specifying particular processes. There is this marked difference however: much of the brevity of the earlier specifications was due to an insufficient knowledge of the characteristics and possibilities of the materials and processes employed, while the brevity today is the result of a definite knowledge gained from long experience and a more comprehensive conception of the fundamental laws governing the efficient transmission of high-frequency currents, of just what each material will do under varying conditions and just what the limitations of any particular process are.

Between the specifications of the late '80's and those of to-day a period intervened in which it was frequently customary to specify minutely the exact process to be employed and the behavior of the finished cable under widely differing conditions, such, for instance, as the specification of just what the allowable capacity should be at a number of different temperatures. And however much future specification requirements may differ from those of today as regards subject matter, owing to advances in the art, the laws governing the propagation of currents along wires are sufficiently well known to make a recurrence of this type of specification unlikely.

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THE TRAINING OF NON-TECHNICAL MEN

BY C. R. DOOLEY

In electrical engineering the proper and efficient arrangement of iron, copper, and insulation, is only a part of the problem. The proper and efficient arrangement of brain and muscle, providing for higher individual efficiency of all classes of men who are to carry on the business of the future, is the fundamental part of the engineering problem and therefore should merit the most careful consideration of an engineering society such as the Institute.

This part of the problem should not be left entirely to the engineering colleges, for they are unable to arrive at a complete solution. In the first place the engineering schools supply a very small number, perhaps less than one per cent, of the men required to carry on the business. In the second place their graduates are practically all led along one line to a single level. There are few if any college courses in salesmanship, foremanship, shop management, etc. Few colleges expect their graduates to become skilled mechanics, tool designers, or even draftsmen. The manufacturer of electrical apparatus needs a few highly trained men to carry on scientific research, but he just as greatly needs laborers, skilled mechanics, efficient clerks, shop directors, inspectors of materials and hundreds of artisans, and all these need training to develop the best that is in each man for the direct benefit of his employer.

The need of special and general training for all classes of men instead of for one class, is strikingly emphasized by the great number of commercial enterprises that are providing for their men systematic training in a combined scientific and practical way.

The educational activities in the vicinity of the Westinghouse interests at East Pittsburg divide themselves into two general classes: 1. The training of the graduates of engineering schools. 2. The training of non-technical men. It is the purpose of this paper to describe the work that is being carried on along the latter line.

The training of non-technical men is further divided into two distinct lines: 1. The apprenticeship system, which includes a certain amount of systematic class instruction given during working hours. 2. The night school, where attendance is purely voluntary. Both of these have a place in the training of non-technical men.

The situation. The present scarcity of skilled workmen is a matter of great moment to the manufacturer. He is vitally concerned in plans for the future that will insure men of all-around skill in their respective lines. He may rely upon the engineering schools for the majority of his managers, but who will broaden and train his workmen? The present highly specialized labor is proving inadequate in many shops for two reasons: 1. The dwarfing of the ambitions of the men. 2. The almost total absence of old-time all-round mechanics, which restricts the transfer of workmen from one section of a shop to another.

This is the age of specialization, but the extreme specialization that is seen on every hand will kill the best impulses of human nature and ruin our national endeavor. Almost every machine shop in the country is filled with special machinists, or rather machine specialists; in short, machine-men. Man is not a machine. To allow him to become a mechanical producer instead of a thinking producer, is not only wrong ethically, but is rapidly being recognized as wrong economically.

That which is best for the individual is best for the concern for which he works. The managers of large concerns are eagerly looking forward to the increase in the productive power of the workmen, and will willingly pay for it accordingly. The question of the future is not how to get a man to do a day's work for the least pay, but how to get the most efficient work out of the man, increasing his pay in proportion.

The apprenticeship system. The development of the boy and not " shop production " should be the watchword of the apprenticeship department of every company. At the works of the electric company already referred to, the apprenticeship department is being developed in a most systematic and careful manner, the first vice-president of the company taking an active part. In this establishment the work of the apprentices is divided into two departments: 1. The shop. 2. The classroom.

In the shop the plan is to devote a certain section to the apprentices. This section is fitted with a complete equipment to furnish shop-practice in all branches of the machinists' trade. In the shop the boys are under the guidance of shop instructors having the rank of foremen. These instructors are all-around mechanics taken from the shop organization and chosen for their interest in young men as well as for their skill as workman. The boys are moved from machine to machine, from operation to operation, in systematic order and are at all times under the guidance of the shop instructors. The boys remain in this section approximately two years. The latter half of their course is spent in the various sections of the shop. During this period they do not have the direct attention of the shop instructors but are under the care of the apprenticeship department and are transferred about the works as is deemed best for the individual boy, according to his natural ability.

In the classroom the instruction is provided on the company's time, and is conducted throughout the four years of the course. This work is a part of the daily schedule, and the apprentices report to the classroom as systematically as to their shop foremen. Special rooms inside the works have been fitted with suitable tables, desks, blackboards, etc., much the same as any ordinary schoolroom. However, the atmosphere is hardly that of a schoolroom, but rather that of a class where the boys are given problems and explanations concerning the things with which they work every day, instead of problems in abstract mathematics. In connection with the character of the class work there are three vital points: 1. The scientific principles underlying the subjects must be taught. 2. These scientific principles can best be presented through the working out of practical problems dealing with the things of the boy's everyday life. This will hold his interest. 3. The same problem must teach him certain facts and specific knowledge concerning the things with which he is working, such as weights, costs, and strength of materials, gear speeds, pulley and belt speeds, etc. In fact, a knowledge of the things with which the problems deal and the facility offered for thinking about these very ordinary things, may be the most valuable features of this instruction.

As a specific case consider the subject of addition of fractions and mixed numbers. Instead of an abstract group of such quantities to be added, the boy is given this problem:

> A shaft has two shoulders. The length from one end to the nearest shoulder is $3\frac{7}{8}$ in. The length between shoulders is 1 ft. $4\frac{1}{2}$ in. The length from the second shoulder to the other end is $4\frac{3}{4}$ in. Allowing $\frac{3}{16}$ in. at each end for finish, what length of stock will be required to make four shafts?

Nor is this type of problem too simple for the average apprentice. Out of a class of 103 beginners, 45 could scarcely add or multiply decimal quantities and knew practically nothing about proportion and percentage.

There is yet another phase of the work without which all else will fail. For want of a better name we call it spirit. It includes loyalty and enthusiasm, not only in the work and the future it holds for the boys, but also in all their daily relations with their fellows—a spirit of service and willingness, confidence in all things and all people, and eternal optimism. This may be illustrated by the following incident: The second week of the operation of the class work included a holiday which happened to come on Monday. One boy in the Monday class complained of his hard luck in losing a period owing to the holiday. Another boy was congratulating himself upon being in the Tuesday class.

At present the class work is scheduled under two general heads: 1. Mechanical drawing. 2. Shop arithmetic. Each of these subjects embraces a certain amount of the general subjects of shop problems, tool construction, tool operation, shop organization, and system, as well as the fundamental science of the subject itself.

The night school. The best organized apprenticeship system, even with its supplemental classroom work, will not satisfy the more ambitious young men. Such men are studying every spare moment; they are taking correspondence courses or are attending night school. They are not satisfied with learning a trade, but have a desire for a broader training leading toward engineering. There is a prevalent feeling that engineering training applies only to college men, that for the 95 per cent of the boys of the country who never finish high school, the problem is one of industrial education with specific training in definite trades. While this is perhaps true in the majority of cases, it is not a foregone conclusion.

A night school is not necessarily a trade school. On the contrary, a night school may do high-grade engineering work, in fact, from some points of view a properly organized night school, or some other form of close coöperation between technical training and commercial practice, may offer the best opportunity for engineering training. One thing that makes for high efficiency in night-school work is the character of the men who pursue it. The schedule of work is necessarily difficult, and hence only the more industrious and ambitious boys will take it up. The very nature of this system is selective in the beginning, but the selection is natural and self-appointed and therefore just. Another thing is the daily contact with the intensely commercial sides of all problems, the theoretical sides of which are explained in the schoolroom. If during four years of the study of theoretical and experimental electricity in the night school, the student is employed during the daytime in a power house, on a wire gang, winding and insulating armatures or assembling switchboards, he will get a type of engineering training that is in great demand.

Six years ago The Casino Technical Night School was started in the vicinity of the manufacturing works already referred to. Its management is independent of any commercial industry, though its activity is encouraged and fostered by the local organizations, including the public school board, the latter furnishing the housing. In the beginning there were half a dozen teachers and a few dozen students who attended classes in drawing, elementary mathematics, and shop practice. There is now offered an opportunity for systematic study in such fundamentals as mathematics, mechanical drawing, mechanics, physics, theoretical and applied electricity, chemistry, shop practice in both wood and iron, theoretical and applied steam engineering, etc. There is a faculty of 25 instructors and an enrolment of about 300 students. The growth and development has been along sure and conservative lines and only as rapid as the demands of the students required, and yet in the 6 years the actual number of hours that each student devotes to the entire course has been increased over seven-fold; from two sessions of 40 min. each, on two evenings for a term of 2 years, to three sessions of 60 min. each, on three evenings each week for a term of 4 years.

The instructors are themselves not only versed in the theory of their respective subjects but each is also actively engaged during the day with his subject within the organization of a commercial factory. The advantages in the way of securing exceptionally trained teachers are therefore ideal.

Attendance is voluntary and a small tuition fee is charged. Admission is extended to all, regardless of occupation or previous education. The low educational entrance qualifications are cared for by a preparatory department. Practically all the students are employed in the various shops in this vicinity for the regulation 9.75 hr. per day besides attending school 3 hr. on three evenings each week. The schedule of work is such that they cannot possibly keep up without devoting several of the remaining evenings of the week to the preparation of their lessons. Though the school has a vacation period from June to September, these men are devoting practically all of their time to study and to work—to the acquisition of scientific knowledge and commercial experience. In addition to this it is a common thing for groups of students to request additional work. During the past year a class of some 15 students met once a week after school—after 9:15 p.m.—to study English. These men not only did this work in addition to their regular schedule but bore the extra expense necessary to maintain the class.

Perhaps it will be thought, this is too much. But is it any more than the aggressive man in commercial activity is doing and expects to do the balance of his life? Is it not exactly what the 25 instructors are doing? These instructors have their daily routine in shop, testing room, drafting room, and engineering department. The pay for their school work is small, but the work is both interesting and broadening. The relation between students and instructors is ideal—they learn and teach with an absolute mutual confidence and personal interest.

This wholesome spirit finds expression in many ways, notably in the conduct of the classroom where matters of discipline are practically unknown; in class organization, the presidents of the several classes organizing themselves into a student council for the furthering of the interests of the school; and in the general interest shown at commencement time when the year's work is drawn to a close with appropriate exercises comprising orations by members of the graduating class and an address by a prominent engineer or educator, and a dinner which marks the very climax of enthusiasm and loyalty.

Nor has the social side of student life been omitted. The boys have organized a glee club, a mandolin club, a basket-ball team, and a base-ball team. They also edit and publish a small monthly bulletin. These clubs are well organized and would do credit to many a college organization.

The total enrolment just before the financial depression was something over 300. For the year just closed it was approximately 250. In general, 80 per cent of those who enroll complete the term's work. Of the 45 men who have been graduated during the past three years, practically all have been steadily advanced in position and responsibility, and 40 are still with their original employers. While no degree can be given the graduates, the character of their work and the positions held by the men after graduation may warrant the assertion that the Casino school is, if not the first night school, among the first to graduate men in engineering. Some of the graduates are doing high-grade engineering work in the engineering department and in the drafting office of the nearby electrical manufacturing company. Others are successful salesmen and many are doing responsible work in the erection department and in the shop organization.

The engineering night school has a large field of activity. At the start its students possess a clear idea of commercial practice which the newly graduated college student seldom has. This early experience instills an appreciation of the value of time and of the value of scientific training that tends to produce the most efficient student. They have learned several years earlier in life that scientific study and commercial practice not only go hand in hand but that they should continue hand in hand throughout life if the highest achievements are to be attained; that there never comes a time when the one can be laid aside and the other taken up. They also know the importance of the routine of life, that from the office boy to the president, it is the fellow who gets the job done who gets the bigger job to do.

While it is not within the province of a manufacturing concern to provide a liberal education for its men, with the present degree of general education among young boys it is within the principles of good business to provide and maintain a training in those fundamental subjects which will assist in developing skilled mechanics and workmen of higher ideals to carry on the business of the future. Further, a manufacturing concern can well afford to assist and encourage the exceptional young man to as high a technical training as he will take.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., July 1, 1909.

THE VALUE OF THE CLASSICS IN ENGINEERING EDUCATION

BY CHARLES P. STEINMETZ

Education is not the learning of a trade or profession, but is the development of the intellect and the broadening of the mind, afforded by a general knowledge of all the subjects of interest to the human race, as required to enable a man to attack intelligently and solve problems in which no previous detail experience guides, and to decide the questions arising in his intellectual, social, and industrial life by impartially weighing the different factors and judging their relative importance. These problems, and thus the educational preparation required to cope with them, are practically the same in all walks of life, and the general education of mind and intellect required by the engineer, the lawyer, the physician, etc., thus is essentially the same. The only legitimate differences in the training for the life's work, required by the different professions, thus are those pertaining to the specific instruction and study of the details of the particular branch of human knowledge by which the student desires to make his living.

For ages the classics, comprising the study of the Latin and Greek languages and the literature of these languages, have been the foundation of all education; but in the last two generations they have been more and more pushed into the background by the development of empirical science and its application, engineering. It is my opinion that this neglect of the classics is one of the most serious mistakes of modern education, and that the study of the classics is very important and valuable, and more so in the education of the engineer than in most other professions, for the reason that the vocation of an engineer is specially liable to make the man one sided. By dealing exclusively with empirical science and its applications, the engineer is led to forget, or never to realize, that there are other branches of human thought besides empirical science, and equally important as factors of a broad general education and intellectual development. An introduction to these other fields is best and quickest given by the study of the classics, which opens to the student other worlds entirely different from our present, the world of art and literature, of Hellas, and the world of organization and administration--and of citizenship—of Rome, and so broadens his horizon beyond anything which can be accomplished otherwise, and shows relative values more in their proper proportion, and not distorted by the trend of thought of his time.

It is true that the classics are not necessary if the aim is to fit the student to ply the trade of engineer, just as that of plumber or boiler maker, and the world, and especially the United States, is full of such men who have learned the trade of engineer. But such learning of the engineering trade can hardly be called receiving an education, and certainly does not fit the man to perform intelligently his duties as a citizen of the republic during the stormy times of industrial and social reorganization, which are before us.

There also is a considerable utilitarian value in the classic languages, as the terminology of science is entirely based on Latin forms with Greek and Latin roots, and while the student may memorize the terms of his profession, it is difficult, if not impracticable, to memorize all the terms of science with which an educated man must be familiar as those of medicine, botany, mineralogy, etc. This however becomes easy to the student of the classic languages, to whom these terms have a meaning. To eliminate the scientific terms of objects from the language is obviously impossible, as the common or English names usually are different in different localities, if they exist at all, and thereby indefinite.

The modern languages are not in the same class with the classic languages, as they open to the student no new world, no field of thought appreciably different from our own, and I therefore consider them of practically no educational value. Their utilitarian value to the college student is negligible, as due to the limited time, the absence of practice, and the large number of other more important subjects of study, very few of the college graduates retain even a rudiment of their knowledge of modern languages, and even those few only because they are especially interested in them, have occasion to practice them, and therefore would probably have learned them outside of college. To the engineer particularly, the knowledge of foreign modern languages offers no appreciable help in following the engineering progress of other countries, as practically all that is worth reading is translated into English either in full or in abstract, and engineering publications written in a foreign language are closed to the reader even if he has some knowledge of the language, by his lack of knowledge of the technical terminology of the foreign language.

Since the modern languages have no appreciable educational value, they should be dropped from the engineering curriculum of the college, as their retention violates the principle of the modern college curriculum, to restrict, owing to the limited available time, the instruction to those subjects which the student can not acquire outside of the college by self-study, or can acquire only under great difficulties. Modern languages do not belong to this class, but are learned just as easily, if not more easily, by self-study and conversation.

Referring to the classics, however, it is true that the methods of their teaching are not the most efficient, and especially the classic literature with which the student is familiarized, is not selected so as to offer the greatest educational value in broadening the student's view, nor so as to attract and retain his interest as much as possible, but rather seems to be the result of survival from previous times.

Thus in Latin the story of war and conquest, of the victory of military organization over mere bravery, in *Caesaris de bello Gallico*, is interesting and instructive, while the Civil war is of less interest. Even to-day *Ciceronis de officiis* is well worth reading, while *Ad Catilinam* is stupefying to the intellect, since any intelligent boy must ask why did the "man afraid of his shadow" not have Catilina arrested and executed for high treason.

In Latin poetry selections from *Ovidii Metamorphoses* are very easy reading, and are a valuable introduction to the classic metre, and interesting in the parallelism of the myths of the classic world with those of other races (the flood etc.); but it is hard to understand the retention of the uninteresting plagiarism of the courtier Virgil in the curriculum, while the most important, in his educational value, and most interesting poet, Horace, is not read at all in most college curricula. Of all Roman writers, Horace probably exerts the most broadening influence on the intellect when read under an intelligent instructor; the change from the distortion in which the relative values of persons and things appear to their contemporaries, to the proper proportion in the perspective of history, probably is nowhere so sharply demonstrated as in the relation between the " *libertino patre natus* " and his " protector " and " patron," Maecenas, whose name has escaped oblivion merely by his favorite's favor, while Horace promises immortality to whatever he addresses, and confers it (*ad fontem Bandusiam*). The reading of Horace probably is the best remedy for discouragement resulting from lack of appreciation of one's efforts, as the engineer and the inventor very often has reason to feel. Also especially the American, who is generally liable to take himself too seriously, might benefit from the sentiment expressed in *Ad Leuconoen*. In short almost every one of Horace's poems is interesting and instructive and conveys a moral which we may well listen to.

In Greek prose, *Xenophontis Anabasis* is interesting and instructive in many respects, and may well be followed by the student with maps of the country traversed by the ten thousand. Selections from Lucian possibly are the nearest approach to Horace in their broadening influence. The Greek drama probably is beyond the scope of reading which can be attempted in a general college course, and also appears to me less important now, where in the modern northern drama we have similar tendencies exhibited. The easy dialect of the κοινη however is within the reach of the student, and at least a part of the new testament may be read in the original and its value can hardly be overestimated in showing the meaningless nature of theological controversies on words of an imperfect translation. The greatest work of the literature of Hellas however is Homer; and here again in many American schools the *Iliad* only is read, possibly from the mistaken notion that it is easier reading, while the far more interesting *Odysee* is slighted, though the latter with its tales of travel and adventure, with giants and monsters, should especially appeal to the American boy, and is of far greater interest and educational value in its minute description of everyday life at the early dawn of human history, in its pictorial expressions of times and occupations, of the time of the day, the coming of night, the dawn, etc. Nowhere possibly is found such a vivid description of omnipotence as in Homer's:

Ἠ καὶ κυανέῃσιν ἐπ' ὀφρύσι νεῦσε Κρονίων·
Ἀμβρόσιαι δ'ἄρα χαὶται ἐπερρώσαντο ἄνακτος
Κρατὸς ἀπ' ἀϑανάτοιο, μέγαν δ' ἐλέλιξεν Ὄλυμπον.

DISCUSSION ON "THE TRAINING OF NON-TECHNICAL MEN" AND "THE VALUE OF CLASSICS IN ENGINEERING EDUCATION." FRONTENAC, N. Y., JULY 1, 1909.

C. P. Steinmetz: In the preceding paper I desired to make a strong plea for the reestablishment of the classics as one of the most important and valuable educational factors necessary to give that intellectual development and broadening of the mind which produces not merely intellectual machines, but citizens of the Republic capable of taking their proper place in the industrial and social life of the nation. From the standpoint of educational value I consider the classics superior to any modern language. I do not mean to say that modern languages should not be learned; very much the contrary; what I believe is that modern languages have no place in a college curriculum. They should be studied privately or as an elective study, and preferably in early youth. Furthermore, I also do not mean to imply that our present method of teaching the classics is particularly perfect. Indeed, the major part of the paper is a criticism of our present method of classical study.

I might say a few words on the origin of the paper. I have noticed for many years that in the higher positions connected with the electrical engineering industry the number of men who have risen without any college education is far out of proportion to what could possibly be the case if in the broad development of the mind the college were all that it should be.

Furthermore, during recent years we engineers have been impressed forcibly with the circumstance that we do not occupy in the public life of the nation the position that we should occupy, and must expect to occupy, owing to the importance of our profession. We have complained that bodies appointed to deal with the relations of the states and the nation to engineering in its industrial and social aspect do not contain a single engineer. When considering the situation, thinking what I would do if I had to appoint such commissions, I was forced to conclude that I also would act in the same manner: I might appoint a man who is an engineer in spite of his being an engineer, but not because he is an engineer. This is an unfortunate situation. The cause of it was brought to my mind more fully by reading the paper presented by Mr. F. P. Fish last May,* not because of the contents of the paper, but because of its style and atmosphere, which are such that no mere engineer could have written it, but a classical scholar.

This is a matter which must be changed. We engineers must insist on occupying in the public life of the nation that position which is due to us as exponents of the most important branch of human thought and work. But before we can do

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* *The Patent Situation in its Relation to Industrial Development*, PROCEEDINGS A. I. E. E., May, 1909, p. 441.

this we must be more than mere engineering machines, we must be broadminded, public spirited citizens, having a general view of things in their right proportion, and not merely knowing all about technical matters and very little of anything else, and having no interest and knowledge of anything beyond our profession.

Frederick P. Fish: It is most unfortunate that engineers do not, as a rule, have the opportunity to study the great authors of Greece and Rome so as to become thoroughly in touch with them. To me they disclose a new and delightful world so different from ours that, by very contrast, I feel better equipped to understand our times and mode of thought. If the Greeks and Romans had had our literature of the nineteenth century, I doubt if they would have been more definitely impressed by the novelty and strangeness of that literature than we are by the classics when we read them.

It is a most healthful and broadening influence to become saturated with a mode of thought and a view of life so different from those with which our own experience makes us familiar. This works in many ways. In studying the life and literature of ancient times, we become more and more thoroughly satisfied as to the essential nature and capacity of man, which have changed very little during the period of recorded history, while at the same time we are deeply impressed with the different lines on which thought and action may develop in man's effort to hold his own against the forces of nature and to strive and prosper individually and in the community relation.

There is no doubt that one who studies the classics is better fitted for sane and wise views on all the social and governmental problems of to-day than would be the case if he relied only upon what he has seen or read of modern times. He surely becomes a better judge of human nature and better able to steer a straight and wise course in the affairs of life, where so much depends upon an adequate recognition of the wonderfully efficient but vacillating and unstable characteristics of man, whether regarded individually or collectively.

I feel the same as to the study of any literature of olden times. No one can become familiar with that of Iceland, Ireland, England, France, Germany, Spain, and Italy of the Middle Ages without having his views broadened and his capacity for dealing with the practical affairs of life increased. The same results follow from a study of the literature of the Oriental countries, the East Indies, Persia, Assyria, and of the early Egyptians. Folk literature, even that of savage and semi-barbarous peoples, is of value in the same way.

The great difficulty is that few men in active work have the time for such study and so much is required in schools by way of definite preparation for an engineering career that there is but little opportunity for anything that seems so remote as ancient literature. It is not worth while even to consider the study of any early literature except that of Greece and Rome, as a preparation for an engineering career, and I am very much afraid that the balance of advantage may reasonably be said to lie on the side of ignoring even these in engineering institutions of learning, that there may be more time for things directly germane to the profession. The curriculum of an ordinary training school for engineers can not be made long enough for even training in the fundamental principles of engineering—which is carried none too far—and the application of those principles to practical work.

But it is a subject for regret that engineers can not in every case have the benefit of a first-hand knowledge of the classics. Some of them get such knowledge outside of school and many read the classical authors in translations, and thus get at least a shadow of the advantage that would come to them if they were to study the original tongues. Translations, however, are unsatisfactory and do not give the spirit of the original. More than that, the mere studying of Greek and Latin as languages, is, in my opinion, of far greater value than is perhaps generally recognized at the present time. Personally, I owe more to the work I did on the classics than to any other branch of my education. I agree that the same advantages do not come from the study of modern languages, but am not certain that under existing conditions I should go so far as to advise the elimination of those studies from the curriculum of a technical institute.

C. A. Adams: I wish to refer particularly to one sentence in Mr. Dooley's paper:

> The development of the boy and not shop production should be the watchword of the apprenticeship department of every company.

That is, in a way, a new attitude on the part of manufacturing companies. For many years they have been extremely interested in the efficiency of machinery, and have devoted much time, effort, and money toward the development of machinery to its highest efficiency; but that most important and most marvelous of all machines called man, has been for the most part neglected. It is refreshing to see this further indication of the modern trend towards a more intelligent and ideal coöperation.

In regard to Dr. Steinmetz's paper, I must confess to mixed feelings which are difficult to express satisfactorily. I have the greatest sympathy with Dr. Steinmetz's general point of view. I believe thoroughly in the value of a careful study of the classics for engineers as well as for men of other professions, but I cannot believe that this study is as vital as here described, or that it accounts for the difference noted between engineers and so-called "men of affairs." Is not this difference due rather to the fact that the *average* boy who selects engineering as a profession does so because his interests are more largely objective? He is more interested in things than in the money that can be made out of them; he revels in the laws of nature and in their application to the solution of material problems, rather than in the complex human relations involved in the work of men of affairs. Sometimes too he may look about him and realize that many of the most successful men of affairs are successful because *privilege* rather than *principle* has been their motto, and that many of the now complex social and economic problems would be greatly simplified, were principle to prevail.

I do not wish to attempt any general comparison of these two types of mind, but rather to point out that they do exist; that their differences, due partly to inheritance and partly to early environment, are ordinarily not much influenced by the study of classics or by the absence of such study; that there is a place and a work for each type, and that it does not necessarily follow that one is higher than the other. The ideal education is that in which each type has full and free opportunity to develop naturally toward its maximum of usefulness and efficiency.

One other opinion that I wish to express is that the work and training of the real engineer are such as to fit him peculiarly for the solution of those numerous troublesome social and economic problems which are so much with us to-day. The work of the real engineer forces him to think clearly and accurately, knowing that he is to be judged not by men but by the results of his work as determined by the operation of invariable laws. He is thus more likely to acquire the habit of seeing these problems without bias of person or class and without the influence of custom or tradition; in other words, he is apt to be more fair-minded than the average man of affairs.

Anyone conversant with easily obtainable facts and statistics in regard to social, political, and industrial conditions in this country to-day, must certainly conclude that there are many legalized sources of unfairness which could be easily removed were it not for the tremendous influence of their beneficiaries. many of whom are men of affairs. I for one am of the opinion that the real engineer will have at least his full share in the removal of these sources of unfairness.

Farley Osgood: The thing that concerns me most is that apparently engineers are being trained for manufacturing or designing purposes only. As yet I have heard nothing of what happens to the young engineer who goes directly into the operating company. The engineer's training must be specific. He must be a specialist. This is desirable, as Professor Adams has said, if he is going to be strictly and only a manufacturing or a designing engineer.

As an operating engineer I can say our greatest difficulty is to get a young college-bred man with a technical training who can think; he can figure, but he cannot think. I agree with Dr. Steinmetz that in order to make a young man think he must be broadly trained. If a young man has a certain ability he can learn mathematics; he can use the slide rule; he can deal with definite things without great difficulty. But problems that confront the operating engineer are unexpected; they come rapidly in quick succession; they may be of an entirely different nature one moment from the next. The operating engineer, primarily and forever must be a quick and a correct thinker.

I cannot agree with Professor Adams that the narrowing down of a man's training is healthful for him, if he has to deal with broad and general problems. Mr. Fish certainly strikes the keynote in saying that young men upon graduation should be able to solve a given problem without difficulty. Without meaning in any way to cast reflections on our designing engineers, I must say that they do get into ruts. There is no question about that. They are so anxious to get ahead of each other in their line of competition, so anxious to become well-known specialists in various lines, that they seem to forget there is anything else going on in the world besides the designing of the particular type of apparatus to which they are giving their time. From the beginning the operating engineer has not only engineering problems to take care of but he has to meet the public; he has to handle the financial side of his problems; and finally, but not by any means the least of all, he has to put his subject in such a manner before his board of directors that they will give him money to spend for the benefit of the stockholders. I do not think that distinct training solely for mathematical or strictly engineering lines will help him in the final and last problem, which is to get money from people who do not understand the engineering business to put into that business. That is the most difficult problem, and the ultimate problem, of the operating engineer.

I see a good many of the young fellows when they graduate from college and make application to our company for employment. We have what we call our kindergarten course, and put the embryo operating engineers through an operating training. This course is not like Mr. Dooley's course, which is exclusively for manufacturing purposes; it is of the same general nature, only along operating lines. Every recently graduated engineer that I have met within the last five years, with very few exceptions, thinks that he must go into the factory. His whole desire seems to be to know how to design and make machines. That is certainly advisable; he must know that at some time or other. But this tendency works hardships for the operators, in getting young men that are willing to tackle the general problems of commercial engineering or business engineering as soon as they get through college. My only explanation of it is that they have not been sufficiently broadly trained to think on general subjects. They feel insecure in taking a position that will make them think of a great many different things at once which have not come to them before, therefore they go to the manufacturing companies. Frequently after they have been with the manufacturing companies for some time they begin to realize that there are other things in the world besides making machines, not the least of which is how to use them. Many of the men who go to the large operating companies come to us as graduates from the courses of the manufacturing companies. This means that a man is graduated at college, at twenty-one; and by the time he gets through the students' course in the factory he is twenty-four or maybe twenty-six years old. He has lost four or five years' training which he would have gotten if he went directly to the operating company from college. If they went directly to the operating company I think they would get on faster and be much broader men at an earlier age.

M. G. Lloyd: I am impressed with the truth of what Dr. Steinmetz brings out as to the broadening effect of the classical studies, and I think we should endeavor to have that broadening influence applied to all our young men. The condition that he mentions is not at all peculiar to the engineer but is general among American men, and furthermore, it is extraneous to the technical part of the engineer's education. On the first point I need not dwell. As regards the second point, I think, in the first place, that languages, not only one's native tongue, but foreign or even dead languages, are subjects that can be taken up very early in a child's education. They present no difficulties that a child cannot successfully master. I think that these things should be taken up, not in our colleges, but in our primary schools. The scientific studies are too exacting to be begun early. Our curricula should be shifted so as to put down languages and kindred studies and put up the scientific studies. There is too great a tendency nowadays to bring science into our lowest schools, where the children are not ready for it and cannot appreciate it, and often cannot comprehend the principles involved, especially where they are not presented by a capable instructor. The study of literature can be taken up in more mature years, and much more easily, if the child has had an early training in the language itself.

As regards the relative merits of the dead languages and the modern languages, I am not sure that I agree with Dr. Steinmetz. I think that as much broadening of the mind and as much deep, philosophic thought can be obtained from the study of Chinese literature; for I understand that men like Confucius, were great thinkers and good writers. I think this breadth of mind can also be obtained from the study of many modern European languages.

I want to emphasize that the student should acquire general culture before attending the technical school; in the technical school his attention should be concentrated upon his technical studies. His technical training should be, of course, as broad as possible; it should include operating as well as designing engineering, and any other aspects of the subject that can be handled. I would emphasize further that the actual broadening value of any study depends not so much upon the study itself as upon the way in which a study is presented. There are numbers of instructors in the classical languages who do not have the slightest broadening effect upon the students, simply on account of the way in which the subject is presented. On the other hand, a well trained instructor can, in discoursing on even a technical subject, treat it in such a way that the student will be led to look upon it broadly, and at the same time be taught to view in the same way the other aspects of life. It is the personal contact with the instructor that counts. As I look back over the educational period of my own life I feel this very deeply—the training that helped to broaden my mind did not depend upon the particular subject I was studying, but largely upon the man under whom I studied.

John C. Parker: The profession owes a considerable debt to the men who are doing the work Mr. Dooley has told us of, in training non-technical men. The actual operation of this training may be local; the significance of the thing is not local, it is not vocational; it is work which is both national and vitally human.

In Mr. Dooley's modesty and generosity toward his students I think he may be doing himself and his collaborators some slight injustice. All of us who have had to do with educational work know how hard it is to keep students up to the mark. It must be particularly hard in teaching night school. It boots nothing to say that these students are the most ambitious among the men who are working hard in the day time. Of course they are, they would not undertake the work if they were not; but I have found by conversation with men who are carrying on this class of work that many of the young men who have all sorts of laudable ambition and who undertake to piece out their daily experience by definite educational processes in the evening, enter the work under a mistaken ambition. They expect to reap an immediate reward. When the period of disappointment comes to the student, it must work hardship for the teacher. Even with the fellows who are not disappointed the teachers must find that after 9 or 10 hours in the shop it is pretty hard to hold their interest and attention. The teachers too, have been working during the day time, and at night they are called on to use the utmost tact and judgment in bringing to the students under their care the real utility of the work.

D. B. Rushmore: What is education for, or what are people after when they seek to obtain an education? At a recent meeting of the Schenectady Section, Dr. Raymond of Union College said he had come to think that the object of life was to be an electrical engineer. He thought perhaps there might properly be introduced into it one other object—that the object of life was to live, and one idea of education was to teach men how to live. All of us have to give attention to other matters besides electrical engineering. One thought that is perhaps expressed more frequently than others is the elementary law of life—that a man's first object is to obtain a source of income. A man has to be an earning power for himself and for those dependent on him. That is the first requisite; possibly that has led to a mistaken notion that that is the only object, which it is not. Apparently, however, it is the first object of our existence. Therefore, our education, whatever else it may be, must be such as to provide for that. A part of our education should, I believe, consist in teaching us subjects which may be turned to practical use as a means of subsistence.

In our capacity for earning power we have to deal with the fact that education is not through when we leave college. I think we have to keep at it through life. In judging a college education, we are only considering the base of the pyramid. We wish to build to a maximum height. If we build that base broadly we may not in the future reach a very great height. Nor, if we build on too small a basis is the structure likely to be very stable, and therefore we shall fail in the same way. Just the right dimensions to build is probably impossible to state, and must be determined as the result of judgment and experience.

Mr. Osgood brought out the interesting point that not all engineers are manufacturing men or college professors. There are many people to whom, from the purely monetary standpoint, it is desirable to leave engineering work and to associate more directly with mercantile life.

A man cannot travel in a great many different directions, and travel very far in any one direction; and if he is going to be throughout his life an engineer, who is going to use scientific facts and to some extent theoretical work in his advancement, he must confine himself to somewhat narrow lines. The culture of general education is something we all desire: it is a source of regret to feel that many of the intellectual pleasures of life must be passed over. We find that a certain percentage of our efforts, whether 50, 60, or 75, whatever it is, must be directed along purely scientific lines in engineering work. How shall we divide the other percentage which deals with influence in the family, social and political life, with the general work we should all like to do in the uplift of humanity —that is something we have to decide for ourselves.

Clayton H. Sharp: These papers and the discussion on them have brought out the situation in respect to engineering education. It is shown that we need in engineering work men of various sorts and degrees of educational training. We have heard of the man who takes an apprenticeship course, and his educational training is ended with the close of that course. He becomes a skilled workman of some kind, indispensable in the engineering field. Another man extends his course by taking night school work, thereby getting a larger theoretical knowledge of his subject. He becomes a man who is valuable in some of the higher grades of engineering work. We also have the graduate of the technical school who has devoted 4 years exclusively to the tasks set by a university or a college. His theoretical training is presumably better and more complete than that of the man who has had only 4 years in a night school. Perhaps his practical training is not so great, but in the long run—and not a very long run either—we should expect the college-bred man to excel the other in point of position and standing in his profession.

Dr. Steinmetz contends, however, that in order that an engineer may reach his complete development, not only as an engineer but also as a well trained leader of thought and of progress, he must have something besides this engineering training. He must have a liberal education. However, we may not agree with Dr. Steinmetz that the study of the classics is the one, or even the best way in which to obtain this necessary cultural education. The study of the classics is of undoubted value, having been tested during all the years which have elapsed since the revival of learning. However, it is quite possible to overrate the value of the study of Greek and Latin, particularly as at present pursued, and, as I understand it, Dr. Steinmetz does not defend the ordinary methods of teaching these languages and the literatures which are expressed in them. I believe that an insufficient time devoted to Latin or more especially to Greek is, as far as cultural results are concerned, time merely wasted, since no mastery of the language such as is necessary for a true appreciation of its literature is gained thereby. To understand the genius and spirit of the literature of ancient Rome, it is necessary to be able to do more than painfully pick out a translation of the *Commentaries of Casear* or of the *Odes of Horace*. We should read a literature in a familiar language, preferably its original language, but we do not appreciate literature when we must translate it. That means a mastery of the language. I believe that, as ordinarily pursued, students do not obtain such a mastery of Latin or of Greek, and that consequently one end which is sought, namely, the absorption of some of the spirit and ideals of ancient people, as expressed in their literature, is missed. The resultant advantage which we obtain ordinarily from the study of Latin and Greek and which is by no means inconsiderable, arises from the mental discipline thereby undergone, and the knowledge acquired of the structure and vocabulary of languages which are fundamental, inasmuch as they underlie a large portion of our own language and a large percentage of the languages of modern Europe.

I believe the same thing applies to the study of the modern languages. The technical colleges at the present time commonly require a certain amount of modern languages for entrance, and introduce a certain amount of study of modern languages during the course. In my experience I have found very few graduates of technical colleges who can pick up a piece of French or German literature, and make anything out of it at all. They stand exactly where I do in regard to the lines of Homer at the end of Dr. Steinmetz's paper: I can read them through, but I do not know what they mean. Now, if the modern languages are to be pursued, they must be studied thoroughly enough to give a mastery of the language which will enable the student to make some use of it, at least to bring him to the point where he is not afraid to tackle the language when he wants to get at some information which is conveyed in it.

To reach the highest development, in the engineer as well as in the man, he must be liberally educated. That education necessarily involves the study of some languages, but it must also include some other things. He will need to know something about the history of the rise of the modern world, as well as that of ancient institutions, of the fundamental principles of sociology, and of the rise and present character of our legal institutions. The study of the history of the common law of England and this country is of the greatest educational value. The history of philosophy is not to be ignored; it is important as presenting an entirely different point of view from the one which he will later obtain when he comes to study the exact sciences in connection with engineering work. All these go towards a liberalizing education which, with Dr. Lloyd, I believe must precede the other. However, when it comes to carrying out these ideas, we are confronted with just the same difficulties with respect to cost that we are confronted with in many engineering problems. It certainly in many cases does cost too much to go through such a course of study as this, and it is impracticable to carry it out. However, I think the best engineering schools are looking forward to the day when they can do what many of the schools of medicine and of law and of theology do. and take only men who have been graduated from a liberal course, preferably a four year course, give them the necessary scientific and engineering training, and turn them out with the degree of doctor of engineering. An engineer who has been graduated on that basis is immediately put on a rather different plane from the one who has taken the courses which are of a purely engineering nature. If we are to have great men of leading and of light in the engineering world in the future, I believe they will be, to a large extent, men who have been through a course of this character.

Jas. G. White: This subject is one of such fundamental and universal interest that I can scarcely refrain from expressing one or two opinions. There is an unquestionable advantage in having these two papers presented simultaneously, and in seeing what we might call the Alpha and Omega of the education of the engineer presented from two opposite sources; one covering such general education as may be added to the ordinary mechanic's and tradesman's training; the other advocating that broad, liberal, and almost universal education, which can be attained only by a very few. Probably all of us realize that such master minds as those of Mr. Fish, Dr. Steinmetz, and Professor Karapetoff would be broadly educated under whatever circumstances they might be trained, and wherever their lots might be cast. Most of us, however, are not blessed with such ability, and it is impossible to cover so large a portion of the field of education.

Even Dr. Steinmetz can cover only a small fraction of the world's knowledge to-day, and most of us must be satisfied with a much smaller fraction of that knowledge.

I believe thoroughly in a study of the classics, and I also firmly believe that this is possible for every engineering student, whether of Mr. Dooley's school, or of the sort that Dr. Steinmetz advocates. My suggestion as to the solution would be that the study of classics may be done, at least partly, in one's own language. We can study the classics of English literature, at least, and the student of Mr. Dooley's school can get real benefit from them. I quite agree with the previous speaker that Latin and Greek, which are alone considered classics in a narrow sense, are of comparatively little value as taught in the majority of universities and colleges. Instead of imparting a training in mental facility, the training is largely a matter of thumb facility in handling lexicons.

I am reminded of a remark made by the Rev. Dr. Boynton. In speaking of the Cornell spirit, he said that Harvard stood for style, as ordinarily interpreted by college men, Yale stood for pluck, as claimed by Yale men, and that Cornell, as he understood it, stood for work. Dr. Boynton said he was prepared to acknowledge that Harvard stood for style and Yale for pluck, and he was also prepared to admit that Cornell stood for work. But, he said, he came from a little freshwater college that many people seldom heard of, a college that he thought stood for something that he had not heard mentioned during the evening, and that was for education. That college was Amherst.

In this discussion regarding the classics I would stand for English primarily. I would like, in arranging curricula, to see more emphasis laid on training in English. This would certainly be very useful to Mr. Dooley's students. In studying the best English authors they can learn to acquire a knowledge of English which will be commercially useful, and at the same time they can learn something of the humanities and something of the philosophical side of life. The essential elements of an education as they occur to me at the moment are: 1. To learn to think. 2. To learn to express one's thoughts. 3. To acquire a fundamental knowledge of the general principles of underlying foundations of the work one expects to do. 4. The ability to find information required in connection with the solution of any problem which may be presented, and to put that information into presentable shape, and to reach a correct solution. 5. The ability to apply this general information in a commercial way.

While the study of Latin and Greek may help us to use correct English, there are many other subjects which are quite as useful, and perhaps of even more value. If we could all have the ideal education, it seems to me that it would include learning, as children, to speak two or three modern languages, which can be done easily. If children play with other children who speak foreign languages, they acquire these languages without apparent effort. If they have a nurse or nursery governess who speaks a foreign language they quickly acquire a foreign language in the same way, but the ordinary engineer is not fortunate enough to be able to have had these facilities.

I believe that a study of Latin, such as is required for the ordinary college entrance examination is very useful as an aid in understanding the derivatives of many English words, and at the same time an excellent mental training, and that, added to such knowledge of Latin, one should have if possible, a speaking knowledge of French or Spanish, or both. Practically a knowledge of Spanish is of much greater value to the American engineer than any other language. Our relations with Cuba, the Philippines, Porto Rico, Central and South America, are so increasingly important, and there will be so many more opportunities offered for business relations with South America, and other Spanish speaking countries than with other foreign countries, that I regard the Spanish language as of utmost importance for commercial purposes. Latin will help with both Spanish and French, so that a moderate amount of Latin is useful from all points of view. Then either Spanish or French, or both, can be acquired by reasonable study preparatory to entering college, if possible, keeping up such study during the college course, and later in some way getting a speaking knowledge of such languages. That can be done by residence in a country to which the language is related, or living with engineers or others who speak the language, or in some similar way. However, it seems to me a given amount of time will accomplish more for the average engineer in acquiring a knowledge of the philosophies and amenities of life, or the channels through which we can contribute most to the world, if applied to other subjects than Latin and Greek.

The general problem is: How can we apply a given and moderate amount of time to get; first, the most useful fundamental training, and secondly, the most useful fund of knowledge. For the exceptional man Latin and Greek are certainly very useful, but for the ordinary student I believe Greek should be omitted entirely, and that Latin should be encouraged only to the extent above outlined. It is fortunate for all of us that the building of the pyramid to which our attention was called by Mr. Rushmore, can be carried to considerable height, even if the foundation is narrow, and that we can from time to time build out the foundations, and build up all the courses to the top, and then add to the top. That is what most of us have to do.

I would advocate strongly the study of English continuously throughout the entire college course, say at least 2 hours a week. This study of English should in later years be a study of classical English, and of clear and explicit expression in English.

The entrance requirements mentioned by Dr. Sever might be advantageously modified by omitting the German requirement, and requiring only one language, either Latin or French. Our own language is based much more largely on Latin than it is on German—German derivations are few. As a basis of acquiring a better knowledge of English, Latin is much more useful for the ordinary engineer or ordinary man of affairs than is German. In the affairs of actual life there is not one graduate, I should say, in ten thousand who will have any occasion to use German. Furthermore, I would require a certain amount of study of such subjects as logic, mental philosophy, and principles of law. For non-technical studies we might take 2 hours of English and 3 hours of general culture subjects throughout the entire course. This would require omitting some of the more technical subjects, but if the object of education is to teach a man to think, and to teach him to express his thoughts, some of the more technical subjects can be omitted without detriment to his general education. If a young man is going into operating work a knowledge of the intricacies of machinery design is not of much use to him. It would be better if one could have a 5-year course, and spend 4 years in general educational work. including mathematics, physics, chemistry, English and general culture subjects, and then specialize as to extremely technical work in the fifth year, after the young man has chosen, to a certain extent, the direction in which his life work is to be pursued. By planning such courses, it is possible to give sufficient of the general knowledge of electricity, for example. This fundamental knowledge can be acquired without going too much into detail, or into the abstruse mathematics or theories. These advanced subjects can be taken up afterwards as one's special bent leads or work requires.

George F. Sever: The subject of technical and engineering education is so large and voluminous that it is impossible to attempt to take up all the points that have been presented this morning and discuss them to a finality. At a three days' meeting in New York last week many professors and engineers discussed quite fully the subject of the promotion of engineering education. I think there was not a single new thought presented before that meeting that was concurred in by any two men. For instance, there were suggestions for a ten-year course, a nine-year course, and then all the way down to a one-year course for the training of engineering students. The University of Missouri has established a five-year course for engineering students. Leland Stanford University is endeavoring to establish a five-year course, the idea in all these longer courses being to introduce subjects other than those of engineering. Acting on Dr. Steinmetz's suggestion, we may have to extend our courses to six, seven, and perhaps even thirteen years, in order to make a man perfect in the use of Latin and Greek.

Dr. Steinmetz and the past-president of Harvard University are certainly not in agreement. Dr. Eliot states that a man can obtain "the essentials of a liberal education" by reading five feet of books, and in that list is included all the best literature in the English speaking world, much more weight being given to English literature than to any other. I would call this to Dr. Steinmetz's attention, although undoubtedly he has already noticed it. At Columbia University in 1897 there was established a definite six-year course open to students preparing for the engineering professions. The student starts in the college and takes three years of a liberal education, which is arranged to include Greek and Latin, or any other language, philosophy, sociology, or any other subject recognized as giving liberal training. The last year in his college course includes all the subjects needed in the first year of his engineering course, so that when he receives his degree of A.B. at the end of three years he will be prepared to start in the sophomore year of the engineering course and pursue the latter for three years, and secure the engineering degree which the university gives at the completion of that course. We have thus established, and only after very careful consideration by the authorities, a six-year course, including all the so-called dead languages as well as the modern languages and the engineering training. Now, if a man enters when he is 17 years old, he will be 23 before he leaves the university, and he will have had this excellent classical training. But the question is, will he advance in the community as a high type of man more rapidly than the trained engineer who has not had this classical training? This is a subject that has been discussed many times, and we have not found that very many men are taking advantage of this six-year course, which includes all that fundamental training which Dr. Steinmetz considers the best for the rounding out of the engineer. It is my opinion, that the engineer after he has had this technical training possesses the capacity for taking up any classical language, analyzing it thoroughly and making himself a scholar outside of the university.

As a rather convincing argument for the above idea, I will call attention to a paper by Mr. Fish entitled, "Continuity of Education," in which he urges most strongly all men, engineers and others, to continue after graduation the education, and the spirit and the inspiration which they received in their college training. I think that is the time when a man should perfect himself in the classics, if he has not had them in the preparatory schools. As an educator I want to point out that Dr. Steinmetz wants us to teach Latin and Greek, and Mr. J. G.

White wants us to teach Spanish. This brings us up to the point mentioned by Mr. Osgood, that he wants men trained to manage corporations. If we continue introducing subjects we are going to have engineering courses 20 years long, and never graduate our men; and if we keep them with us too long they will become absolutely stale. We are drawn upon continually to inspire students, but like a storage-battery we get, at the end of the season, entirely discharged, and it takes a long time to get back again our inspiration to stimulate ideas in the men. We can only turn out an average product, although there may be certain stars in that product who will make distinguished successes in certain lines, but we cannot develop all the men for a particular interest. We give all the students in our engineering schools during the first year a perfectly uniform course on the engineering fundamentals, such as mathematics, chemistry, physics, drawing, etc., and in the second year they take calculus, analytical mathematics, quantitative analysis, and drawing, and other fundamental subjects. Then they begin to diverge more widely and take those subjects in the different courses which they will need in their future practice.

To accomplish this we require 18 hours of lectures and recitations per week, and oftentimes five and six afternoons devoted to laboratory and drawing room work per week. How to get in all the subjects which are considered so essential in four years I fail to see, and many of my colleagues entertain that same feeling. So that we are obliged to take the supply as it comes to us from many preparatory schools, require certain preparation for entrance, and then try to turn out the average man.

C. A. Adams: I must have expressed myself poorly indeed to be classed by Mr. Osgood as an advocate of a narrow education. This would seem particularly strange as I am now connected with and have been instrumental in bringing about the establishment of a school of engineering which requires a college degree of students seeking admission. The principal object of this plan is to encourage the laying of a broad foundation, and it is a fact that about one-half of the men seeking entrance to this school have been students of the classics, usually in their secondary school period where such study is likely to be most effective.

The point which I had hoped to make was that among the young men entering the engineering profession there are various types of mind, each with its particular field of usefulness and each requiring a different training for its best development; and that the lack of a classical training is not necessarily synonymous with a narrower education. This is much more true to-day than it was 30 years ago, owing to the greatly enlarged opportunities for the study of the literatures of other peoples than those of Greece and Rome, as well as for study in those vitally interesting fields of government, economics, social ethics, etc. I also wished to suggest the possibility that even the engineer with a so-called narrow training may prove to be a very useful citizen.

Mr. Osgood's remarks concerning designing engineers and the study of design show that he has in mind the routine mechanical computer and not at all the real designing engineer. I am particularly interested in design problems and use such problems in my teaching work, not because I expect to make designing engineers out of all my students (since I know that only a small percentage of them follow this line of work) but because such problems, carefully followed up, seem to offer one of the best means of cultivating the habit of careful, thorough analysis of any problem presented, and the habit of clear, independent thinking, the very thing the lack of which Mr. Osgood deplores.

Mr. Rushmore made one statement with which I wish to take issue—he said that the object of education is to enable us to provide for our own existence and for that of those who are dependent upon us. That may be one of the objects, but I feel very strongly that more emphasis should be laid upon the fact that the great object of education is to develop and maintain a maximum of happiness. That maximum of happiness does not depend upon how much money we can earn, but it does depend upon whether or not we are working in that field for which our particular talents best fit us; in that field where we can contribute most to the society of which we are a part.

C. R. Dooley: The fundamental idea of the night school is to train all-round men, to make them able to use their minds and their hands, and as Dr. Steinmetz mentions in the opening paragraph of his paper, able to attack new problems whatever they may be, to solve them right, and solve them quickly the very first time they see them.

Professor Adams and Mr. Scott have both referred to the many different kinds of men, suggesting that there may be demands for many different kinds of education. With an increasing number of kinds of educational systems, the problem of early selection becomes increasingly more important. The parents, and the teachers in the common schools, should be able to direct the general trend of the higher education of children. That, I believe is the highest responsibility.

One graduate of this year's class went to one of the large traction companies in New York. I am sure he will make a very excellent operating man. I was pleased to send him out to such a promising field for his beginning. I mention this only to show that part of our work, the night school feature of it, is broad enough to cover all phases of the profession, which any student may choose to enter.

The matter of holding the boys' interest and keeping them in school is seldom thought of by the instructors. I think the success of the school is due, first, to the personal interest that the instructors have in the boys and their work; secondly to the fact that the instructors are fully informed on their subjects—the students respect the information they get as being as near as possible to truth—thirdly, which is by far the greatest reason, that the boy has worked long enough at his everyday tasks to appreciate that he needs what Mr. Osgood says he lacks, namely, the ability to think. He views life from the workman's standpoint. He knows that he needs to correlate his thinking abilities with the manipulation of his fingers. It is this complete appreciation of the situation that holds the boy down to business.

Geo. H. Gibson (by letter): Engineering projects are, and should be, undertaken primarily to serve human uses and they can be carried out on any considerable scale only by social, human means, as coöperation, conference, organization, salesmanship, and other agencies included within the scope of business and affairs. Therefore, worldly wisdom, practical psychology based on observation of and experience with human nature, is as worthy of any man's study as are steam, electricity, or steel girders.

Dr. Steinmetz directs attention to the precious records of human experience preserved in the literary productions of ancient Greece and Rome. But is he not carrying the point too far when he urges the study of Greek and Latin to the exclusion of French and German? The content of these ancient languages is available in more or less perfect English translations, and nothing more will ever be added. On the other hand, French and German literature grows day by day; and this is particularly true of technological literature which is, indeed, valuable to the engineer who is pushing ahead into new developments only so far as it is new. If one waits for it to be translated by the journals or by text-book compilers, he will remain always a year or two behind the times; and many excellent original papers and monographs are never translated.

Illustrating the value of foreign technical literature, the writer makes a practice of searching carefully the various digests and indexes, including several published on the other side, with a view to catching all new developments in certain lines. It is his experience that the amount of original information appearing in the German and French engineering journals is at least equal to, if not greater, than that appearing in the English and American engineering journals.

This is especially true as to lines that might be classified under mechanical engineering, including, for instance, such subjects as steam turbines, high-pressure and high-efficiency centrifugal pumps and blowers, chemical processes for water purification, heating and ventilating practice, steam condensers and accessories, etc.

This may be due to greater activity in research, or it may be due to less reticence among investigators on the other side in giving results to the public; but nevertheless the fact remains that if the specialist wishes to keep up with the month-by-month progress of his line—and in many lines innovations appear in such rapid succession that that is commercially essential—he must read the French and German technical papers or else have them read for him as they appear.

As showing how incompletely the "state of the art" is presented in American technical periodicals, only recently the writer came across an article in a French journal summarizing the latest developments in steam condenser practice in both Europe and America. This article not only covered some recent and very ingenious condenser work done in Europe, but also gave the gist of the more important patents taken out in the United States. It contained, therefore, much information that so far had not appeared in our own papers. So by carefully following these foreign papers we are better able to keep in touch with what is going on next door. The most satisfactory way of doing this is to read or glance through the articles one's self rather than to trust to translations or abstracts. In order to do this one must read French and German, which therefore have a practical value to the engineer that Mr. Steinmetz would seem to deny to the modern languages. Further, it is the writer's experience that in reading on a subject with which he is somewhat familiar the difficulties of a foreign vocabulary are greatly minimized and that, therefore, the acquaintance with a foreign language which can be obtained in the usual college course will serve to good purpose. The technical terminologies of French and English for example, are largely identical.

A. E. Kennelly (by letter): While wishing to endorse what Dr. Steinmetz has said about the value of the classics and of ancient languages in education, I think that he hardly does justice to the corresponding value of modern languages, and I submit that these also have claims to be recognized.

It is, perhaps, open to debate whether the modern languages of Europe offer so great a range of variation in mental perspective, or in the working philosophy of life, as do the classics; but it can hardly be doubted that in ideality, poetry, humor, and subtlety of intellectual discrimination, the languages and literature of modern Europe are on equal terms with the languages and literature of ancient Greece and Rome.

Moreover, I submit that no education can claim to be liberal which does not give to the possessor at least a reading knowledge of one modern language besides the mother tongue.

H. W. Fisher (by letter): I feel that my Greek and Latin have been a help to me in many ways, but I think more practical good might have been obtained had I spent less time on them and more on English. Once I heard a paper read before the Engineers' Society of Western Pennsylvania, the style of which was so noticeable that afterwards those present, as if by common consent, made special mention of the author's diction, although, from the engineering standpoint, the paper was of a high order.

I believe that our engineering colleges should accumulate a library of papers of this kind and require the students to make a special study of them at some part of the college course.

During the last two years I have become interested in the international language Esperanto. In it I find much that is most valuable in giving me a clear and logical idea of grammar, of language, and how idioms should be translated, etc. Now that this language is being adopted so largely by international societies and is being taught in so many schools, I believe that at least one year of Esperanto previous to the study of other languages would be invaluable as a mental drill, and would acquaint the students with the fundamental roots of Latin, and the most important European languages. Afterwards he could use Esperanto in conversation, or correspondence with foreigners, which I have done, much to my personal satisfaction.

J. Dalemont (by letter): The paper by Dr. Steinmetz shows the importance of the question of classical education for engineers. The same question has been agitating the minds of Europe for some time past, particularly in France and Belgium, where there is a tendency to cut down the time devoted to the study of dead languages. This, however, should not be used as an argument against Dr. Steinmetz's contention, as it is quite possible that in these countries too much time has hitherto been given up to the classics.

There are two points on which I think most people will agree, namely: 1. The elite of all cultured classes in any country should receive an intellectual training, which will allow them to meet on common ground, when discussing social, economic, and political conditions.

2. The engineer, of all men, can least afford to ignore social problems, because of his responsibilities, which are often greater than those of most men, and of the far-reaching effect of his work, but particularly, because of his close connection with industrial activity, which is becoming more and more the centre of modern life.

From these two fundamental facts we may conclude that the training of the engineer should have something in common with that of the other professions. As all high intellectual careers suppose a special higher education, it is to the college that we must look for some method of exerting on the mind of every student the same general influence; and in order that his mind shall bear this universal stamp, the question of the choice of the studies imposed on him by the college curriculum becomes a very important one.

It remains to be considered what studies are especially adapted to the formation of the judgment in considering social conditions. It cannot be denied that an adequate knowledge of ancient civilizations tends to develop an observant as well as a philosophical mind, two qualities of especial value in a close study of modern life. It is this disciplinary training of the mind which will enable the engineer to assume in society the place which Dr. Steinmetz would have him fill.

But we may here ask if it is advisable to exact that such studies be pursued by all students in the Greek, Latin, or other dead languages. It has often been held that as far as the training of the judgment is concerned, a study of these ancient civilizations through the medium of translations is as beneficial as if made in the original. It seems to me, however, that the study of ancient languages is most beneficial to the mind and may be considered as the starting point of all high intellectual culture. If colleges were frequented exclusively by the intellectual elite, it would be an easy matter to decide upon a curriculum which would be suitablé for all. But such is not the case. Very wide indeed, and justly so, are the roads leading to a college education, and the elite—based solely on the result of work and effort, in accordance with the requirements of our modern spirit and the interests of society at large—is the outcome of a slow process of selection and elimination among the thousands of young men who yearly set out on these roads. Here arises the real difficulty in deciding this question of the humanities.

Should every student be required to follow a course of studies which would be of benefit only to the few making up this elite? Certainly not. The course of study should not be chosen for the latter only, but should be adapted to the needs of every student—whatever career he embraces. In retaining the study of the classics, therefore, some effort should be made to modernize the system of teaching them, so that they may be of benefit in preparing the mind to face the requirements and responsibilities of modern life. To my mind, a college course should not be considered as an immediate means of making a livelihood, as such a mission belongs more properly to the professional course.

The foregoing remarks are in no way opposed to the principle of classical education; they are merely intended to call attention to the fact that the studies in connection with such an education should be kept within certain limits. If at the present moment there is a desire in Europe to curtail the study of dead languages, it is because that country is suffering from too great a development of classical education. It must be remembered that the study of the classics, like the study of the positive sciences, will not only impart a certain knowledge, but will moreover determine a certain mentality. The mentality of the poet is not that of the business man, while that of the scholar is not exactly that of the engineer. They may have certain points of resemblance, yet the differences between them will not allow of their being formed in exactly the same mould or in the same intellectual atmosphere.

To sum up, if the advantages of the classics and the necessity of teaching them are incontestable, it would, on the other hand, seem injudicious to impose a classical course on all students indiscriminately. It might be beneficial, as is done in the colleges and lyceums in France, to allow the student the option among several combinations of studies, or again, as in the German universities, to allow him a certain liberty in choosing some of the courses which he is to follow.

Ralph D. Mershon (by letter): I entirely agree with Dr. Steinmetz that breadth of education is desirable. I agree that the study of the Greek and Roman civilizations will conduce to that end. But I do not agree that the study of Greek and Latin constitutes the most effective means of arriving at breadth of training or that such study will, in itself, lead to knowledge of the Greek and Roman civilizations.

The "average man" (that mysteriously elusive individual with whom we must necessarily deal in such discussions as this) who studies Greek or Latin, or at least the average American student of these languages, is kept too busy struggling with the intricacies of the language itself to get much appreciation of the subject-matter of the text. Such mastery of the language as he may achieve in a college course is not sufficient to make it an adequate vehicle for beauty of sentiment or depth of thought. Such appreciation as he attains of the art and literature and such knowledge as he acquires of the philosophy, religion, and politics of the Greek and Latin civilizations come through studies supplemental to that of the languages; studies pursued in English and which could be just as well pursued without any reference to the Greek and Latin languages. The truth of this may be easily verified by comparing notes with those whose college courses have been along classical lines. That it should be otherwise, would mean the study of these languages to an extent hardly expedient for the average man, certainly not expedient for the engineer. This being the case, the broadening influence of Greek and Latin is confined, mainly, to the discipline resulting from the study of language as such.

In general, it seems to me much better to get the discipline through the study of modern languages, mathematics, and such other subjects as will give it and in the end leave the student with an equipment of value to him in after life—of much more value than Latin or Greek could possibly be. Such study, accompanied by studies in English bearing upon the Greek and Latin civilizations, would accomplish the result aimed at and in a manner much more satisfactory and expeditious than the study of Greek and Latin. This course is especially expedient in the case of the large majority of American technical students, who are limited as to means and must make every minute devoted to education count for its fullest worth. For those who are so inclined and have the time and means at their disposal, the study of Greek or Latin, or music, or art, or any other study the pursuit of which may be considered rather as a luxury than as a necessity in the matter of breadth of training or of utility, would be a highly delectable preliminary to an engineering education; and advisable, if the individual be of a grain to take so high a polish and still be effective in the daily grind of a useful life.

The utilitarian advantage mentioned in the paper as incident to the study of Greek and Latin; namely, that of easy comprehension of scientific terms, is of considerable moment only in special cases; but even then it would hardly justify the immense amount of time such study entails. I fail to see why it would not be better to expend the time necessary to the memorization of the comparatively few terms employed in science rather than the vastly greater amount of time necessary to memorization in the study of these languages.

I know one engineer in whose experience such " small Latin and less Greek " as is his portion has been of little value; while his experience with French, the only modern foreign language he has studied, is quite contrary to that ascribed to modern languages by Dr. Steinmetz. His French has helped him in engineering work (and otherwise) in spite of the lack of practice, because not all foreign works of value are translated into English, or, at best, tardily. He has found scientific French easier than any other kind, in spite of the technical terminology and this, I believe, is the experience of most other students.

Dr. Steinmetz speaks of the value of a broad education in fitting the individual

> To perform his duties as a citizen of the Republic during the stormy times of industrial and social reorganization which are before us.

Here again I am in sympathy with him as to the end, but not entirely as to the means. Anything which may contribute toward each taking his proper and intelligent part in the change which must come, is to be ardently desired. The first essential requisite to this end is not broader training, but utilization of such training as may now be had. Until the intelligent men of this country, until the engineers—since we are addressing them—realize that they have civic duties and will conscientiously attend to them, each to the extent of his ability, increased breadth of training will not accomplish much in increasing the efficiency of citizenship. Until engineers shall cease to be too busy to attend to such duties; until they are willing to give to them some measure of the attention and thought they would devote to an engineering proposition; until they come to consider them duties in the full sense of the word, instead of evading them and taking a sneaking pride in such evasion; little will be accomplished in bettering citizenship no matter how education may be broadened. When such a change of mental attitude has been wrought, broader training as improving citizenship will be effective, and not until then.

After all, I question whether breadth of mind and independent thought are not more effectively fostered in the student by breadth of mind in his preceptors than by any special course of study. A course of study, in itself of the narrowest kind, may be made broad by the administration and direction of a broad mind; a mind from which the student will unconsciously absorb that which will influence him to larger reading and thought during his college course, and give him such an impetus in this direction as will persist after he has left college. For breadth of training cannot be attained in the brief span of a college course, any more than can the mastery of any given subject; and the college course is, at best, but a preliminary training and guide to the later self-training and independent thought, leading to the desired end.

There are a number of other points in the paper open to question, such as the definition of education; the sweeping implication that engineering is the application of empirical science; the implication that the engineer is limited to a single vocation, and the statement that this vocation necessarily tends more to onesidedness than the vocations of men in other callings. But these are points beside the main issue.

The paper appears to me inconsistent, and to one unacquainted with the author might appear pedantic, in that, although addressed to those having presumably no knowledge of Latin or Greek, it contains a number of Latin and Greek citations and allusions, and ends with a Greek quotation.

C. P. Steinmetz (by letter): I am glad to be able to agree with most of the speakers, even with those who can find no use for the classics in the training of the professional electrical engineer. We do not need the classics if we take the narrow view that the purpose of the college is to train the human animal to perform the functions of a professional electrical engineer, just as we train some wild animals to perform some other functions or tricks. But in this case we should stop talking of college graduates as educated men. What I was aiming at was the education of the intelligent being to perform the duties of citizenship in the field of the electrical engineer.

If we desire to train boys to be professional electrical engineers then naturally, no matter how much we lengthen the courses, we cannot expect to produce at the same time competent designing engineers and operating engineers and consulting engineers and corporation managers and constructing engineers and commercial engineers, etc. That is not what I desire. It is not what Mr. Osgood wants, as I understand him, to have the college turn out operating engineers. What he complains of is the rather insufficient development of common sense and ability to think in the product of the present college, which results from the narrowness of the professional training. It is this defect which I desire to obviate by advocating a broadening of the education.

Mr. Rushmore has well expressed the purpose of education as being for the purpose of teaching the boy to live; that is, to get the highest satisfaction out of life in its relation to the human race at the present time, and the human race of past ages as recorded in their literature, their work, etc., and the relation to the future of mankind, the work and the life of the human race in the future. For this purpose it is necessary to teach him to earn money. To live satisfactorily we must have money. The earning of money is the means but is not the purpose of life, and I consider it as the great fault of our present age, and especially of our nation, that we largely mistake, in this respect, purpose and means. And just here a retrospection into ages where a clearer view existed on the relation of the purposes of life and the means of living, where money was not the standard of success, is especially beneficial.

In my paper I have attempted to outline the situation and to suggest one remedy, in the study of the classics. I do not desire to say that is the only one. There are other factors contributory to that broad education. To mention only one, since its educational value is frequently not realized—college athletics. I have not attempted to suggest methods of accomplishing the result, because I believe that the means of broadening the education will be developed with increasing rapidity by the acceleration afforded by the pressure from within and without the engineering profession.

What I would like to see is a classical academic course interposed between the classical high school and the technical college, and then to have the college work succeeded by a year of practical experience in a manufacturing or operating company—one year of graduate work rounding off the education. This would mean 12 years from the entrance in the high school to the entrance, as master of engineering, into the profession. It is a long time, only 1 year less than that demanded by the German gymnasium and university. Very many boys could not afford it. There are many who could afford it but do not avail themselves of it; some because of the inherent desire of American boys to become independent and self-supporting as early as possible, when they lack the experience and intelligence to realize the necessity of education; others, because their parents have succeeded in life without a college education, or with a very meagre education, and do not realize that what was sufficient in former times when the world was young, will not be sufficient in the times that are coming.

What can be accomplished without greatly lengthening the course is to establish the classical languages, Latin and Greek, as entrance requirements in the school or college, devoting the time which many colleges devote to modern languages to classical literature and languages.

Coming to immediate possibilities: what I would like to see introduced; what I believe can be done immediately; what I should urge, is to recognize the classical languages as equivalent to the modern languages in the entrance to college and in college studies. That is, where one to two languages are required for college entrance, the student should have the choice of any of these five languages—Latin, Greek, French, German, and Spanish, and from these languages he should be allowed to choose those which he desires to continue in his college course, thus leaving the language study in college elective among these five languages. That can be done, and should be done immediately.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., July 1, 1909.

POLE-FACE LOSSES

BY COMFORT A. ADAMS, A. C. LANIER, C. C. POPE, AND C. O. SCHOOLEY

INTRODUCTION

The object of the experiments recounted below was to establish a reliable and if possible a *rational* quantitative relation between the pole-face losses and the principal variables involved therein. The work was originally undertaken as a supposedly small part of a larger investigation without any realizing sense of the amount of work involved or of the difficulty of obtaining reliable results. Another time the method employed would be modified in the light of this experience, but although the results are not altogether satisfactory from the standpoint of the investigator, they are sufficiently accurate for most practical purposes, and it is believed more reliable than those heretofore published.

The experimental work was so recently completed that it will be impossible at this time to give the results, or their analysis, in a thoroughly digested form.

THEORY

In any dynamo-electric machine with a toothed armature the magnetic flux density at the pole-face opposite a tooth is greater than that opposite a slot, and as the armature rotates, the teeth carry waves of flux across the pole faces; that is, each point on the pole face is subjected to a pulsating flux density which gives rise to eddy currents in the mass of the pole face. Some energy is also dissipated by magnetic hysteresis, but at the ordinarily high tooth-frequencies the eddy-current loss predominates; with solid pole faces the hysteresis loss is negligible. In any case these phenomena are so complex from the standpoint of quantitative analysis that it is practically impossible to separate the two losses.

Were it not for the magnetomotive force of the eddy currents themselves the flux would distribute itself, both outside and inside of the pole shoe, in such a way as to correspond to the minimum total reluctance; that is, the flux pulsations would gradually die out and the flux tend toward uniform density in proceeding from the pole face back into the mass of the pole shoe. But the eddy currents materially hasten this equalization in their effort to damp out the flux pulsations of which they are the result. This effort to equalize the flux density is maximum at the surface of the pole shoe where the maximum pulsation takes place, and it undoubtedly alters to some extent the flux distribution over this surface.

Within the pole shoe the disturbance is propagated in the familiar manner of electromagnetic waves, the attenuation constant being very large, owing to the high permeability and conductivity of the medium and the relatively high frequency of the pulsation, the penetration wave-length being very short for the same reason.

With solid pole shoes and average constants the wave is practically damped out at a distance back from the pole face equal to about one millimeter, the pulsation being thus confined to a very thin surface layer.

With laminated pole shoes the conditions are quite different. This difference can easily be understood by reference to Figs. 1 and 2. Fig. 1*a* is a plan view and Fig. 1*b* an elevation of a solid pole shoe, together with the teeth. Fig. 1*c* shows an assumed sinusoidal flux variation at the pole face. In Fig. 1*a* approximate eddy-current paths are shown in light lines; the directions as indicated by the arrows correspond to a right-to-left movement of the teeth across the pole face. The transverse portions of the currents are the ones which produce the damping of the flux pulsations and are predominant in the case of solid shoes; they will be referred to as the *damping currents*.

With ordinary proportions of teeth and pole face, those parts of the eddy currents in the circumferential direction are relatively small; their tendency is to screen the center of the pole from the flux pulsations and to drive the latter to the two circumferential edges; these circumferential portions of the eddy currents will therefore be called the *screening currents*. With solid pole shoes the screening currents may safely be neglected.

Fig. 2*a* is a plan view of a portion of a *laminated* pole shoe showing the approximate eddy-current paths at the pole face, and Fig. 2*b* is an elevation of the pole shoe. Except for the laminations, Figures 1 and 2 are intended to represent the same conditions.

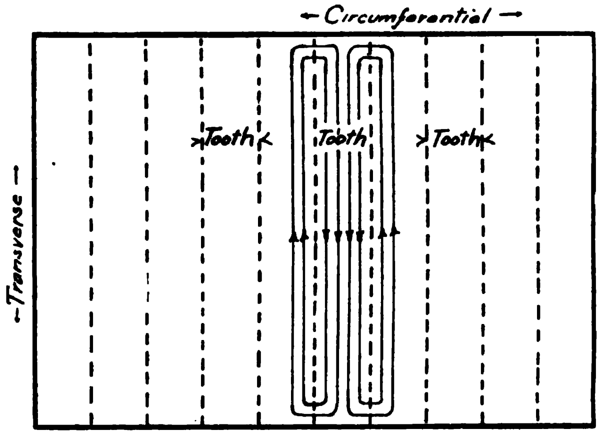

Fig 1a

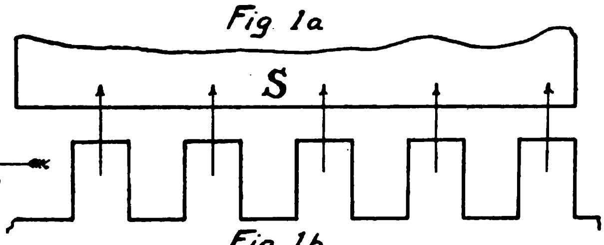

Fig. 1b

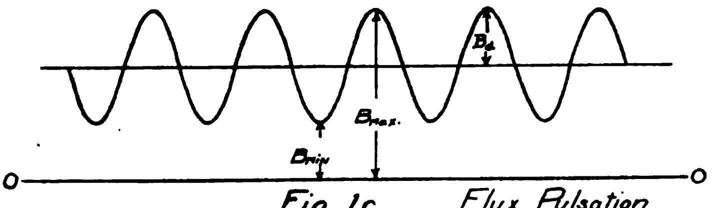

Fig 1c Flux Pulsation at Pole Face

In the case of laminated pole shoes represented in Figs. 2a and 2b the circumferential or screening currents predominate, and the transverse or damping currents are not only greatly reduced in magnitude but also in effectiveness; that is, the pulsations will penetrate much deeper into the pole shoe and the advantage of the laminations will be considerably neutralized.

Both the damping and the screening currents have the same origin and nature. The damping currents try to check the penetration of the flux pulsations into the pole shoe perpendicular to the face, and the screening currents tend to check the penetration of the flux pulsations into the laminæ from the side surfaces towards the center. The chief difference is that

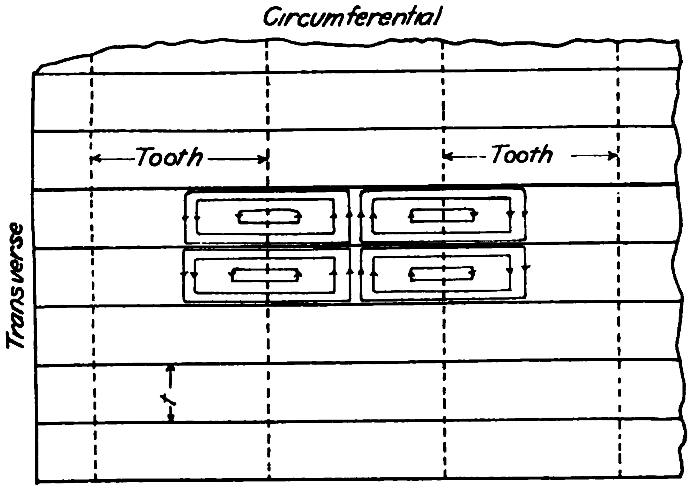

FIG 2a

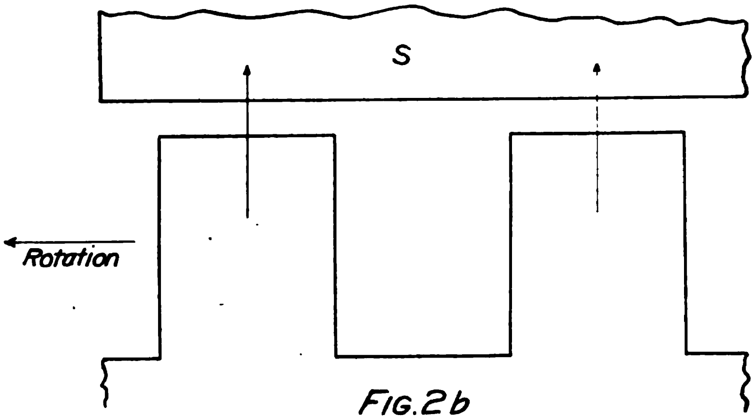

FIG. 2b

whereas the damping currents tend to force a more uniform circumferential flux distribution the screening currents tend to disturb an otherwise uniform transverse flux distribution across the section of the laminæ. Both tend to increase the reluctance of the magnetic circuit and to decrease the eddy-current loss. The screening currents, however, tend to increase the hysteresis loss, other things being equal.

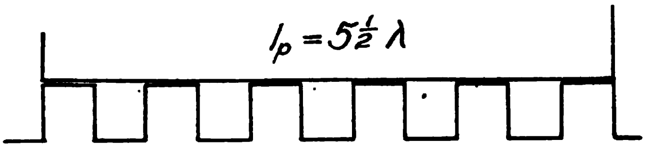

FIG. 3.

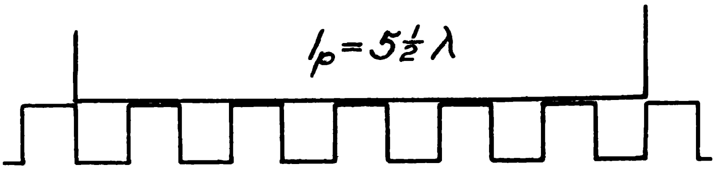

FIG. 4.

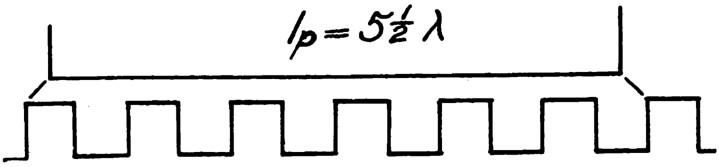

FIG. 5.

There is another source of energy loss in the pole face which is in some cases of considerable magnitude. It is that due to the *pulsation of reluctance of the main magnetic circuit* caused by a variation in the number of teeth under a pole. For example, if the pole arc (l_p) is just five and a half times the tooth pitch (λ), and if the air gap be very short, there will be positions of the armature where there are six teeth under a pole face and other positions where there are only five, there being a variation of reluctance of about 15 per cent between these two positions (see Figs. 3 and 4). Such a variation would cause a pulsation of flux through the whole magnetic circuit and a consequent loss of energy. Of course this variation could be largely eliminated by chamfering the corners of the pole shoes.

On the other hand if the air gap be larger, say about equal to one-quarter of the tooth pitch, the fringing from the pole corners would add about a half tooth pitch to the equivalent pole arc, making it just about six times the tooth pitch. In this case there would be practically no reluctance variations, since the number of teeth under the equivalent pole arc is constant (see Fig. 5).

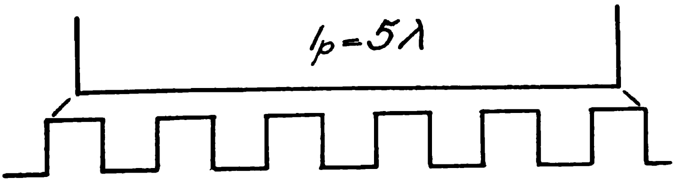

FIG. 6.

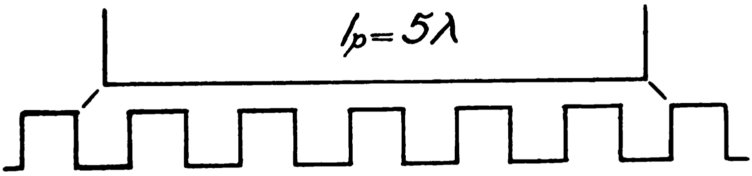

FIG. 7.

If the actual pole arc is just six times the tooth pitch, the minimum reluctance pulsations occur with a short gap and the maximum with a fairly long gap (see Figs. 6 and 7).

As an example, consider the apparatus used by Wall and Smith[1] for the investigation of pole-face losses. The pole face

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[1] Institution of Electrical Engineers, London, June, 1908, Vol. 40, p. 577.

was solid, with square corners, and the actual pole arc was just three and a half times the tooth pitch. Thus with fairly long gaps the reluctance pulsation loss was a minimum, and with very short gaps a maximum. The pulsation was very large at short gaps owing to the large percentage of reluctance variation, probably about 25 per cent. As this part of the loss was not recognized at the time, it made the pole-face loss appear to increase with decreasing air gap at least twice as rapidly as it should have done. This entirely masked the phenomena under consideration.

This loss was also overlooked in the results of Dexheimer's experiments,[2] where considerable discrepancies can thus be accounted for.

Returning now to the damping currents and screening currents, these have both been analysed theoretically, but each independently of the other, the former for the case of solid pole shoes by Potier[3] and Rüdenberg,[4] and the latter for laminated cores by Steinmetz.[5]

Solid pole shoes. Consider a solid pole shoe subjected to tooth flux waves, and neglect the circumferential or screening currents.

Let λ = the tooth pitch in cm., and

v = the velocity of the armature periphery in cm. per second.

Analyze the circumferential flux distribution curve at the surface of the pole face into its fundamental and harmonics, (the wave length of the fundamental being λ), and consider separately the loss due to each.

Let B_1 = the amplitude of the fundamental pulsation, and

B_n = the amplitude of the nth harmonic.

Let μ = the permeability of the pole face and

ρ = its electrical resistivity in absolute electromagnetic units.

Then it can be shown[3 & 4] that the pole-face loss in watts per sq. cm., due to the fundamental pulsation wave, is approximately

$$P_1 = \frac{B_1^2}{8\pi}\sqrt{\frac{v^3\lambda}{\mu\rho}}\,10^{-7} \qquad (1)$$

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[2] "Die Gleichstronmaschine," E. Arnold, Vol. I, second edition, page 649.

[3] L'Industrie Electrique, 1905, p. 35.

[4] Elektrotechnische Zeitschrift, Vol. 26, 1905, p 181.

[5] "Transient Phenomena", p. 355.

and that the corresponding attenuation constant is approximately:

$$\beta_1 = 2\pi\sqrt{\frac{\mu v}{\rho\lambda}} \tag{2}$$

It is somewhat surprising that in equation 1 the pole face loss is proportional to the 3/2 power of the velocity (and therefore of the tooth frequency) rather than to the second power. But this is after all only reasonable, since the greater damping action at the higher frequencies reduces the equivalent depth of the active layer; that is, the attenuation constant is larger and the flux wave does not penetrate as deeply into the pole shoe.

In applying equations 1 and 2 to the harmonics of the flux pulsation, it should be remembered that whereas λ, the tooth pitch, is also the circumferential wave length for the fundamental, the circumferential wave length for the nth harmonic is, $\lambda \div n$.

Neglecting the influence of the damping currents and of saturation upon the flux distribution at the pole face, B_1, B_2, B_3, etc., are proportional to the average pole face density B and may be written,

$$B_1 = k_1 B, \qquad B_2 = k_2 B, \qquad B_3 = k_3 B, \text{ etc.}$$

Then from equation (1),

$$P_1 = \frac{10^{-7}}{8\pi} k_1^2 B^2 \sqrt{\frac{v^3\lambda}{\mu\rho}} \text{ and } P_n = \frac{10^{-7}}{8\pi} k_n^2 B^2 \sqrt{\frac{v^3}{\mu\rho}\frac{\lambda}{n}} \tag{3}$$

The ratio of the amplitude of the nth harmonic to that of the fundamental or the per cent of nth harmonic is, $k_n \div k_1 = a_n$.

Then:

$$P_n = P_1 \frac{a_n^2}{\sqrt{n}} \tag{4}$$

and the total pole-face loss in watts per square centimeter, is:

$$P = \frac{10^{-7}}{8\pi} k_1^2 B^2 \sqrt{\frac{v^3\lambda}{\mu\rho}} \left(1 + \frac{a_2^2}{\sqrt{2}} + \frac{a_3^2}{\sqrt{3}} + \text{etc.}\right) \tag{5}$$

or

$$P = \frac{10^{-7}}{8\pi} k^2 B^2 \sqrt{\frac{v^3\lambda}{\mu\rho}} \tag{6}$$

where
$$k^2 = k_1^2 \left(1+\frac{a_2^2}{\sqrt{2}}+\frac{a_3^2}{\sqrt{3}}+\text{etc.} \right) \tag{7}$$

The watts per square inch of pole face is given by equation (6*a*) where B = average pole face density in maxwells per square inch, v = peripheral velocity of the armature in feet per second, λ = tooth pitch in inches, and ρ and μ are the same as before.

$$P'' = 1.65 \times 10^{-7}\, k^2 B^2 \sqrt{\frac{v^3 \lambda}{\mu \rho}} \tag{6a}$$

Thus $k\,B$ is the amplitude of the *equivalent* sinusoidal pulsation, and the problem resolves itself into the determination of k. The k's and the a's are obviously wholly dependent upon the shape of the flux distribution curve, which in turn is wholly dependent upon b, the ratio of slot opening (w_s) to the tooth pitch (λ), and q, the ratio of slot opening to air gap (δ). Unfortunately the k's and the a's are exceedingly complex functions of these two variables, even under the assumption made above as to neglecting the effect of damping currents and saturation upon the pole-face flux distribution.

Of the two variables involved in k, b ($= w_s \div \lambda$) has for open slot machines a fairly narrow range of variation, being rarely found outside of the range from 0.4 to 0.6 with an average of 0.5.

Then if b is fairly constant, k is largely dependent upon the ratio

$$q = w_s \div \delta$$

that is, with a given value of b, k will be a function of q. As a general determination of k appears to be practically impossible, it will be necessary to consider a few special cases in order to get an idea of the nature of its variation.

For very large gaps, q is small and k obviously approaches zero.

For four other points (q = 2, 6, 12 and 24, and $b = 0.5$), flux distribution curves were carefully worked out with the aid of the experimental results of Wall.[7] These curves were then analyzed and k^2 computed according to equation 7. The resulting values of k^2 are plotted in Fig. 8.

For larger values of b, k would be somewhat larger, and smaller for smaller values of b. But within the ordinary range these differences are small.

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[7] T. F. Wall. Journal of the Institution of Electrical Engineers, June 1908, Vol. 40, p. 550.

In using Fig. 8 it should be remembered that even if the flux distributions had been determined accurately from the static standpoint, the eddy currents in the pole shoes tend to alter the static distributions at the surface in the direction of decreasing their variation. The reluctance of saturated teeth also tends in the same direction. Neither of these sources should under ordinary conditions give rise to considerable variations from the results shown in Fig. 8.

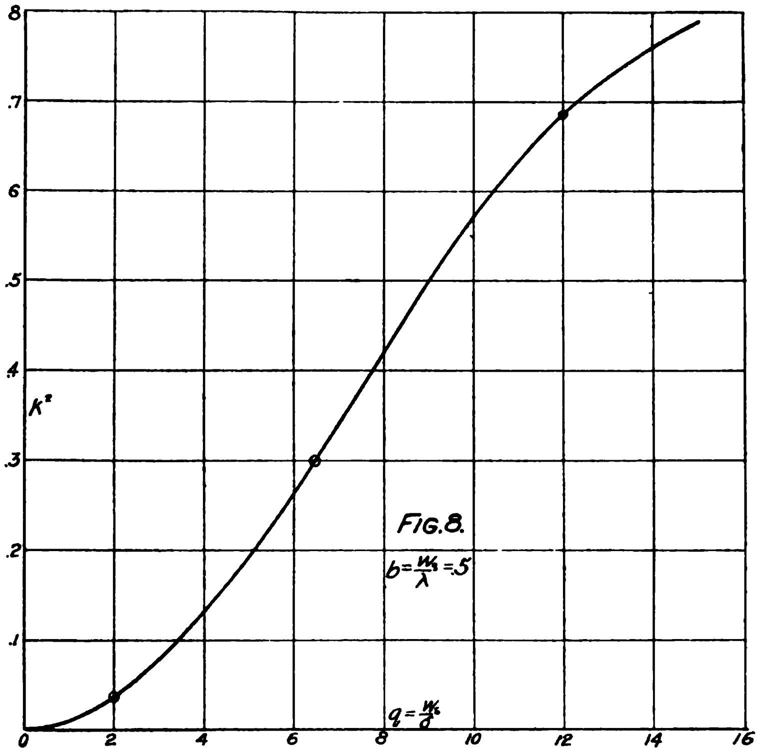


FIG. 8.

Equation (6), together with Fig. 8, thus gives a fair idea of the factors which determine the pole-face losses in the case of solid shoes.

Laminated pole shoes. Although any reasonably complete analytical treatment of this case would be extremely complex and tedious, if not impossible, it is possible with the aid of equation 6 (for solid poles) to make some roughly quantitative deductions as to the effect of laminations.

Referring to Fig. 9, assume the eddy currents to flow in symmetrical paths as shown, and consider the element *a b* of the damping current. This element experiences exactly the same electromotive force as in the case of the solid pole shoe, but the resistance of its path is $\left[1+\left(\frac{\lambda}{2t}\right)^2\right]$ times as great as for the solid shoe, where t is the thickness of the laminations and λ the tooth pitch. These damping currents will thus have the same effect with respect to those of the solid shoe as if the specific resistance were increased in the ratio $1+\left(\frac{\lambda}{2t}\right)^2$, or approximately $\left(\frac{\lambda}{2t}\right)^2$. This assumes the same quality of iron in the two cases. It will also be observed that the system of damping currents thus established does not cross the full thickness of the laminæ although the more important longer currents which flow in the longer paths do flow nearly across. The effect of this restriction in length of the damping currents is obviously to

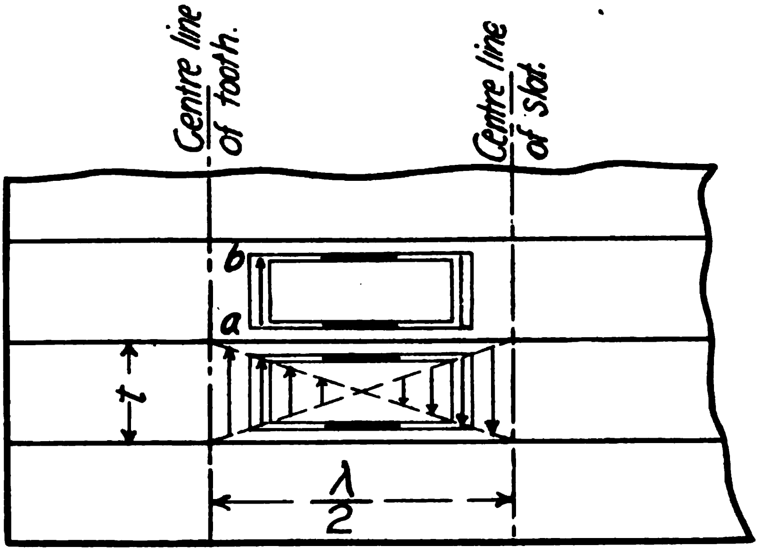


FIG. 9.

reduce the damping effect, to allow the flux to penetrate deeper near the lateral surfaces of the laminæ, and thus to increase the loss slightly.

Thus with the same quality of iron as in the solid shoes the principal effect of laminating may be represented by an increase of specific resistance in the ratio $\left(\frac{\lambda}{2t}\right)^2$. By introducing this ratio into equation 6 together with a constant a to take account of the shortened damping-current paths, we obtain for the watts per square centimeter of pole face for laminated pole shoes:

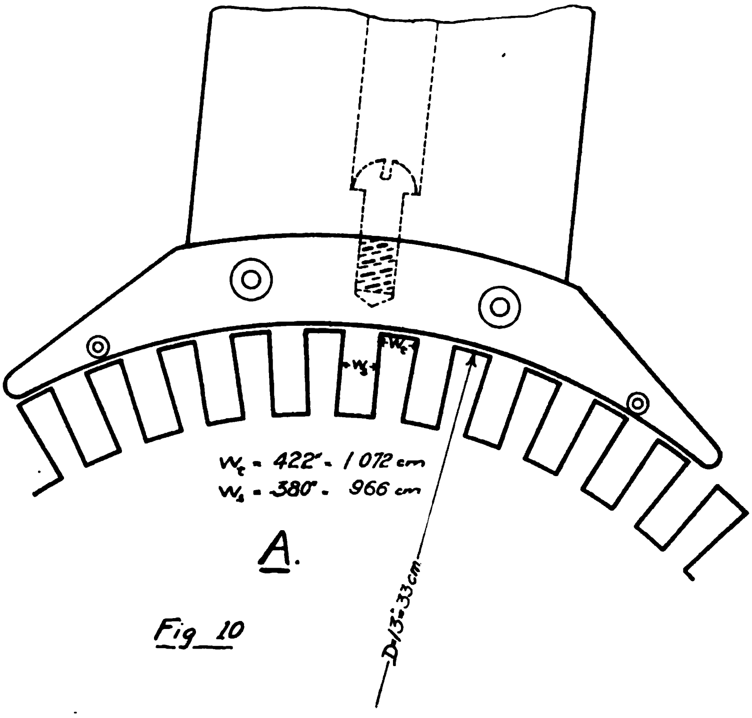


Fig 10

$$P_l = P a \frac{2t}{\lambda} \tag{9}$$

or
$$P_l = \frac{10^{-7}}{8\pi} k^2 B^2 a \frac{2t}{\lambda} \sqrt{\frac{v^3 \lambda}{\mu \rho}} \tag{10}$$

or
$$P_l = 7.96 \times 10^{-9} a t k^2 B^2 \sqrt{\frac{v^3}{\mu \rho \lambda}} \tag{11}$$

It is interesting to note that whereas the solid pole-shoe loss is proportional to $\sqrt{\lambda}$, that for the laminated shoes is inversely proportional to $\sqrt{\lambda}$.

Reduced to the same units as for equation 6*a*, the watts per square inch are:

$$P_l'' = 3.3 \times 10^{-7}\, a\, t\, k^2\, B^2 \sqrt{\frac{v^3}{\mu\, \rho\, \lambda}} \qquad (11a)$$

It should be noted that perfect insulation of the laminæ is assumed, otherwise P_l will be larger.

These theoretical equations are crude, not only because of the assumptions and approximations involved in their development but also because no account whatever is included of numerous minor sources of loss, some of which become prominent in certain limiting cases; but they serve very well as a basis for the interpretation of the experimental results. Experimental results without some such interpretation are apt to have a very limited range of usefulness, or in some cases to be worse than useless.

EXPERIMENTAL RESULTS

Apparatus. The machine employed was provided with detachable poles and pole shoes, and with three armatures, each with a different number of teeth. Three sets of pole shoes were used, one set of solid annealed steel castings, one set of 0.014 in. laminations, and the third set of 0.06 in. laminations.

The laminated pole shoes were held together by insulated bolts and were held on the poles by screws tapped in from behind so as to leave the pole face unbroken. The pole shoes were bored concentric in place; they were then taken down, the tool burrs were removed, and the poles carefully replaced.

The air gap was varied by means of shims placed behind the pole pieces. As the pole face could not be concentric with the armature at all gaps without reboring for each gap, an equivalent corrected gap was computed when necessary.

The dimensions of the pole shoes and armature teeth are given in Figs. 10, 11, and 12.

The losses were measured by running the machine light as a motor, measuring the input and subtracting the other losses as below.

Constant-speed tests. The field current and armature voltage were varied over a wide range in such a way as to maintain a constant speed of 1246 rev. per min. By plotting a curve of watts lost *versus* volts, the friction loss was determined. This, together with the armature copper and brush losses, was then subtracted from the total to get core loss plus pole-face loss. By plotting core loss plus pole-face loss versus air gap and extending the curve slightly the core loss was determined. This was then subtracted to get the net pole-face loss.

Constant flux tests. The exciting current was maintained constant and the speed varied over a wide range by varying the armature voltage. The object of these tests was to check the exponent of v in equations 6 and 11.

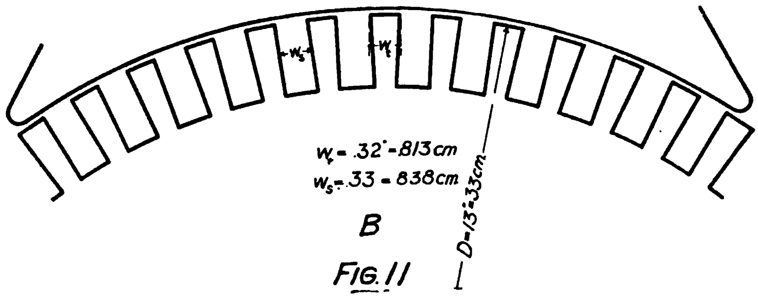


FIG. 11

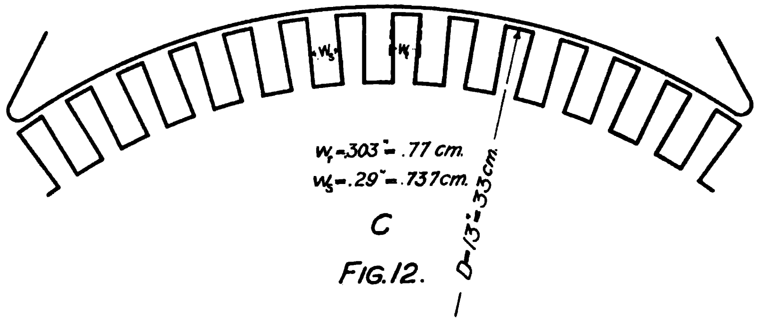


FIG. 12.

These two tests were made with numerous combinations of three armatures, three sets of pole shoes and five air gaps.

Errors. The greatest care was observed in the conduct of the experiments, the measurement of the air gaps and in working up the results; but errors undoubtedly crept in, in addition to those inherent in the method. Of the latter the following are the most obvious; (*a*) errors due to heating of pole shoes and consequent change of specific resistance; (*b*) errors due to distortion of flux under pole face by armature current; (*c*) variation of the friction loss during the test; (*d*) variation of core loss with air gap.

a. The heating element was largely eliminated by starting the tests cold and not carrying them far enough to cause a troublesome rise of temperature. Within the range of the results given below the maximum temperature variation was less than 20 degrees cent. which means about 3 per cent variation in the pole-face loss, since the specific resistance enters equation 6 as the square root.

b. The distortional effect is negligible except for short gaps, being much larger of course for the solid poles and least for the 0.014 in. laminations. But this error becomes rapidly a serious one when it once begins to count, since it means an increase in armature core loss, which increase—by the method of elimination already outlined—appears in the pole-face loss; thus the apparent pole-face loss is doubly increased. This effect results in raising the apparent exponent of v and of q in the loss equation.

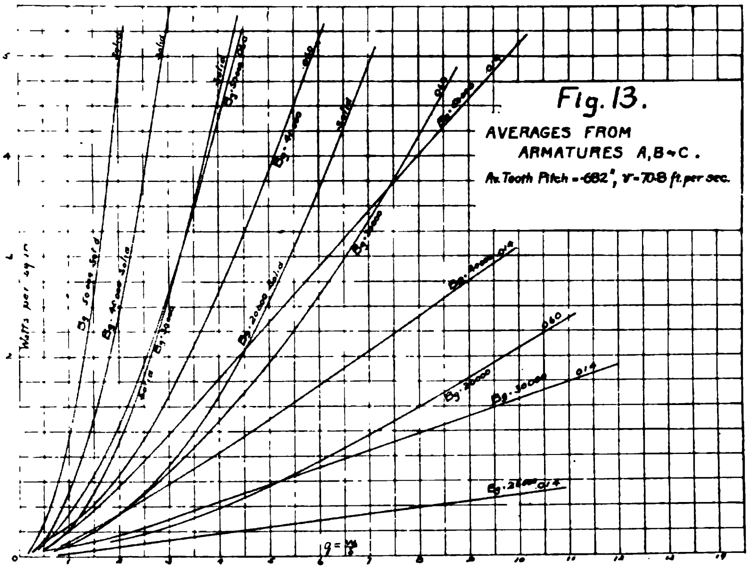


Fig. 13.

AVERAGES FROM ARMATURES A,B+C.

Av. Tooth Pitch = .682", v = 70.8 ft. per sec.

c. A large part of the friction being brush friction, this item was subject to an appreciable variation although the greatest care was employed to keep the commutator clean and of uniform polish. All brushes except two, one positive and one negative, were removed from the holders during the tests.

d. The longest gap obtainable was not long enough to eliminate the pole-face loss entirely, hence it was necessary to prolong the curves, (*pole-face loss + core loss* versus *gap*) in order to separate the core loss from the total; but although this prolongation can be made and the core loss determined with a very fair degree of accuracy, the result is the long-gap core loss which is undoubtedly less than that with a very short gap. This error would tend to raise the apparent exponent of q.

The friction error is more or less erratic, but the other three increase with the pole-face loss, the heating error being subtractive and the other two additive. They thus neutralize each other in part, although the heating error is probably less than the other two.

Exponents. By plotting P versus B (for constant speed) on logarithm paper, the exponent of B was determined. By similarly plotting P versus v (for constant B) the exponent of v was determined.

The average exponent of B taken from some forty-five sets of observations is

2.5 for the solid pole shoes
2.4 for the 0.06 in. laminations, and
2.3 for the 0.014 in. laminations.

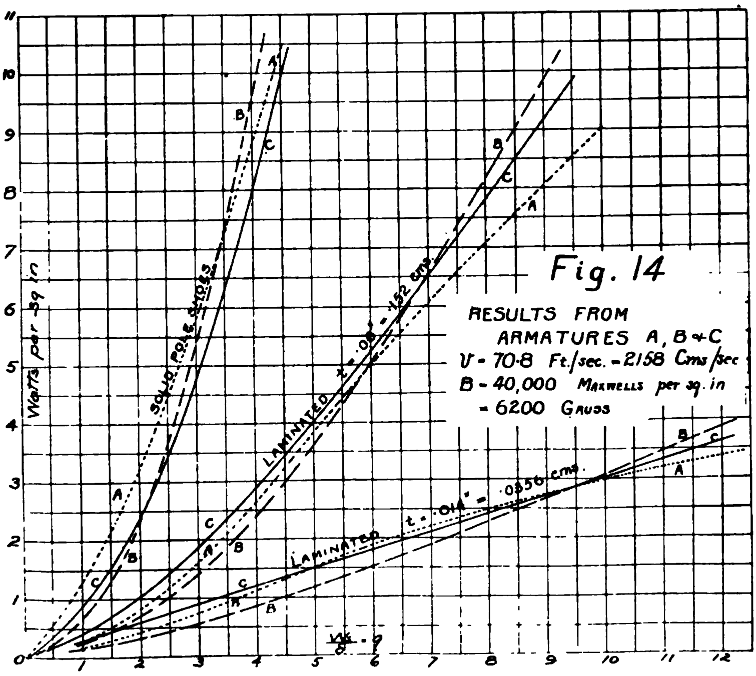
The fact that the exponent is larger than 2, is probably due, partly to the decrease of permeability at high densities and partly to eddy currents in slot conductors and other abnormal localities. These hardly seem sufficient however to produce as much increase in the exponent as that observed. In the experiments of Wall and Smith both distortional and core-loss errors were practically eliminated and they obtained an exponent for B of 2.1 for solid pole shoes. This should stand as fairly reliable were it not for the predominance of the reluctance pulsation loss in their experiments, and for the fact that only a single set of observations was made.

It is interesting to note that in these experiments the armature core loss itself increased about as the 2.1 power of the flux density; this is doubtless due to the distortional increase.

The average exponent of v was 1.55, a little larger than the theoretical value of equation 6. The apparent excess is probably due to distortional errors.

The variation in λ between the three armatures was not enough to check its exponent, but its effect is quite obvious in the curves of Fig. 14.

An inspection of the computed curve of k^2 in terms of q, (Fig. 8) and the curves of P versus q in Fig. 13, will show that while these curves are not all clearly exponential with respect to q, some of them are very close to that form throughout a considerable part of their length. If it were possible thus to express k^2 as a simple exponential function of q even over a moderate range of that variable, it would be possible to formulate the pole-face loss in a comparatively simple manner.



To this end the theoretical and experimental results were plotted on logarithm paper and the exponents of q averaged.

The lower part of the curve of Fig. 8, covering the working range up to $q = 6$, gave an exponent of 1.8. With armatures B and C the reluctance pulsation loss, increasing with decreasing gap, increased the apparent exponent of q, but the reverse was true of armature A and the average of all three should be fairly reliable; it is, 1.88 for the solid pole shoes, 1.50 for the 0.06 in. laminations and 1.22 for the 0.014 in. laminations.

The lower exponents for the laminated shoes are at least partly due to the *screening* effect within the section of each lamina, tending to force the flux and the eddy currents to the lateral surfaces. This screening is not at all negligible at the high tooth-frequencies employed in the experiments here described, even with the 0.014 in. laminations. The effect of the screening is to decrease the eddy currents by contracting the eddy-current paths and to increase the hysteresis loss by confining the same amount of flux in a reduced cross-section. Both of these effects tend to reduce the exponents of q. Another factor which contributes to a greater extent to these low exponents, is the reluctance pulsation loss which, although small for the long gaps, is large when compared to the small pole-face losses, and thus lifts the lower parts of the P versus q curves by a considerable amount; but the experimental exponents are nevertheless fairly reliable for practical purposes, since they represent fairly average conditions and include the reluctance pulsation losses.

Comparing Fig. 8 with the experimental curves of Fig. 14 it will be observed that the curves for armatures B and C do not show the inflection of Fig. 8, but that the curves for armature A show even an earlier inflection. The reason for this is that the reluctance pulsation loss which in B and C increase with q, in A decreases with q, hiding the inflection in the first case and emphasizing it in the other. As between B and C the former has the larger reluctance-pulsation loss at very short gaps partly because of the larger tooth pitch and partly because of the better ratio between the pole arc and tooth pitch. Thus the B curve crosses the others in each case in the upper range of values.

Formulation of experimental results. Disregarding variations in μ and ρ, the results of the experiments described above may be roughly summed up in the following semi-empirical formulæ. In c.g.s. units, as for equations 1, 6 and 11, they are—

For solid pole shoes:

$$P_s = \frac{2.65}{10^4}\left(\frac{B}{10^3}\right)^{2.5}\left(\frac{v}{10^3}\right)^{1.55} q^{1.88}\sqrt{\lambda} \qquad (12)$$

For 0.06 in. laminations:

$$P_{.06} = \frac{0.985}{10^4}\left(\frac{B}{10^3}\right)^{2.4}\left(\frac{v}{10^3}\right)^{1.55} q^{1.5}\frac{1}{\sqrt{\lambda}} \qquad (13)$$

For 0.014 in. laminations:

$$P'_{.014}=\frac{0.705}{10^4}\left(\frac{B}{10^3}\right)^{2.3}\left(\frac{v}{10^3}\right)^{1.55}q^{1.22}\frac{1}{\sqrt{\lambda}} \qquad (14)$$

In inch units, the same as for equation 6*a*, these equations become:

For solid pole shoes:

$$P_s'' = \frac{12.9}{10^4}\left(\frac{B}{10^4}\right)^{2.5}\left(\frac{v}{10}\right)^{1.55}q^{1.88}\sqrt{\lambda} \qquad (12a)$$

For 0.06 in. laminations:

$$P_{.06}'' = \frac{4.62}{10^4}\left(\frac{B}{10^4}\right)^{2.4}\left(\frac{v}{10}\right)^{1.55}q^{1.5}\frac{1}{\sqrt{\lambda}} \qquad (13a)$$

For 0.014 in. laminations:

$$P_{.014}''=\frac{3.15}{10^4}\left(\frac{B}{10^4}\right)^{2.3}\left(\frac{v}{10}\right)^{1.55}q^{1.22}\frac{1}{\sqrt{\lambda}} \qquad (14a)$$

These apply only to the particular conditions of the test as to reluctance pulsation loss, insulation of laminations, μ, ρ, etc., and should be used accordingly. The reluctance pulsation loss was larger in these experiments than with the ordinary chamfered pole tips, but not large enough to give more than a reasonable margin in calculation.

Curves. The most important experimental data from the practical point of view are summarized in the curves of Fig. 13, which show the relation of P (the pole-face watts per square inch) to q (the ratio of slot opening to air gap).

Curves for several densities and for the three different sets of pole shoes are shown. Each curve represents an average for the three armatures and corresponds to a speed of 1246 rev. per min. or a peripheral velocity of 70.8 ft. per sec. = 2160 cm. per sec.

The only apparent reason why the results from the three armatures averaged above should differ, is that the tooth pitches are different; but since λ enters equation 6 as the square root, any moderate difference such as exists between these three armatures does not produce a considerable difference in the pole-face loss. In the present instance this difference was partly masked by the loss due to reluctance pulsation. This will appear from a consideration of Figs. 10, 11 and 12. These figures show that with armature *A* the reluctance pulsations were a maximum with a fairly long gap and a minimum with a very short gap, while with armatures *B* and *C* the reverse is true. Thus the losses in *A* should be relatively large for long gaps (small *q*) and relatively small for short gaps (large *q*.) This is what actually occurs, as shown by Fig. 14, where all the

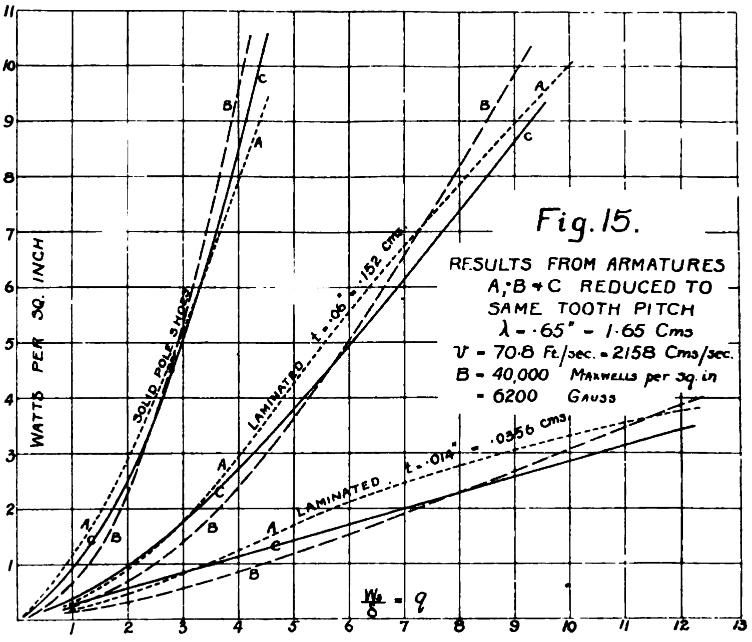


Fig. 15.

RESULTS FROM ARMATURES A, B + C REDUCED TO SAME TOOTH PITCH
$\lambda = .65'' = 1.65$ Cms
$V = 70.8$ Ft./sec. $= 2158$ Cms/sec.
$B = 40{,}000$ Maxwells per sq. in
$= 6200$ Gauss

curves correspond to the same mean gap density, (40,000 per sq. in. or 6,200 per sq. cm.), the three groups of curves correspond to the three sets of pole faces, and the three curves of each group to the three armatures.

While the curves of the three groups are not all perfectly consistent on this point the general tendency is well marked.

Since armature *A* has the largest λ it should have the largest pole-face loss in the case of the solid pole shoes, and the smallest in the case of laminated pole shoes [see equations (6) and (11).] This is borne out roughly by the curves of Fig. 14, if the reluctance pulsation effect be averaged out.

In Fig. 15 the curves of Fig. 14 are reduced to a common value of λ according to equations 6 and 11. This brings out the reluctance pulsation loss still more plainly.

The averaging of the curves of the three armatures, in Fig. 13, averages the effect of reluctance pulsation to a certain extent, since with armature A this loss is larger with long gaps, whereas with armature B and C it is larger with short gaps. But although this averages two armatures against one, in the one the reluctance pulsation comes with long gaps where the true pole-face loss is very small and the per cent effect is thus relatively large; in fact it probably more than overbalances the other two armatures in the cases of laminated pole shoes, as indicated by the q exponents.

Effect of laminating pole shoes. The theoretical ratio of solid-pole shoe loss to laminated-pole shoe loss, other things being equal is, (see equation 9) $K = a\, 2\, t / \lambda$ where a is a constant slightly greater than one, t the thickness of the laminations. and λ the tooth pitch. Take 1.25 as an approximate value of a; then the ratio is, $1.25 \dfrac{2\,t}{\lambda}$. Take a value of λ equal to the average for the three armatures; it is $\lambda = 0.67$. Then for the two thicknesses of laminations employed $K_{0.014} = 0.052$ and $K_{0.06} = 0.224$. The observed average values of these ratios taken from the average curves of Fig. 13 are $K_{0.014} = 0.11$ and $K_{0.06} = 0.278$. The apparent discrepancy is undoubtedly largely due to the imperfect insulation of the laminations; in fact this was practically demonstrated by the following experiment. After the last regular test with the 0.014 in. laminated pole shoes, the bolts were loosened a little, when it was found that the loss was reduced to 70 per cent of its previous value, which materially closes the gap between the observed and the calculated ratio. This loosening would have been carried further, but owing to the manner of supporting the laminated pole shoes it was not considered advisable. They were still tight enough to hold the shoes together firmly when supported by two half-inch screws tapped directly into the back side of the laminations.

Another factor which contributes considerably to this discrepancy is the reluctance-pulsation loss which adds a much larger percentage effect to the laminated-shoe losses than to those of the solid shoes.

A probable change in μ and ρ from the solid to the laminated shoes may also account for a part of the discrepancy.

It is thus reasonable to assume that with perfect insulation between the laminæ and with the reluctance-pulsation loss eliminated, the calculated losses would check very closely with the observed losses. The greater discrepancy in the case of the thin laminations is due to the much greater number of partly insulating surfaces, and to the greater percentage effect of the reluctance pulsation loss.

Additional pole-face losses. There are other losses which sometimes add to those here measured for the laminated pole shoes; they are chiefly due to transverse rivets and to the large heads of flat-head screws sometimes used to hold on the laminated shoes.

Except in the case of reluctance pulsations, the rivets do not contribute much to the total loss, owing to the very slight penetration of the tooth flux waves, (about 0.03 in. or 0.04 in.).

The large screw heads do, however, make a considerable addition; for example, the pole shoes which originally accompanied the machine under test had screw heads which occupied 7 per cent of the pole-face area. These pole shoes were of 0.06 in. laminations, so that taking the experimental ratio above, the screw heads would add about 30 per cent to the pole-face loss. With 0.014 in. laminations well insulated the same screw heads would add about 100 per cent to the loss.

Minimum air-gap. Owing to the numerous variables involved, it is impossible to make any general rule as to the smallest allowable air-gap or the largest allowable value of q, but a careful study of the curves of Fig. 13 together with equations 6 and 11 should make possible a reasonably intelligent decision for any given case.

Comparison of theoretical with observed results. Although the numerical coefficients and exponents in the wholly theoretical equations cannot be expected to give satisfactory practical results in a problem involving so many complex relations, it may be interesting nevertheless to see how closely these results compare to those observed. The observed results for comparison are obtained by averaging the three curves in each set of Fig. 15. In making the theoretical computations k^2 is taken from the curve of Fig. 8; μ is taken as 2000 and ρ as 1.5×10^3 in absolute electromagnetic units; a in equation 11 is taken as 1.25; $\lambda = 0.682$ in. $= 1.73$ cm. $v = 70.8$ ft. per sec. $= 2160$ cm. per sec.

In Fig. 16 are plotted the three averaged observed curves, one for each set of pole shoes and all for the same density, 40,000 per square inch. The light line curves were computed from equations 6 and 11 and the data assumed above, for the same conditions.

It is thus evident that when the imperfect insulation of the laminations and the reluctance pulsation loss are taken into account, and when it is remembered that μ and ρ are not at all accurately known, the theoretical results compare very well with those observed.

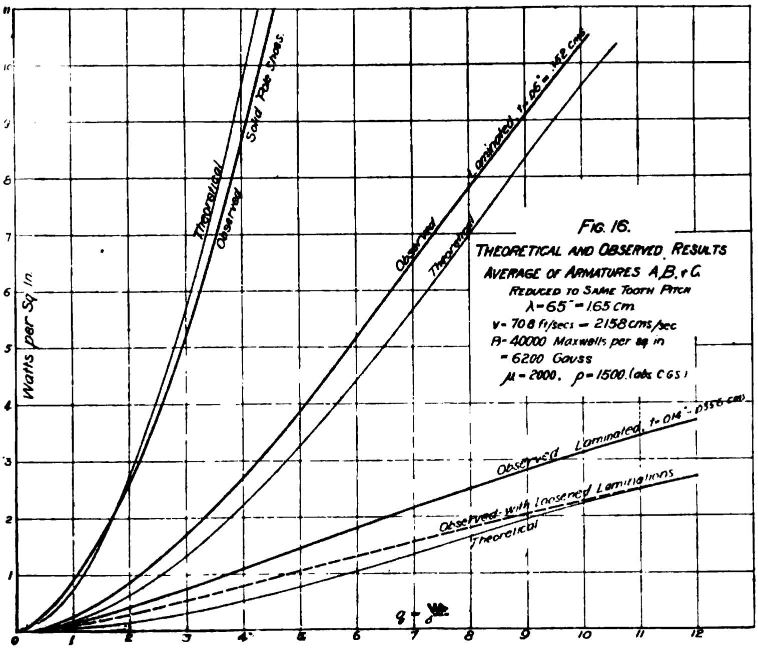


FIG. 16.

THEORETICAL AND OBSERVED RESULTS

AVERAGE OF ARMATURES A, B, & C.

REDUCED TO SAME TOOTH PITCH

$\lambda = .65'' = 1.65$ cm

v = 70.8 ft/secs = 2158 cms/sec

B = 40000 Maxwells per sq in

= 6200 Gauss

$\mu = 2000$, $\rho = 1500$ (abs CGS)

Distortion due to armature reaction. All the results thus far obtained apply only to no-load conditions, but the effect of armature distortion is easily taken into account. Given the dimensions and data of the machine, lay out the full-load flux distribution and compute the *form-factor* (ratio of root mean power to average value) of this curve. Multiply the no-load loss by this *form-factor*.

Design considerations. It will be interesting now to compare the watts lost per unit of pole-face area with the useful watts developed in the equivalent armature area, as their ratio will give the per cent pole-face loss.

Let $\triangle$ = the peripheral armature current (ampere conductors per inch of periphery),

v = peripheral velocity of armature in ft. per sec.

B = mean pole-face density maxwells per sq. inch.

Then the useful watts developed per sq. in. of pole face is

$$P_0'' = 12\, v \triangle B\, 10^{-8}$$

Taking the pole face watts per sq. in. from equation 12*a* for solid pole shoes:

$$P'' = 12.9 \times 10^{-4} \left(\frac{v}{10}\right)^{1.55} \left(\frac{B}{10^4}\right)^{2.5} q^{1.88} \sqrt{\lambda}$$

$$q_{pf} = \frac{P''}{P_0''} = \frac{1.07}{10^3} \left(\frac{v}{10}\right)^{.55} \left(\frac{B}{10^4}\right)^{1.5} \left(\frac{\triangle}{100}\right)^{-1} q^{1.88} \sqrt{\lambda}$$

This shows clearly what factors determine the per cent of pole-face loss, and makes it possible to consider intelligently the question of pole-face lamination as a rational part of design.

For example, take $v = 50$, $B = 40{,}000$, $\triangle = 400$, and $\lambda = 0.7''$ then in order to keep q_{pf} within one per cent it is necessary to keep q below 1.6 for solid pole shoes. For 0.06 inch laminated pole shoes q could be increased to 3.1, and for 0.014 inch laminated pole shoes q could be as large as 5.9 without raising q_{pf} above one per cent. For other values of B, v, $\triangle$, and λ these percentages would change somewhat.

It is obvious from the above results that it is quite possible to get values of q_{pf} considerably above one per cent without exceeding ordinary proportions.

Although there are other considerations than that of pole face loss which frequently control the choice of the air gap and of the pole shoe type, it is hoped that the experimental results and analysis above presented may help toward a more rational consideration of these questions.

A paper presented at a joint meeting of the Seattle Section of the American Institute of Electrical Engineers and the Northwest Electric Light and Power Association, Seattle, Wash., September 8, 1909.

PROTECTION OF ELECTRICAL EQUIPMENT

BY P. M. LINCOLN

The subject that I wish to discuss in this paper is the protection of electrical apparatus and transmission lines from the danger of breakdown to which such apparatus is subjected by electrical surges. The most frequent and severe source of electrical surges is lightning. There are other causes, arising from the operation of a transmission line and the electrical apparatus that goes with it to make up a complete plant. For instance, switching, particularly on the high-tension side, may give rise to surges. Also grounding of high-tension transmission lines, particularly if the ground be an arcing one; for instance, such as would occur were the limb of a green tree to come occasionally in contact with one of the conductors of the line. Also a short-circuit on the transmission line or on other electrical apparatus may give rise to an electrical surge.

The question which I wish particularly to discuss in this paper is, therefore, the manner in which such surges may arise and the best protection to supply in order to prevent them from damaging either the apparatus or the service. I do not expect in this discussion to bring out anything new. The most that I could possibly expect is to bring a new viewpoint to some who are interested in long-distance power transmission and the protection of transmission circuits from damage and interruption.

What is meant by the term " surge "? This is a fair question and should have a straightforward answer. If this question were to be asked of a Steinmetz, he would fill pages with differential equations and $\int$ signs of integration and finally give an answer (as he has already done) in the form of a mathematical formula.

Such an answer, although it tells the story, is unfortunately useless to the average long-distance transmission line operator, since it requires the mind of a trained mathematician to interpret such an answer as well as to make it.

For my own part I have found that a proper conception of the phenomenon of electrical surges can be much better conveyed to the mind by using an analogy. The use of a proper analogy conveys a concrete idea rather than an abstract one, and the mind can much more readily grasp the idea in that shape than when it merely consists of abstract ideas which must always be associated with such electrical terms as volts, ohms, henrys, microfarads, etc. Any analogy must be used carefully, since in many points of comparison it is apt to fail. If improperly used, it may lead to conclusions entirely wrong; but if properly applied it will lead the average mind to a much clearer conception of what is going on than can be obtained by any consideration of abstract quantities.

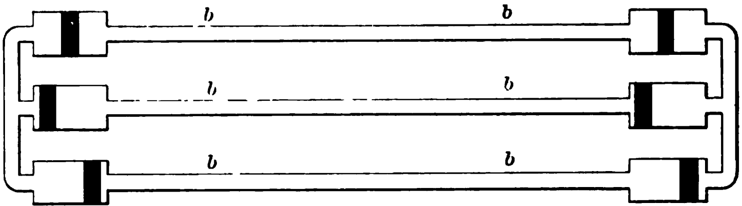


Fig.1

In many respects the following hydraulic analogy is similar to the electric circuit, and I trust that its description will be of assistance to some in gaining an idea of an electric surge. Suppose we replace a three-phase alternating-current generator, transmission line, and receiving apparatus with a hydraulic arrangement as shown in Fig. 1. In this Fig., *a* is the piston pump with the three pistons 120 degrees apart. *c* is a duplicate of pump *a*, whereby the work done by *a* is transferred to *c*; *b b b* are pipes connecting *a* with *c*. The likeness to an alternating-current power transmission system is accentuated in our analogy by the fact that the water or other liquid in the system simply oscillates through the pipes *b b b* from generator pump *a* to motor pump *c*. In order to endow this hydraulic system with the functions of an electric circuit we will have to imagine that the walls of pipes *b b b* are perfectly flexible; for instance, made of pure india rubber. This introduces into our hydraulic system the analogy of static capacity in the electric system. If we imagine that water is to be used in the hydraulic analogy, the weight or inertia of this water introduces into the hydraulic system the equivalent of inductance or reactance in the electric system. Since the water in passing back and forth will have certain losses due to friction against the walls of the pipe and pumps, the idea of ohmic resistance of the electric circuit is transferred to the hydraulic analogy.

If we wish to imagine the effect of increasing static capacity, we may do so in our hydraulic analogy by imagining the walls of the pipe to become more flexible; for instance, made of thinner walls of rubber. For a transmission line without capacity we would have to substitute a hydraulic system with perfectly rigid and inflexible pipes. Increasing inductance or reactance may be represented in our analogy by increasing the weight and therefore the inertia of the liquid pumped; for instance, by substituting mercury for water. Increasing electric resistance may be represented by smaller, rougher, or longer pipes, thus increasing the frictional resistance. It is further necessary to assume that the volume of the pump cylinders is large compared with the volume of the pipes connecting the two pumps; and to gain a proper idea we would have to imagine further that the speed of the pumps is slow, say one stroke per minute or so.

Now if we can keep our imaginations under proper control and can carry this hydraulic analogy in our minds we are prepared to investigate the nature of an electric surge by means of this analogy. Suppose we suddenly inject into one of the flexible pipes *b b b* at some point between pumps *a* and *c*, an amount of liquid which will instantly swell the pipe at that point to some three or four times its normal diameter for a length of some eight or ten diameters. This would be analogous in the electric system to the effect of lightning. A cloud discharges in the neighborhood of a high-tension transmission line. The area of the transmission line which has been covered by the cloud is relatively small. The discharge of that cloud releases in the transmission line a certain amount of static electricity in addition to the normal amount of current present due to the action of the generators and receiving apparatus. What happens next? It is much easier for the imagination to follow this in the analogy than in the actual transmission line. If the pipe is not strong enough the wall breaks; that is, an insulator punctures or "slops over," and the accumulation of water, [electricity] in part at least, escapes. If the walls of the pipe are strong enough to stand the strain; that is, if the insulators do not break down, a wave or surge begins to be propagated in both directions. The distended walls of the pipe bring their elastic force to bear upon the enclosed liquid and the accumulated "lump" of water begins to de dissipated in both directions. Inertia of the liquid together with the pressure on it from the elastic walls will cause it to assume successive forms which are probably very much like those shown in Fig. 2. The accumulation of liquid will become longer and thinner, and it finally divides into two separate lumps as it travels from the point of disturbance in both directions. At the point of disturbance the tendency to break the walls is a maximum, and this tendency becomes less and less as the wave or surge proceeds from the point of disturbance. However, should the surge encounter a weak place in the walls, a break may occur in some place comparatively remote from the point of disturbance.

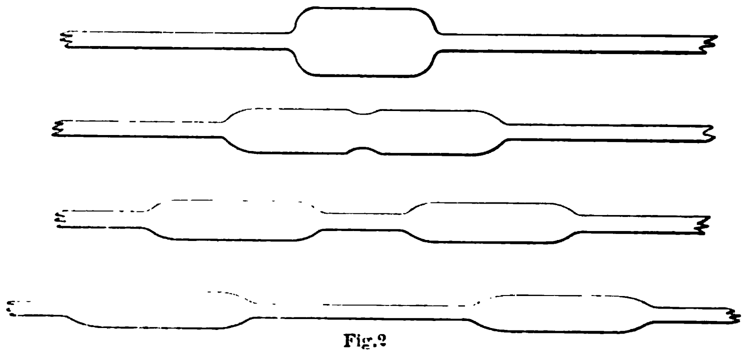


Fig. 2

Now, what happens when this wave or surge reaches the electrical apparatus at the ends of the line? For the purpose of considering this question, we should have to replace our pumps with something that would behave like a transformer or generator in an electric system. Now generator and transformer windings have two important differences from an equal length of transmission line, in that both the capacity and inductance per unit length are largely increased. In our hydraulic analogy the increase in capacity per unit length may be represented by imagining a much thinner walled pipe for the generator. The increase in inductance per unit length may be represented in the analogy by an increase in the specific gravity of the liquid, say by substituting mercury for water. I have endeavored to give a graphic representation of these modifications in Fig. 3.

b_1 is the transmission line with relatively heavy walls, although still flexible, and a light liquid contained therein, say water.

b_2 is the generator which has relatively thin but still perfectly elastic walls containing a heavy liquid, say mercury.

When the wave or surge that has been started out on the line b_1 reaches the point p; that is, the terminal of the generator or transformer, it is obvious that the following things will occur:

1. A part of the energy of the incoming wave will be reflected and will therefore travel back through the line b_1 from the point p.

2. The remainder will begin to travel through part b_2, the generator or transformer; but the speed of its propagation will be very much reduced, because the liquid being set in motion is very much heavier and also because the forces acting upon it through the elastic retaining walls are much smaller.

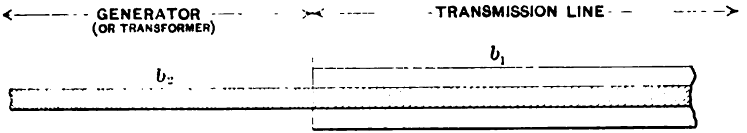


Fig. 3

3. The steepness of the wave-front during its propagation through b_2 will be very much increased over that obtaining in b_1, on account of the action of the same forces as noted in the above paragraph.

I have allowed my own imagination rather free play, and give in Fig. 4, 5, 6 and 7 my idea of how the wave will modify itself when being propagated from medium b_1 to medium b_2. Probably the most noteworthy modifications during this transfer of the disturbance from b_1 to b_2 is the abrupt increase in the steepness of the wave-front. For instance, consider the points p_1 and p_2 in Fig. 5. At p_1 there is a tendency to burst the pipe; that is, to break down the insulation to ground; but there is also a heavy stress tending to break through from point p_1 to point p_2. Suppose that the portion b_2 of our pipe, instead of being straight as indicated in the diagram were to be coiled upon itself, and that one complete coil took place in the distance from p_1 to p_2, then there would be a tendency for the liquid at point p_1 to break through the walls of the pipe into the neighboring coil at p_2. This is exactly what occurs in the electric system. An incoming surge, in penetrating the turns of electrical apparatus, causes an

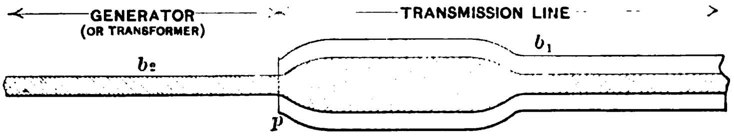


Fig.4

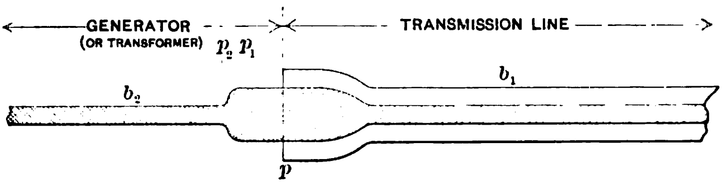


Fig.5

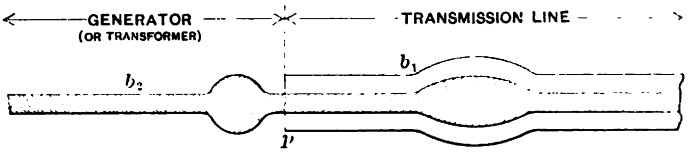


Fig.6

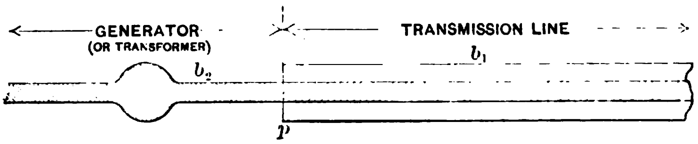


Fig.7

excessive voltage strain between adjacent turns. The momentary breakdown or snapping across of this surge from one turn to the next will do no particular damage unless such breakdown is followed by the dynamo current and an arc is thereby established. If this later event occurs then the break does tremendous damage. In my opinion, practically all the failures in generators, transformers, etc. which can be traced directly to lightning or other surges are due to a breakdown between turns rather than to a break in the insulation from conductor to the ground. There is, of course, due to the normal operation of the apparatus, an insulation strain from conductor to ground and also one between adjacent turns. A surge momentarily increases both of these strains. The strain to ground may be thereby increased 20 per cent, 50 per cent, or perhaps 100 per cent, or even somewhat more; the strain between turns may thereby be increased twenty times, fifty times, one hundred times or even more. A surge, therefore, throws a much larger increase on the insulation between turns than it does on the insulation to ground. From certain observations that I have made, it is my opinion that the momentary strains between turns, particularly near the terminals of the apparatus, may approximate a considerable percentage of the terminal pressure. This is a danger in electrical apparatus which has not been sufficiently appreciated in the past.

It is evident that the protection of electrical apparatus from such dangers as are outlined in the above consists in:

1. Making the apparatus so that it will stand large momentary voltages between turns. This consideration shows the great advantage possessed by transformers, particularly oil-insulated, over generators. It is possible to insulate transformers between turns to a much higher degree than any generator can be, particularly where oil is used.

2. Limiting by use of proper lightning arresters the size of the wave or surge that may enter the electrical apparatus. Reverting to the hydraulic analogy, if we should provide a hydraulic relief valve at the point *p*, Fig. 5, it would have the effect of removing at least a part of the excess liquid at the instant the strong pressure on the walls occurs. If this relief valve were to be set so that it operates at a pressure of, say, only 20 to 30 per cent above that caused by the pumps while in normal operation, then this relief valve would not affect the normal operation and would also limit a surge or wave entering part b_2 to an amount which could not exceed 20 or 30 per cent above normal pressure or voltage. This indicates the function of the ideal lightning arrester. It prevents any electrical surge which has a value of 20 to 30 per cent greater than normal voltage from entering the electrical apparatus. This is the utmost that any lightning

arrester can do. The electrical apparatus itself must be so designed that it will take care of an entering surge which is not more than 20 or 30 per cent above line voltage.

Reverting again to the hydraulic analogy, suppose our relief valve has a relatively long discharge pipe, say one-one-hundredth the area of the incoming pipe *b* in Fig. 1. The time during which the excess pressure exists at *p*, Fig. 5, is relatively small. Such a pipe attached to the relief valve would be utterly unable to discharge a sufficient amount of the liquid to relieve the pressure. As a consequence, the size of the surge entering part b_2 would be but little reduced by such a relief valve. This is analogous to what occurs with a lightning arrester having a large ohmic resistance in series with it for the purpose of preventing the dynamo current from following. This indicates in general why this type of arrester is inferior to the electrolytic. The electrolytic type of arrester, once broken down, has almost a zero resistance to ground and therefore allows the maximum possible reduction of the surge before it enters the electrical apparatus.

Another method of protection that has shown itself of considerable value both in theory and practice (as a protection from lightning) is the overhead grounded guard-wire. The theory of this kind of protection is as follows:

Any conductor that is entirely enclosed or surrounded by another conductor cannot have induced thereon a static charge which originates from any action going on outside the surrounding conductor. For instance, a lead-covered electric cable cannot be directly subjected to lightning disturbances because of the protective action of the surrounding lead sheathing. The overhead ground-wire acts to a certain extent in the same manner. Although it does not entirely surround or enclose the high-tension wires which it protects, it does so partly and to the extent that it does enclose or surround the high-tension wires it provides the same protection as does the lead sheath to the underground cable. In the electric transmission circuit the voltage of the charge which would otherwise be induced upon the transmission line is kept down by the presence of the guard wires.

Still another method of protecting high-tension transmission lines is to ground the neutral of the lines. This grounding may be done either by connecting it solidly to the ground or by putting in a greater or less resistance between the neutral point and the ground. To just what extent this grounding of the neutral, either completely or partly, is of value is a moot question among engineers. As I see it, the question of grounded neutral versus ungrounded may be considered from two viewpoints: first, from the viewpoint of protection of the apparatus or equipment; secondly, from that of the protection of the service.

First: protection to apparatus. The advantage in a solidly grounded neutral, so far as protection to apparatus is concerned, is that the normal voltage to ground can under no conditions rise to more than about 58 per cent of the normal voltage between conductors. This advantage is, of course, of the utmost importance when considering insulation strengths to ground of the various apparatus involved.

On the other hand, the disadvantage of a solidly grounded neutral is that every ground which occurs develops immediately into a short-circuit, and these short-circuits in turn cause severe mechanical stresses to be set up in the windings of the transformers and the generating apparatus.

With a grounded neutral, therefore, it is reasonable to expect that the windings of the transformers and generators will be subjected to much more frequent shocks than without such a ground. Also owing to the fact that every ground immediately becomes a short-circuit, and that at the points of short-circuit the arc will cause considerable destruction, the system with the solidly grounded neutral will be subject to more frequent destrictive arcs both on the line and in the apparatus where there is probability of such arcs developing.

It is my opinion that so far as protection to apparatus is concerned, the advantages of grounding the neutral very much outweigh the disadvantages; and if protection to apparatus alone were to be considered, I would have no hesitation in recommending a solidly grounded neutral.

Secondly, protection to the service. As mentioned above, the disadvantage of a solidly grounded neutral is that every ground develops immediately into a short-circuit. With a voltage such as is always used in high-tension transmission, (say 44,000 and above) there will always be a sufficient voltage at the point of arc to cause that arc to continue until the power to that particular section of line is cut off. This fact almost invariably will cause an interruption of power whenever a ground occurs at any point on the transmission system.

This would not be so materially a disadvantage were it not for the fact that experience has again and again demonstrated that lightning storms will very often cause insulators on the line to arc across or puncture. With the neutral solidly connected to ground, each one of these punctures and flash-overs means an interruption of service. If the line were not solidly grounded, it is probable that many of these flash-overs would not interrupt the service, since a flash-over involving only one conductor might simply mean that the other two conductors on the transmission line would momentarily rise to a potential nearly double normal while the arc at the defective insulator, as well as the voltage to maintain the arc, would disappear.

In view of the difficulties which the line is apt to encounter with a solidly grounded neutral, many engineers prefer to ground through a resistance instead of connecting the neutral solidly to ground. In order to be of use, the resistance between the neutral and ground must be relatively high, and further it must be able to carry a considerable current for at least a short period of time. In other words, it must be capable of dissipating a very considerable amount of energy for a short period. A satisfactory type of resistance for this grounding service is difficult to obtain. Cement columns have been used, but these are unsatisfactory owing to the extreme variability of their resistance. Also if the current through them is maintained for an appreciable time, the heat developed is apt to crack or even to burst them. After studying the question from various angles, I have come to the opinion that a metallic form of resistance is the proper one to use for this purpose. The main disadvantage of this form is its cost, but its advantages are sufficiently great to overcome this disadvantage.

To recapitulate briefly: the protection against surges of electrical equipments, including both the apparatus and transmission lines, may be furthered by adopting some or all of the following methods.

1. *The overhead guard-wire.* This has the ability of keeping down the quantity of electricity which a given lightning discharge is capable of superposing upon a transmission line. In practice it has shown itself to be a valuable device in many instances of high-tension transmission.

2. *The use of efficient lightning arresters is essential.* They should be of a type which will allow a free discharge of static electricity from the transmission line whenever the voltage of the charge exceeds normal by a certain predeterminable amount.

With a proper equipment of such lightning arresters, the size of the surge which may enter electrical apparatus is limited.

3. *The grounded neutral.* Grounding solidly prevents the potential of a neutral point of a transmission line from departing from ground potential. This in turn will prevent the normal operation of this line from causing more than about 58 per cent of line voltage to appear between any conductor and ground. Grounding through a resistance has the same effect, to an extent depending upon the amount of resistance used.

4. *Insulation between turns.* The analysis in the preceding discussion shows that it is highly essential to insulate electrical apparatus between turns so that it will stand a momentary potential which is many times that normally put upon the insulation. The consideration of this point shows at once the enormous advantage of using transformers upon a transmission line in distinction to connecting generators direct. The amount of insulation that can be used between turns in a generator is limited by the necessity of placing the winding in relatively small slots. In a transformer this consideration does not operate to nearly so great a degree, owing to the fact that the space occupied by the windings is, so to speak, in one piece instead of being divided into a large multiplicity of small slots. Also the presence of oil in the case of the transformer gives it an advantage which the generator cannot have under any conditions.

A paper presented at the 239th meeting of the American Institute of Electrical Engineers, New York, October 8, 1909.

TELEGRAPH AND TELEPHONE SYSTEMS AS AFFECTED BY ALTERNATING-CURRENT LINES

BY JOHN B. TAYLOR

General. In the early days of the electrical industry the telegraph practically had the field to itself. The telephone and electric light were introduced at about the same time, and later on the alternating-current systems gradually came into general use for lighting, general power, and railway purposes. At the outset, the telegraph systems made use of earth return and continue to do so at the present day. The telephone systems started out to use an earth return, but soon found that satisfactory service, except in isolated cases, could be obtained only with metallic circuits. The power systems (this term includes alternating-current systems whether used for lighting, for power or for railway purposes) have until recently almost invariably used metallic circuits, which, when properly installed and under normal conditions, cause little interference to telegraph and telephone lines. Abnormal conditions, however, such as grounds, open circuits, and the like, upset the normal balance, giving strong external fields, both electrostatic and electromagnetic, which are likely to make trouble for sensitive systems in the immediate neighborhood. Recently the single-phase railway system has come into prominence. With this system the conditions are continuously very similar to those conditions which exist occasionally but of short duration on the power systems.

The great increase in the transmission industry means that power circuits are continually becoming longer, voltages higher, and the amount of energy transmitted greater, with more or less corresponding increase in disturbance to the weaker brothers. Steam railroads have in many cases presented the most natural and logical right of way for pole lines, with the result that power wires and signaling lines are likely to be in proximity.

The telegraph, telephone, and power systems, while rendering different classes of service, are all essential to present methods of living and carrying on business. The purpose of this paper is to give a general statement of power transmission and telegraph and telephone conditions as they exist, with special reference to combinations which may make trouble if simultaneous operation is attempted in too close proximity.

It should be borne in mind that induction between circuits is a mutual affair, the principal distinction being that a high-voltage transmission line conveying perhaps 1000 to 5000 kw. is not disturbed by, nor even able to detect, a few extra volts derived by induction from a telegraph line on the other side of the highway. The converse of this proposition is by no means true, and this points to the desirability of power transmission systems doing everything possible to keep the stresses and strains in the ether within the boundaries of their own right-of-way, and the equal importance of telegraph and telephone apparatus and lines being so constructed and maintained that they will be, as far as possible, independent of stresses and strains which may be unavoidably introduced into the portion of the ether which they occupy. An adequate consideration and solution of the problem necessarily involves an intimate study of the characteristics and sensibilities of telephone and telegraph instruments as well as a calculation of disturbing electromotive forces and currents induced in their circuits with values depending upon all the various features of construction and operation of the power lines.

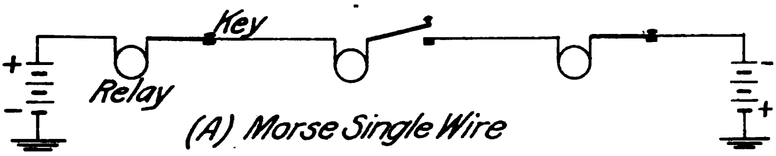
Telegraph systems. The telegraph circuit, with few exceptions, is made up of a single wire and earth return. The typical Morse system is represented in Fig. 1, Diagram A, showing relays, keys, and a battery at each end of the line. Relays are usually of 150 ohms resistance, and the normal working current is in the neighborhood of 40 milliamperes, although many circuits having a large number of intermediate stations make use of 37.5 or 35-ohm relays and on these circuits the current will probably average nearer to 50 than to 40 milliamperes.

Diagram B shows a typical arrangement of duplex circuit, in which case relays are polarized with differential windings. This arrangement does not permit the insertion of intermediate stations.

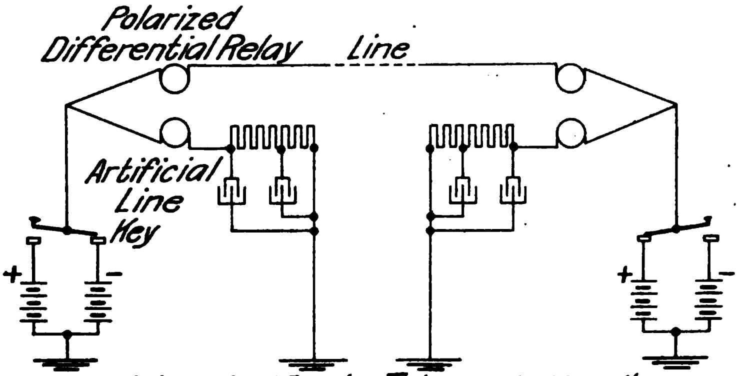
A quadruplex system is an extension of the duplex, by placing in circuit a second differential relay so adjusted as to respond only to currents greater than those required for operating the polar relay, and means for changing the strength of current.

The duplex system ordinarily uses current of 12 to 15 milliamperes and the quadruplex uses three to four times this current, say 35 to 50 milliamperes, for actuating the neutral relay.

As far as the main line circuit is concerned, these two systems include nearly all the various types of high-speed, automatic printing telegraphs, etc., the main difference being in the types of relay and local apparatus controlled by them, as well as the duration and polarity of signals and the code used. For example, the Rowland system recently described in an Institute paper,* is essentially a duplex system, the octoplex capacity being obtained by assigning the line for short intervals of time to one of the four operators at each end in succession.



(A) Morse Single Wire



(B) Typical Duplex Telegraph Circuit

FIG. 1

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* The Rowland Telegraphic System, by Louis M. Potts, PROCEEDINGS, A. I. E. E., April 1907, p. 409.

The frequency of the currents for hand transmission probably averages in the neighborhood of 8 to 10 cycles, although this is a crude way of putting the matter, as signals are short and long, interspersed with spaces. The Wheatstone automatic system, when working up to an extreme speed of 600 words per minute, gives alternate pulses in the line corresponding roughly to 240 cycles per second. The Rowland system as described uses approximately 100 cycles for octoplex working and 50 cycles for quadruplex working. The inertia of the armature of the standard 150-ohm relay, and other features of its magnetic design, will not permit this relay to follow very rapid alternations so that on the high-speed, automatic-working, special constructions of the Siemens or Wheatstone type are used.

All relays are provided with ready means for adjusting the air-gap, length of stroke, and tension of retractile spring, where such is used. Any data on the sensibility of relays are therefore greatly dependent on these various adjustments. Furthermore, adjustments are continually being made by the operators to compensate for variable leakage of the line, due to weather conditions, and also to compensate for variable current and lag, depending on the relative positions on the line of sending and receiving operators. It is therefore impossible to make a general statement that a certain number of milliamperes added to or subtracted from the normal direct current, due to inductive influence, will disturb or completely upset the working, and that a lesser superimposed current will not be felt.

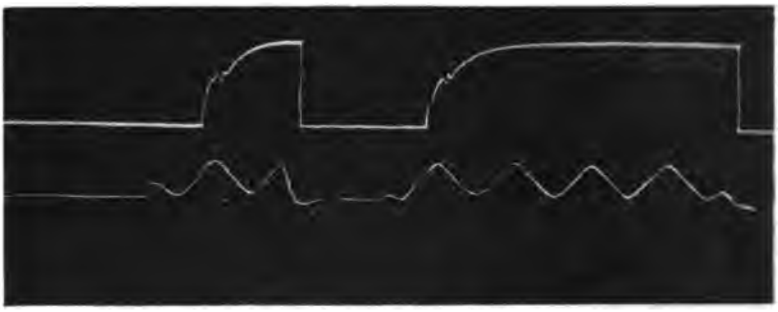


FIG. 2

Experienced operators recognize their friends by the way the instrument "talks," quite as distinctly as those who are not operators recognize handwriting or the sound of the voice. This is stated to bring out the point that disturbances on the line which do not actually upset the working may make considerable difference in the comfort or state of mind in which the operator does his work.

In order to give some idea of the characteristics of the standard 150-ohm relay, tests have been made under the following adjustments:

Magnetic air-gap 0.07 in.

Length of stroke at contacts 0.015 in.

Spring tension so that relay would pick up at 40 milliamperes direct current, and let go at 30 milliamperes.

Under the above conditions, 25 cycles alternating-current current to cause relay to chatter on the back stop, was 31 milliamperes.

Current to cause relay to pull up to front stop sufficient to start chattering in local sounder, was 62 milliamperes.

With 40 milliamperes direct current in relay—superimposed 25 cycle current to cause relay to break contact on the front stop, 20 milliamperes.

As stated above, different adjustment of gap, length of stroke, and spring tension would give quite a different set of current values. Oscillograms, Fig. 2 shows the current in main line relay and in local sounder with 25-cycle alternating current superimposed on line.

The impedance of a standard 150-ohm relay at 25 cycles is given below at different air-gaps.

Air Gap	Impedance	25-cycle current when measuring impedance
0.12 in	465 ohms	89 milliamperes
0.11 "	474 "	88 "
0.10 "	488 "	86 "
0.08 "	515 "	82 "
0.06 "	555 "	77 "
0.05 "	580 "	74 "
0.04 "	650 "	67 "
0.03 "	725 "	61 "

Special apparatus on telegraph lines. Where a telegraph disturbance is slight, improvement may be effected by one or more of the following expedients:

Increasing impedance of line.

Increasing working current.

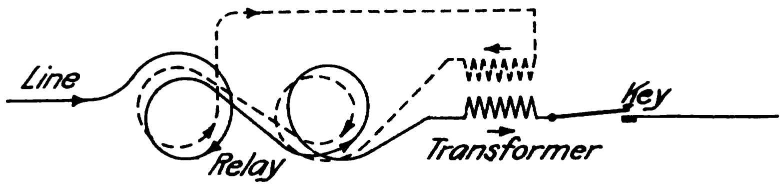
Shunting apparatus with condensers or non-inductive resistance.

Placing short-circuited secondary winding on relay.

Placing neutralizing winding on relay.

Using back contact of relay with reversing sounder.

By placing additional resistance and reactance in the telegraph circuit, the superimposed alternating currents will be reduced in proportion to the increase of impedance. At the same time the battery should be increased to maintain the normal direct current, at its usual value. By working the line at a higher value of direct current, the percentage increase and decrease due to induced alternating currents will be less, with consequent reduction in the disturbance of the relay. Shunting the relay with a condenser or a non-inductive resistance diverts a portion of the alternating current from the inductive winding of the relay. While a condenser bridging a single relay will help this particular instrument, it will not help the line as a whole. By placing the relay winding over a thick copper tube or on a copper spool, alternating currents will be induced in the copper tube which will tend to oppose the effect of the alternating current in the winding.



Differentially Wound Relay with Neutralizing Transformer

FIG. 3

In the second winding of a differential relay, currents in opposite direction to the alternating currents in the main winding may be introduced by means of a small transformer connected as shown in Fig. 3.

Since the signaling currents in a telegraph line are of the nature of alternating currents, it can be seen that any of the above choking, shunting, absorbing, or neutralizing devices will tend to make the action of the relays sluggish; and as soon as the frequency of the signaling currents equals or exceeds that of the induced currents, these devices will become a hindrance rather than a help.

When the telegraph line is open, the relays are against their back stops; and with the line open, there would be no current, either direct or alternating, except for leakage and capacity effects. The air-gap is also at its greatest, so that the relay is less likely to be disturbed while on the back contact than when on the forward contact. By taking the local circuit from a back contact on the relay, and adding a reversing sounder the inductive disturbance may be less noticeable. This is a combination known as a "bug-trap," having been devised by Mr. Edison in the early days of the quadruplex. It is also possible to accomplish a similar result by using a flexible or spring contact

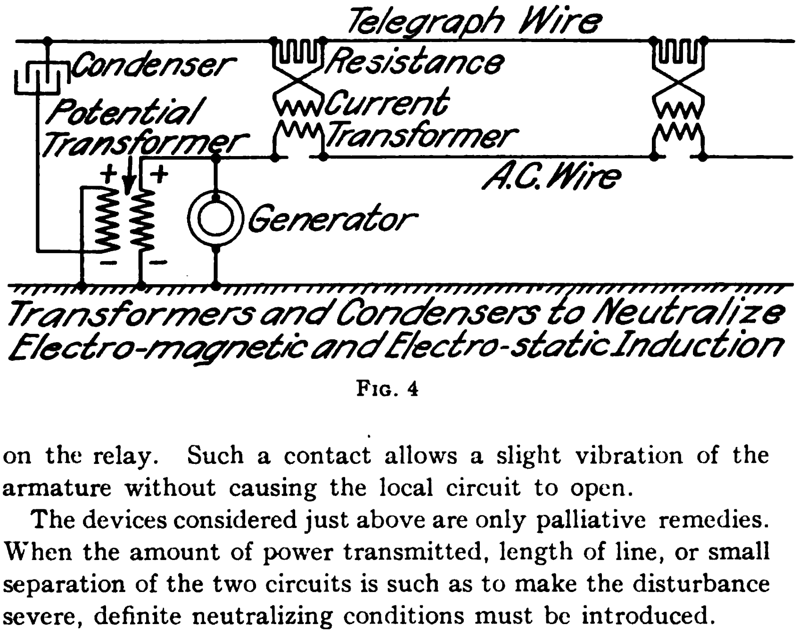


FIG. 4

on the relay. Such a contact allows a slight vibration of the armature without causing the local circuit to open.

The devices considered just above are only palliative remedies. When the amount of power transmitted, length of line, or small separation of the two circuits is such as to make the disturbance severe, definite neutralizing conditions must be introduced.

If we can introduce into a telegraph circuit voltages equal and opposite to those derived by electromagnetic induction, and at the same time supply to the line the charge demanded by electrostatic induction, we shall succeed in neutralizing the inductive effects. Fig. 4 shows one way in which this idea may be worked out. Current transformers connected in a disturbing wire introduce into the telegraph line a voltage proportional to the current in the transformer. Since on a railway the position of the load is shifting, it would be necessary to divide the line into sections, with a transformer for each. The shorter the sections, the more exact the neutralization. Electrostatic induction is neutralized by using condensers in connection with potential transformers as indicated. The proper charge can be obtained by varying the capacity of the condensers or the voltage applied to them.

Instead of using current derived directly from the disturbing wire for the purpose of neutralizing, this neutralizing current may be derived from a special neutralizing wire placed close to the disturbed telegraph wires. Since the neutralizing wire has practically the same exposure as the telegraph wire, the same voltage will be induced in each, and a suitable 1:1 transformer makes proper change of polarity so that voltage induced directly in the telegraph wire is annuled by that induced in the neutralizing wire. This arrangement while effective is not exact, on account of magnetizing currents, earth currents, phase distortion, and the like.

Metallic circuit telegraph systems. In spite of all of the arrangements of alternating-current circuits which may be employed to eliminate or reduce disturbing inductive effects, in some situations it may be cheaper or more desirable to make use of a metallic circuit for the telegraph. Any form of metallic circuit telegraph will be less sensitive than a circuit with earth return, but the full benefit of the metallic circuit is to be derived only when following the " balancing " principles to be stated more in detail when discussing the telephone.

The metallic telegraph may be operated on either the series or multiple connection, and either of these connections properly installed will be perfectly balanced. The same might be said of the telephone system, although as far as the writer is aware a balanced metallic series telephone system has never been used.

Inductively considered, corresponding points on the two wires of a telephone or metallic circuit telegraph system are at the same potential. Slight differences in potential due to the difference of field strength in the 10 or 12 in. separating two wires in practice is made insignificant by frequent transpositions, and small charging currents must flow back and forth from one section to another, owing to the slight difference of potential between the two wires. Pieces of apparatus such as telephone receivers, bells, or telegraph relays, "bridged " between the two wires are, therefore, free from inductive currents. If the apparatus be connected in series, in order to preserve the balance it must be differentially wound, an equal winding being cut into each side of the line. With such an arrangement, on account of the differential action of the two windings, induced currents or electrostatic charges flowing from one section of the line to another section will not affect the instrument.

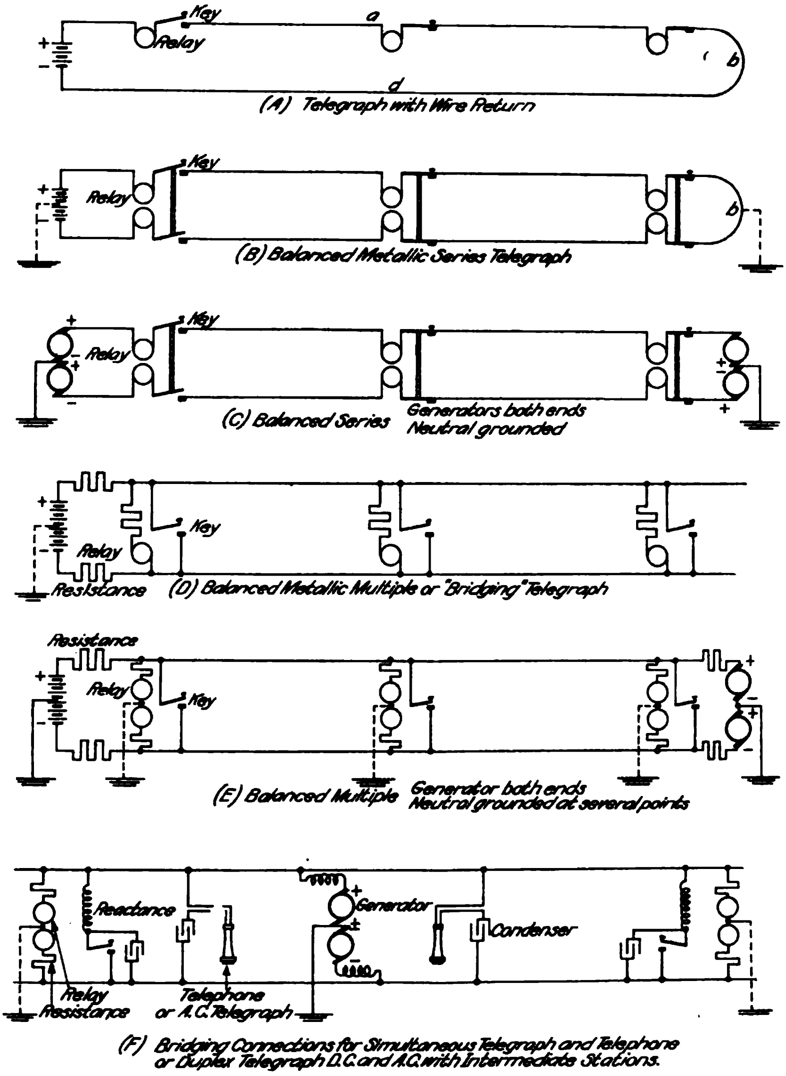


FIG. 5

Fig. 5 shows several connections which may be used for the metallic circuit telegraph. Diagram A shows an ordinary series telegraph system with wire return in place of earth return. If the conditions are such that electrostatic effects can be neglected, this arrangement, though not balanced, will be satisfactory.

Diagrams B and C show a balanced metallic series telegraph. In this case the relay must have double windings differentially connected. Double-pole keys are also essential. Diagram B shows a battery, which may be grounded at the neutral point or may be ungrounded; and similarly the ground at the end of the line, *b*, may or may not be employed. The purpose of the neutral ground in all these cases is to keep the system as a whole at approximately earth potential. In Diagram C, generators are shown at each end of the line, the neutral connection being grounded. With this arrangement, balanced metallic circuit lines may be connected to the usual office generating equipment, as this equipment consists of positive and negative machines at approximately the same voltage, with one terminal grounded.

Diagrams D and E show a metallic circuit telegraph system with relays connected in multiple, or bridged between two sides of the line. With this arrangement it is essential to have the relay wound to as high resistance as practicable, and it may also be advisable to place additional resistance in series with each relay. Resistances are inserted between the battery, or the generator, and the line of sufficient value so that closing any one of the keys will cause the potential at all the relay terminals to fall sufficiently to cause the relays to operate. Diagram D shows a battery at one end of the line only, while diagram E shows an energy supply from both ends. This latter diagram shows the neutral points of the battery and generators grounded, and the possibility of grounding the neutral points of relays is also indicated.

Diagram F shows a combination of the metallic-circuit bridging telegraph with the metallic-circuit bridging telephone. In place of the telephone there might be substituted one of the various forms of alternating-current telegraph. This arrangement, being balanced for both the alternating-current telegraph instruments, as well as for the direct-current instruments, would be free from inductive disturbances, and similarly would not cause disturbance in neighboring circuits, a trouble frequently experienced with alternating-current telegraph systems. In other words, the two wires so connected result in two independent circuits (with intermediate stations if desired) thus providing the service facilities that the same two wires furnish when connected as simple grounded lines.

An incidental advantage of the bridging connection of telegraph lines is the ability to establish an emergency or temporary station at any point by merely attaching suitable apparatus to the two wires.

Telephone systems. As stated previously, the early telephone systems copied telegraph practice in making use of a single conductor with earth return, but since it is only in isolated cases that a grounded telephone is at all satisfactory, and since when in the vicinity of other wires it is almost invariably quite unsatisfactory, we shall, for the purpose of this discussion assume throughout that the telephone is operated on a two-wire metallic circuit.

The whole science of having a perfectly quiet telephone line is dependent on the Wheatstone bridge principle, that no current will flow in the wire or instrument connecting two points at the same potential, even though these two points are on conductors carrying currents of considerable magnitude. The practical application of this principle requires that each wire of a telephone circuit shall have the same resistance, the same inductance, the same capacity, and the same insulation resistance; and more exactly, that these conditions of equality shall hold, not only for the circuit as a whole, but for each and every short section of the circuit. Still more exactly these conditions of equality must hold for the entire range of frequency to which the apparatus is sensitive and for currents of any magnitude that are likely to be introduced into the circuit.

In practice these ideal conditions can be attained only approximately, even after making numerous transpositions of the two conductors. An Institute paper by Mr. F. F. Fowle,* dealing with the question of transpositions, and the practice of making these transpositions sections 0.5 mile long in order to reduce to a negligible amount the cross-talk from neighboring telephone circuits, shows the extreme sensibility of the telephone receiver.

The varieties of telephone apparatus, both signaling and talking, and the methods of connecting to meet various requirements, are innumerable. The two general types of magneto

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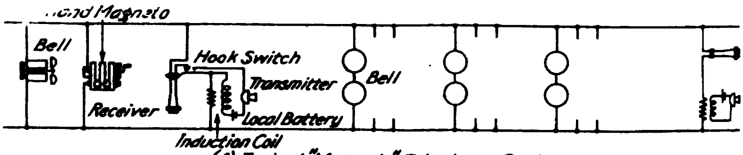
* "The Transposition of Electrical Conductors," Trans. A. I. E. E. Vol. XXII., p. 659.

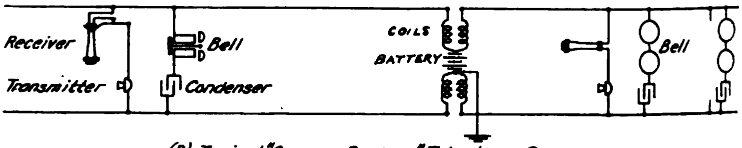
and common-battery systems are shown diagrammatically in Fig. 6.

Where the telephone circuit serves also for a telegraph line, the fact that the telephone is on a metallic circuit does not make the telegraph circuit metallic. For this reason, the same general considerations that apply to any telegraph line will apply to telegraph service obtained from telephone wires in the usual way.

Ringing, or calling currents, on telephone lines are commonly alternating at the rate of 16⅔ cycles per second, although lately the increased use of harmonic ringers calls for frequencies as high as 66. Hand generators are commonly wound to give between 50 and 100 volts on open circuit; this may be reduced to 10 volts or less at the end of a long line with many stations, and still be expected to ring the bell. Bells are commonly wound to 1000 ohms resistance, although many of the longer lines, with many stations use bells wound to as high as 2500 ohms resistance. The current taken by a standard 1000-ohm bell at 16⅔ cycles, 75 volts, is approximately 25 milliamperes. Fig. 7 shows the regulation of a five-bar hand magneto of standard type when connected with a load of 1000-ohm bells.



(A) Typical "Magneto" Telephone System



(B) Typical "Common Battery" Telephone System

FIG. 6

Numerous forms of protective devices are employed on telephone lines but nearly all consist of fuses and discharge gaps to ground, made up of small pieces of carbon separated by perforated mica, only a few mils in thickness. 300 to 400 volts is probably a fair figure for the breakdown point of these carbons when separated by 5-mil mica.

The actual magnitude of currents in telephone lines, resulting from speech sent into the transmitter, cannot be given with any accuracy. The strength of the battery, the special characteristics of the transmitter, the ratio of transformation in the induction coils, the constants of the line, not to mention the intensity of the voice, and the manner in which it is directed into the transmitter—all these are factors affecting the value of this current. For the purposes of this discussion, however, we may assume that on short lines the current may be as high as two or three milliamperes, while at the receiving end of long lines the current may be less than the one hundredth part of this and still be sufficient for the proper understanding of conversation.

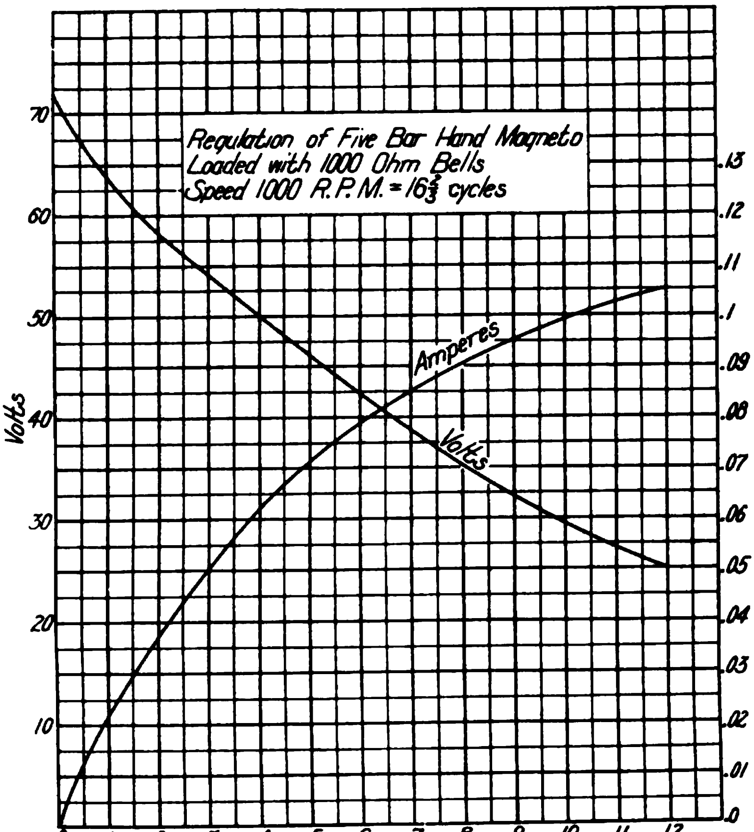


FIG. 7

The frequency of speech currents (for commercial telephone quality) is probably included between 200 and 2000 cycles. Probably the most important of these currents lie between 700 and 900 cycles. The writer believes it has been for some years the practice of the telephone companies to consider 800 cycles as the one frequency best representing the general range, and to

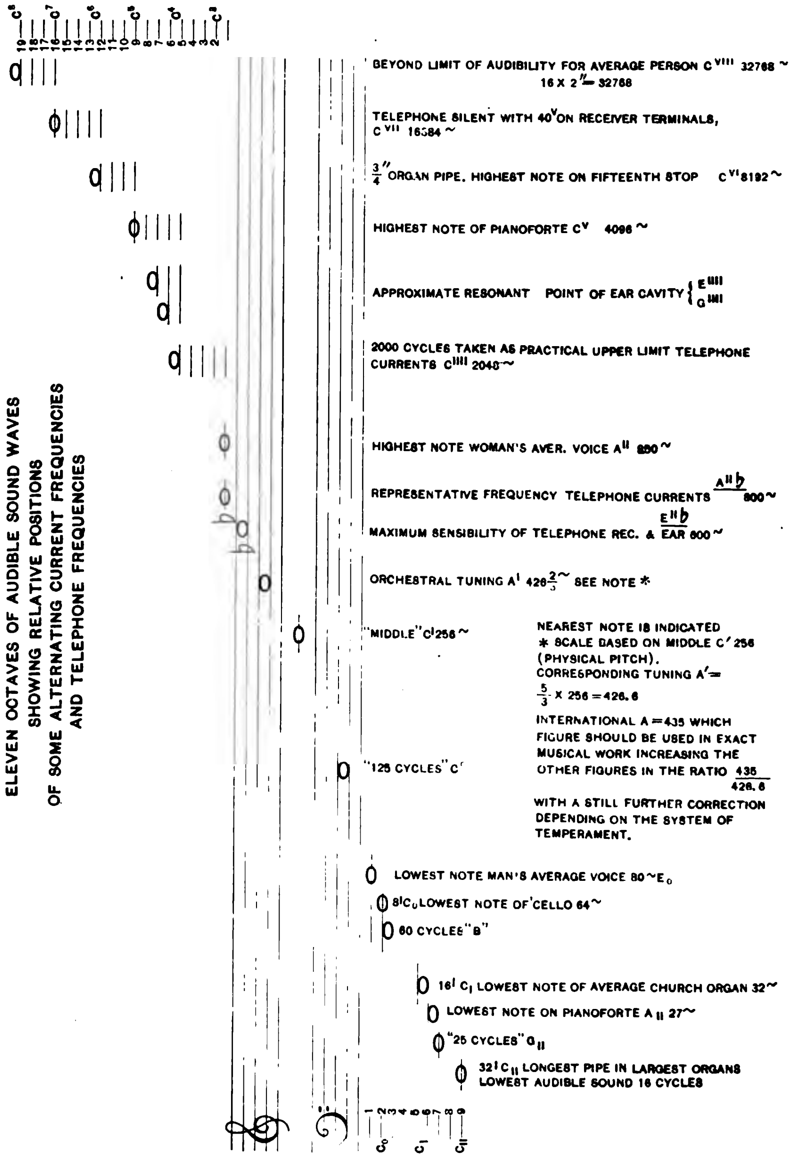


FIG. 8

make use of this frequency from small alternating-current generators when making quantitative measurements on different pieces of apparatus. How this figure was originally arrived at the writer has not been informed, but observations of telephone speech currents, which he has carried on by the aid of the oscillograph, tend to show that, roughly, 700 cycles is the prominent frequency in a man's voice. It is somewhat higher, say 900 cycles, in a woman's voice.

Fig. 8, shows a musical scale on which are noted the various frequencies referred to in this dissertation, and other frequencies that may serve to give a clearer idea of the various tones referred to.

The difficulty of naming a value of current sufficient to cause interruption or disturbance, mentioned while discussing the telegraph system, is even greater when considering the telephone system. To state the number of years of continuous sound that could be produced by one kilowatt-hour will serve no useful purpose in this paper; but of more practical interest are the curves of sensibility to different frequencies as given by Lord Rayleigh* and by Mr. Fowle† in the paper previously referred to, and by the writer's recent experiments. These curves, Fig. 9, were all made on a different basis of comparison, which accounts for the large differences in actual magnitudes of current; but attention is particularly called to the fact that, comparatively speaking, the sensibility, at say, 25 cycles, as shown by all of these curves, is not even of the same order of magnitude as the sensibility at, say, 600 cycles.

These curves are combined physical and physiological effects, as no attempt has been made to separate the influence of natural period of the telephone diaphragm. The size and weight of diaphragms in use seem to have been derived empirically and the small difference among so many makes it worthy of note.

Fig. 10 shows oscillograph records of the vowel sound " I" (as in mach*i*ne) taken from two different makes of transmitter. Curves *A* and *B* were made with the same arrangement of induction coil and transformers between the transmitters and the oscillograph vibrator, while Curve *C* was made with the same transmitter as Curve *B*, except that a single induction coil or transformer was in the circuit. The close similarity

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* " Theory of Sound," Vol. I, p. 473.

† " The Transposition of Electrical Conductors," Trans. A. I. E E, Vol. XXII, p. 659.

between Curves *B* and *C* show that the distorting effects of a transformation must be very small. The great differences, therefore, between Curve *A* and the others must be due to the difference in natural period, and amount of damping, of the two makes of transmitter.

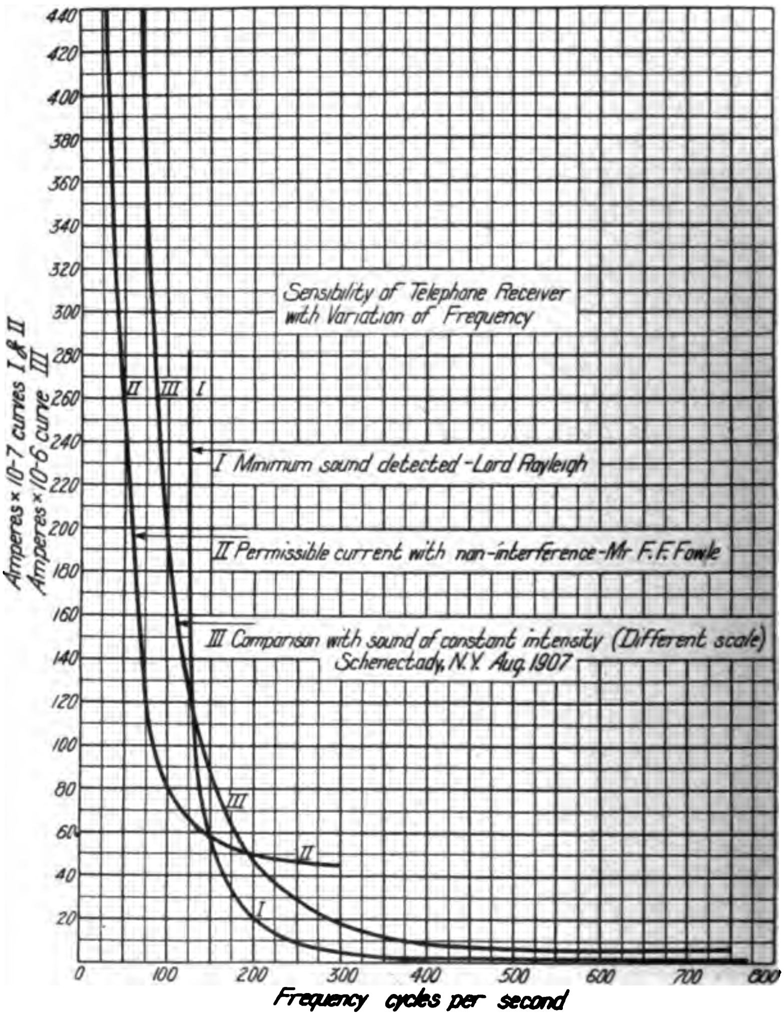

FIG. 9

Physiological phenomena having more or less bearing on this question of telephone sensibility are briefly stated below.

FIG. 10A

FIG. 10B

FIG. 10C

A. The lower limit of audibility is given by Helmholtz* as 25 to 30 cycles. Later investigations by Messrs Preyer and Ellis† place 15 cycles as the extreme low limit. Tests of this sort depend almost entirely on the intensity of the sound, and there is great danger in confusing some of the harmonics with the fundamental. The writer believes that he has actually heard a 25-cycle tone from a telephone receiver, but this could be heard only after taking precautions to obtain a smooth wave shape, by passing a comparatively large current through the receiver, and by holding the receiver very tightly against the ear, in a sound-proof booth. The vibration of the diaphragm at 25 cycles could be plainly felt by touching with the finger at a current value much below that required for an audible sound.

B. The upper limit of audibility, while apparently more definite, varies with different observers, 30,000 cycles being the figure ordinarily assigned for the upper limit, although some persons may hear sounds as acute as those corresponding to 40,000 cycles. The telephone receiver is not well adapted to respond to these very high frequencies, and a rough test made by the writer indicated that the sound was practically lost at 12,000 cycles, even though there was a pressure of 30 to 40 volts directly on the receiver terminals. When making this experiment it was noticed that as the high-frequency generator accelerated or came to rest there were certain frequencies which gave marked increase in sound. While investigation of this point has been by no means complete, the accompanying rough curve, Fig. 11

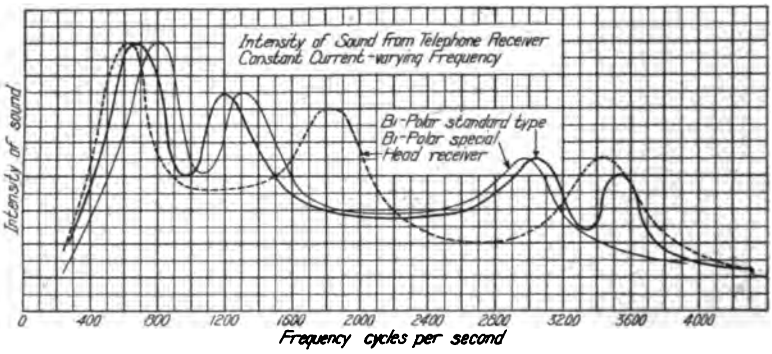

FIG. 11

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* "Sensations of Tone," Helmholtz, p. 116.

† "Sensations of Tone," Translator's note, p. 116.

is given as a matter of interest. While on this matter, it should be noted that for musical purposes sounds higher than 4000 cycles are considered of little or no value.

C. Low tones tend to drown out or diminish the apparent intensity of higher tones.* The ear apparently fixes its attention on the lower tone. This point is well recognized by musicians who rate a complex tone according to its lowest partial, even though the magnitude of this partial is small compared to that of some of the higher harmonics.

D. The ear itself, containing a column of air, should have its own natural period; this period Helmholtz places† in the neighborhood of e'''' to g'''', roughly, 2600 to 3200 cycles. Consequently the ear is especially sensitive to sounds corresponding to its own period.

E. Continuous sounding of a tone tends to deaden the ear to appreciate this particular tone.‡ Consequently, there is less difficulty in talking over a noisy telephone line where the noise is of constant pitch and intensity, as compared with the difficulty of talking over a line where the noise is continually varying in pitch, intensity and quality.

Telephones for high-tension transmission line service. Quick and reliable telephone service between generating and receiving points is an important factor in maintaining service over high-tension transmission lines. Power transmission companies almost invariably have their own private lines, and usually on the same poles or structures that carry the transmission wires. There have occasionally been serious accidents to users of such telephones at the time of accidental contact between telephone and power wires; and at other times the inductive effects due to unbalanced conditions cause differences of potential between telephone system and ground. which can by no means be neglected. The telephone is, therefore, very likely to be out of commission just at the time when tangles on the power system make communication necessary in order to resume service. Various points in connection with this phase of the transmission problem were well brought out in an Institute paper§ and accompanying discussion several years ago.

In order to safeguard the users of telephones, the telephone

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* " Theory of Sound," Lord Rayleigh, Vol. II, p. 444.

† " Sensations of Tone;" p. 116.

‡ " Theory of Sound," Lord Rayleigh, Vol. II, p. 446.

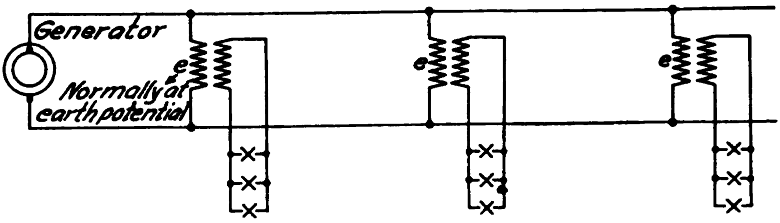
§ " The Transposition and Relative Location of Power and Telephone Lines," P. M. Lincoln, Trans., A. I. E. E., Vol. XX., p. 245.

Fig. 12—Installation of telephone, with Y-109 insulating transformer and combination fuse lightning-arrester and disconnecting switch.

insulating transformer shown in Fig. 12 has been developed. This transformer is given a high-potential test of 25,000 volts between windings which come to line and those connected to instrument. The combination disconnecting-switch, fuse, and lightning-arrester, shown in the same cut, has the ordinary small-gap carbon plates across the terminals of the transformer, but such gaps are not used between line and ground. Discharge gaps to ground are made adjustable, the intention being to set these just beyond the point that the maximum induced potential, under abnormal conditions, will strike. As this potential is not likely to be much above 8000 or 10,000 volts, the 25,000-volt test insulation in the transformer is expected to protect the instrument even in the possible event of actual contact between telephone lines and wires of systems operating at 25,000 volts or higher. Both primary and secondary of this transformer may be double wound, permitting series or parallel connection, as may be best for various line conditions, and also making available a neutral point which may be grounded where such a ground is serviceable. The neutral point is of service in case it is desired to signal or telegraph over the telephone line.

On any telephone system eternal vigilance is the price of first-class service. The insulation always has a tendency to become worse, and change in resistance at connections will upset the balance. So long as the telephone line has the field to itself, the closest attention need not be paid to these points. However, when in the neighborhood of other conductors, departure from a theoretically perfect balance immediately begins to be felt, and much more attention must be paid to transpositions and insulation. While the writer states nothing new, he wishes here to emphasize the importance of bringing the insulation of the telephone system as a whole into first-class shape before wasting any time or money on transpositions. In many cases, when a telephone line becomes unsatisfactory, it is the practice to cut in more transpositions. If these have previously been located at every tenth pole, they may be doubled up, placing one at every fifth pole. Probably there are few telephone lines, on the same poles with power lines, where transpositions at every fifth pole are any more effective than at every tenth pole. While with some forms of transposition there is no objection to placing as many as the line will hold, those forms which involve cutting the wires and making splices are likely to have imperfect joints, with consequent loss of balance. In general, the more transpositions the more likelihood of high-resistance joints. We have also seen a fantastic arrangement of see-sawing the two conductors of the telephone line up and down from pole to pole in the vain hope that a noisy line would be quieted in this manner.

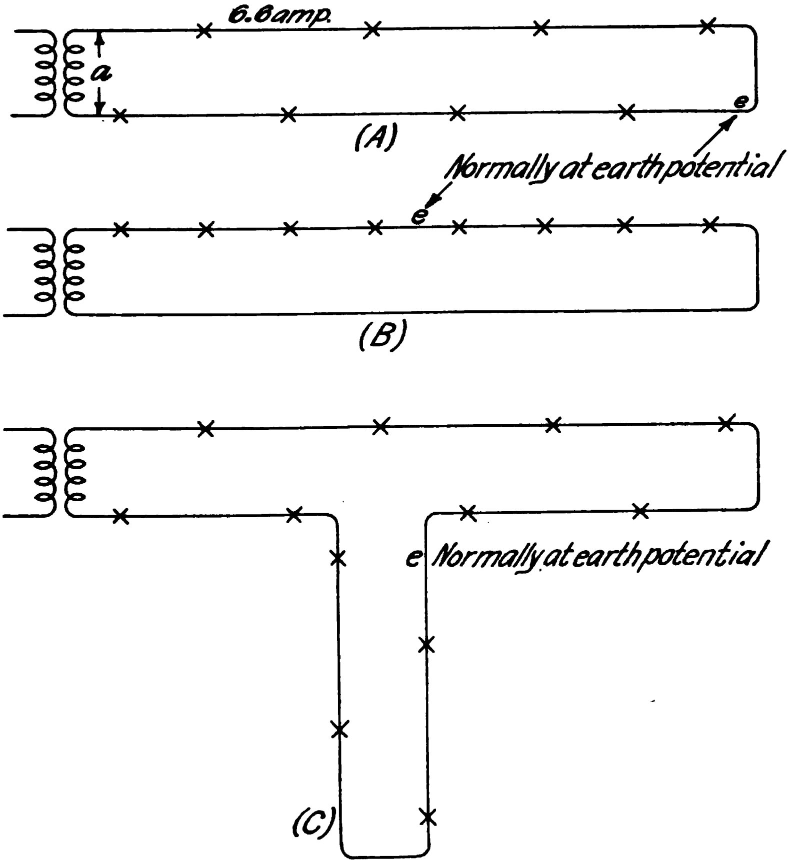
In a recent instance, additional transpositions were placed in a telephone line, and also in the power line, with small improvement in service. The trouble was eventually found in some transmitter dry batteries, which were placed away from the instrument in a damp location. It is the habit of telephone manufacturers to make common connections between the primary and secondary circuits of their instruments in the endeavor to save, either a few inches of wire, or an extra contact at the hook switch. This means that unless attention is paid to every inch of the telephone system, it is poor economy to replace the cheap pony glass on the outside line by high-grade porcelain.



Representative Diagram for Single-phase Lighting System

FIG. 13

Alternating current systems.—The earliest alternating-current systems were operated single phase and used mainly for lighting purposes, from a large number of small transformers. This system is represented diagrammatically in Fig. 13. Being a metallic bridging system free from grounds, the fields which may cause disturbance to neighboring wires are comparatively weak. Since these lighting systems usually supply the same customers that are also supplied with telephone service, local telephone lines are especially likely to be in proximity to such circuits. The further objections of property owners to tree-trimming, and to duplicate pole lines in residence sections, usually result in occasional grounds on the lighting circuit, or the telephone circuit, or both, with attending noisy lines. Since the various feeders in the local distribution are connected in parallel to the same bus-bar, a ground on any one feeder upsets the electrostatic balance of all the others. It is also possible on such a system to have a ground simultaneously on both sides of the circuit, which may result in unbalanced currents and electromagnetic inductive effects; but on account of the usually high resistance of tree grounds, etc., such currents are likely to be small and of slight disturbance compared with the unbalanced electrostatic effect.



Typical Arc Lighting Circuits

FIG. 14

An ideal metallic circuit telephone system should not be affected by exposure to fields of any strength, but the great differences between ideal and practical construction are such that not infrequently a heavy ground on a 2300-volt local lighting system will be felt on all the telephone lines in the exchange.

Another local alternating-current system is that used for series arc lighting, represented diagrammatically in Fig. 14. These circuits usually carry 6.6 amperes, and with 50 lamps in the circuit the potential between wires at the point *a* is approximately 4000 volts. This potential is reduced by 80 volts as each lamp is passed in succession. More inductive disturbances have been felt from circuits of this character than from the typical lighting circuits discussed above, mainly in instances where the lamps have been connected to the wires with little regard to preserving the balance. For example, diagram B shows all the lamps connected in one side of the circuit, the other side serving merely as a return. In such a case that point of the system at earth potential would be somewhere near the point indicated, instead of at the end of the line. In other cases the two sides of the circuit are not kept together, in the attempt to save wire by looping down one street and up another as shown in diagram C. A side-branch cut in tends to give a similar unbalanced electrostatic potential as the arrangement B, although this arrangement is in general not so bad as where all the lamps are cut into the same side of the circuit. In addition to the greater inductive disturbances from unsymmetrical placing of lamps and looping of circuits, these arc circuits are more likely to be grounded than the multiple lighting circuit, partly on account of the higher voltage.

The next system to be considered is the three-phase system represented in typical diagrams of Fig. 15 *A* represents the simple three-phase system supplying three-phase load, either through banks of transformers or directly. With this system the very nearly equal capacity between each of the wires and ground tends to maintain the neutral point of the system at earth potential as indicated by *e*. At any given instant the algebraic sum of the potentials of the three wires (measured to earth) is equal to zero, and the algebraic sum of the currents in the three-wires at any location on the system, is also equal to zero. Consequently, unless the three-wires are widely separated, the external fields, both electrostatic and electromagnetic, are weak. An accidental ground on any one of the three conductors dis-

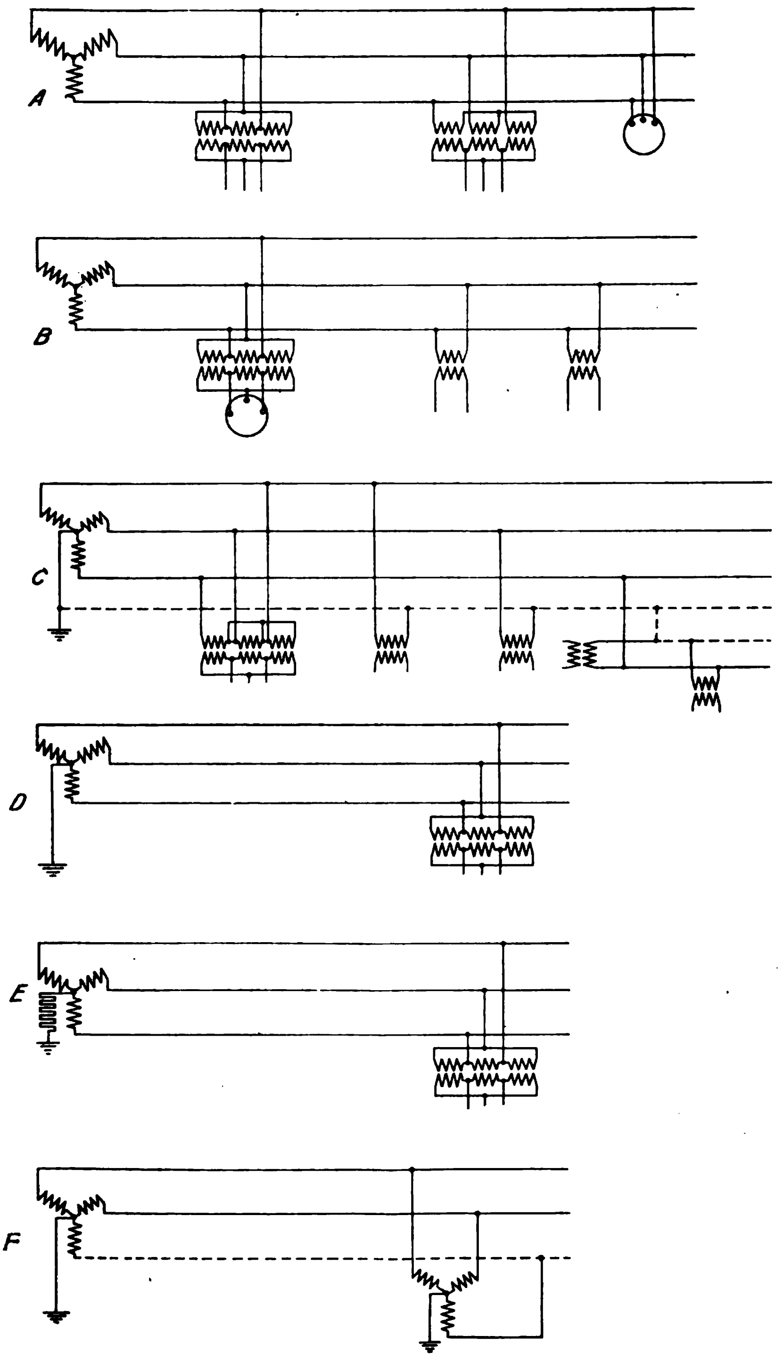


FIG. 15—Typical three-phase distributing systems.

turbs the electrostatic balance, with results similar to a ground in the single-phase system previously considered.

B shows a three-phase system used for both power and lighting. As indicated in this diagram, it is not unusual to extend any two of the conductors to make a single-phase distributing line. This arrangement, even with perfect insulation of the system, displaces the neutral point from earth potential, as indicated by *e*, a greater or less amount, depending on the relative capacities of the three-phase branches and single-phase branches. From such a mixed system we might, therefore, expect electrostatic induction. Electromagnetically, however, this system is as well balanced as the preceding. A similar condition may arise on a balanced system of distribution through the blowing of a fuse.

C shows a four-wire, three-phase system as occasionally used for combined lighting and power distribution. In this case a fourth conductor is connected to the neutral, which may or may not be grounded. Motors and three-phase transformer banks may be connected as in the simple three-phase system while lighting transformers are connected between any one of three conductors and neutral conductor. This system is on a par with *B*, when the neutral point is not grounded. When the neutral point is grounded, a single-phase branch as indicated between *d* and *e*, will obviously have the same effect as a single-phase line with one conductor grounded.

D shows a three-phase system with the neutral point definitely maintained at earth potential. Neglecting line drop and regulation of the system, a ground on any one conductor does not disturb the electrostatic balance but does upset the electromagnetic balance, as in this case the current, determined by the resistance of the fault and the earth return, flows over one wire and returns to the neutral through the earth.

E shows the neutral point grounded through a resistance. With this arrangement, a ground on one conductor will usually disturb both the electrostatic and electromagnetic balance. The relative disturbance of each sort depends on the resistance of the fault and neutral resistance.

F shows a three-phase system on which the neutral point is grounded at both the generating and receiving ends of the line. From the standpoint of disturbance, this is very similar to D. From the operating standpoint, the grounded neutral at both ends permits continued operation in emergency with either one or two of the wires out of service. When running on two wires, the electrostatic disturbance will depend on whether the third wire is alive without carrying current, or whether it is dead through being disconnected at both ends. Any operating condition which causes currents to flow from one neutral to the other through the earth, will also unbalance the circuit to some extent. In all of this discussion it has been assumed that the electrostatic capacity to ground of the generator and transformer windings is small compared with the capacity of the distributing wires whether in underground cables or overhead lines.

The practice of transposing three-phase lines varies between no transpositions at all to transpositions every mile. For the average system, transpositions are of no value unless the telephone or telegraph wires are near enough to be affected. Too many transpositions, besides being of little service, tend to weaken the line and increase the difficulties in locating trouble.

Harmonics and irregularities. When the electromotive force wave of a generator, as measured between the neutral and one of the terminals, contains third harmonics, and other harmonics which are multiples of the third, these harmonics are in the same phase relation in the three windings. Grounding the neutral point brings the potential wave of these particular harmonics on all three of the line wires in the same phase relation. Electrostatically considered, therefore, with reference to the third harmonic the three wires may be regarded as a single wire whose potential to ground varies at triple, and multiples of the triple, frequency. The possible resulting disturbance will depend entirely on the magnitude of these harmonics. The writer knows of but one case where trouble was experienced with telephone lines as the result of grounding the neutral point of generators, and in this case there was nothing to show whether or not the telephone line was in fair condition for exposure to the high-tension transmission line. In several tests made it has been impossible to tell, from the telephone line, whether the neutral connection was grounded or not. In one instance an ordinary telephone receiver was connected between ground and the neutral of a 2000-kw. 13,200-volt generator, in service and feeding, through several thousand feet of cable and six or seven miles of transmission line, a 1500 kw. synchronous converter. The noise was no greater than is occasionally heard on a commercial telephone line in trouble. This somewhat dangerous experiment was performed only after finding that the triple-frequency charging current on this system was too small to be measured on commercial alternating-current instruments.

Variable permeability and the hysteresis and eddy-current losses in transformers result in a distorted wave of exciting current. This distorted current-wave can be resolved into third harmonic components which may, for certain combinations of transformer connections, result in third harmonic potentials between three wires (regarded as one) and ground. For other connections, triple-frequency currents may circulate through a circuit made up of transmission wires and ground.

The symmetrical construction of field poles and winding of alternating-current generators causes positive and negative waves to be of the same shape, and hence free from evenly numbered harmonics.* These even harmonics, nevertheless, may be introduced into a power system if transformers or other pieces of apparatus contain iron which is permanently magnetized. Ordinarily, transformers are free from permanent magnetism, but in circuits involving earth return there may be a considerable direct current passing through the windings, derived from neighboring direct-current trolley systems, etc., Oscillogram, Fig. 16 shows the exciting current in a transformer which has, at the same time, direct current in its windings. The general tendency in such cases is for the waves to be peaked and flat topped in succession.

FIG. 16—Oscillogram, exciting current in 75-kw. transformer with direct current in winding. Upper curve, e.m.f. on transformer. Lower curve, exciting current

Even where the generated electromotive force wave is com-

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[*] See " Even Harmonics in Alternating Current Circuits," PROCEEDINGS A. I. E. E., July 1909, pp. 963–970.

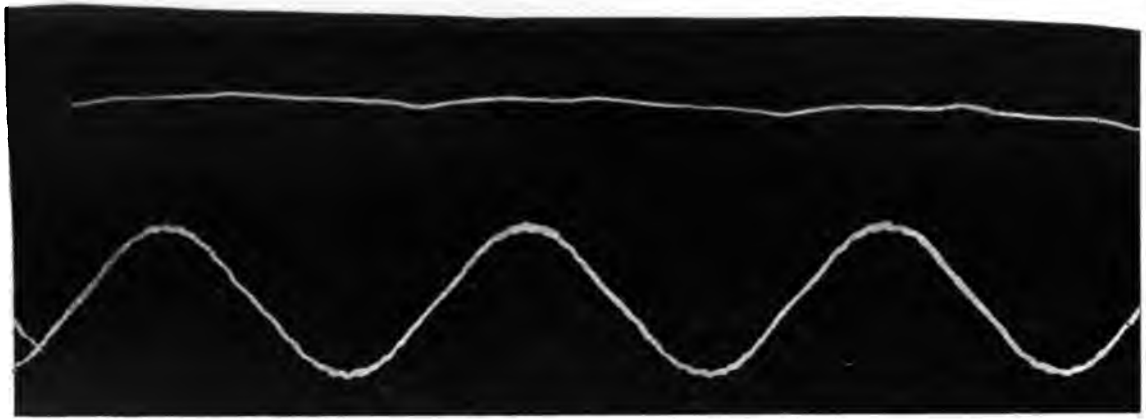


FIG. 17A—Oscillograms on single phase railway
Upper curve is current—locomotive not running. Lower curve is trolley potential

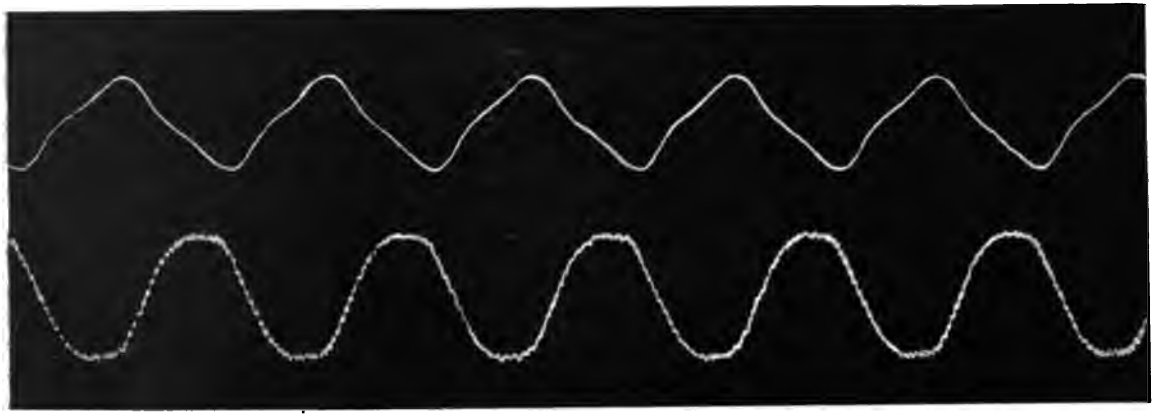


FIG. 17B—Oscillograms on single phase railway
Upper curve is current taken by locomotive. Lower curve is trolley potential

paratively free from harmonics, the various pieces of apparatus on the system will all have their effect on the potential wave. An instructive experiment on this line is to connect a telephone receiver in series with a small condenser, to alternating-current house-lighting mains. The number of strange noises heard in such a case, due mainly to induction motors on the system, will be a surprise to any one who has not tried this simple experiment.

Oscillograms in Fig. 17, show electromotive force waves on a single-phase trolley system under no load, and when commutating series single-phase motors are in operation.

Oscillograms Fig. 18 show the charging current between telephone line and ground, the same being in proximity to a single-phase trolley wire. Curve *a* is the charging current between the telephone line and ground with cars at standstill, and Curve *b* with cars in operation.

On account of the much greater sensibility of the telephone receiver to sounds of high frequency, these irregularities in the potential wave, although of much smaller magnitude than the fundamental frequency, are much more likely to be heard in neighboring telephone lines, when transpositions and other points of balance have not been given close attention. A condenser connected between alternating-current wires and earth, will, to a certain extent, absorb these high-frequency irregularities.

It should also be noted that the various neutralizing connections later discussed, as well as neutralizing for the fundamental frequency will, to some extent neutralize also for higher frequencies.

Single-phase railway. The several typical diagrams of Fig. 19 show the transformation and distribution arrangements for the latest addition to the alternating-current field—the single phase railway.

Diagram A shows the single-phase system in its simplest form. One terminal of a single-phase generator is connected to earth and the other to an overhead trolley conductor. The return circuit is made up of steel rails and earth. Neglecting line drop, the overhead conductor is at the same potential throughout and there being no neighboring conductor of opposite polarity, there will result electrostatic fields of constant strength irrespective of number of cars in operation. From the standpoint of inductive disturbances, this is the worst arrangement that can be made with the single-phase railway system. Electromagnetic effects will be proportional to the length of transmission and to current, and vary with load and distribution of cars.


CURRENT BETWEEN TELEPHONE AND GROUND
E.M.F.
MAGNETIZING CURRENT OF THE CAR TRANSFORMER

FIG. 18A.

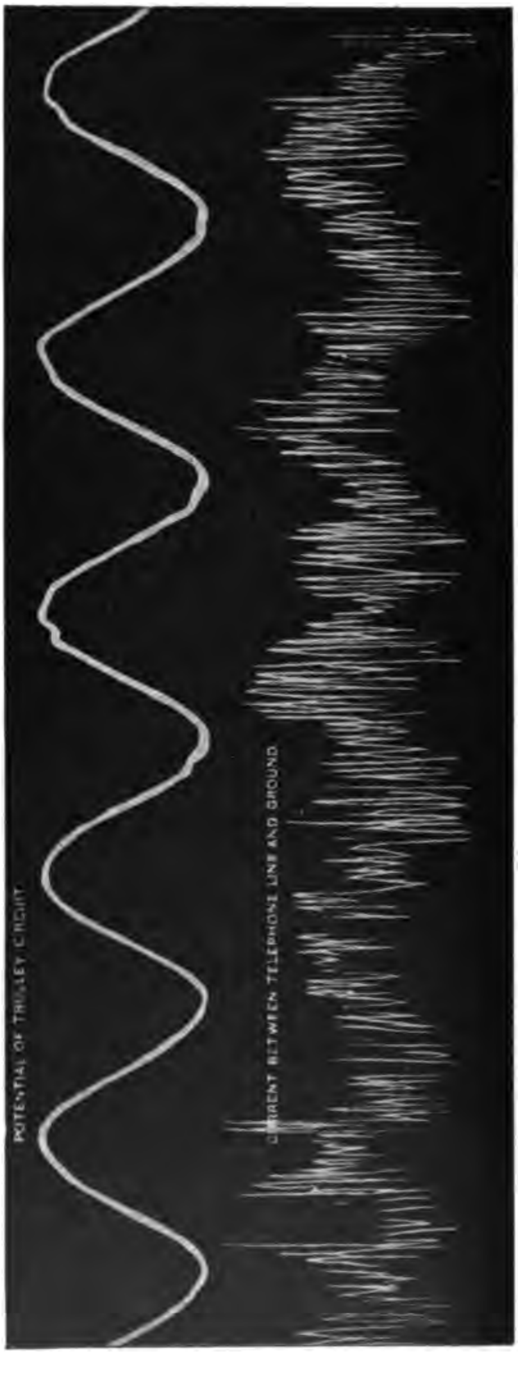

POTENTIAL OF TROLLEY CIRCUIT
CURRENT BETWEEN TELEPHONE LINE AND GROUND

FIG. 18B

Diagram B is just as bad electrostatically, but by locating the generating station at the middle of the line, instead of at the end, the maximum length of feed is reduced to one half, and, depending on the running schedule of the cars, there may be a still further reduction in magnetic inductive effects through more or less neutralizing action from currents in opposite directions, to supply cars each side of the generating station.

Diagram C is an extension of B through the addition of transmission line and transformer sub-stations. Again considered from an inductive standpoint, this is better than B only through the feasibility of reducing the length of the individual sections. Diagram D is essentially the same as C except that transformer connections have been so made that alternate sections are of opposite polarity. Consequently, the equal exposure of a telephone or telegraph line to the same number of positive and negative sections will practically neutralize the effects of electrostatic induction. In this connection it should be noted that there will be charging currents flowing back and forth in a neighboring telegraph wire from the portion opposite the section of single-phase trolley of one polarity, to the neighboring section of opposite polarity. If there be intermediate stations on the telegraph line, these charging currents, flowing from one section of the wire to the other, may be sufficient to disturb the relay. From a railroad point of view, a section of trolley wire fed from a single sub-station is likely to tie up the whole road if a single sub-station goes out of commission. The circuit arrangement next to be considered obviates this difficulty by the use of trolley sections continuous between sub-stations, thus giving duplicate feed.

Diagram E shows a typical arrangement of a single-phase trolley wire continuous between transformer sub-stations. In this arrangement all trolley sections are of the same polarity with corresponding electrostatic effects. From the standpoint of electromagnetic induction, however, this system of distributing has marked advantages. Assuming equal transformer potential at two adjacent sub-stations, a car midway between stations will draw equal current from the two sub-stations. These equal currents flow equal distances but in opposite directions, with a consequent neutralization of the electromotive force induced in neighboring telegraph or telephone wires. This neutralization also holds for positions of the car when other than at the half-way point, for while greater current will flow from the nearer sub-station, this greater current flows through a shorter length of trolley wire than does the lesser current from the farther sub-station.

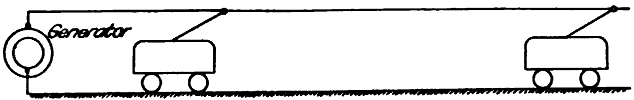
The next step is to combine the two arrangements as shown in diagram F, where trolley sections are fed from both ends, and alternate sections are of opposite polarity. This arrangement requires either two transformers at some of the sub-stations, or, what amounts to the same thing, a transformer with two secondary windings.

In the various distribution schemes already discussed, the neutralizing action, if any, is the differential effect between two or more sections. At any given point there is no neutralizing action, either electrostatic or electromagnetic. Consequently these arrangements are effective only where a telegraph line runs parallel to a number of sections at approximately the same distance.

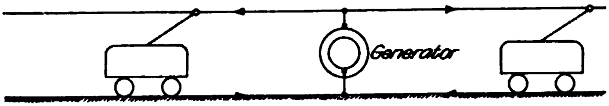
While it would be possible, it is by no means easily practicable to have a double-trolley, single-phase railway system; and, considered inductively, such a system would be on a par with any of the other metallic-circuit, alternating-current systems.

The various distribution arrangements for a single-phase railway, as shown in Fig. 19 and just considered, require no additional conductors, although the transformer sub-stations to accommodate the special arrangements may be an added item of expense.

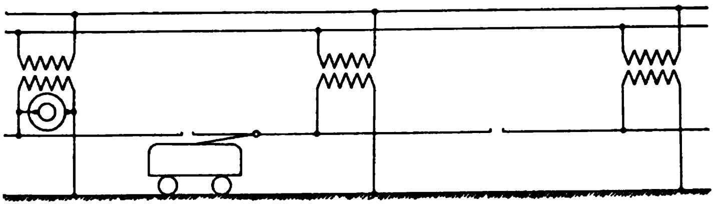
We will next consider the several distribution arrangements requiring additional conductors. Fig. 20 shows several schemes of distribution designed more or less to represent metallic circuit conditions, still retaining the single trolley. Diagram A shows a potential-neutralizing conductor erected in proximity to the trolley wire. By means of one or more transformers, this wire is maintained at approximately the same potential to ground as the trolley wire, but always of opposite polarity. Such a conductor will neutralize the electrostatic fields. It is more or less obvious that this neutralizing conductor might be placed nearer to a telegraph line than is the trolley wire, in which case a proper transformer ratio could be selected to neutralize the potential at the position of the telegraph wires. Such an arrangement, however, would be most effective for a single line of telegraph and would involve either extensive calculations or experiments to insure the best results. By having the neutralizing wire as close as possible to the trolley wire, no calculations or experiments



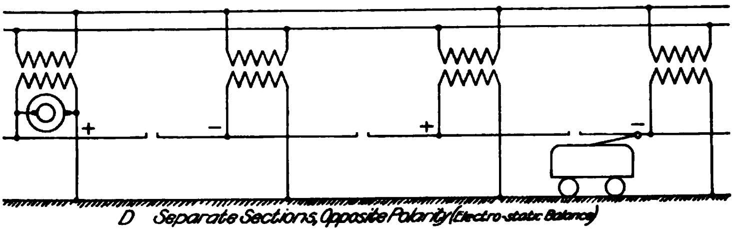
A Feed from One End



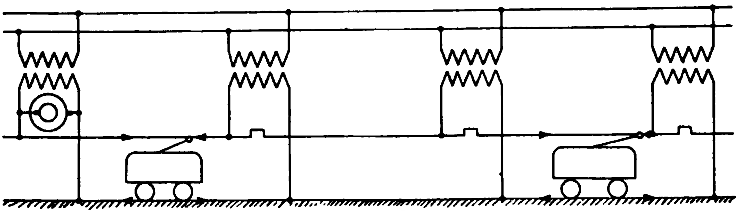
B Direct Feed, Generator at Middle of Line



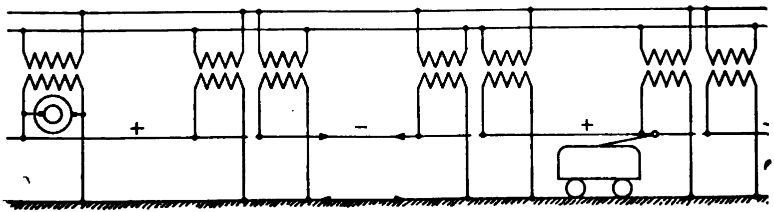
C Separate Sections, Same Polarity



D Separate Sections, Opposite Polarity (Electro-static Balance)



E Electro-magnetic Balance

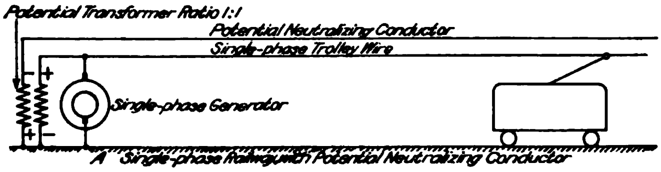


F Electro-static and Electro-magnetic Balances

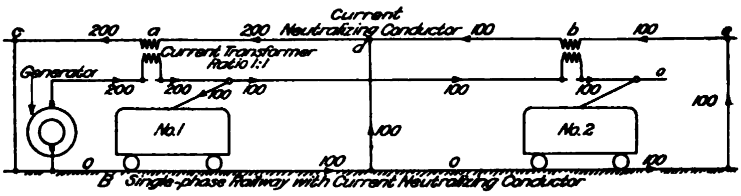
FIG. 19.—Distribution Systems for Single-phase Railway

are necessary, and the same wire will neutralize equally well for various telegraph lines, even if on opposite sides of the track and at various distances.

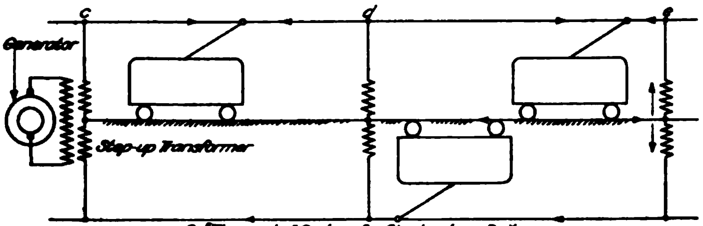
Diagram B shows a current-neutralizing conductor in proximity to a trolley wire. This conductor must be of the same carrying capacity as the trolley wire, and current transformers, ratio 1:1, are cut into the trolley wire and neutralizing conductor at intervals. Midway between these transformers the neutralizing conductor is connected to the rail. The purpose of this scheme is obviously to cause equal currents to flow in opposite directions in the trolley wire and neutralizing wire. For certain positions of the cars, the neutralizing action will be insufficient: for other positions of the cars, an over-neutralized condition will result. By using a number of transformers, approximate neutralization may be obtained. The objection to this and similar arrangements is the extra expense of the neutralizing conductor and transformers, and the greater chance of shutdown due to the



A Single-phase Railway with Potential Neutralizing Conductor



B Single-phase Railway with Current Neutralizing Conductor



C "Three-wire" System for Single-phase Railway
Same Conductors serve for Transmission and for Trolley

FIG. 20.—Neutralizing Conductors for Single-phase Railway Distribution

quantity of high-tension apparatus distributed along the line. As against the expense of the extra conductor it should be noted that such a circuit will have small self-induction as compared with the usual single-phase circuit with overhead conductor and earth return. The inductive drop will therefore be considerably less, which may be an important factor in some cases.

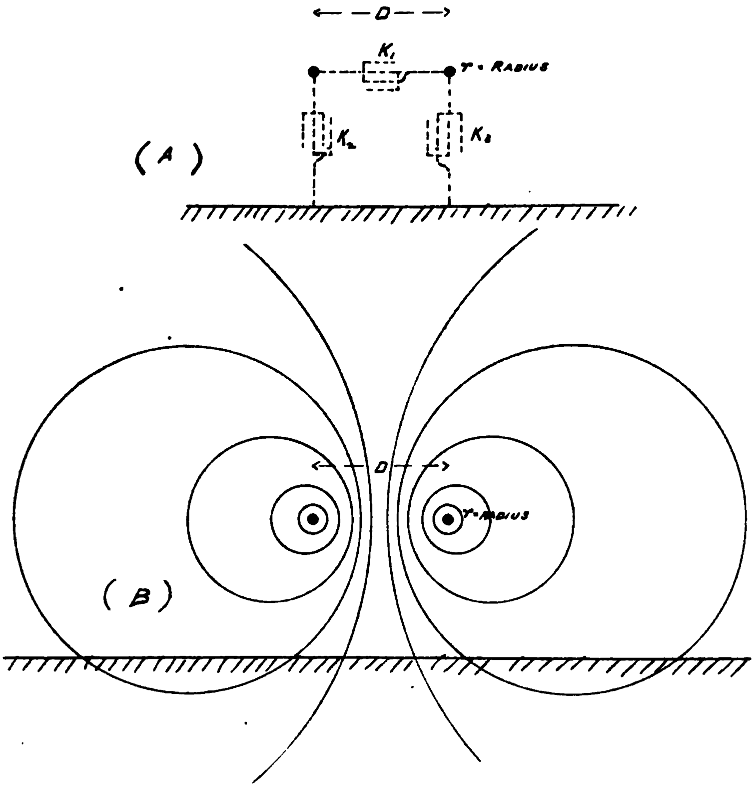


FIG. 21—The usual formula for capacity between wires is

$$C_{\text{m. f. per mile}} = \frac{0.01942}{\log_{10} \frac{D}{r}} \quad \text{(Diagram A.)}$$

This neglects effect of capacities to earth K_2 and K_3

The usual formula for inductance of a 2-wire circuit is

$$L_{\text{m.h. per mile}} = 0.0805 + 0.741 \log_{10} \frac{D}{r} \quad \text{(Diagram B.)}$$

This formula neglects the fact that some of the magnetic flux cuts the earth.

By installing a potential-neutralizing conductor as described in Diagram A, and a current-neutralizing conductor as well, metallic circuit conditions are approximated. A single current-neutralizing conductor of sufficient carrying capacity might serve for trolley wires over two or more tracks, and similarly a single potential-neutralizing conductor might serve for more than one trolley wire, either by increasing its size or the voltage supplied to it.

Diagram C shows an arrangement where the same conductor tends to neutralize for both current and potential. Looked at from one point of view, this arrangement is similar to the Edison three-wire system, the rail return being the neutral. Compensators, or 1:1 transformers, keep the two conductors at equal and opposite potentials from earth, and the second conductor may or may not be used as a trolley wire. In the case of a double-track road, both conductors could advantageously be used as running conductors. This arrangement can be regarded as a high-tension transmission system of double the working trolley voltage. The transmission conductors thus form two working trolley conductors with neutralized electrostatic effects, and partly neutralized electromagnetic effects.

Calculation of inductive disturbances. While plenty of formulas for calculating self-induction, mutual induction, and capacity of circuits are readily available in handbooks and text books, the practical cases in which we are interested are, in general, very complex, on account of the number of wires at different and unknown potentials, varying distance from ground, varying distance from disturbing wires, etc. In general, a calculation of inductive effects can be taken only as showing the proper order of magnitude. Where the earth forms one side of the circuit, it is usual to assume that the earth, right up to the surface, acts practically as a perfect conductor. Again, other formulas dealing with metallic circuits neglect entirely the effect of the earth, which, to be consistent with the other formulas, should still be regarded as a perfect conductor in proximity to the wires under consideration. For example; consider Fig. 21.

Let diagram A represent two conductors whose capacity is to be determined. This is given by the formula:

$$C_{m.f.\ per\ mile} = \frac{0.01942}{\log_{10} \dfrac{D}{r}}$$

It should be noted, however, that this formula, although that ordinarily given, does not take into account the added capacity due to the proximity of the earth. This added capacity may be regarded as composed of two condensers in series, as indicated. Where the two wires are comparatively close together and a considerable distance from the earth, this additional effect may be neglected, but as the distance between the conductors is increased the effect of the earth may predominate.

Similarly in Diagram B, consider the self-induction of the circuit made up of two conductors. The self-induction is proportional to the magnetic flux included, but it is apparent that some of this flux will pass through the earth, which still being regarded as a more or less perfect conductor, will circulate eddy currents, which in their turn set up counter-flux, thus making the self-induction of the circuit lower, the nearer the wires are to the earth. Therefore, any formula for capacity or inductance which takes no account of the relative position and conductivity of the earth must be regarded as approximate only.

The purpose of this paper is not to develop methematical formulas for the various combinations of alternating-current power circuits and telephone and telegraph circuits, under conditions which might be more or less closely realized in practice. As soon as we have to deal with more than three or four conductors, the formula becomes so complicated as to be practically unmanageable. This, taken with the fact previously stated, that all these formulas depend upon assumptions as to conductivity of the earth, etc., not actually realized, and which are unknown quantities, makes it appear preferable to present two or three typical formulas and curves for simple cases, leaving the calculation of complex circuits to those who delight more in mathematical exercises than in experimental determinations of values.

We must make some assumption regarding the conductivity of the earth, and the path taken by return current in the earth. In the usual formulas for capacity and inductance of circuits the assumption has been made that the earth acts practically as a perfect conductor. This assumption appears to be sufficiently exact, as far as the electrostatic effects with which we are interested are concerned, since the wires are usually at distances of about 20 ft. from the earth, so that the charging currents are relatively small. Even high resistance at the earth's surface could cause the potential at the surface of the earth, beneath the wires, to differ but very slightly from true " earth " potential.

Return currents in the earth, however, are of an entirely different order of magnitude, so that the path taken by this return current will tend to be that which offers the least resistance. This return path of lowest resistance will be modified by the fact that the farther the return circuit is from the overhead wire, the greater will be the inductive drop, which, in its turn, will tend to cause current to flow nearer to the line conductor. The actual or effective return, therefore, will be

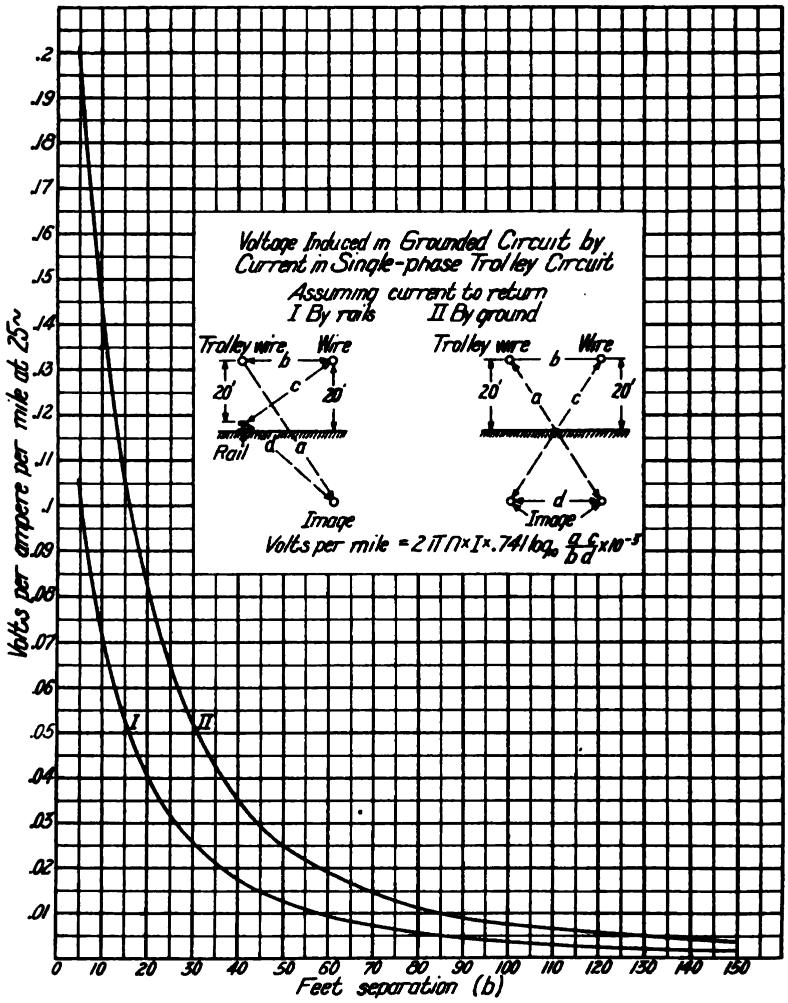


FIG. 22

determined by a combination of resistance and inductive effects, in a given case depending largely on nature of soil, amount of moisture at different depths, proximity to bodies of water,

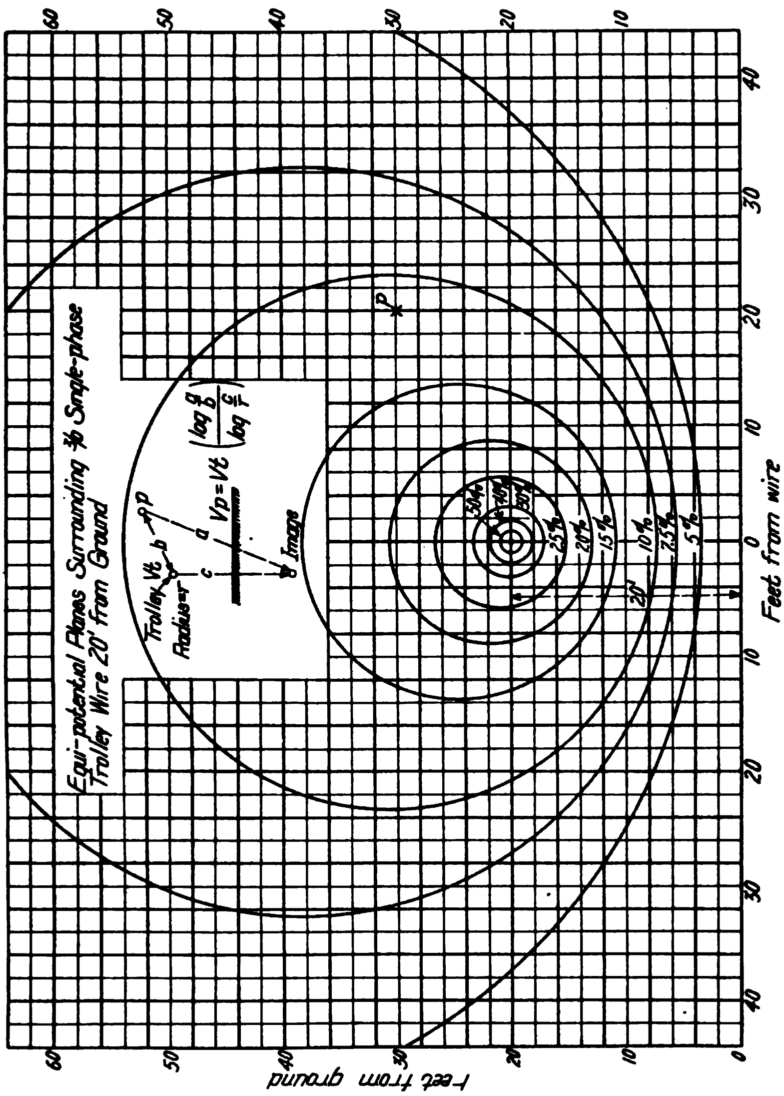


Fig. 23

water mains, gas mains, and rails of neighboring traction systems.

However, in order to deal at all with the question, it is necessary to make one assumption or the other; either that the earth is an insulator or a perfect conductor. The various formulas are based on the latter assumption. With this assumption it can be shown that the effect of distributed charge or current is the same as though this charge or current were concentrated on a

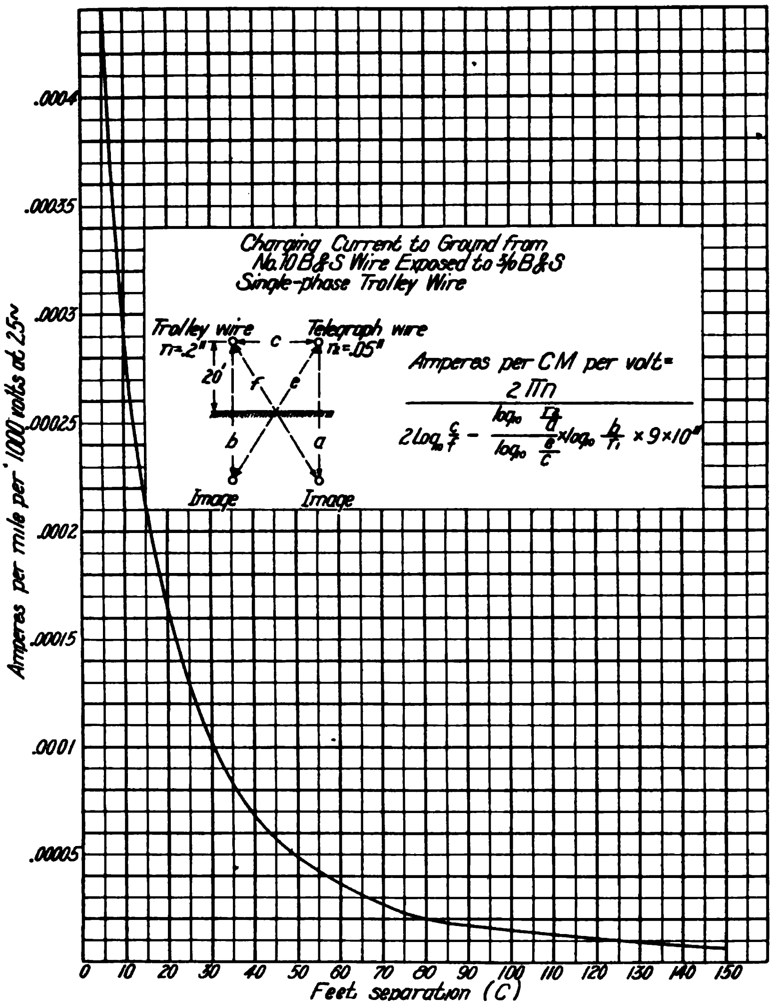


Fig. 24

wire as far below the ground as the wire in question is above the ground; in other words, on what would be the "image" of the overhead conductor if the surface of the earth formed a mirror. This means that where the earth forms a return circuit to a conductor 20 ft. in the air, the effective separation of the two conductors, and hence the self-induction, will be that corresponding to a two-wire circuit with conductors 40 ft. apart instead of 20 ft. apart.

In calculating the inductive effects from a single-phase railway, we may, on the one hand, assume that all of the current returns by way of the rails, which will lead to too low inductive values, as some of the current is almost certain to leave the rails and return by way of the earth. On the other hand, the image assumption may also lead to too small inductive values on account of the imperfect conductivity of the earth. The

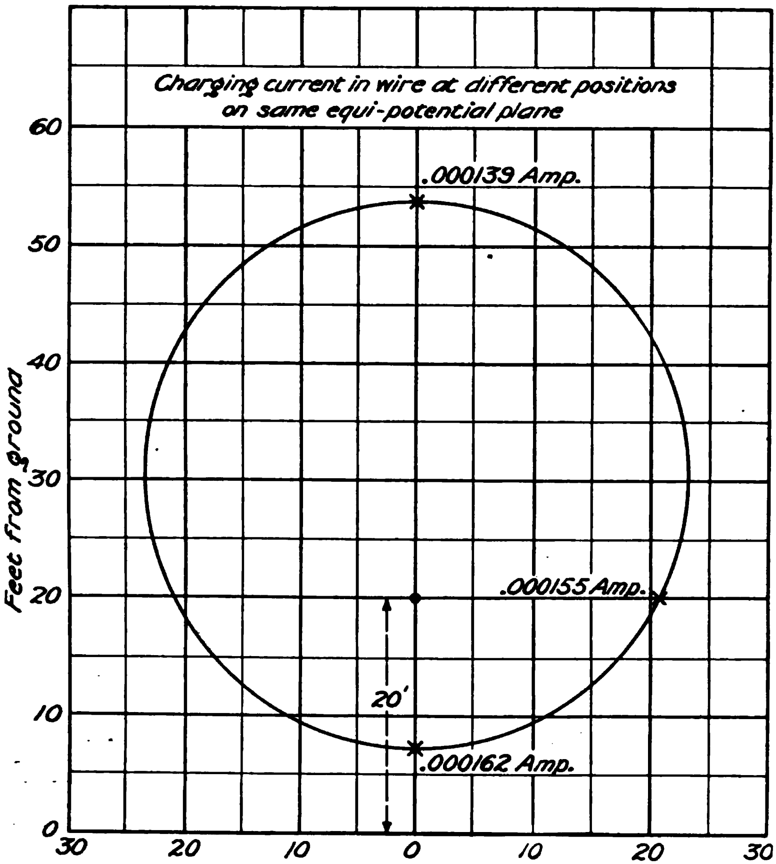


FIG. 25

true inductive value, therefore, will be influenced by the amount of current leaving the rails, and also on the effective path taken by this current. In the absence of definite experimental determination of inductive action in and from a given circuit, we usually assume the image as the effective return conductor.

The electrostatic potential at any point depends on the relative positions and charges of other conductors in the neighborhood. The charging currents, therefore, flowing into a grounded wire will not be the same when it occupies different positions, even though the potential on the wire when insulated is the same for the different positions considered. This is because of the reaction of the induced charge. For example, Fig. 26 is taken from Fig. 23, and the circle represents the 10 per cent potential surrounding the 000 trolley wire 20 ft. from the

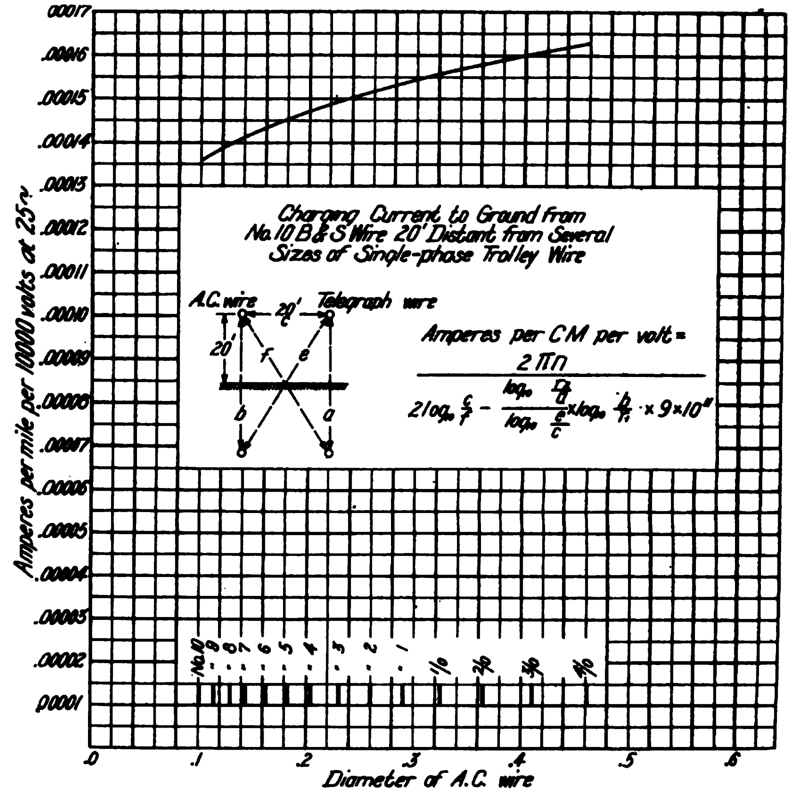


FIG. 26

ground. A wire occupying any position on this circle would show the same potential to ground, if measured by an electrostatic voltmeter. However, the charging current when the wire is grounded will vary for different positions on the circle. This charging current will be a maximum when the wire in question is directly below a disturbing wire, and a minimum at the position directly above, and for other positions will have some intermediate value. The figures against three positions are charging current per mile at 25 cycles for each thousand volts of the trolley wire.

The effect of a change in size of wire on an electrostatically induced charging current is slight, provided the two wires are well separated. The curve in Fig. 25 shows the charging current in a No. 10 wire 20 ft. from a 0000 trolley wire, and the reduction in current as this is gradually decreased from 0000 to No. 10 B. & S.

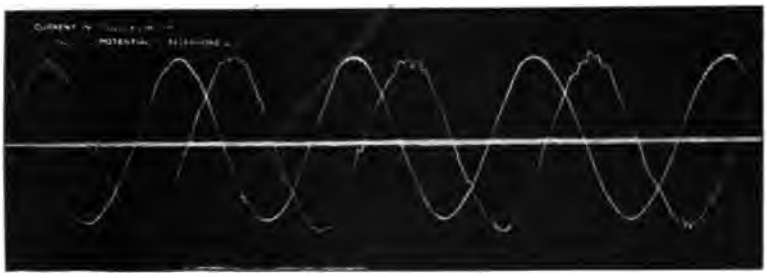


FIG. 27

VI. *Comparison of electromagnetic and electrostatic effects.* The resulting disturbances in any telegraph circuit will be due to electromagnetic and electrostatic effects; that is, the two factors must be combined vectorially, the angle of this combination depending on the power-factor of the load and various constants of the telegraph circuit. Oscillogram Fig. 27 shows current in a single-phase trolley circuit, and electromotive force induced thereby in a neighboring telegraph loop. The high-frequency irregularities on the induced wave are due to the addition of electrostatic effects. The current in the circuit due to electromagnetic induction will obviously be a maximum when all the keys are closed. An electrostatic charge will flow in from both ends of the line when all keys are closed; under other conditions this charge must all be supplied from the ground at one end of the line. It should be obvious, therefore, that the nature of the disturbance experienced will depend on whether electromagnetic or electrostatic induction is the predominating factor. Below are given in parallel columns some of the features of electromagnetic and electrostatic inductive effects.

TABLE I

Electromagnetic	*Electrostatic*
Varies with load.	Constant effect.
Varies with position of car.	Independent of position of load (neglecting line drop).
Induced electromotive force in proportion to frequency.	Open circuit potential (to ground) independent of frequency. Charging current if grounded, in proportion to frequency.
Induced electromotive force proportional to length.	Open circuit potential (to ground) independent of length.
Current in closed telegraph line practically independent of length. (Assume total impedance increases proportional to length.)	Charging current, when grounded proportional to length.
Induced current in instruments greatest when all keys are closed.	Charging current in some instruments greatest when distant key is open.
Practically same current in all instruments.	Current a maximum in some instruments, while zero in others.
Line resistance and reactance an important factor limiting current.	More in the nature of a constant current effect.
Generally the predominating effect in telegraph lines.	Generally the predominating effect on telephone lines.
Slight shielding action obtained from neighboring conductors.	More effective shielding action from neighboring conductors.
Slight shielding obtained by placing in lead-sheath cables, or by placing underground.	Effective shielding by use of lead sheath cables.

SUMMARY

All working conductors are surrounded by electromagnetic and electrostatic fields. These fields induce electromotive forces and charges in neighboring conductors. With an ideal metallic circuit, external fields are a minimum. Similarly, an ideal metallic circuit may be in fields of any strength without being disturbed.

Practical considerations prevent these ideal conditions from being realized. Hence currents will be induced in any conductors wherever placed as a result of currents and potentials on other conductors. Disturbance results only when these induced currents are of sufficient magnitude to be objectionable.

Commercial telephone lines have little margin to meet disturbing conditions more severe than normal. An increase of telephone currents to three or four times their present values would doubtless result in great disturbance to other wires in the same telephone system and require new standards of construction and maintenance. The same statement applies to telegraph systems.

Theoretically a balanced telephone line can be operated in proximity to alternating-current wires. This is not true of a telegraph line, as there is no way of balancing a circuit that uses earth return.

Where trouble is experienced on a telephone line it may be possible to clear the line by putting the system in first-class condition. Where trouble is experienced on a telegraph line, some change in the apparatus or circuit arrangements will be necessary.

For any given case, all the features of the power system and signaling system should be taken into account with a view to arriving at the proper procedure to reduce or to eliminate the disturbances.

DISCUSSION ON "TELEGRAPH AND TELEPHONE SYSTEMS AS AFFECTED BY ALTERNATING-CURRENT LINES." NEW YORK, OCTOBER 8, 1909

President Stillwell: From the earliest days men have found themselves discussing and frequently quarreling over property interests. In comparatively modern times the question of right-of-way has been raised frequently in an acute form as between railroads and streets and wagon roads belonging to municipalities or townships; and for a considerable number of years also, more especially in Europe, there have been questions in regard to what I may call aerial rights-of-way, the right to sunlight intercepted by the erection of buildings.

The question of right-of-way in ether is strictly modern. It arose first in the shape of damage caused by electrolysis, due to the utilization of the earth by electric railways, as return conductor for the currents used for motive power; the electrolytic action set up by these currents causing, in some cases, more or less damage to existing sub-surface structures. This interference has raised and is still raising some interesting questions in regard to prior rights. These questions have not been fully adjudicated, but the courts in general have decided substantially that no individual interest can own the earth; that adjustment must be sought along reasonable lines; and that the principle of give and take must be recognized.

It is the business of scientists, particularly of those who have to do with applied science, as have the members of this Institute, first to ascertain the facts in any case of this kind and then to seek by scientific means to eliminate causes of conflict; in brief, to find a cure, or a preventive, rather than to let the conflicting property interests go to the length of opposing each other in the courts. The procedure should be science first, and then, if science cannot find a cure, the principles of justice and fair-play may be relied upon to effect a final adjustment. It is highly important, I believe, that engineers should take the reasonable and just view and not the partisan view on questions of this kind.

The action of a committee of the American Water Works Association some years ago illustrates the opposite policy. The recommendation of that committee was adopted by the association named, and it stands to-day as the pronouncement of that association in regard to what should be done in respect of conditions that cause electrolysis. The position is unsound and could not be maintained for a moment in a court of justice. That an engineering body, or a quasi-engineering body, should take a position unsound and unreasonable is unfortunate. The position taken amounts, in effect, to a declaration that electric railways shall not be permitted to use a grounded return; that they shall keep off the earth and shall double trolley all lines.

We are fortunate in this Institute in having a membership that is interested primarily in scientific facts, and in finding reasonable and effective remedies for difficulties as they arise. I have very great pleasure in introducing Mr. J. B. Taylor, who will read the first paper before the Institute on this interesting apparent interference with the operation of telegraph and telephone systems by parallel alternating-current power circuits.

Charles F. Scott: The interference between electric circuits is of three fundamental kinds. An adjacent circuit may receive from an alternating-current circuit: 1, effects due to leakage; 2, effects due to electrostatic induction; and 3, effects due to electromagnetic induction. These interferences are not separate and independent, but are often intermingled in an intricate and confusing way. A brief reference is made in the paper to a method of neutralizing the effect of a single-phase railway circuit upon an adjacent telegraph circuit, which I have been personally much interested in and will therefore describe in some detail.

Some years ago it was recognized that the inductive effects produced in a circuit adjacent to a single-phase railway in which a large current is carried a long distance would probably cause disturbances in the adjacent circuits, and that these disturbances could not reasonably be avoided by readjustments or modifications of the circuits in any simple way. When, therefore, the inductive action is likely to go beyond moderate limits, some means becomes necessary for counteracting its effects in the telegraph wires. From the information and experience at hand at that time I concluded that the electromagnetic induction would be the most serious element, and I set about to devise some method of counteracting it.

The first and most obvious arrangement that presented itself is one to which Mr. Taylor has referred, in which a transformer has one coil in the trolley circuit and a second coil connected in series with the telegraph wire in such a direction that the electromotive force of the secondary of the transformer opposes the electromotive force induced in the telegraph line. This is in effect a special form of transposition. In ordinary transposition the adjacent sections of the circuit are transposed so that the induction in one section opposes that in the adjacent section. It is impracticable, however, to transpose a telegraph line with earth return, so additional sections in the form of transformer secondary coils are introduced which can be reversed; each section of line in which an electromotive force is induced by the current in the railway circuit is followed by a transformer secondary coil in which an equal and opposite electromotive force is induced by the current in the primary coil.

This plan might serve for a definite fixed condition, but railway operation unfortunately involves many variables. As the load is shifting, induction in the telegraph wire will change continuously as the train moves, while the induction in the transformer changes instantly when the train passes it. Moreover, the induction in the telegraph line is not proportional to the current in the trolley wire, but depends also upon the proportion of the current which flows in the rails and that which flows in the earth. This variable proportion is dependent upon the number of tracks, the distance from the train, and other conditions.

I then proposed to wind the primary of the transformer differentially by including certain turns in series with the trolley and other turns in series with the rail, so as to make the electromotive force induced in the transformer more nearly equal to that induced in the line. While this did not offer a complete remedy, it appeared to be a step in the right direction and worthy of trial. I turned the matter over to Mr. A. J. Sweet, asking that he design a transformer for trial test. In a few days he reported that he had studied out a modification that would overcome the fundamental objections to the transformer with double primary coils. He then described a method, that was adopted on the telegraph circuits paralleling the electrified portion of the New York, New Haven & Hartford Railroad. The method is briefly referred to in Mr. Taylor's paper.

A neutralizing circuit having practically the same exposure as the telegraph wire is employed as the primary circuit for supplying the neutralizing transformer. This in turn gives a secondary electromotive force practically equal to that induced in the telegraph wire. The two are connected in opposition. A careful study of this system brought out its many advantages. Experimental tests were made, both in the laboratory and in connection with a single-phase interurban railway on which, during the tests, very heavy currents were employed in order to induce a considerable electromotive force in the circuit under test.

In order to appreciate more fully the intricate problem which is presented it is interesting to note the principal variables that affect the electromotive force produced in an adjacent wire:

1. The current in the trolley wire, the amount of which varies with the load.

2. The current in the rails. The return current divides between rails and earth in different proportions under different conditions.

3. The current in the earth and the effective position of this current. Suffice it to say that the actual effective current does not flow where the mathematical image directs, but diffuses itself in accordance with unknown physical conditions within the earth and scarcely less mysterious laws of distribution.

4. The phase of the current, which is not the same in the trolley, the track, and the earth.

5. The length of exposure, which depends upon the varying position of moving trains.

6. The distance from the railway or primary circuit to the telegraph wire. In a road with two or more tracks, any one of which may be in service, the effective distance is liable to change without notice.

Now all of these variables have their effect upon a telegraph wire, and there is no other place where a like effect is produced. Therefore, a circuit on the same poles that carry the telegraph wires—and having therefore substantially the same electromotive force in it as is induced in the telegraph wires—should be made to introduce a counter electromotive force in the telegraph wire, so that the counter effect may vary in the same way as the initial effect. When the transformer primary coil is connected in series with the neutralizing circuit, the electromotive force produced upon a secondary coil having the same number of turns as the primary will be slightly less than the induced electromotive force in the primary circuit on account of the drop due to resistance of the neutralizing circuit. In order that the electromotive force on the secondary may be equal to that induced in the telegraph circuit, it is obviously necessary to have a few more turns on the secondary coil than on the primary. By using a suitable number of turns, the electromotive force on the secondary is made practically identical with the electromotive force in the telegraph wires. The tendency for alternating current to flow in the telegraph circuit is therefore eliminated. As a matter of fact, there is a slight difference of phase between the secondary electromotive force of the transformer and that of the telegraph wire. Methods have been proposed, and tested, for reducing or eliminating this difference of phase, but it has not been found necessary in practice to employ them.

As the secondary coil carries no alternating current, the transformer acts as if on open circuit. The transformer may therefore carry a number of secondary coils, each connected to its own telegraph circuit. It is found that the secondary coils introduce but little impedance into the telegraph circuits, and that the increased mutual induction between telegraph circuits is inappreciable.

The arrangement and capacity of the neutralizing transformer are adapted to the particular conditions in which it is to be placed. The neutralizing circuit is grounded just beyond the ends of the exposed section. If this is long, two or more neutralizing transformers may be installed, and the neutralizing circuit may preferably be grounded midway between adjacent transformers.

Some time before the electric service was inaugurated on the New Haven road, the engineers of the telegraph company made inquiry in regard to the conditions which might be anticipated. These conditions were discussed and the above-described system of neutralizing transformers was explained. Tests followed, and a request was made for general specifications for the installation of the system. This was prepared and a transformer was designed for the service. An order was placed for a number of transformers about a year before the electric service was started. The transformers were built and installed and are now operating as originally designed. The transformer is of the simplest type and is adequate for handling a large number of telegraph circuits. The transformers along the New Haven road are arranged for the accommodation of thirty telegraph wires. Preliminary tests were made by A. W. Copley as soon as current was available, in order to determine the best ratio of primary and secondary turns and to observe the operation of the system. It was found that the residual electromotive force is only a few per cent of the induced electromotive force. It was also noted that the neutralization became less effective when a large number of telegraph circuits were connected. It was found that the direct current in the telegraph circuits magnetized and saturated the core of the transformer, which in turn increased the primary magnetizing current and the loss in the primary circuit. This could be obviated by reversing the battery on part of the telegraph circuits or by introducing an auxiliary direct-current coil. These precautions have, however, not been introduced in practice.

It may be noted in connection with this system that it is independent of the railway circuits. There is no introduction of coils into the trolley or the rail circuits. There is no danger of connection between trolley circuits and telegraph wires due to defects in the transformers. There are no moving parts or elements requiring adjustment.

It was found that the electrostatic effect upon the telegraph wires, although paralleling a 10,000-volt trolley at a distance of only a few feet, appears to be nil on the New Haven system. This is presumably due to the considerable number of telegraph wires which probably distributed the charge among themselves, and, as these wires are grounded in regular service, the effects due to electrostatic induction have introduced no serious effects, and, indeed, have failed to be discovered.

Mr. Taylor's paper is, as he states, a general one and introduces a number of suggestions indicating an academic standpoint, as they are suggestions illustrating the principles involved in certain theoretical methods rather than methods to be carried out in practical specifications. Nevertheless, I think it not unlikely that some of his suggestions might be taken by persons not familiar with engineering conditions as rather simple and easy remedies for overcoming all practical difficulties. For example, it is very easy do draw on a diagram a potential neutralizing conductor parallel and close to a trolley wire; but the running of a second conductor having a difference of 20,000 volts in potential from a trolley, and maintaining it in close proximity to the trolley wire, is easier on paper than it is over a railroad. Again, the suggestion is made of running a second wire for carrying the return current. It is not a simple matter to support and maintain a heavy grounded conductor near the trolley wire. With regard to the arrangements that I am just referring to, the middle diagram of Fig. 20, shows a transformer electrically linking the trolley wire and an overhead return conductor, the purpose being to carry the return current by the overhead conductor instead of by the track; and it is stated on the top of the next page that the inductive drop may be considerably less than with the earth as a return, which may be an important factor in some cases. I doubt whether under practical conditions that would be found to be so. True, the two conductors are fairly close together; but when the track and the earth constitute one conductor, it is of such large diameter that the self-induction of the circuit is due principally to the overhead conductor.

If, then, the two wires—one the trolley wire and another wire of the same size—be placed, say, two feet apart, the self-induction of the circuit will be somewhat in excess of the self-induction of a circuit consisting of the trolley wire and the track return. The resistance lost in the track and earth return is usually quite small compared to that in the trolley wire. A second wire overhead for the return of the current will considerably increase the resistance lost in the circuit. If that resistance loss is about the admissible limit, then adding a second wire would tend to double that loss; hence the size of the conductors would have to be doubled, making the total weight of the conductor in the trolley and in the return some four times as great as that required in the trolley alone, when the track and earth return is employed.

I notice at the bottom of Table I, under electromagnetic induction, the statement that a slight shielding action is obtained by placing wires in lead-covered cables, or by placing them underground. That is, I think, correct if it is understood that ordinarily the effect is a very small part. I have found many persons who think that if any overhead wire were buried, all of its troubles would be a thing of the past and that electromagnetic induction would not seek it in the earth. On the other hand, the electromagnetic lines which surround a conductor are not affected by the earth, so that whether a wire is placed a little above or a little below the surface of the earth does not make much difference. Thus if a cable is 20 ft. from the trolley, and is midway in height between track and trolley, it does not matter whether the ground is low and the cable is supported on poles, or whether there is a high bank at the side of the track and the cable lies in the earth. It is the position of the cable and not the position of the earth which is of consequence. There may be a little flow of current in the lead shield which will tend to neutralize the field, but that is of minor effect. So that speaking generally, the burying of a wire in a lead-covered shield or cable has, I think, very little effect in reducing the electromagnetic induction.

A. W. Copley: I have had an opportunity to make extensive experimental investigations on the New York, New Haven & Hartford Railroad to determine the nature of disturbances in neighboring telegraph lines caused by current in the railroad power circuit, the causes of such disturbances, and to suggest remedies therefor. In the light of the results of these experiments, there are several points in the paper to which I wish to call attention. Mr. Taylor has given some data for the amount of alternating current that caused chattering in one particular telegraph relay with one particular adjustment. He has said that it is impossible to make a general statement covering all the various conditions of instruments and circuits.

I wish to give similar data obtained by me on artificial lines that were made to approximate closely several conditions obtaining on actual lines. Bad weather conditions were approximated by placing leakages between lines and ground. Several different adjustments were made on the telegraph instruments by a telegraph expert when there was no alternating current in the line, these adjustments being made to correspond with what might be met with in practice. After each adjustment, alternating current was introduced into the circuit in increasing volume, until it began to affect the working of the instruments. The ratio of the alternating voltage to the working direct voltage was then taken. This was tried for alternating currents of both 25 and 15 cycles, and on simplex, duplex, and quadruplex circuits.

The first tests, on simplex circuits were made with box relays in the circuit. These are relays which act as sounders, and with them no local circuit is necessary. These relays showed the effects of the alternating voltage at very low values, the signals becoming uneven and "mushy." This is because the relay gives a sound proportional to the strength of the blow of the armature, and the alternating current varied this strength so as to make some signals strong and some weak. The box relays are seldom used in actual circuits, and therefore no data were recorded under this condition.

The usual simplex circuit uses neutral relays that close local sounder circuits. With these the intensity of the armature stroke has little to do with the distinctness of the signal. Tests made with these relays gave the ratio of allowable alternating voltage to direct working voltage as about 0.5 for 25 cycles, and 0.4 for 15 cycles. The ratio was found not to vary greatly from these values with considerable variations in the circuit conditions, and adjustments of the instruments. Duplex circuits were less sensitive: the ratio in this case averaged 0.9 for 25 cycles, and 0.7 for 15 cycles.

Quadruplex circuits were by far the most sensitive, and showed a great deal of variation; but average values of 0.2 and 0.15 were obtained for the ratios at 25 and 15 cycles respectively.

Results on actual lines confirm closely the above results. Thorough tests in actual lines were made with simplex circuits, but only limited tests were made with either the duplex or quadruplex on actual lines—the ratios given are, of course, only approximations, but they may be taken as practical working limits. I would add, further, that although the allowable 15-cycle voltage is only about 75 per cent of the allowable 25-cycle voltage, the voltage induced by a given amount of current at 15 cycles is only 0.6 of that induced at 25 cycles. Therefore the telegraph lines are slightly better off under the influence of the lower frequency.

It is seen, then, that the disturbance can be overcome if only the working direct voltage is made high enough; this is quite an effective method as long as the direct current is not increased above allowable limits. The method is substantially the same as the second remedy given by Mr. Taylor; that is, increasing the working current. If it is undesirable to increase the current, but increase of voltage is allowable, a combination of his first and second methods may be used—increasing the impedance or resistance of the lines, and at the same time the direct voltage, holding the current constant.

The last remedy, the bug-trap arrangement, might be emphasized. Tests made with this device showed that it was possible to work a simplex line in which the alternating induced voltage had several times the value of the direct voltage; but it was found to be inapplicable to cases where the alternating voltage varied. If the induced voltage is steady the arrangement is quite efficient; if not, the relays must be constantly adjusted.

The reason for the good performance obtained is that as the contact in the local circuit is made on the back contact of the relay, the local circuit is always definitely closed when the sender's key is opened, at which time no current, either alternating or direct, is flowing through the relay. With the sender's key closed, the armature of the relay chatters against the front contact, which is dead, but does not rebound far enough to touch the live back contact. Therefore the local circuit is definitely opened.

The other remedies suggested have been tried, but with little success.

Mr. Taylor has devoted several pages to the calculation of inductive disturbances. He has indicated the importance of knowing the positions and the volumes of the currents in the various parts of the circuit. In particular, it is necessary to know the volume and effective position of the earth current. By effective position I mean the position at which, if all the earth current were concentrated, the same inductive effects would take place as do actually occur. This will be different for wires at different distances from the road, because of the wide distribution of current in the earth. Tests have shown, however, that it can be assumed for practical calculations at one position for wires within a considerable distance.

From theoretical statements in Mr. Taylor's paper, it appears that part of the return current would be found in the rails and part at the image of the trolley wire. But tests made on the New Haven road and at other places indicate that the effective position of the earth current is far below this image; in fact its depth is in the order of ten times the depth of the image.

The amounts of the rail and earth currents were investigated, and the results have been published as part of my discussion of a paper by J. B. Whitehead at the Atlantic City Convention, in 1908.* The figures were also published in the November, 1908, *Electric Journal*. When it was found by test on single-track roads that the earth current was as high as 60 per cent of the trolley current, calculations were made which closely verified this result. Charles F. Scott at that time made calculations for two- and four-track roads, in which the effective diameter of the overhead conductors and the track are much greater than in a single-track road. This condition naturally produced a different magnetic field in the earth below the track, and a different distribution of the earth current, as well as a different ratio between rail and earth currents. The result of the approximate calculation led us to expect about 75 per cent rail current. Subsequent tests showed 80 per cent.

Mr. Scott stated in an editorial in the *Electric Journal*, in November, 1908, that the earth current is largely due to inductive rather than to resistance effects. Supposing the track to be insulated from the earth, and an insulated wire to be buried at a depth of several yards under the track, one end of the wire being connected directly to the rails—then a voltmeter connected between the other end of the wire and the rails will measure a considerable induced secondary voltage. This is in addition to the resistance drop in the rails, the primary circuit being the trolley wire and rails, and the secondary circuit the rails and the buried wire. If the voltmeter be short-circuited, a current will flow in the underground wire. Similarly the earth acts as a connection between the ends of the track, and if the latter be not insulated, current will flow from the rails into the earth.

In Fig. 22 Mr. Taylor gives curves, showing the induced electromotive force in neighboring circuits for the two conditions of all current returning by rail, and all returning at the image of the trolley wire. As the effective position of the earth current has proved to be so much lower than the image, and the amount of this current is fairly large, the curves are of little value practically. It is not, however, impossible to fortell approximately the induced electromotive force in a telegraph line. From the tests made on single-track roads we were able to calculate an effective position of the earth current, and from this, together with the calculated proportion of earth current, it was possible to calculate the voltage which might be expected on the New Haven railroad. The actual induced voltage checked to within 10 per cent of the values calculated a year before current was put on the line.

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*PROCEEDINGS, A. I. E. E., December, 1908, p. 1733.

W. S. Murray: I think the best way to discuss this subject, at least from the railroad point of view, is to confine my remarks as closely as possible to the actual facts of the situation. The New York, New Haven & Hartford Railroad Company in their electrification zone has certainly greatly abused the adjacent telegraph and telephone lines by inflicting them with inductive troubles. Without diminishing one iota the meritorious achievements incident to the invention and use of the telegraph and telephone, yet I believe that public opinion, in estimating the usefulness of these three great agents of convenience, would grant, and not unselfishly, in the sense of " the survival of the fittest ", both written and unwritten rights to the railroad. I do not mean to intimate that, by virtue of its predominance over the other two conveniences the railroads should be permitted to abuse their rights and privileges; but if real progress is to be considered, the value of things must be regulated by their importance, and while apparent injustice sometimes may be rendered in the working out of this law of order, in reality public rights of convenience have been conserved.

Mr. Taylor's paper interests me in three different ways: first, because the information presented is concisely stated, and shows the hard work of the author in his effort to offer something useful; secondly, it gives me a clear picture of the troubles that the telegraph and telephone companies have had with a commodity we give them, that in the giving does not cause us any trouble at all; and, thirdly, because I am interested in a single-phase, alternating-current railway that, on account of the arrangement of its circuits, gives to the telegraph and telephone wires in its vicinity the maximum amount of inductive troubles.

Ever since alternating current was transmitted over wires it has been a nuisance to nearly every other electric circuit in the immediate neighborhood. Its only saving grace has been its association with things of maximum importance. The mitigating excuse for its existence is it accomplishments.

Familiar ground is covered in that part of the paper which is confined to the several schemes of arranging wires to neutralize both electrostatic and electromagnetic induction. All of these arrangements were considered during the preparation of our electrification plans. Distribution by polyphase circuits and reversals of direction of current flow by the transformer method were both considered; but all economic features were met, as far as the transmission system was considered *per se*, by the distribution of a single voltage in a single-phase throughout the complete system. Though conscious of the fact that this decision prescribed severe inductive troubles upon the lines of the adjacent telegraph and telephone companies, yet in the same moment of this decision we united with them in a search to find the remedy for their difficulties. The cost to the railroad company partly to eliminate the inductive effect of its power circuits would be many times that to the telegraph and telephone company to guard against this effect. Mr. Taylor's paper intimates this conclusion; our actual calculations justify it.

In regard to the summary given at the end of Mr. Taylor's paper, I am in agreement with the statements made in the first paragraph, except the last sentence. It seems to me that the ideal metallic circuit, if subjected to a magnetic field, would be disturbed to the extent of having its potential raised above the earth; for example, one standing on the ground and touching the circuit would receive a voltage in proportion to the frequency, length of circuit, and number of lines of force cut.

I agree with the second paragraph.

I agree with the third paragraph, assuming that no auxiliary apparatus is used to meet the disturbing condition.

I agree with the first sentence of the fourth paragraph, but ask if the compensating transformer that derives its primary voltage from both earth and wire potential does not virtually provide a secondary voltage in complete compensation for voltage in the telegraph wire and its ground return?

I agree with the fifth and sixth paragraphs.

In order to ascertain the actual conditions that exist to-day, and give some line on the results obtained in an effort to compensate for the induction suffered by lines adjacent to our electrification, on Tuesday, October 5—a few days ago—a conference was arranged, at which were present Messrs. N. E. Smith superintendent of telegraph, B. D. Hubbard, chief operator in the general offices of the New Haven road, and Michael Kelly, district repairman, stationed at Stamford, Conn., in charge of all repairs in the electric zone for the Western Union Telegraph Company. Mr. Hubbard being constantly stationed at the end of the telegraph lines that pass through the electric zone, Mr. Kelly being in charge of such repairs as were required to these lines, and Mr. Smith being in general charge of telegraph operation, it occurred to me that a general conference would develop the difficulties experienced and the methods pursued to rectify the troubles—all of which would throw light on the actual results obtained since the electrification zone between Stamford and Woodlawn has been considered as completed.

The memorandum of categorical questions I asked at this conference is as follows:

Question. How many telegraph lines are you operating in the electric zone?

Answer. Ten railroad lines, seven Western Union, and three spares.

Q. Would these lines be operative without the use of compensating transformers?

A. No.

Q. By reason of the induction present have you ever had any burnouts on these lines?

A. Not since full commercial railway service has been in operation. (Mr. Kelly, however, offered an interesting commentary at this junction. He explained that upon one occasion during the early part of preliminary operation the continuity of the track was broken as a return circuit to the power house by inserting insulating joints at three places. This break caused a rise of voltage and consequent increase of current in one of the compensating transformers, and resulted in the burning out of the transformers. Upon another occasion the telegraph line was crossed with the high-tension railroad circuit, with the attendant result of burning out another compensating transformer. Except for these two cases in the preliminary stage of operation, it seems that no compensating transformers have been lost.)

Q. Are there ever times when by reason of induction any of the lines became inoperative?

(In answer to this question Mr. Hubbard explained that at times, principally during the morning and afternoon—the periods of heavy traction load—the buzzing on one of the through lines between New York and Boston was so severe as to be just outside the limit of adjustment of the instrument, and for a minute or two it would be necessary for the operators to cease communicating. This particular line is known as 72. It developed, however, that this wire from Bridgeport to Boston has an iron circuit, while the other lines from New York to Boston are of copper throughout. I have suggested the use of a copper wire from Bridgeport to Boston, thus increasing the conductivity of 72, which will cut down the ratio of induction to working current. In the event of this rectifying the trouble, it may then be said that at no time will any of the twenty wires in the electric zone be inoperative, due to induction. It is fair also to add that Mr. Hubbard explained the excessive buzzing described on 72, as quite exceptional.)

Q. Has the Western Union Company made any complaints concerning the ten wires which lead from our electric zone to their New York office?

A. No complaints in the last year, beyond ordinary telegraphic troubles.

Q. Are there any complaints made about the wires by the operators in the general offices of the New Haven road?

A. None.

Q. What is the extra maintenance required by reason of the addition of the compensating transformers on your telegraph lines in the electric zone?

A. There are more fuse blow-outs, escapes, and grounds.

Q. Are these troubles so numerous as to affect the efficiency of telegraphic transmission?

A. There have been no complaints in regard to the availability of the lines for service. These new occurrences simply require an extra inspection, which was not required under the old conditions.

Q. Under what conditions do you experience these troubles?

A. The failure of an insulator on the catenary system is generally the cause of a telegraph fuse blow-out, the starting of an escape, or a ground. (This effect is pointed out on the first page of Mr. Taylor's paper.)

Q. How often do you inspect the compensating transformers?

A. Each transformer is inspected about twice a month.

Q. Do fuse blow-outs, escapes, and grounds occur in any one particular point on the electric zone?

A. Yes, at Portchester, for example, where telegraph lines run more closely to the high-tension wires than at any other part of the zone.

It is fair to say that the index of efficiency in telegraphic service is the number and reliability of messages per unit of time. Likewise in railroading its index is the number of locomotive-miles per engine failure. Our records for the month of July 1909, show that the electric locomotive mileage was 14,000 miles per engine failure, while for steam the figure was 6238 miles per engine failure. Thus the steam record was less than 45 per cent as good as the electric.

In conclusion the writer cannot refrain from pointing to the two kinds of trouble—surmountable and insurmountable. The New Haven electrification, in turning out trouble to its friends, the telegraph and telephone, was not selfish and did not forget to lay a few eggs in its own nest. Some of these were hatched, but I am glad to be able to add that this class of offspring lived only long enough to make a record of its birth. While the first installation of the single-phase system as arranged on the New Haven road produces maximum induction, it is not uninteresting to note that as extensions of this system take place, by reason of power stations delivering current that virtually divides itself in equal amounts and in opposite directions along the righ-of-way, the inductive effects will tend to eliminate themselves, and the future will be more free from them than the present.

Charles P. Steinmetz. I consider Mr. Taylor's paper as particularly inportant because it is a complete and explicit exposition of the relations between the two classes of electrical transmission—the transmission of power and the transmission of intelligence.

We know that electric power circuits may, and occasionally do interfere with their weaker brothers, the telegraph and the telephone systems. The problem before us now—which is not a problem of interest only to the power engineer or the railway man or the telegraph engineer, but one of great importance to the electrical engineering industry at large—cannot be solved by saying that we are power engineers and expect the telegraph and telephone systems to take care of themselves. This would be as unfair and as untenable as it would be for the telegraph or telephone engineers to say: we were the first ones in the field and must not be interfered with, and we insist that the electric power systems shall be installed in such a manner as not to interfere with us. As stated by President Stillwell, the latter short-sighted policy has been manifested by the American Water Works Association.

Mr. Taylor's paper shows us that from the engineering point of view neither of these policies is tenable, and that the question can only be solved by coöperation between these two classes of engineers. The power engineer must make some concessions in the arrangement of his system to reduce interference, and the telegraph and telephone engineer must be willing to go to some inconvenience to protect his system against interference which cannot be avoided by the power engineer. It behooves us power engineers to give consideration to our weaker brothers, the telegraph and telephone systems, who are being interfered with by our circuits and who cannot interfere with us; for while we are to-day the stronger, sometime we may be the weaker, and then ready to cry out for protection when powerful ether waves from nearby wireless telegraph stations cause trouble in our low-voltage lighting circuits.

While with the advance of the electrical industry we are obliged to specialize more and more, at the same time this advance brings us closer together and makes us more and more dependent upon each other, obliges us more to consider the interests of others and not simply our own particular field. Mr. Taylor's paper is, therefore, of extreme interest not only to the telephone and telegraph engineer, but also to the power engineer, by drawing attention to these interferences and showing how they originate, or what character they are, and indicating in general the arrangements which may be used to mitigate or obviate them. Obviously, the paper can be only a broad outline, since it is the first paper on the mutual relation between the telegraph and the telephone on one side and electric power on the other side. It is therefore regrettable that the telegraph and telephone engineers could not be induced to discuss the subject here and to give us the benefit of their ideas.

Coming to a more specific discussion of the paper, Fig. 14 shows a diagram of an arc circuit which goes out on one street and comes back on another street in another part of town, looping a city block or an entire city district. Such loops of overhead alternating arc wires are extremely bad for the telephone and telegraph circuits, but fortunately they are going more and more out of use.

I cannot agree with Mr. Taylor's explanation of the greater frequency of grounds on arc circuits as being due to the higher voltage. It appears to me that the fact that arc circuits are more liable to faults and grounds than primary distribution circuits is due to the nature of their load. The arc circuit feeds directly into the consuming devices—arc lamps. The primary distribution circuit feeds only into transforming devices - transformers which are relatively small in number and can be very well insulated—while the arc lamp cannot be insulated to stand the voltage between the arc circuit and the ground and therefore must remain a part of the arc circuit, is to be considered as alive, and leads to a greater liability of trouble from grounds and faults by contact with trees, etc. This condition is aggravated by the limitations in the location of arc circuits, which cannot choose their path, but must run wherever arc lamps are desired, even if they have to go through trees, etc. The primary distribution circuit has a greater choice of its path in choosing the location of the transformer so as to give the least chance to interference. The result is that the arc circuit is always much more liable to grounds. Incidentally, a ground in an arc circuit is very much less troublesome, because current and power are limited. For this very reason it has become almost the general custom where arcs are operated from alternating-current systems to separate the arc circuit by a transformer from the primary distribution system; that is, to use constant-current transformers instead of the cheaper constant-current reactances.

I do not quite agree with Mr. Taylor on the improbability of trouble from the third harmonic of the generator wave, for the reason that my first introduction to the third harmonic took place ten or twelve years ago when we grounded the generator neutral in the Mechanicsville–Schenectady transmission. The telephone line on the same poles was put out of service entirely, and we were obliged to take off the ground—and then the telephone line operated again. Undoubtedly by a proper arrangement of telephone wires and power wires, as described in Mr. Taylor's paper, operation could have been made satisfactory; nevertheless, as it was installed, the telephone circuit was satisfactory with an ungrounded neutral and was not satisfactory with a grounded neutral. At that time we took an oscillogram of the neutral current and found the third harmonic very greatly distorted by the ninth harmonic. Since the frequency was 40 cycles, the ninth harmonic, of 540 cycles, was fairly close to the maximum sensitivity of the ear. This illustrates what Mr. Taylor has said, that one may expect more trouble from the higher harmonics of the generator, since these higher harmonics have a greater physiological equivalent in the ear than has the fundamental.

Regarding the image conductor, its meaning is frequently misunderstood. The image conductor; that is, the image below the ground, of the trolley wire, does not mean that the center of the return current is in it. It means: if we assume that the ground is a perfect conductor and that the return current therefore does not penetrate at all below the ground, but flows entirely at the surface of the ground, as a current sheet, then the inductance of the trolley wire against this current sheet at the surface of the ground would be the same as the inductance of the trolley wire against the image conductor. As the ground is not a perfect conductor, the current does not flow at the surface but flows at least partly some distance below the surface; as a result thereof the inductance of the trolley is not that of the trolley wire against the image conductor but is greater, corresponding to an image conductor deeper below the ground, as was mentioned by Mr. Copley as a result of the tests on the New Haven system. Especially in a steam railroad system, where the road-bed and the soil near the surface are probably of relatively high resistance, the current returns, not at the very surface but at a considerable distance below it. This means that the equivalent return conductor, that conductor below the ground which would give the same self-inductance to the trolley wire, would be very much deeper than the image conductor. The image conductor must not be mistaken for the center of the return current; it is a representation of the current sheet at the surface.

The great difficulty with the theoretical investigation of these disturbances is the complexity of the circuits for which we have to calculate the mutual inductance and the mutual capacity, and here we find that the greatest trouble is in the calculation of the mutual capacity. Regarding the mutual inductance, some uncertainty may exist in the location of the return circuit as to whether it is close to the surface or deeper in the ground, but the difference in the numerical value produced thereby is not very great. In his conception of the lines of magnetic force, Farady has given us such a beautiful illustration of the magnetic field that we can see it and calculate the magnetic inductance mathematically while knowing exactly what we are doing. This induces confidence in our results. Unfortunately, in the field of electrostatics our mathematical theories are still those of the early dawn of electrical science; we are still dealing with conceptions as they were developed in those days, before the law of conservation of energy, when heat, electricity and magnetism were " imponderables ", forms of matter without weight. We speak of such non-existing things as the electrostatic charge of a conductor, the surface density of the electrostatic charge, and discuss the static self-potential of the conductor There is no such thing as an electrostatic charge of a conductor. Since Faraday's time, in the field of magnetism we do not speak of the magnetic charge of a magnet, but in electrostatics we still have the antiquated conception of an electric charge, instead of considering the effect as an electrostatic field in space. What is necessary now is that some Faraday give us as clear a conception of the electrostatic field as we have of the electromagnetic field, so that we can deal with the lines of electrostatic force, not with the antiquated conception of electrostatic charges which are suitable for mathematical formulas, but in which we cannot see physically the meaning of the mathematical representation; for, so long as we cannot see the physical meaning, we can have no confidence in the correctness of the methods we are using.

Unfortunately at present the probability of the reduction of the conceptions of electrostatic phenomena to the same simplicity and obviousness, if I may so term it, as that of electromagnetic phenomena is unlikely, since most of the investigators have been carried away by the prevailing fad of representing the phenomena of electric power flow, not as Faraday and Maxwell did, as conditions of stress in the space—as an electric field—but as due to the migration of some form of dematerialized matter, the electrons, between the molecules of matter. Before we can get a clearer conception it will be necessary for some genius to take up this electronic theory and separate the mass of chaff from the few grains of truth, and so make the ionic theory a useful instrument of research instead of a stumbling block to the advance of exact science, as it is beginning to be at present. Then we will have the electrostatic field as tangible as the electromagnetic field is now.

At present, when dealing with electrostatic phenomena, such as the mutual capacity of circuits, the only way I can find that is at all satisfactory and not liable to confuse one, is not to calculate the electrostatic capacities at all, but to calculate the electromagnetic inductance and get the capacity from the inductance by the relation existing between the two by means of the velocity of light. The product of capacity and inductance equals the square of the length divided by the square of the velocity of light. Thus we get the capacity, mutual as well as self-capacity, from the inductance of the circuits, and do not need to consider particular methods of calculating capacities. In calculating capacities from inductance by the velocity of light, the error is that the actual electric velocity is slower than that of light, due to the energy loss in the electric circuit, which retards the velocity. If, however, as inductance we do not use the total inductance of the conductor, but only the external inductance—the logarithmic part—then we eliminate the effect due to the energy loss and get the exact value of the capacity.

L. C. Nicholson (by letter): The author points out the slight cause for transposing a three-phase power line, unless telephone or telegraph lines are near enough to be affected, and in general advises against transpositions for the average case. He does not advise us how near is "near enough", however, and the general conception is that the farther away a telephone line is from a high-tension transmission line the better. To a certain extent this is true, but the limiting distance is not necessarily that determined by inductive effects which could be offset by transpositions, but rather it is that distance which we may call "respectful", which is determined by mechanical considerations, such as liability to accidental contact due to breakage of wires or other similar causes. We wish to cite a concrete case resulting from several years' operation of high-tension, high-power lines in close proximity to parallel telegraph and telephone lines, and to note the negligible inductive and static effects with and without transpositions in the power circuits.

The three-phase, 60,000-volt, 25-cycle transmission lines of the Niagara, Lockport & Ontario Power Company from Niagara Falls to Syracuse run parallel and closely adjacent to the same company's private telephone lines for a distance of 200 miles, and to Western Union telegraph and telephone circuits for 125 miles. The separation between the power lines and the private telephone line varies from 150 ft. to 10 ft., the average distance being about 50 ft., and between the power lines and Western Union lines the average distance is about 70 ft., though frequently not more than 30 ft.

The power lines are transposed only where they are parallel to the Western Union circuits in a manner mentioned below. The private telephone line is a copper circuit on separate poles on the power line right-of-way. The wires are transposed ten times per mile. The Western Union circuits consist of one continuous two-wire telephone circuit transposed twice per mile, and eighteen telegraph ground-return circuits using from 70 to 250 volts storage-battery current.

Originally, and before voltage was put on the power line paralleling the Western Union circuits, transpositions were carefully put in to prevent inductive effects. In a distance of 105 miles, thirty 120-degree transpositions, or ten total transpositions were placed at intervals varying from 3 to 5 miles. The distance between consecutive transposition points was calculated separately for each case from the average separation between the power and telegraph lines, using as a basis one 120-degree transposition every 4 miles for 80 ft. separation between circuits.

After more than a year's operation of this line transmitting some 6000 h.p., during which time no disturbance of any kind arising from normal operation was felt on the adjacent telephone or telegraph lines, eighteen of the thirty transpositions were changed so that the upper conductor was no longer transposed, but remained the upper conductor for a distance of 57 miles. The two lower conductors were transposed 180 degrees at the original transposition points. The remaining twelve 120-degree transpositions covering 48 miles were unchanged. Evidently the 180-degree transposition scheme gives a circuit equivalent to a non-transposed single-phase circuit, the two conductors of which are in a vertical plane with, in this case, 6 ft. separation. During two years' operation of this line with loads as high as 15,000 h.p. no disturbance has been felt on adjacent parallel telephone and telegraph circuits during normal operation. In view of this experience, transpositions of the power wires is considered entirely unnecessary, and in subsequent lines which have been built contiguous to foreign circuits no transpositions have been made.

As stated above, neither the private telephone system nor the Western Union telephone or telegraph circuits can detect the presence of the power circuits when operating normally. However, when a ground occurs on one phase of the power line the electrostatic unbalancing causes chattering of telegraph instruments and sometimes blows fuses in the telegraph or telephone circuits. These disturbanccs are always of short duration, being usually less than 20 sec., which is the maximum time a ground can remain on any part of the system before being automatically cut off. Electromagnetic effects of a ground are felt only slightly on account of a high resistance placed in the neutral connection to earth of the sending transformers, which allows the passage of approximately 30 amperes earth current. Formerly when the system was operated with a thoroughly grounded neutral, the electromagnetic effects were considerable on account of short-circuit currents to earth, sometimes burning out fuses, relays, and lightning arresters.

Short-circuits between wires do not ordinarily cause inductive disturbances, since when they occur they are nearly always confined to a single location and do not involve the earth as a conductor.

Other forms of abnormal operations have been experienced and their effects upon parallel circuits noted. Single-phase power transmitted over two wires of a three-phase line causes no disturbance.

The combination of transmitting three-phase power approximately one-half the total distance and single-phase power the remaining distance, after the manner shown in *B*, Fig. 15, has never caused any inductive disturbance of any kind.

Transmitting power three-phase over duplicate lines separated from each other several miles, using two conductors of one line and one conductor of the other line to make up a single three-phase circuit, causes disturbances which appear to be due entirely to electromagnetic induction. Thus, normal voltage on only one wire of either line causes no trouble unless considerable three-phase load is delivered—using two wires of the other line—showing that the purely electrostatic effect is negligible under conditions of normal voltage. When, however, a ground occurs on one phase, causing full line-potential to exist between the other two phases to ground, the electrostatic effect shows up in a mild form, as mentioned above.

In general, experience shows that with separation between power and telephone lines as mentioned above, transposition of power wires is unnecessary; that transient electrostatic and electromagnetic effects accompanying grounds on the power line are mild and of slight consequence; that the only class of disturbances that will cause trouble to telephone or telegraph instruments is caused by heavy electromagnetic effects induced by short-circuit currents passing through the earth for considerable distances, as may occur in star-connected, high-power, high-voltage systems which operate with a grounded neutral.

J. C. Barclay (by letter): Mr. Murray has made an assertion to the effect that there is no interference with the telegraph service due to the operation of the single-phase system on the New York, New Haven & Hartford Railroad. This is far from being correct. It is true that by means of the neutralizing transformers interposed in the telegraph circuits at two-mile intervals along the electrified zone, the working of the wires has been rendered more or less feasible, where otherwise complete demoralization of the service would have undoubtedly resulted from the disturbances induced therein; but the impression sought to be conveyed that these transformers have proved a panacea for all the inductive ills to which the wires are subjected, is not at all justified by the facts in the case.

There are various reasons why the neutralizing apparatus is not entirely effective under the present conditions of installation. In the first place, escaping currents from direct-current trolley systems find access to the primary windings of the transformers, the cores of which become magnetized, and diminish the degree of neutralization that might otherwise be secured. The working currents of the telegraph circuits in passing through the secondary windings also excite in the transformer cores an amount of magnetism that varies in proportion to the number of telegraph keys that happen to be open or closed, with corresponding variations in the neutralizing values. And, on account of phase-distortion, the counteracting electromotive forces developed by the action of the transformers are not directed in a manner to bring about complete nullification, even though the magnitude of the nullifying forces could be made equal to that of the disturbing forces.

As a result of such conditions, residual voltages and currents of varying intensity are ever present in the telegraph wires, the detrimental effects of which depend, more or less, upon the length and character of the circuit, and the strength of the working current; but are mostly manifest under unfavorable climatic conditions when the sensibility of the receiving apparatus to such currents is at a maximum.

Tests have shown that these residual or superposed electromotive forces in the wires possess an average pressure of about 15 volts even under normal operating conditions, and although the legibility of the received signals on the regular Morse apparatus may not, as a rule, be perceptibly impaired thereby, there is, nevertheless, a marked depreciation in their character or quality that tends materially to affect the efficiency of the service; for, to quote Mr. Taylor in the paper above alluded to:

> Disturbances on the line which do not actually upset the working, may make considerable difference in the comfort or state of mind in which the operator does his work.

From what has been said with regard to the effects observed on the comparatively insensible Morse apparatus, it naturally follows that the more delicate instruments employed in high-speed and multiplex systems feel more acutely the influence of the disquieting currents; and it may be stated as a matter of fact that such systems can only be operated over wires extending through the electrified zone at a considerable sacrifice of speed and efficiency under the most favorable conditions, and not at all under abnormal conditions of working.

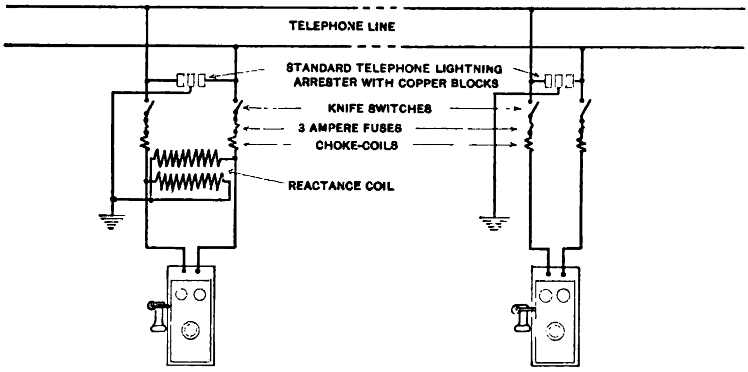
There is no disposition on the part of the writer to be hypercritical in regard to this matter, but as the result of practical experience the fact cannot be too strongly stated and emphasized—that the costly and cumbersome transforming devices, which, in addition to other disadvantages, necessitated the sacrifice of three copper wires to provide a neutralizing circuit, as well as the complete transposition of all the telegraph wires at each of the ten transforming stations along the affected zone, have not brought about a condition in the working of the wires that can in any way be regarded as satisfactory from a telegraph point of view.

A. L. Cook (by letter): In considering the protection of telephone lines for high-tension transmission line service, Mr. Taylor describes an insulating transformer that has been developed to enable a telephone system to be safely used even when a considerable difference of potential exists between the telephone line and ground. The apparatus he describes would undoubtedly protect the user of the telephone, but there are a number of objections to its use. Where there are a large number of telephone stations installed on a long line, it is generally necessary to ring all of the bells simultaneously when calling one of the stations. In this case a considerable amount of current must be transmitted through the transformer at the ringing station and supplied to the transformer at the other stations. In addition to the current actually required for ringing the bells, the magneto-generator must supply the magnetizing current for all the transformers on the line; and while this may be small for a single transformer, with a large number of stations the current required for this purpose would certainly impair the ringing qualities of the line. When talking over the line the voice currents also suffer this same double transformation, and even with the best design possible there is sure to be a noticeable effect on the talking qualities. Unfortunately, the best design of a transformer for ringing service is not the best for talking, consequently any commercial design must be a compromise between these two conflicting requirements. Tests of the particular type of transformer illustrated by Mr. Taylor indicate that the use of one of these transformers affects the talking qualities of a line to about the same extent as would the introduction of five miles of ordinary No. 19 dry paper-insulated telephone cable.

The equipment described is also relatively expensive in first cost, since the cost of the protective apparatus illustrated is more than double that of a good magneto telephone instrument of the type commonly used in this class of work. The principal objection to Mr. Taylor's arrangement is, however, that it does not eliminate the dangerous potential from the telephone system, and for this reason it is only safe to use the line at points where the protective apparatus is installed. It would, therefore, be dangerous for a patrolman to attach a portable telephone set at any point on the line unless he carried around with him the full protective equipment illustrated, which is out of the question because of its size and weight. If patrol stations are located along the line with this protective apparatus installed therein, the telephone system would be very expensive. There is also the objection that with the existence of a high voltage on the telephone line, it becomes more difficult to maintain the system in a satisfactory working condition. If the power wires are not transposed, a high voltage will exist on the telephone line even under normal conditions, and there would be more trouble from leaks on the line, causing a noisy circuit. Even the use of better insulation is only a partial remedy, as the existence of the high voltage would tend to increase the chance of leaks developing. If the power wires are transposed there would normally be no appreciable voltage on the telephone line; but in the event of a ground on a power wire there would be a a very high potential induced, and the insulation of the telephone system might break down at just the time when such a failure would be most serious in its consequences.

The writer believes it is generally better to prevent any possibility of there being a high potential between the telephone line and ground, rather than to attempt to use for purposes of communication what is virtually a high-tension line, so far as danger to life is concerned. The voltage induced on the telephone line may be eliminated by grounding the two wires through reactances or resistances. This method has been used by a number of engineers under widely different conditions, and as far as the writer knows has proved entirely satisfactory. A reactance is more suitable than a resistance for this purpose, as it can be designed to give a very low-resistance path to ground while at the same time the path between the two telephone wires may have a very high impedance to both the ringing and talking voltages. This is accomplished by winding the two circuits on the same iron core, in such a way that the currents flowing to earth through the windings of the reactance neutralize each other as far as any magnetizing effect on the iron core is concerned, and consequently the impedance to ground is only that due to the ohmic resistance of the windings. For the ringing and talking voltages, however, the two windings are in series, so that they offer a high impedance to the working currents; and since these are not subjected to any transformations by the protective apparatus, the maximum efficiency of the line is obtained. In addition to the reactance coils, it is, of course, necessary to provide discharge gaps, set to break down at a low voltage, so that in the event of an accident to the protective coils the telephone line will be grounded and thus rendered safe. With a proper equipment of this character, a patrolman can safely tap the telephone line at any point and communicate with the station, using an ordinary portable set for the purpose. The cost of this type of protection is also considerably less than that described by the author, particularly where there are a large number of stations on the line.

The writer had occasion a few years ago to devise a protective system for a telephone line operated in connection with a 65-mile, 44,000-volt, three-phase transmission system. This was a single line with the telephone wires carried on the same poles, about 5 ft. below the bottom power wires. The power wires are given a complete transposition between successive load points and the telephone line is transposed at every sixth pole. The system operates without a grounded neutral. Under normal conditions there is no measurable voltage between the telephone line and ground, and the talking qualities of the line are very satisfactory. Measurements were made with one of the power wires grounded, using a voltmeter and potential transformer, and it was found that at normal line voltage, under these conditions, there would be a difference of potential of about 10,000 volts between the telephone wires and ground. An ammeter connected between the two telephone wires and ground showed that there were about 5 amperes flowing. Suitable reactance coils and protective apparatus, arranged as shown in Fig. 1, were installed at two points on the line, and the same tests repeated. It was then found that with normal voltage on the line, and one of the power wires grounded, the voltage on the telephone line was only 14 volts. The telephones could be used very satisfactorily under these conditions, and there was no evidence of any disturbing earth currents flowing between the two reactance coils.



ARRANGEMENT AT STATIONS HAVING REACTANCE COIL

ARRANGEMENT AT OTHER STATIONS

Fig.1

A. W. Copley (by letter): The question brought up by Mr. Taylor as to whether the self-induction of a circuit consisting of a trolley wire with a wire return would be greater than with rail and earth return, is easily settled. A circuit made up of a 4/0 trolley wire with 100-lb. rail return has constants as follows for a 25-cycle, single-track road:

[*] Resistance volts for 100 amperes per mile,

Trolley	26
Rail	3
Total	29

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[*] Proceedings A. I. E. E., December, 1908, p. 1733.

Reactance volts per 100 amperes per mile,

Trolley wire (internal)	1.3
Rails	1.5
Due to field between trolley wire, and return circuit	44.2
Total	47
Impedance—total	55.3

In order to obtain the same reactance with wire return the trolley and return wire must be separated by a distance x determined by the formula:

Reactance volts per mile per 100 amperes $= 5.28 \times 1.92 \log x/0.78$ radius of wire.

This formula holds true when the return wire is of the same size as the trolley wire. It includes not only the reactance due to the field between the wires but also that due to the field inside the wires, hence it represents the total reactance of the circuit.

The radius of the 4/0 wire is 0.20 ft. On placing the reactance equal to 47, and solving the equation for x, the result is 1.6 ft. In other words, the reactance of a circuit consisting of the trolley wire and a return wire at a distance of 1.6 ft. is 47 volts per mile, which is equal to the reactance of the normal circuit consisting of the trolley wire and the ordinary track return.

It is obvious that a greater separation between the wires would cause an increased reactance, consequently Mr. Scott is correct in asserting that a separation of 2 ft. between the wires would cause a greater reactance than that of the normal circuit with track return.

It may be further noted that the resistance drop for the circuit with the 4/0 return is 52 volts per 100 amperes per mile, instead of 29 volts with the normal conditions using the track return. It follows, therefore, that the overhead return circuit will probably involve increased inductance, increased cost of copper, and an increased resistance loss, unless a very large amount of copper is installed.

The reason that the reactances of the trolley-track circuit is low is on account of the large effective diameter of the return circuit. The radius of the conductor does not enter, however, into the formula for obtaining the voltage induced in an entirely separate circuit, such as a telegraph line and its return, this voltage being proportional to the logarithm of the ratio of the distances from the telegraph line of the trolley and its return circuit. Hence the voltage induced in the telegraph circuit is dependent upon the effective depth of the current in the earth.

Frank F. Fowle (by letter): It has long been clearly understood that an electric circuit transmits energy, not through the body of its conductors, except to an almost negligible extent, but through the dielectric surrounding the circuit. The conductors are but a guide for the energy in its course of transmission through the dielectric. The extent of surrounding dielectric which is energized is also known to depend upon the geometric disposition of the conductors in a plane perpendicular to the circuit. The more widely the conductors are separated, in this plane—voltage, power, and frequency remaining constant—the more extensive becomes the body of energized dielectric.

Theoretically the dielectric is energized, in a direction transverse to the circuit, to an infinite distance; but the dielectric stresses diminish at increasing distances from the circuit in a much faster ratio than the distance. The respective intensities of the electric and magnetic fields are expressed, for any given point, by logarithmic functions of the distances from the point to the wires of the circuit, in a perpendicular plane. When the point is at a great distance from the circuit compared with the distances between the conductors composing the circuit, the field intensities become very small and diminish indefinitely as the point moves away from the circuit.

The phenomenon of induction occurs when a second circuit is placed in parallel relation with the energized circuit, at such a perpendicular distance from it that the field intensities have appreciable values. The second circuit will then have upon it electromagnetically induced electromotive forces and electrostatically induced charges. The second circuit will absorb a portion of the energy of the first circuit, derived from the dielectric through which it is transmitted.

By reason of the fact that telephone and telegraph systems operate with low voltage and low power, with sensitive apparatus, they are exceedingly subject to interferences from systems of high voltage and high power. The phenomenon of induction between such systems is, it is true, a mutual one, and telephone and telegraph systems induce disturbances in power systems. But the disturbance to the latter is infinitesimal, for two reasons: first, the initial energy in telephone and telegraph systems is relatively weak of itself; and, secondly, the extremely weak induction in the power circuit virtually vanishes in comparison with the initial energy in the power system.

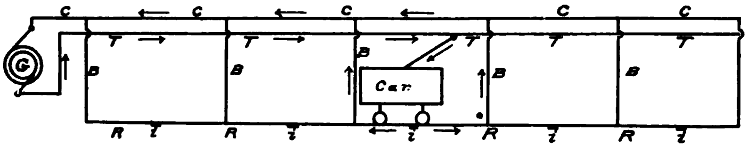
When telephone and telegraph systems exist in parallel proximity to high-voltage, high-power systems, then there is usually interference with the telephone and telegraph systems. This interference varies in degree with the distance between the systems, with the voltage, current, and frequency of the power system, with the geometrical configuration of the power circuit, with the presence of harmonics in the voltage wave and the current wave in the power circuit, with the existence of normal or abnormal grounds on the power system or on the telephone system, with the use of metallic or ground return circuits in the telephone and telegraph systems, and with the system of transposition employed in any or all of the systems.

The problems or difficulties which such a situation presents have two aspects; one of these is the legal aspect and the other is the technical or engineering aspect. Both are of great interest to the engineer. The legal problem, stripped of all details, appears to be one of ownership or right of use of the ether. When a telephone system parallels a power system at a distance of, say, 50 ft. and both systems hold secure legal titles to separate, out adjoining, physical rights-of-way, the inquiry is whether the power system is trespassing in a legal sense, when some of its energy is transmitted through the space over the telephone right-of-way, to the damage and impairment of the operation of the telephone system. Certainly it cannot be held that any one interest or group of interests is entitled to the exclusive use of all the ether. The public requires both transportation and communication, and therefore the public interest requires that this problem be so solved as to harmonize the conflicting interests to the greatest possible degree, without distributing the burden unfairly on either. In the general sense this situation closely resembles the electrolysis problem, where the interests of the street railways and those of municipalities or private companies operating water works are in conflict as to the right of the railway companies to utilize the earth as a return conductor. In the latter case it is undoubtedly a complete preventive of damage to require the railways to use the double-trolley system; and so also it is in the case of the alternating-current systems of traction as regards their disturbance of telephone and telegraph systems. But from the railway point of view a cure so drastic seems unreasonable and burdensome. It remains for engineers to work out, if possible, a solution that will more completely harmonize these opposite interests.

The problem before the engineer naturally divides itself into two lines of investigation, one relating to means of prevention and the other to means of restriction. Mr. Taylor's paper deals with both of these. The means of prevention apply naturally to the railway system, while those of restriction apply to telephone and telegraph systems. Prevention, rather than restriction, is greatly to be desired, if feasible and economical. Fig. 19 and 20 of the paper bring out very clearly some of the means of partial prevention.

The value of a ground-wire, as a means of diminishing the spread of the electrostatic field, is quite important. The following case has come to the writer's attention. A single-phase traction system operating at 3300 volts and 25 cycles, carried on the trolley pole-line a 33,000-volt, 25-cycle, three-phase transmission, a metallic telephone circuit, and a ground-wire erected for the protection of the transmission line from lightning. When the system was put into operation the ground-wire had not been provided with earth connections. It was found that the induced potentials on the telephone line were extremely troublesome and dangerous. But after the ground-wire had been earthed every few poles, the troubles with the telephone line disappeared in large measure, and it became possible to use it, whereas it had been practically impossible before. Of course a potential-neutralizing conductor would theoretically be even better, but it could not then serve the further purpose of a lightning guard.

The writer afterward made a series of observations of the induced potentials in a telephone system, parallel to the traction system just mentioned. He found that the potentials appeared simultaneously with the passage of trains over the traction line, and observed also that there was no potential when there were no trains on the line or when the trains were at standstill. If there had been any electrostatic induction of appreciable magnitude, the observed potential could not have been zero in the absence of trains on the line. These observed potentials were also of a widely fluctuating character, and corresponded generally with the fluctuations of trolley current. There were three trolley sections fed from two sub-stations, the middle section being fed from both ends, and it was observed that the position of the train was a factor in the magnitude of the induced potential. The last mentioned factor was difficult of analysis owing to the varying distance between the traction line and the telephone line.



G - Generator.
T - Trolley Wire.
R - Rail.
C - Return Conductor.
i - Insulating Track Joints.
B - Track Connections To C.

FIG. 1

The electromagnetic field will be greatly restricted by means of a current-neutralizing conductor, as Mr. Taylor says. It is fundamentally necessary for maximum efficiency that the neutralizing conductor be as close to the trolley wire as feasible, and that it carry a current equal to the trolley current in magnitude, but 180 degrees out of phase with it. The writer proposed such a conductor some years ago and endeavored, but unsuccessfully, to have it tried out on a small single-phase road, in 1906.

The features of this arrangement appear in Fig. 1 and 2. The return conductor in this arrangement fulfils largely the functions of a ground-wire as well. The use of sectional track insulators, or insulating rail joints, is proposed in order to diminish the flow of current in the track further than otherwise would occur; the track sections can very conveniently be made to correspond with the lengths of signal blocks, if automatic signals are desired. In the latter case the overhead conductor would be connected to the middle of an inductive track bond, which would be connected in turn between the rails; or only one rail might be used for the propulsion current, reserving the other for signaling purposes.

On account of the impedance drop in the return conductor, there would be some leakage to earth from the rails. The arrangement shown in Fig. 1 is therefore not perfect. Series transformers may be employed to remedy this defect, as shown in Fig. 3. These transformers are arranged with their primaries in series with the trolley wire and their secondaries in series with the return conductor.

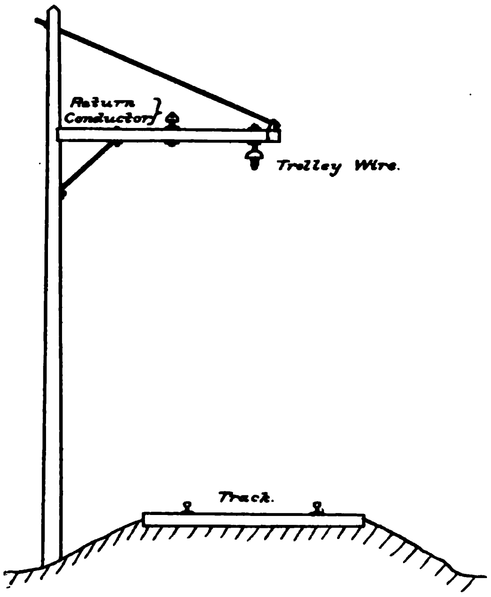


FIG. 2

I cannot agree with Mr. Taylor's statement that these transformers should have a 1:1 ratio. The ratio must be such that with currents of equal magnitude in primary and secondary, but 180 degrees out of phase, the secondary induced electromotive force will just overcome the impedance drop in the return circuit, or such portion of it as corresponds to the section in which the transformer is situated. The ratio will depend, therefore, upon the impedance of the return conductor. The magnitude and phase of the secondary terminal electromotive force may be regulated by means of shunts on the primary or the secondary, or both; and by variation of the primary or secondary turns, and by the latter in combination with the shunts before mentioned.

The means of prevention, as applied to single-phase traction systems, may be summed up as follows:

1. One or more overhead conductors for the purpose of neutralizing or restricting the electromagnetic and electrostatic fields.
2. Means for limiting the flow of current in the track to short sections.
3. Means for maintaining the entire track at zero or earth potential as nearly as possible.

Turning now to means of restriction as applied to the telephone and telegraph systems, there must first be recognized one fundamental difference of great importance between these systems. This is the use of transposed metallic circuits in (the best) telephone practice, and the use of earth return circuits in telegraph practice. Mr. Taylor has shown several metallic circuit schemes for telegraph transmission, but none of these is in general use in this country. Telegraph systems suffer from induction in a far worse degree than telephone systems, because of the use of the earth return. But to require the telegraph companies to convert their systems over to metallic working would be, from their viewpoint, a much more drastic remedy than to compel the traction companies to use the double trolley. The change from grounded working to metallic working in a telegraph line would halve the number of physical circuits and double the investment per circuit mile. The effect which this would have upon rates is obvious; and the final result of such a considerable increase of rates would be a material loss of business, and public inconvenience.

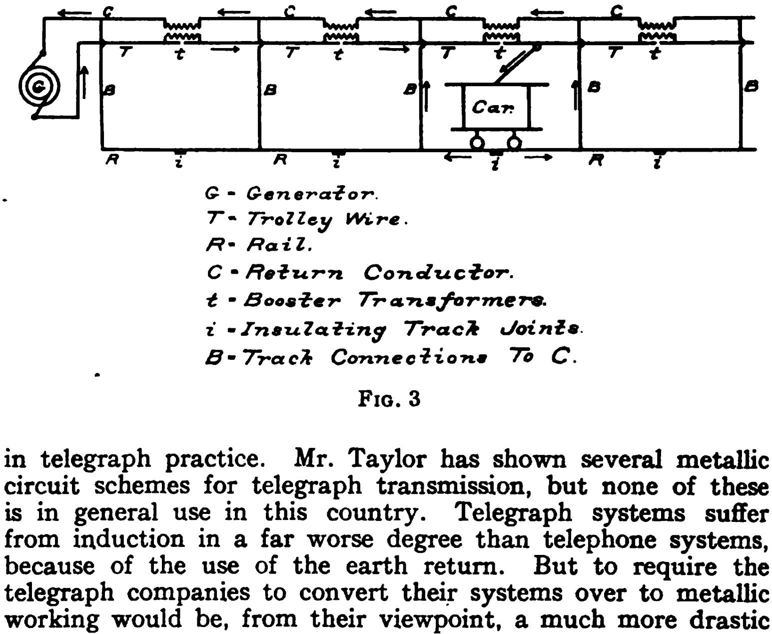


FIG. 3

All telephone and telegraph circuits are separable into two divisions, one overhead and one underground. The overhead circuit is, for the great part, bare copper and iron wire, carried on pony glass insulators of relatively poor insulating qualities when dirty and wet. The leakage resistance of such circuits varies excessively with the weather. The underground circuit is in cable and possesses properties which remain substantially constant. This difference renders the overhead circuit the most difficult one to remedy.

Circuits in cable have been quite successfully treated in a few instances, by means of compensating transformers. Such circuits are not subject to electrostatic induction because of the enveloping metal sheath, which acts as a shield or electrostatic screen. The magnetic field, however, penetrates this sheath and gives serious trouble.

On overhead bare wire circuits the compensating transformers do not meet all the changing conditions with respect to leakage, but still afford some relief. The practice in regard to line insulators has remained substantially unchanged for many years. The form of insulator in use is well known to be no more than adequate as regards surface leakage, but any improvement in this respect seems to have been prevented by considerations of expense. The arrival of new conditions makes it now very desirable to experiment with improved insulators, with the object of making the line insulation more stable under weather variations. Such an improvement would improve telegraph working in general, particularly quadruplex working. The " common " side of a quadruplex is the first to fail in bad weather, whereas the " polar " or duplex side is very reliable; the failure of the common side is attributable to low insulation. The working of loaded telephone lines is also seriously impaired by low insulation. Here again the use of better insulators will improve the service.

Mr. Taylor mentions the practice of telephone companies in using a frequency of 800 cycles as the average of the general range of telephonic frequencies. A general figure of 750 cycles has been used considerably, because this value gave fair agreement between the results of speech transmission tests over actual lines and the results of calculation from theory. A complete theoretical investigation cannot be made by the use, however, of a single frequency. For practical purposes a range from 100 cycles to 2500 cycles is quite satisfactory, using steps of 100 to 200 cycles.

The point made by Mr. Taylor in reference to the need for more careful attention to electrical balance in telephone instruments and apparatus is very well taken. The necessity for high insulation can be added to this.

I cannot agree with Mr. Taylor's conclusion that grounding the neutral of a three-phase system at one or more places is not of material consequence. The effect of this depends upon the existence of a triple-frequency harmonic in the voltage wave;

where this is not present there will be no change of consequence in the induced disturbance in parallel systems. But where it is present there will be a serious increase, due to the fact that the resultant vector of three such harmonics is a single wave which tends to elevate the potential of the whole system above the earth, and if the neutral is grounded at two or more places, earth currents of triple frequency will result. This phenomenon has been observed and reported, so that the possible effect of grounding the neutral cannot be ignored. Considering electromotive force and current waves of equal amplitude, their effect by induction upon parallel systems will increase with their frequency, so that a triple harmonic may have a considerable effect although its magnitude may be quite small compared with the fundamental wave.

The formulas given by Mr. Taylor for two-wire metallic circuits are, as he says, those commonly given, but do not take into account the presence of the earth. The effect of the earth is given in the following formula,

$$C = \frac{0.07768}{2 \log_{10} \left(\frac{4 h^2 d^2}{m^2 (4 h^2 + d^2)} \right)} \qquad (1)$$

where m is the conductor radius, d the conductor separation, and h the altitude above the earth. This formula is deduced from the theory of images. It may be put in the form

$$C = \frac{0.07768}{2 \log_{10} \left[\left(\frac{d^2}{m^2} \right) \left(\frac{\frac{4 h^2}{d^2}}{1 + \frac{4 h^2}{d^2}} \right) \right]} \qquad (2)$$

The factor $\left(\frac{\frac{4 h^2}{d^2}}{1 + \frac{4 h^2}{d^2}} \right)$ expresses the effect of the earth, and this is very much less than 0.1 per cent when $\frac{2h}{d}$ has ordinary values in practice. The circuit must approach within a very few feet of the earth before there is any appreciable effect. The same is true of the formula for inductance. It should be stated that these formulas all apply to balanced circuits only, or the condition that at any instant the algebraic sum of the wire potentials is zero and the algebraic sum of the currents is zero. The theory underlying the deduction of all these formulas has been given by Maxwell and Heaviside. The latter has deduced many of the formulas and discussed them in his "*Electrical Papers.*"

The theory of images presumes that the earth is a perfectly conducting body of infinite extent, but it is of course well known that this assumption is not borne out. In fact, the vagaries of earth conductivity have long been troublesome and perplexing. This does not of itself destroy the value of the method of images, but it requires a very careful consideration of the effect of the earth's resistivity upon the distribution of earth-return currents. Instead of a true image we find a distorted image, with its centre far below the centre of the true image. The consequent effect is an increase of the inductive phenomena. Much of the experimental work that has been carried on in the field, in connection with the New Haven electrification, must throw a good deal of light on the real character of the image, and it is to be hoped that we may have the benefit of those researches.

Mr. Taylor contends that an ideal metallic circuit is operative, in theory, in a foreign field of any strength. It is true that such a circuit may, by great care and labor, be perfectly insulated and balanced in a strong foreign field, so that it may operate. But under such conditions it possesses a serious defect; it is like a mass in unstable equilibrium. The slightest leak or unbalance throws it out of service, and moreover it cannot be connected or switched to another circuit whose insulation or balance is not high. Besides this, there is the possibility that the circuit as a whole may be elevated in potential, above the earth, to a dangerous degree; if its potential above earth is sufficient, the arresters will discharge continuously. For instance, an exposure, at 30 ft. distance, 20 ft. above the earth, to single-phase trolley conductors carrying 1000 amperes at 25 cycles, for a linear exposure of 30 miles, would keep the ordinary telephone protector in continuous arc until the fuses act. The arresters in these protectors are commonly set for about 350 volts. This potential between line and earth would give painful shocks to persons using the line, should they accidentally place themselves in its path; and it would be certain to shock linemen, and other employes. It seems to the writer, therefore, that Mr. Taylor's contention in this matter is not well founded.

J. B. Taylor: Mr. Scott referred to the fact that the tests on the New Haven road showed no disturbance due to electrostatic induction, and he attributed it to the number of telegraph circuits on the pole line. With this conclusion I agree. Another case where the trolley voltage was the same and the separation of circuits similar, electrostatic induction was felt; but in that case the line instead of carrying twenty or thirty wires, carried only three or four. In other words, the combined capacity of the twenty wires takes up the charging current with a small portion of it on each wire.

Mr. Scott has characterized some of the diagrams as theoretical rather than practical. With that I agree, too. However, one that he picked out (the return conductor with current transformers to prevent return of current by rails and earth) is actually installed in England to meet Board of Trade limitations on difference of potential between points on the rails.

Mr. Copley's tests on allowable induced voltage on telegraph circuits, including simplex, duplex, and quadruplex, are valuable, and their publication, as well as publication of values from tests showing division of current between rail and earth, should be appreciated by all who may be asked to forecast or solve similar problems.

The discussion of relative importance of railways, telegraph and telephone systems, by Mr. Murray, with comparison of electric locomotive records and steam locomotive records and the doctrine of " the survival of the fittest ", opens up interesting questions many of which are outside of the scope of my paper under discussion.

Mr. Murray has taken exception to one or two statements in my summary, to which I will reply as follows:

A circuit so installed that it can be touched by one standing on the ground could hardly be classed as " ideal." However, it may be well that he has called attention again to the fact that a quiet telephone circuit may possess a disagreeable or dangerous potential to earth. Regarding his question if the compensating transformer does not provide complete compensation for voltage in the telegraph wire. I must say that the compensation is not *complete* on account of disturbing factors such as earth currents, resistance losses, differences of wave-shape, phase, etc. The compensation may be effecive for certain line and instrument conditions, but not sufficiently complete to be effective for more sensitive systems. With the compensating transformer as with the general problem, it is all a question of relation between final resulting disturbance and sensibility of apparatus.

J. B. Taylor (by letter): I shall have to agree with Mr. Scott's statement that the self-induction of a circuit of two wires separated by 2 ft. is nearly the same as that of a circuit consisting of one 4/0 wire 20 ft. from the earth, if in the calculation the earth is regarded as being a conductor say 400 ft. in diameter with its center 220 ft. from the 4/0 wire. Hence, Mr. Scott seems to be justified in his objection to my general statement applying to diagram *B* of Fig. 20, that a boosted return circuit " will have small self-induction as compared with the usual single-phase circuit with overhead conductor and earth return."

Mr. Copley's later contribution to the discussion gives observed values on inductance of trolley wire with earth return, which are in agreement with the above. More properly I might say that the observed values of self- and mutual-induction give us the knowledge of current distribution in the earth justifying the assumption of such a figure as 400 ft. an equivalent diameter of the (earth) return conductor.

Mr. Copley I think has misunderstood my discussion of the effective position of return current with a single-phase railway. I did not state that " part of the return current would be found in the rails and a part at the image of the trolley wire " but that " the image assumption may also lead to too small inductive values on account of the imperfect conductivity of the earth. " I believe that a smaller value than 200 ft. below the surface of the earth, (that is, ten times the depth of the image) will be found as effective position of return current on single-phase roads of less length than the New Haven, or on roads where the trolley voltage is less and sub-stations at fairly short intervals are necessary.

Dr. Steinmetz objects to my statement that the grounded neutral on a three-phase system is not a likely source of trouble to telephone or telegraph systems, and a contribution from Mr. Fowle also takes up this point. At present I know of one system where slight 75-cycle disturbance is felt on telegraph lines as result of exposure to a 25-cycle, three-phase system with neutral grounded at both generating and receiving points. Some of the transformer magnetizing current at triple frequency returns by earth and is responsible for this slight disturbance. I still feel that with generators of average wave shape and transformers worked at not too high density, the troubles from grounded neutral are small as compared with other possible sources of disturbance.

Mr. Nicholson's contribution gives interesting experience on a long line transmitting large amounts of power. The unusual form of transposition which he describes as having come about through successive changes brings out the fact that the mutual induction between circuits, the planes of whose wires are at right angles, may be zero for certain relative locations.

Mr. Cook discusses the relative advantages from the standpoint of safety of telephone lines grounded at the center point of reactive coils versus the use of the insulating transformers. The telephone line with neutral grounded, is, as Mr. Cook claims, more comfortable to handle, but from the standpoint of safety I believe that too much reliance should not be placed on such a system. The telephone line may be broken or open between the grounded points and the person handling same, so that it seems wise in either case to ground a telephone circuit which is likely to be dangerously charged whenever it is necessary to handle same. The practice in this respect should be similar to the best practice on high-tension lines themselves. The risk from handling such a telephone line is reduced as the number of grounded coils is increased, but this involves increased difficulty in maintaining the line quiet; and I have found many telephone lines which were not sufficiently well balanced to be quiet after such grounded coils were installed, no matter how carefully the coils themselves might be balanced. Grounding the telephone line at more than one point also gives opportunity for earth currents and induced currents of large magnitude to pass over the line, and resistance at joints or unequal resistance of the two sides of the line makes the line noisy with the comparatively large currents flowing.

Regarding Mr. Fowle's suggestion that transformers causing return current to flow in a supplementary conductor should have a ratio other than 1:1, the following considerations seem to apply.

The impedance of the return circuit determines the voltage at which the boosting transformer operates, and with a 1:1 transformer practically the same voltage will be found at the primary terminals as at the secondary terminals. If the ratio is other than 1:1, primary and secondary voltages will stand in the ratio of the numbers of turns and the currents in the two windings will be in an inverse ratio. Since the transformer must be magnetized sufficiently to produce the required voltage there will be some magnetizing current in the primary circuit not found in the secondary. This magnetizing current in a properly designed transformer is a small percentage of the total current, but since this magnetizing current is found in one winding and not in the other it must be returned by way of the earth. In other words, such transformers operate, not as the common transformer at constant voltage and magnetic density, but as series transformers at variable voltage and variable density, depending on the amount of load and impedance of the secondary circuit.

I agree with Mr. Fowle that it would be extremely hazardous to attempt telephone service over a typical 30-mile line at 30 ft. distance from a wire carrying 1000 amperes, 25 cycles, with earth return. I have made no contention that operation in such an extreme case is practicable or even possible with present apparatus and general methods of construction. However, I see no reason to modify my statement that *theoretically* a metallic circuit is operative in fields of any strength and practically can be operated in fields too strong to permit usual telegraphic operation with ground return.

DISCUSSION ON "TELEGRAPH AND TELEPHONE SYSTEMS AS AFFECTED BY ALTERNATING-CURRENT LINES." BOSTON SECTION, OCTOBER 20, 1909

A. S. Richey: My experience in this connection has been almost entirely with the private or operating telephone lines of electric railways. In such cases the telephone lines have been strung on the same poles that support the trolley wire, direct-current feeders, or alternating-current transmission lines. In most instances all four classes of wires were carried on the same pole line. In my first telephone experience in connection with three-phase transmission lines the alternating voltage was 16,000, and our telephone construction (perhaps blindly) followed the old practice where the only interference was from 600-volt, direct-current trolley and feeder. The two telephone circuits, extending about 100 miles, were alternately transposed every half-mile, and the jack-boxes, located at about quarter-mile intervals, were simply wooden boxes with the bottom and lower front entirely open to the weather. The operating contacts were brass posts mounted right on the wood, and consequently formed a pretty good ground on the telephone circuit every quarter-mile. Due to the fact, however, that the ground was the same on each side, the telephone circuit remained in balance, and we got very good results. Our aim in the maintenance of good telephone service was, as Mr. Taylor recommends, "to keep the line in first class condition." Our greatest trouble in so doing was in equalizing the resistance and insulation of both sides of the circuit. Poor electrical connections at joints in the wire affected the first, while tree-grounds, principally, affected the second condition.

Later on, in building another 125 miles of transmission line, the voltage in this case being 30,000, the telephone transpositions were made on a single insulator without cutting the line wires. This greatly reduced the number of joints, and not nearly so much trouble was experienced from loose connections. I have attributed our good service on these telephone circuits: first, to good construction and careful maintenance; secondly, to the fact that the partial ground on both sides of the circuit at every jack-box brought the line, electrically, very near the ground; thirdly, to the probable shielding effect of the 600-volt, direct-current feeder which was carried on the same cross-arm as the telephone circuits.

In most of my experience "the disturbers and those disturbed" have been one. In the operation of several hundred miles of interurban railway, where the train despatching and a great part of the company's business communication between stations, offices, power stations, and sub-stations is done over telephone lines which parallel the company's own transmission lines, the telephone is, in a way, as important as the transmission line—at least one can not well be operated without the other. In such a situation the operator is as much interested in the disturbance as in the disturbing influence, and he must solve the problem.

I think that some protective apparatus such as that described in the paper should invariably be used whenever, as is the case with most transmission lines and interurban railways, telephone wires are carried on the same poles with high-voltage transmission lines.

Sewall Cabot (non member): I should like to point out that where telegraph lines are run on a metallic basis it would be necessary to establish repeater stations wherever it is desired to connect the lines with existing lines run on a ground-return basis. In the case of the telegraph systems on a multiple basis shown in Fig. 5, I should like information concerning an actual test of this method of operation, as in practice I think it would considerably slow down the speed of transmission.

I should like information regarding the commercial feasibility of transposing the three-wire trolley system mentioned in the paper, so as to render the telegraph and possibly the telephone lines immune from inductive disturbances.

John B. Taylor (by letter): The form of telephone transposition referred to by Professor Richey, as made on a single insulator, has come into general use because it is superior to the old form involving several joints in the line. In some cases a telephone line on brackets has been transposed without cutting the line or making use of special transposing insulators, by placing the two brackets on opposite sides of the pole at the transposition point and spiralling the line one-half turn.

Mr. Cabot has raised some practical working objections to the metallic-circuit multiple telegraph system, and as far as I am aware such a multiple system has never been given a commercial working trial.

The three-wire trolley system would naturally be undesirable from the railroad man's point of view. The great difference of potential between the two trolley wires (double the normal working voltage from each wire to ground) would make the general insulation question more difficult, and still further objections and difficulties would be introduced at transposition points requiring section insulators. This and other schemes shown in the paper are given merely as indicating lines of action tending to improve matters. The conditions are always so variable as regards both the transmission and signalling systems that what might be considered impracticable in one case might be found feasible in another.

A paper presented at a meeting of the San Francisco Section of the American Institute of Electrical Engineers, San Francisco, Cal., October 29. 1909.

SOME PHASES OF TRANSFORMER REGULATION

BY W. A. HILLEBRAND AND S. B. CHARTERS, JR.

The following paper is based upon experiments conducted at Stanford University during the past two years upon the regulation of transformers under varying conditions. The first test was made upon a single phase, 200-watt, 11,000/110-volt meter-transformer. Owing to the importance of voltage and phase regulation in such a transformer, particularly when applied to the measurement of a large amount of power, a knowledge of its behavior in this regard is extremely desirable.

The remaining tests were made upon power transformers variously connected to polyphase networks, for the purpose of determining the cause and probable extent of the unbalancing in polyphase connections that occurs under certain conditions.

The connections investigated were:

Three-wire, two-phase system of distribution.

Open delta.

Scott two-phase to three-phase transformation.

Inasmuch as any transformer in a group feeding into a polyphase network behaves precisely as it would when operated from a single-phase circuit under similar conditions of load and power-factor, the performance of the group of transformers is to be explained on the basis of the performance of its individual units as single-phase apparatus.

In Fig. 1 are shown regulation curves for a 4-kw. single-phase transformer operating at unity power-factor, and at 70 per cent power-factor leading and lagging.

Fig. 2 shows the relation between primary and secondary electromotive forces in the single-phase transformer with a 1:1 ratio, considered as a simple impedance connected across the circuit. The fact we wish principally to emphasize by means of this diagram is that the impedance of the transformer causes not only a variation in the amount of secondary voltages but also a displacement in phase.

With leading current the secondary electromotive force is displaced more than if the power-factor were unity, and still more than if the current were lagging. This general relation is shown in Fig. 3.

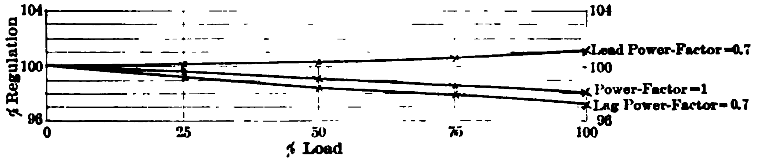


FIG. 1

Meter-transformer. Since in most installations special transformers are inserted between the power mains and the instruments, the accuracy with which the power is measured depends not only upon the inherent accuracy of the instruments but also upon the regulation, both voltage and phase, of the transformers. Thus, if the secondary pressure of the meter-transformer is lower than it should be, due to loading, the power recorded will be less than the real value. Also, if the phase-angle between the currents in the pressure and field coils of the meter differs from that between line pressure and current, a second error is introduced.

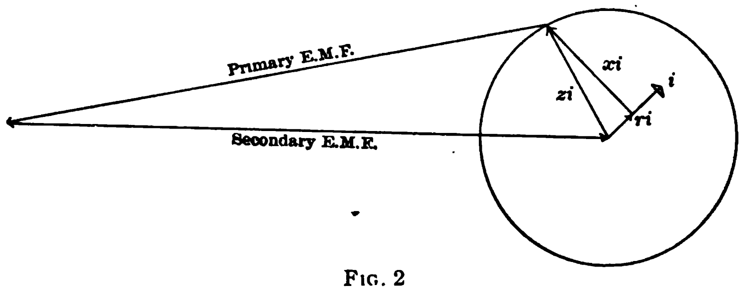


FIG. 2

It is well known that meter pressure transformers are provided by the manufacturer with additional secondary turns to compensate for the drop due to loading, so that when used at their specified load they give their rated voltage ratio; and to give this ratio the load should be as nearly as possible that for which the transformer is compensated. It is comparatively easy in this way to compensate for voltage-drop at any given power-factor, but this will not compensate fully for the drop at a different phase relation between current and electromotive force.

Theoretically it should be possible, by making the resistance very large in proportion to the reactance, to design a transformer of perhaps poor voltage regulation at unity power-factor but one which would give nearly the same drop over a range of power-factors much less than unity.

Fig. 3

An effort to accomplish this end might have been made in the transformer tested, in which the dimensions are as follows:

Ratio of turns—100; 1 approximately.
Primary resistance = 5900 ohms.
Primary resistance in secondary terms = 0.59 ohms.
Secondary resistance 0.306 "
Equivalent resistance = 0.896 "
Impedance, in primary terms 9824.0 "
Impedance, in secondary terms 0.9824 "
Equivalent reactance = 0.406 "

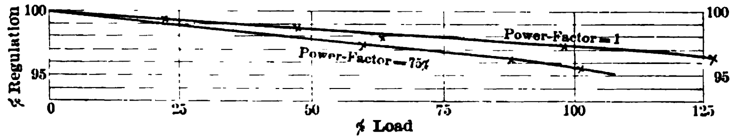


Fig. 4

Voltages—11,000 to 110.
Capacity—200 watts.
Full-load secondary current = 1.82 amperes.

This shows an equivalent resistance of somewhat over twice the equivalent reactance, proportions entirely different from those in the ordinary power transformer, but in spite of this fact the voltage-drop varies widely with the power-factor, as shown by the curves in Fig. 4.

For full-load current between unity and 75 per cent power-factor there is a difference of 1.6 per cent in the voltage-drop, the total drop being for the first case 2.7 per cent and for the second 4.3 per cent; quantities so large where the measurement of any considerable amount of power is concerned as to necessitate, for accurate results, that the transformer be compensated at the factory not only for its specified load but also at the power-factor at which that load operates. Otherwise the meters should be calibrated with the transformers to which they are connected.

Three-wire, two-phase connections. Turning now from the meter-transformer to the subject of polyphase connections, we will take up the question of distributing two-phase power over three wires. This connection was investigated because it is largely used in the distribution of power, and the belief has been expressed that the throwing of quarter-phased currents together into a common conductor will cause voltage unbalancing and phase distortion. This opinion is expressed in a recent and popular laboratory text book, in which a diagram is given to show that such effects are produced. Like so many diagrams of this nature, however, in order to show anything at all the proportions are so greatly distorted that the figure fails to represent practical conditions.

In Fig. 5*a* is given a diagram, the proportions of which are likewise distorted, which, it is believed, takes account of all of the factors in the three distributing wires that affect the voltage as delivered to the receiver.

T_1 and T_2 are the quadrature source electromotive forces.

Φ_1 and Φ_2 are the receiver electromotive forces.

r_1, r_s, and r_2 are the resistances of lines *a*, *b* and *c*, respectively, and are all assumed to be equal.

x_1 is the reactance of line *a* with respect to circuit *a b*.

x_s, is the reactance of line *b*.

x_2 is the reactance of line *c* with respect to circuit *b c*.

i_1, i_s, and i_2 are the currents in *a*, *b*, and *c* respectively.

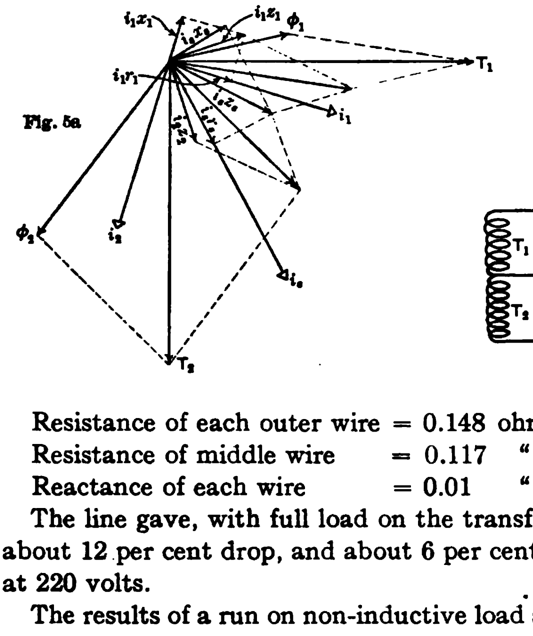
There is also a transformer electromotive force in circuit, *a b*, induced by current in line *c*, and a similar electromotive force in circuit *b c*, induced by current in *a*, but it is doubtful if these are ever of appreciable value, so they have been omitted from an already crowded diagram.

The impedance drop in the middle wire, $i_s z_s$. Fig. 5*a* does not combine symmetrically with T_1 and T_2 in producing the receiver electromotive forces Φ_1 and Φ_2. It is this fact which causes the increase in phase-angle between the receiver pressures and the difference in their values.

In drawing conclusions from this diagram it must be borne in mind: first, that the resistance and reactance of the individual leads are magnified out of all proportion; secondly, that the currents are assumed to remain equal and in quadrature. In an actual case, particularly if the load consist of induction motors, the last condition will not hold true, because as soon as any unbalancing of voltage or phase occurs, unequal currents with different power-factors are drawn, which check to a large extent the tendency to unbalance.

Two 4-kw. 2200/220- or 110-volt transformers were connected to a receiver through a line 95 ft. long, consisting of three wires spaced 6.5 in. apart, the outer wire being No. 12 B. & S. and the middle of the same wire doubled for 41 per cent of the distance to give the same drop as either of the outer wires.

Fig. 5a



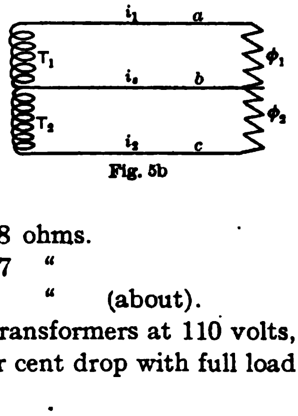


Fig. 5b

Resistance of each outer wire = 0.148 ohms.
Resistance of middle wire = 0.117 "
Reactance of each wire = 0.01 " (about).

The line gave, with full load on the transformers at 110 volts, about 12 per cent drop, and about 6 per cent drop with full load at 220 volts.

The results of a run on non-inductive load are given in Table I.

TABLE I

	Volts		Amperes		Angle phase difference	Per cent unbalance
	Phase A	Phase B	Phase A	Phase B		
No load....	110.4	110.5	0.	0	90° 48′	.09
Load.......	97.4	96.1	34.15	34.05	94° 57′	1.34

These figures, showing an unbalance of 1.25 per cent and phase distortion of 4° 9′, are of interest to the extent that they support the theoretical conclusion that there should be unbalance and phase distortion as a result of this connection.

When furnishing power to an induction motor at 220 volts the figures were, Table II.

TABLE II

	Volts		Amperes		Angle phase difference	Per cent unbalance
	Phase A	Phase B	Phase A	Phase B		
No load....	220.8	220.1			89° 46′	0.3
Load.......	195.2	198.0	18.23	19.8	92° 4′	1.414

Here there was an unbalancing of only 1.11 per cent and a shift in phase of 2° 18′.

In a diagram similar to Fig. 5*a*, which would attempt to show all of the electromotive forces in their relative proportions for our particular line, the vectors representing the line losses would be of almost microscopic size. This leads to the conclusion borne out by our experimental results, that for any case likely to be met with in practice the unbalancing or phase distortion will not be serious.

The same reason that led us to investigate the subject of three-wire, two-phase distribution, also prompted the experiments on the open delta and Scott T, to determine to what extent these unsymmetrical connections may lead to unbalancing or phase distortion.

Open Delta. Fig. 6 shows two transformers connected in V on a three-phase circuit with a three phase, delta connected, non-inductive, load.

The currents in branches a', b', and c' are in phase with the electromotive forces in their respective branches. Current in transformer $c\ a$ is the vector sum of currents in a' and c'. Similarly, current in $c\ b$ is the vector sum of currents in c' and b'.

In Fig. 7 are shown the vector relations of electromotive forces and currents in the load circuit.

Electromotive forces a' and b' are also the transformer electromotive forces $c\ a$ and $c\ b$, respectively. See Fig. 6. The sum of currents in c' and a' is $c\ n$ and the sum of currents in c' and b' is $c\ m$.

An inspection of this Fig. shows that in transformer $c\ b$ the current is lagging by 30° and in transformer *c a* it is leading by the same amount. That is, each transformer, on non-inductive load, operates at 86.6 per cent power-factor. The result of this can be readily seen by referring back to Figs. 1 and 3. The effect of leading current in transformer *c a* is to hold up the secondary voltage and shift it in phase behind its phase position on no load. In transformer *c b* the lagging current causes a greater drop in voltage, but shifts the phase less than in the other.

In Fig. 8 the triangle *c a b* represents the balanced electromotive forces of Fig. 6. Triangle *c a' b'* shows the electromotive forces on non-inductive load.

The effect of drawing load has been to destroy the equality of voltages and to change the angle between the two transformer electromotive forces.

It should be borne in mind that the angle between the transformer pressures *a c*, *b c* and *a' c*, *b' c*, Fig. 8, is actually the exterior angle *c*, or 180 degrees minus the angle here given. Thus, the actual effect of the delta connection is slightly to increase the angle between the two electromotive forces. For convenience in graphical representation the supplementary angle has here been treated.

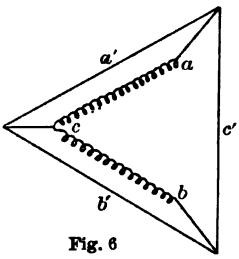


Fig. 6

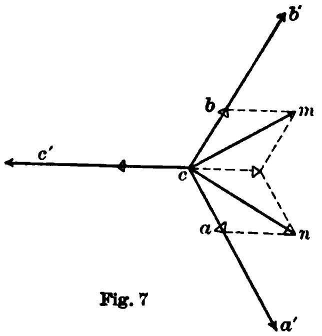


Fig. 7

In table III are shown the results of loading two 10-kw. transformers in this manner.

TABLE III

	Electromotive force			Per cent unbalance	Angle 'C' Fig. 8
	Phase 1	Phase 2	Phase 3		
No load	254.4	253.2	253.4	0.472	59° 58′
Load	246.6	240.3	236.6	4.05	58° 13′

Balanced non-inductive load, 50 amperes per phase. Phase 3 is the open phase.

With these particular transformers carrying approximately full-load current, there was an unbalancing of 3.58 per cent and a change of 1° 45′ in the phase-angle between their pressures. A convincing demonstration of the fact that the current in one transformer is leading was obtained by inserting a choke-coil in series, which caused an immediate increase in wattmeter reading, the current and voltage remaining practically the same.

The regulation on non-inductive load is chiefly of theoretical interest. The induction motor when operated from such a system exerts its customary regulating effect so that unbalancing and phase distortion are by no means so pronounced. Unfortunately, we had but one three-phase motor, which could load the transformers to only about half of their capacity so that regulating effects were not very marked. In Table IV are presented, however, comparative readings on non-inductive and induction motor loads of approximately equal value, which show relatively a greatly improved performance on inductive load over that on non-inductive load, although the unbalancing in either case was slight.

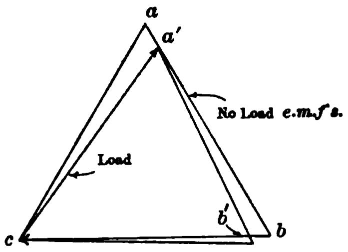


FIG. 8

TABLE IV

	Electromotive force			Per cent un-balanced	Angle	
	Phase 1	Phase 2	Phase 3			
Non-inductive... Load........	232.1	230.3	231.7	0.776	60° 12′	no load
	229.2	224.4	223.9	2.31	59° 11′	load
Inductive load..........	233.6	230.2	232.1	1.45	60° 3′	no load
	226.0	224.3	222.5	1.55	59° 21′	load

Phase 3 is the open phase. The currents were 27.9 and 27.2 amperes per phase for the non-inductive and the inductive loads respectively.

For the non-inductive load the unbalance and phase distortion were 1.53 per cent and 1° 0′. For inductive load they were 0.1 per cent and 0° 42′ respectively.

The above results are of value only as a check upon the theory that explains the regulation of V-connected transformers. In the most unfavorable case, when full-load current was drawn by a non-inductive receiving circuit, the unbalance was between three and four per cent. On inductive load the unbalancing would doubtless be considerably less, so that, judging from the performance of these two 10-kw. transformers, which are representative of modern apparatus, the unbalancing resulting from the V-connection or open delta is not likely to be serious, a conclusion doubtless in accord with practical experience.

When supplying induction motors with power-factors of from 85 per cent to 90 per cent, one transformer operates at about unity power-factor and the other operates at a power-factor of from 50 per cent to 55 per cent, lagging.

With initially unbalanced primary circuits, the transformer with the high voltage draws a heavier current, which, however, if the power-factor of that circuit is the high one, will on that account exert a correspondingly less regulating effect; whereas the low power-factor current in the other transformer will exert a relatively greater effect, so that there may be no improvement in line conditions with load, a particular case in which induction motors fail to balance up the line. This is brought out in TableV.

TABLE V

	Electromotive forces			Currents			Per cent un-balance
	Phase 1	Phase 2	Phase 3	1	2	3	
No load	230.1	216.8	223.8	0	0	0	5.8
Load	225.0	212.2	218.6	24.0	19.4	26.15	5.7

Referring to Fig. 6, phase 3 is the open phase *a-b*. Currents 1 and 2 are currents in transformers *a-c* and *b-c* respectively. Current 3 is the current in the lead wire from the junction point *C*.

Theoretically, then, the V-connection of transformers will cause unbalancing, due to the different power-factors at which the two operate; but with well designed apparatus supplying induction motors, this unbalancing should be small. With initially unbalanced circuits conditions may be such that the induction motors fail to exert any regulating effect.

These conclusions are based upon experiments in which the electromotive force was nearly sine wave in form. Where a pronounced third harmonic is present the pressure across the open side is much distorted, which might cause trouble aside from any phase distortion or unbalancing of the fundamental.

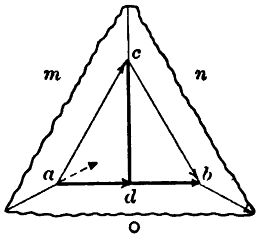


FIG. 9

Scott T-connection. Fig. 9 gives the phase relation of current and electromotive forces in a system of two transformers T-connected, supplying power to a balanced, non-inductive load. *a b* represents one transformer and *c d* the other.

From this diagram it will be seen that currents of different phase relation flow in the two halves of the transformer which constitutes the top of the T. In one half, *a d*, the current is leading by 30 degrees and in the other half lagging by the same amount. This means, according to the curves in Fig. 1, that the regulation in the two halves will be different. Side *a c* of the delta electromotive forces will tend to hold up its voltage and side *b c* to drop off.

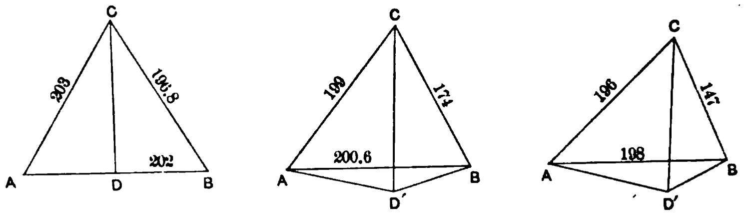


FIG. 10

This is shown in Fig. 10, which represents to scale, no-load, half-load, and full-load voltage readings taken with the two 10-kw. transformers used in the tests on the open delta. The lines *a d'* and *d' b* show that the arithmetical sum of the voltages in the two halves of the transformer *a b* is no longer equal to the electromotive force between its terminals. The unbalance from no load to full load was 22.7 per cent.

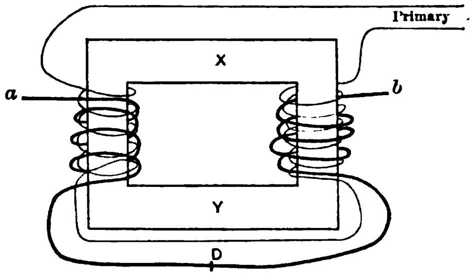


FIG. 11

These transformers are of the core type, with a primary and a secondary coil on each leg, wound for 2200 or 1100 to 220 or 110 volts.

In the run represented in Fig. 10 both primary and secondary coils were connected in series. That is, one-half of the secondary, represented by vector *a d* Fig. 9, occupied one leg, and the second half *d b* occupied the other leg. This is shown in Fig. 11.

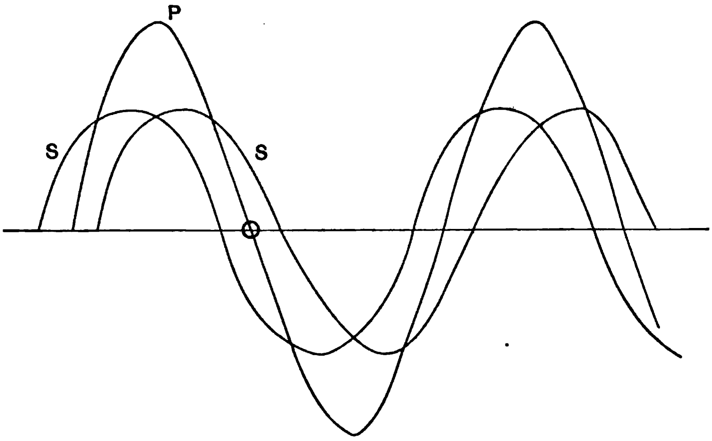


FIG. 12

The significance of this fact is as follows: in ordinary single-phase operation the ampere-turns between points *x* and *y* on the core are zero. That is, there is no magnetomotive force tending to establish leakage flux viȧ the route $x\,y$. When, however, leading current flows in leg $a\,d$ and lagging current in leg $b\,d$ this is no longer true

In single-phase operation the draught of load-current draws current from the primary whose ampere-turns neutralize the secondary load ampere-turns. In this case, however, with primary coils in series, but one load-current can flow, which can only neutralize the vector sum of the two secondary currents. This relation is shown in Fig. 12, which represents the primary and secondary currents reduced to a 1:1 ratio.

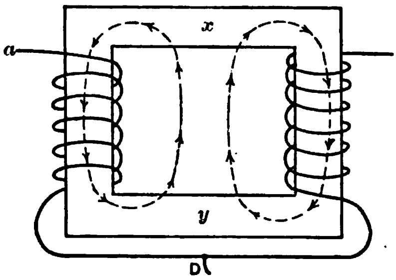


Fig. 18

At the instant represented by point o, Fig. 12, the primary ampere-turns are zero, but in the two secondary coils the ampere-turns are equal and opposite. This condition is represented in Fig. 13. At this instant the ampere-turns between x and y are 50 per cent of the maximum ampere-turns of either secondary coil. The result is an enormous leakage flux with consequent atrocious regulation. So great was the leakage flux with our particular transformer that the case became hot, due to eddy-currents set up by the stray field.

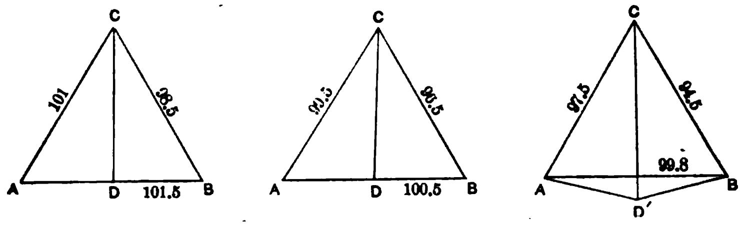


Fig. 14

With primaries in series as before, but secondaries in parallel, furnishing 110 volts, instead of 220, the regulation is greatly improved, as shown in Fig. 14, which represents no-load, half-load, and full-load voltage readings with the secondaries of both transformers in multiple.

The unbalancing from no load to full load is 2.3 per cent as against 22.7 per cent for the series connection.

When secondaries are connected in parallel the condition represented in Fig. 12 holds true for each leg of the transformer; but as the secondary winding on each core is split into two concentric coils, one completely covering the other, the ampere-turns of the two halves at the instant *o* neutralize each other, not only with regard to a path through the core but also with regard to the path *x y*, as shown in Fig. 15. For the sake of clearness the two halves of each secondary coil are shown separately.

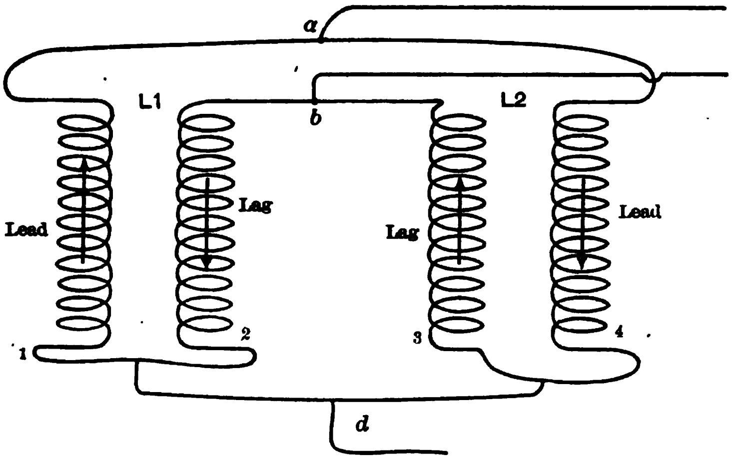


FIG. 15

The result is a greatly reduced leakage flux with consequent improvement in regulation.

By cross-connecting the secondaries, that is, by connecting terminals 1–3 and 2–4 together respectively, the condition shown in Fig. 15 could be realized for the series connection, with secondary voltage of 220, and good regulation would result, but the regulation with secondaries in parallel would then be poor.

As a further experiment, the two halves of the primary winding of transformer *a b*, Fig. 9, were each excited by means of separate transformers at 1100 volts, equivalent to placing the two primary coils in parallel across an 1100-volt circuit. With secondaries connected in series, the secondary current in one leg is leading and in the other lagging, but with each primary coil supplied independently of the other, it could draw a load current whose ampere-turns would at all times equal those of its corresponding secondary, as in the single-phase transformer. The result was small leakage flux and good regulation.

TABLE VI

	Electromotive forces			Per cent unbalance	Average amperes per phase
	Phase 1	Phase 2	Phase 3		
No load.........	221.8	220	220	0.82	
Load............	200	194.6	192.0	4.0	41.9

With this connection the unbalance from no load to full load was only 3.2 per cent as against 22.7 per cent for both primaries and secondaries in series. The currents were 41.9 and 47.1 amperes per phase for the parallel and series connection of primaries respectively.

As a final experiment three transformers were used, *a b* and *d b*, Fig. 9, each consisting of half of an independent transformer. This does away with complications due to leading and lagging currents in the same transformer and gives good regulation whether primaries are connected in series or in parallel.

Using three transformers, the unbalancing from no load to full load, secondaries in series, was 0.85 percent. With secondaries in parallel the unbalancing was 0.63 per cent. These were for non-inductive loads. When operating induction motors the unbalancing was less, or even an improvement over no-load conditions; for, not having a tap on the transformer used as the stem of the T that was approximately 86.6 per cent of the base, the secondary voltages were initially unbalanced between one and two per cent.

Our tests were all based on transformation from two to three phases. When transforming from three to two phase, it is the primary of one transformer that carries different power-factor currents in its two coils, but the effect would be the same as with similar currents of equal ampere-turns in the secondary coils, so that any conclusions drawn from these experiments should apply equally well to both cases.

Wherever serious unbalancing is caused by T-connected transformers transforming from two to three phase, or the reverse, it is probably due to excessive leakage flux caused by different power-factor currents that circulate in the two halves of the transformer comprising the top of the T. This leakage flux may be greatly reduced and regulation correspondingly improved:

1. By proper interlacing of the transformer windings; secondaries if transformation is from two to three-phase; primaries if the reverse.
2. By joining in multiple the two halves of the transformer used as the top of the T, on the side that connects to one of the two-phase circuits.
3. By using three transformers, where available.

In conclusion, we wish to acknowledge our obligation to Professor Harris J. Ryan for the assistance which we received from him on numerous occasions during the conduct of these experiments.

DISCUSSION ON "SOME PHASES OF TRANSFORMER REGULATION." SAN FRANCISCO, OCTOBER 29, 1909

F. E. Geibel: The paper tonight has been very interesting, more so because we have had actual tests from which the conclusions have been drawn. As explained, the action of transformers in groups, or in banks, depends on the action of the single-phase transformer, and the authors have touched briefly on the single-phase transformer and meter potential transformer before going to the banks.

Unbalancing on the banks of transformers, as we have seen, is largely taken care of by the induction motor and synchronous apparatus. Again, in the case of power transformers, or transformers for delivering power, we are not so much concerned in the phase angle difference; what we want on the other side is voltage, and with as little drop as possible. As the regulation is affected at high power factors mostly by the resistance, and at low power factors mostly by the reactance, in a well designed transformer, both are kept as low as possible. In the case of the meter transformer, however, the phase angle difference between the secondary and primary e.m.f's. plays a more important part and affects considerably the wattmeter readings.

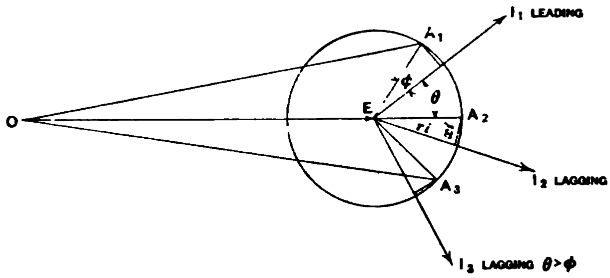


FIG. 1

The authors have found that, in the meter transformer under test, the equivalent resistance is about twice that of the equivalent reactance. Since the power factor of an alternating current circuit is the cosine of the angle whose tangent is x/r, we have for the power factor of this transformer, 0.91 approximately.

In the accompanying diagram $O\,E$ represents the secondary e.m.f., $E\,I_1$, $E\,I_2$ and $E\,I_3$, the secondary current at different power factors, and A_1O, A_2O and A_3O the corresponding primary e.m.f's. From the figure it is seen that on passing from leading current to lagging current, the angle of lag exceeding the angle of lag of the transformer, we pass from a condition of lagging to a condition of leading phase angle difference between primary and secondary e.m.f's., the two e.m.f's., being exactly

180 degrees apart when the power factor of the load is made the same as the power factor of the transformer.

The power factor of a meter load is approximately 0.75 to 0.8 and on the meter transformer under discussion, a load of this character would give a condition of leading phase angle difference. Thus, while the poor regulation of the transformer would cause a wattmeter to indicate low, the leading phase angle difference decreases the angle between current and potential and causes the meter to indicate high—the two effects to a large extent neutralizing.

The meter transformer, although not showing up so well when regulation alone is considered, has been found to be very accurate, especially when used on loads for which they have been designed.

In the July number of the PROCEEDINGS Mr. Robinson has gone into this matter very thoroughly and has also taken into account the phase angle difference of the meter itself.

W. F. Lamme: The problem of transformer regulation is usually a very important one. As noted in tonight's paper, there are three elements to be considered:

First—The ohmic resistance.

Second—The inductance.

Third—The leakage flux.

In the paper is given a case in which large flux leakage takes place, with certain connections. But in every transformer there is a slight leakage between the primary and secondary coils, and this leakage is different in different transformers, and even in different arrangements of coils in the same transformers. The more closely interlaced the primary and the secondary coils are, the better is the regulation, and vice versa. In other words the more perfectly the magnetic flux set up by the primary coils is forced through the secondary coils, the better the regulation. This is, or should be, a question of considerable interest to all engineers. But, I believe, definite information upon the subject is largely confined to factory circles.

It is interesting to study the regulation of transformers with non-inductive and with inductive load. With a non-inductive load the regulation of a transformer is, of course, nearly equal to the ohmic drop, and the inductance has little effect. With an inductive load the inductance of the transformer comes into effect, and the effect of the resistance is lessened, depending upon the power factor of the load. From the above it may be inferred that the regulation of two transformers may be different with non-inductive load, and nearly the same with inductive load.

In recent years more care has been given to this question of regulation for lower power factor. The point just mentioned is best illustrated by two sets of curves. One showing the regulation of a series of transformers from one to fifty kilowatts operating with non-inductive load. The second curve showing the same transformers operating with an 80 per cent power factor load. In these sets of curves are three types of transformers. A core type, a shell type, and one of the newer types of transformers. At 100 per cent power factor you will note all of the types agree very closely in regulation, taking them size for size. But the regulation is poorer the smaller the size of the transformer. All this is natural, and to be expected, for economical design limits us to this condition. But at 80 per cent power factor the regulation of the same sizes are wide apart. And the regulation of the older type is quite erratic, whereas the regulation of the two newer types are not so erratic. Also note that the newer types have nearly the same regulation from the smaller to the larger sizes.

As to transformers for operating meters, we note from the paper that these transformers are compensated for the conditions under which they are supposed to operate. This is important. If the transformer is compensated to operate say, one wattmeter, correctly, the same transformer will not operate two wattmeters correctly. And in the second case there may be an error of several per cent. Therefore, in the purchase of such transformers, it should be the practice of the party purchasing the same to name the conditions of operation.

Combinations of transformers to change from three-phase to two-phase, or from two-phase to three-phase, are made at the expense of regulation, as well as at a loss in efficiency. By the example in the paper, you see that it is important to know how to make some of these combinations properly. Otherwise the regulation and losses will become excessively bad. And, as a result, there may be a burnout of one of the transformers.

Mention was made in the paper of unbalanced primary voltages and their effect on the secondaries. This is a very important matter, especially in power transmission work. In such work we rarely see balanced conditions on the delivery line. Sometimes the unbalancing is very bad. I have in mind one case of a 30-h.p. three-phase induction motor operating from three 10-kw. transformers. One of the three transformers burned out without apparent cause. Our investigation showed the division of load between the three transformers as follows: First, 14 kilovolt-amperes; second, 10 kilovolt-amperes; third, 6 kilovolt-amperes. The 14-kilovolt-ampere transformer burned out, due to unbalanced condition of line. The above transformers were at first connected delta to delta. They were changed to delta primary, star secondary, after which the loads divided much better than they did at first.

B. G. Lamme: The authors of the paper of the evening have called attention to the unbalancing or distortion of voltage and phase which may be obtained with various unsymmetrical combinations of transformers. They have also stated that induction motors tend to reduce such distortions. It may be added that synchronous motors and converters also tend to reduce the distortion. But all such correcting effect is obtained at a certain expense, usually in the capacity of the correcting apparatus.

Distortion of phase, and of voltage, both tend to produce unequal currents in induction and synchronous motors, including converters. If one leg of a supply circuit is of higher voltage than the others, while the motor generates equal counter e.m.f's., current will so flow in the motor that the motor e.m.f's. are distorted in the direction of the line distortion, while the currents tend to correct the line e.m.f. The limit is when the line and motor come to balanced condition with respect to each other.

This unbalancing in the currents affects the capacity of the motors. The total copper loss may not be greatly increased, but the losses in individual coils, or circuits, will be changed. At the limiting capacity of the motor, the heating of individual coils fixes the rating, as a rule, and not the loss as a whole. Any unbalancing in current, therefore, affects the heating of the individual coils, and thus reduces the limiting capacity. This is true for induction and synchronous motors. But for synchronous converters the case may be still worse.

In converters, the armature copper loss is normally much less than with a corresponding direct-current machine, or if the converter was run as a straight direct-current generator. This is due to the fact that the same winding is used for the incoming alternating current and the outgoing direct current. Part of the alternating current input is fed directly in the direct current, while part is transformed to mechanical energy, and back to direct current electrically. In consequence, when transforming three-phase to direct current, the armature copper loss is only 57 per cent of straight direct current operated with same armature while with two-phase (or four-phase in reality), it is 38 per cent, and with six-phase it is 26 per cent. But this 26 per cent loss is not uniformly distributed in the armature. The average loss in the various armature coils depends upon their position with respect to the tap-offs to the collector rings. The highest loss is next to the tap-off, this being about 60 per cent of direct current Therefore, the coil next to the tap-off is liable to be overheated under extreme condition of load.

If the power factor is not 100 per cent, then this loss curve is greatly affected. At about 95 per cent the loss in the tap-off coil goes up about 100 per cent. And at still lower power factor it goes much higher. Therefore, a low power factor greatly reduces the ultimate capacity of a converter, depending upon the size, and general design of the windings, number of phases, etc. Unbalanced voltages or phases, due to unsymmetrical transformer combinations will have a bad effect on the capacity of any converter, and care should be taken, with such machines, to furnish balanced supply conditions.

The fact may be of interest that 60-cycle synchronous converters, as a rule, can be operated at lower power factors than 25-cycle converters as normally constructed. This is not due to any peculiar merit of 60 cycles, but is due to the fact that 60-cycle converters usually have many more poles than 25-cycle, and if parallel wound, as is usually the case with large sizes, the smallest armature strap conductor which is safe for mechanical reasons, is much larger than necessary for electrical purposes.

It has been found in practice where unsymmetrical transformer combinations have been used for step-up purposes, that a similar arrangement should be used for stepping down. For instance, if the Scott, or T combination is used to step up from two to three-phase, then a T should be arranged for stepping down to motors, with the head of the step-down T across the same wires as the head of the step-up T. The same is true of other unsymmetrical combinations. In this way some of the inequalities cancel instead of accumulate.

In connecting unsymmetrical transformer combinations in parallel, there is usually a possibility of cross currents between them, unless all are arranged across the polyphase lines in a similar manner.

In conclusion it may be said that all unsymmetrical systems should in general, be avoided. Such systems originate, as a rule, in an attempt to save in first cost of a system or installation, but in the end they are generally much more expensive than true balanced systems, when reduced capacity of apparatus, etc., are taken into account.

J. W. White: In regard to the inquiry on the effect of frequency changes upon the accuracy of primary recording wattmeters, and particularly upon a 60-cycle meter operating upon a 25-cycle circuit, I would say that in the first place the potential coil of the meter would probably burn out on account of the excessive current. The potential transformer might do likewise, as the capacity of a 60-cycle transformer operating on a 25-cycle circuit is but 69 per cent of its rating, due to excessive magnetizing current. However, if this did not occur the meter would run fast.

Consider first the potential transformer.

In the ideal potential transformer the phase displacement in the secondary circuit would be offset by a capacity effect, and in Fig. 2, *O E* or *O B* would be the impressed e.m.f. and *O a* would be the effective e.m.f.

If, however, the phase angle of displacement is leading or lagging, a condition will exist similar to *O B* or *O BB*. If operating on a lower power factor, *R I* would remain constant with *X I* diminishing in proportion to the frequency. If *O E* and *O a* coincide, a lowering frequency would have no effect inasmuch as the inductive reactance is offset by the capacity effect and thus the effective e.m.f would be higher and the amount of compensating effect in the transformer's secondary winding can be less.

If, however, the reactance effect in the transformer is leading or lagging to produce *a BB* or *a B*, then the phase displacement of the transformer is equal to *BB O E*, or *B O E*.

If, as in Fig. 2, (*BB′ a″*) the power factor of the circuit (not the transformer) passes from leading current to lagging current, the angle of lag exceeding the angle of lag of the transformer, the angle of phase distortion with reference to the secondary is further increased, while on the other hand if the power factor of the circuit is leading and the power factor of the transformer lagging the two would tend to compensate and cut down the angle of phase displacement.

The same condition would exist if the opposite were true, *i. e.* if the angle of phase displacement of the transformer were leading and the power factor of the circuit were lagging the two would tend to compensate, while if the power factor of the circuit were leading the resultant phase angle with reference to the secondary of the transformer would be greater.

From the above it is at once evident that in lowering the frequency $X\,I$ would be diminished and whether leading or lagging would cause the angle $B\ a\ E$ to be decreased and thus reduce the angle of phase displacement.

From the above can be deduced that lowering the frequency of a potential transformer will tend to reduce the phase angle of displacement if leading or lagging. (This would, if any thing, cause the meter to run faster.) If the transformer capacity is balanced by the inductance there will be relatively no change.

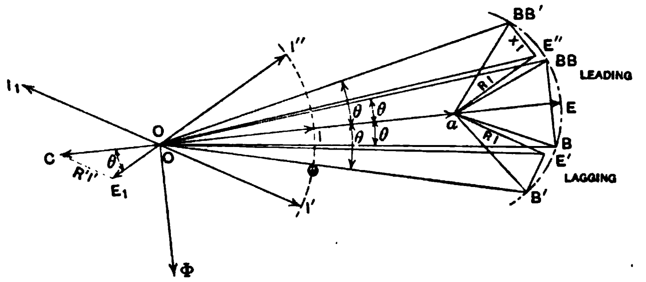


FIG. 2

With regard to the regulation of the transformer and the effect of the resistance of the coils upon regulation, let the line I represent the harmonically varying flux in the core. $O\,a$ represents the useful part of the primary electromotive force and $O\,c$ the total electromotive force induced in the secondary coil. The line $O\,I$, represents the secondary current and the line $O\,I''$ represents the primary current. The total primary electromotive force E' exceeds $O\,a$ by the amount $R\,I$ (parallel to I') and the electromotive force E, at the terminals of the secondary coil falls short of $O\,c$ by the amount $R'\,I'$ parallel (to I_2).

When the angle θ ($a\,O\,I'$) is nearly zero (secondary receiving circuit non-inductive) then $R\ I$ and $R'\,I'$ are nearly parallel to Oa and $O\,c$ respectively, so that $O\,a$ is much less than E' in value and E' is much less than $O\,c$ in value. On the other hand, when the angle θ is nearly 90 deg. (secondary receiving circuit containing a large inductance of a condenser) then $R\,I$ and $R'\,I'$ are nearly perpendicular to $O\,a$ and $O\,c$ respectively, so that $O\,a$ is nearly equal to E' in value and E_1 is nearly equal to $O\,c$ in value Therefore the regulation of a transformer is largely affected b coil resistance when the secondary receiving circuit is non inductive, but scarcely at all affected by the coil resistance when the secondary receiving circuit contains a large inductance or a condenser.

This accounts for the even regulation curve shown by Mr. Lamme illustrating the regulation of the type S transformer operating on low power factor, and this is characteristic of any type of transformer (multiple) operating under the same conditions.

With regard to the operation of the meter on 25-cycles refer to Fig. 3.

Let $O\,E$ = Impressed e.m.f.
$O\,C$ = Current non-inductive.
$O\,C'$ = Current inductive.

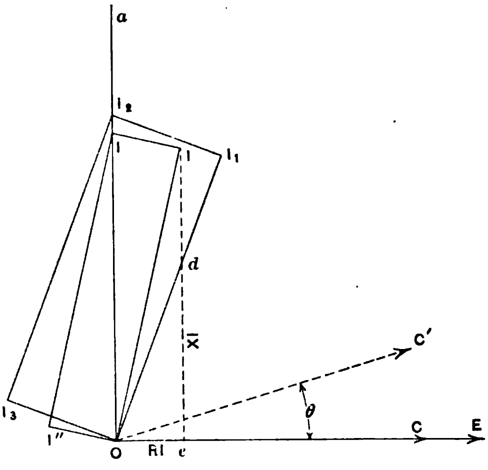


Fig. 3

$O\,I$ = Current in potential circuit.
$O\,I''$ = Current in lagging coil.
$O\,I'$ = Resultant current effect in potential circuit.

From the above it is at once evident that with a lowering frequency the impedance of both the potential and lagging windings will be decreased and the current flow, therefore, increased, thus increasing $O\,I'$, causing the meter to run fast.

In addition to this it is also evident that with the decreased frequency the reactance factor of the potential circuit, *i. e.* $X\,I'$ will be decreased 5/12, *i. e.* 25/60, making $X\,I$ equal to $d\,e$ instead of $I\,E$. This will bring the angle of lag of the potential winding to $O\,I_1$ making it necessary, therefore, to add an increased effect on the lagging coil to bring the resultant effect back to I_2 as the recorded power of the meter is equal to $O\,C \times O\,E \cos O$, and if the meter is not corrected it is therefore evident that with

$O\,I'$ increased and an error introduced equal to $I\,O\,I_1$, the correction factor would be cos $I\,O\,I_1 + O\,I_2 — O\,I'$. In commercial service a pertinent example is noted in meters designed for operation on both 140 and 60 cycle circuits, which are double lagged, one coil being left open circuited on 140 cycles but short circuited through resistance when operating on 60 cycles.

From the above, therefore, three points are evident:

A. A lower frequency will reduce the error of phase displacement in a transformer except wherein a unity power factor condition exists in the transformer winding. In this latter case there will be no change.

B. The regulation of transformers is vitally dependent upon resistance of its windings and its relative regulation is not affected as greatly on low power factor as in comparison with high power factors.

C. Integrating meters operating on lower periodicities than that for which they are designed will run fast and the effect of a lower frequency on the primary transformer for such a meter will be cumulative with that of the meter itself.

S. G. Gassaway: I was somewhat agreeably surprised with the paper tonight as the gentleman did not include a lot of difficult mathematical formulae, which we expect to get from one coming from the University. The speaker tonight mentioned the V and Scott connections. The power factor of the V connections is 86.6, this has another meaning if you will consider it. It means that if the load has a power factor of 100 per cent the power factor in these transformers is 86.6. In other words, you have approximately 15 per cent greater transformer capacity than the capacity of the load connected. In the T connection we have a power factor of 92.8 per cent. In other words, you have something like 8 per cent more kilowatt transformer capacity than you have load connected.

The regulation of a transformer is really a sort of measure of the care with which it is constructed. A more carefully constructed transformer has better regulation. Regulation is important in the transformer that is being used for lighting, because the candle power of the lamps varies with the potential. In converter work, regulation is not so important because it can be taken care of by series reactive coils which allow for line drop, etc. and thus you obtain any regulation desired. Likewise with motor generators the regulation of the transformers is not important.

Regulation depends on a number of factors, one of which is the reactance or impedance of the transformer. If the transformer is not carefully constructed, and there is considerable flux leakage, that means the impedance is higher; in other words, poor regulation.

In the smaller sizes of transformers, we find the transformer is generally of the core type, because it is cheaper to make and it is lighter, but it has not in general as good regulation as a transformer of the shell type. The reason for this is obvious, because in the shell type transformers there is a better opportunity for interlacing the coils thus preventing magnetic leakage. There are other reasons for using the shell type, especially in larger transformers, than that of regulation alone. In the shell type the coils can be arranged more advantageously for cooling and thus prevent hot spots which would be likely to occur were the very large capacity transformers made in the core type. It is possible to brace the coils more securely in the shell type, repairs are more readily made, and there are many other features which make the shell type desirable in large capacities.

Some of the first transformers that were designed had very poor regulation notwithstanding the care taken in designing them, and on investigation the cause was found to lie in the large eddy current loss in the casing due to the case being located too close to the core, thus causing a large flux leakage. On experimenting it was found that there would be little or no loss in the case if it were not located closer than three inches to the core.

The impedance of the transformer varies greatly with the spacing or arrangement of the coils. Some experiments were made on the core type of transformer on varying impedance, and it was found that impedance could be varied from 2.4 per cent to 150 per cent by spacing the coils. We found that when we had all the primary coils on one leg and all the secondary coils on the other leg of the transformer coil, the impedance increased until we reached as high a figure as 150 per cent, depending on the number of coils and how well those coils themselves were placed on the transformer.

The regulation of a transformer has another feature to be considered. We know the load divides itself amongst transformers in bank according to the relative admittance, I believe it is called, which is commonly taken as the kilowatt capacity divided by the impedance volts or the percentage in impedance volts. As I said, the regulation depends on the impedance; therefore, if the impedance is large, the regulation is poor, the relative admittance would be small, and we find that the transformer does not take its proper share of the load if it is connected with transformers that have better regulation.

C. L. Cory: I am very much interested in the paper this evening because it has given us an opportunity to understand the regulation of the transformer in a much broader sense than we do ordinarily. Summing up what has been said by the different speakers this evening it may be said that the regulation of a transformer, except as regards the change of the load, depends upon the resistance and reactance, and, by the way, reactance does not always mean inductive reactance, but it may mean condenser reactance as well. The regulation of a transformer, again depends upon leakage. An ideal transformer would be one in which the primary turn and each secondary turn occupy exactly the same physical space.

The paper this evening has interested all of us because it takes up the transformer from two different points; one, the transformer which is used for meter purposes, that is the potential transformer, and the other, the practical transformer, which Mr. Lamme has chosen to call, the unsymmetrical transformer.

A number of people in this room probably remember the series of tests made about two years ago where it was decidedly important to determine the accuracy of meters working not on 60 cycles, but on 50 cycles; where the current was to be 10,000 measured volts; where the power factor would vary between 100 per cent and 80 per cent and where the magnitude of energy was to be about 5,000 kilowatts.

The checking of meters was a simple matter, but the checking of potential transformers and series transformers was an entirely different matter, and inasmuch as in this particular case an error of about one-half or one per cent represented a loss or gain to the company of about $5,000, accuracy was of some consequence.

To get at the method of determining this phase relation of primary and secondary between transformers of one manufacture and one of different manufacture, they were sent to the bureau of standards, and these transformers were operated not exactly at 60 cycles, but at 50 cycles, 48 and 52 cycles, and were connected as per instructions at the bureau of standards with reference to a standard 150-volt 200-ampere indicating instrument, and also each transformer of its particular type to a 5-ampere wattmeter that was used to measure the power. When these results were turned over to the company having charge of the tests it was found that the capacity of potential transformers had a great deal to do with the regulation; in other words, it determined that while one transformer had a great deal of insulation the other one did not have so much.

I should say that it was exceedingly dangerous, and subject to a very great error, to use a transformer and meter which were designed for 60 cycles on a 25-cycle circuit. In the first place you are running a very great risk of burning out your potential transformer, but under any circumstances I doubt very much whether, unless you knew definitely the curve showing the relation of the phase angle and the power factor, you could ever tell whether your meter was reading fast or slow. I am not quite sure but that under some conditions the meter would read fast and under others it would read slow.

F. V. T. Lee: The trouble particularly in regard to two-phase and three-phase or T connection has been well known in the past, but I think this is probably the first time that a good many of us have had an opportunity of having somebody explain the true inwardness of the trouble. I remember one case that may be of interest where a plant was installed in the northern part of California, and for reasons of economy it was necessary to use three-phase transmission. It was desirable to take two-phase machines and connect them for three-phase with the T connection. For some reason it was necessary to use two-phase motors. Some strange results were obtained, and what really happened was exactly as illustrated by the authors this evening. Unfortunately the winding of the generator did not allow for adjustment and the result was that special generators had to be built, which overcame the trouble, and when received from the factory the generator leads and the motor leads were all carefully tagged as to how they should be connected, so no mistake could be made.

Those days have gone by, but it is necessary to have papers of this character, so that those who have not given it special attention will look out for it, and those who have met the trouble will see the solution. These academic papers really should not be stigmatized as being academic, for the reason that they come from the University where they have the time and opportunity to give these problems theoretical treatment, which those in practice haven't time to do.

G. C. Holberton: Apparently the discussion of the paper has shown us that there are errors of regulation. The author referred to regulation of power transformers, or lighting transformers such as we are using in practice, and that particular regulation is a matter that we can watch and if it is a very serious thing we notice it, but in the matter of transformers used for meters we cannot. I think for that reason we should go into it even further than has been gone into tonight. In the discussion tonight, as I take it, it has been brought out that there are errors, all of which are over one per cent. If these errors are cumulative we may have an error of several per cent, which I am safe in stating we cannot determine in the ordinary way. If we have two or three different kinds of errors, any one of which amounts to over one per cent, we are getting into very serious condition. It is no uncommon thing in the present state of or business to have bills running about fifteen or twenty thousand dollars monthly. When there is an error of two or three per cent, it is a very serious matter. I don't think the ordinary meter tester is capable of making an accurate test involving the current transformer and the potential transformer. The apparatus would be too bulky to carry around. I think it is necessary for some one to take up the subject from a practical standpoint and make these tests, which have been made at laboratory—make them under practical conditions.

W. A. Hillebrand: I have only one thing to say, and that is with reference to Mr. Lamme's remark about the effect of the power factor on the capacity of the converter, especially in the heating of the coils near the point at which the tap is brought out. Mr. Charters and I spent about three months last year investigating the behavior of induction and synchronous motors under various conditions. These were small machines, to be sure, not over 10 h.p. at most, but they showed the power factor to be extremely sensitive to even slight variations in either amount or phase relation of the applied electromotive forces; much more sensitive than might be expected from the inconsiderable current unbalance that occurs under these conditions.

General view of Great Northern three-phase locomotive [Hutchinson]

A paper presented at the 240th meeting of the
American Institute of Electrical Engineers
New York, November 12, 1909.

THE ELECTRIC SYSTEM OF THE GREAT NORTHERN RAILWAY COMPANY AT CASCADE TUNNEL

BY CARY T. HUTCHINSON

The first three-phase installation on a trunk line railway in the United States was put into operation early in July of this year at the Cascade Mountain tunnel on the Great Northern Railway, in the State of Washington, about one hundred miles east of Seattle.

I purpose in this paper giving a general description of the plant with especial reference to the electric locomotives, together with a brief statement of its operation for the short period since it has been put into service; this record will of necessity be somewhat sketchy, as there has not been sufficient time to accumulate full data for the various conditions of operation that will be met with in service, especially the performance during winter.

In general the plant comprises a hydroelectric generating station, operating under a head of 180 ft., having a capacity of approximately 5000 kw. in generators at 6600 volts and 25 cycles; a transmission system operating at 33,000 volts, delivering energy to a sub-station where it is transformed to 6600 volts, at which pressure it is supplied to the overhead conductors and to the locomotive by way of an overhead trolley; on the locomotive the pressure is reduced by three-phase transformers to 500 volts for the supply of the four three-phase motors with which each locomotive is equipped.

The Great Northern Railway crosses the Cascade Mountains through a tunnel 13,873 ft. long; this tunnel is on a tangent and has a uniform gradient of 1.7 per cent; rising to the tunnel from Leavenworth, on the east, the ruling grade is 2.2 per cent, and

21 per cent of the total distance of 32.4 miles from Leavenworth to the tunnel is on the ruling grade. From Skykomish on the west to the summit the ruling grade is 2.2 per cent, and 44 per

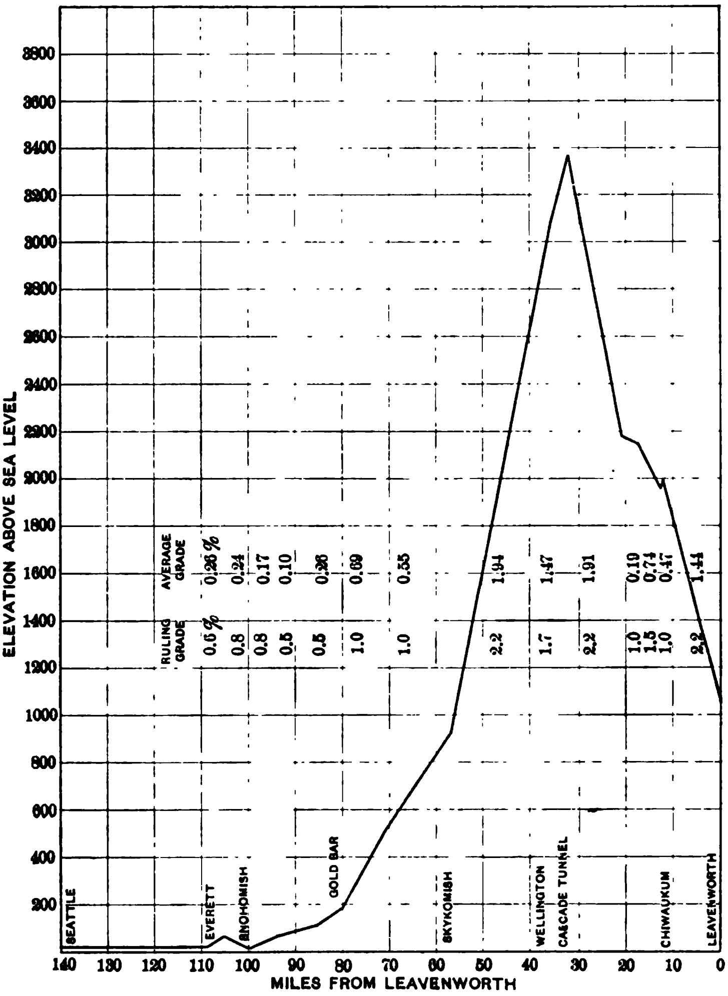


FIG. 1.—Profile of Great Northern Railway—Leavenworth to Seattle

cent of the distance of 24.8 miles is on the ruling grade. Fig. 1 shows a condensed profile of this section of the road; the average up grade from Skykomish to Wellington is 1.94 per cent and from Leavenworth to Cascade, 1.37 per cent.

The operation of the tunnel with steam locomotives was at all times difficult and frequently very dangerous on account of the heat and smoke from the locomotives. Crows Nest coal, which is exceptionally free from sulphur and gas-forming materials, was used for the tunnel service. It was the custom to clean the fires of each locomotive and to put on just sufficient coal to carry it through the tunnel. In the tunnel the rails became very wet from condensed steam, and were frequently covered with a layer of coal soot and ground sand, making them very slippery. The temperature in the locomotive cab was almost unbearable, rising at times as high as 200 deg. fahr. Under ordinary circumstances it required from twenty minutes to an hour for the tunnel to clear itself of gases, but on days when the wind was changeable, the passage of the gases from the tunnel would be stopped by the change in the direction of the wind, and they would pocket. Under such circumstances, work in the tunnel was very dangerous. There are refuge chambers containing telephones every quarter of a mile, but it was a difficult matter to keep these instruments in order, on account of the gases, smoke, and moisture.

The tunnel is lined with concrete throughout its length, and is in good condition. The roof is practically dry. The entire tunnel drips more or less from condensed steam just after the passage of a train, but is comparatively dry at other times. The temperature changes at the top of the tunnel are very rapid, varying from atmospheric temperature to several hundred degrees fahr. from the heat of the locomotive exhaust. For these reasons this tunnel is the limiting feature to the capacity of the Great Northern Railway for hauling freight across the mountains.

Mallet compound engines are used on this division, one at the head of the train, and one pushing. The mountain section as a whole also fixes a limit to the capacity of the road, on account of the slow speed necessitated by heavy traffic; it is impossible for steam locomotives to haul heavy trains on the mountain at a greater speed than seven or eight miles per hour.

The plant described herein is designed for use over the entire mountain division, by extending the system of conductors and building additional stations; it was not designed for the operation of the tunnel alone, although even if the problem had been the handling of the traffic through this tunnel and its approaches only, the three-phase system would in all probability have been selected, on account of its greater simplicity and less cost. The choice of the system to be used was under consideration for more than a year; the three-phase system was finally decided on, plans were prepared, bids obtained, and the contract for the four locomotives let on June 22, 1907.

The original problem was to provide equipment to handle a train having a total weight of 2000 tons, excluding the electric locomotives, over the mountain division from Leavenworth to Skykomish, a distance of 57 miles. The system was to be first tried out at the Cascade Tunnel.

The tractive effort required to accelerate a train having a total weight of 2500 tons on a 2.2 per cent grade, using 6 lb. to the ton for train resistance and 10 lb. to the ton for acceleration, making a total of 60 lb. to the ton, is 150,000 lb.; this would require four locomotives of a tractive effort of 37,500 lb. each. The railway company's engineers limited the weight on a driving axle to 50,000 lb.; therefore four driving axles per locomotive are needed, giving a coefficient of adhesion of about 19 per cent. This is a measure of the maximum power required. The locomotive was, therefore, designed to give a continuous tractive effort of approximately 25,000 lb., and it was expected that four would be used with a train maximum weight. But the locomotive as built greatly exceeds this specification.

GENERAL DESIGN OF LOCOMOTIVE

The locomotive as built is shown in Fig. 2. The principal data of locomotive are as follows: total weight 230,000 lb. all on drivers; two trucks connected by a coupling, each truck having two driving axles; a three-phase motor connected by twin gears to each axle; gear-ratio, 4.26; diameter of driving wheels 60 in.; synchronous speed of motor 375 rev. per min. giving a speed of 15.7 miles per hour at no load, dropping to 15 miles per hour for a load corresponding to the one-hour rating. The motors are wound for 500 volts and are completely enclosed and air-cooled; clearance between stator and rotor, ⅛ in.; trolley pressure, 6000 volts; each locomotive has two three-phase transformers reducing the pressure from 6000 to 500 volts, arranged with taps so that 625 volts may be used on the motor.

The distribution of the total weight of the locomotive is as follows:

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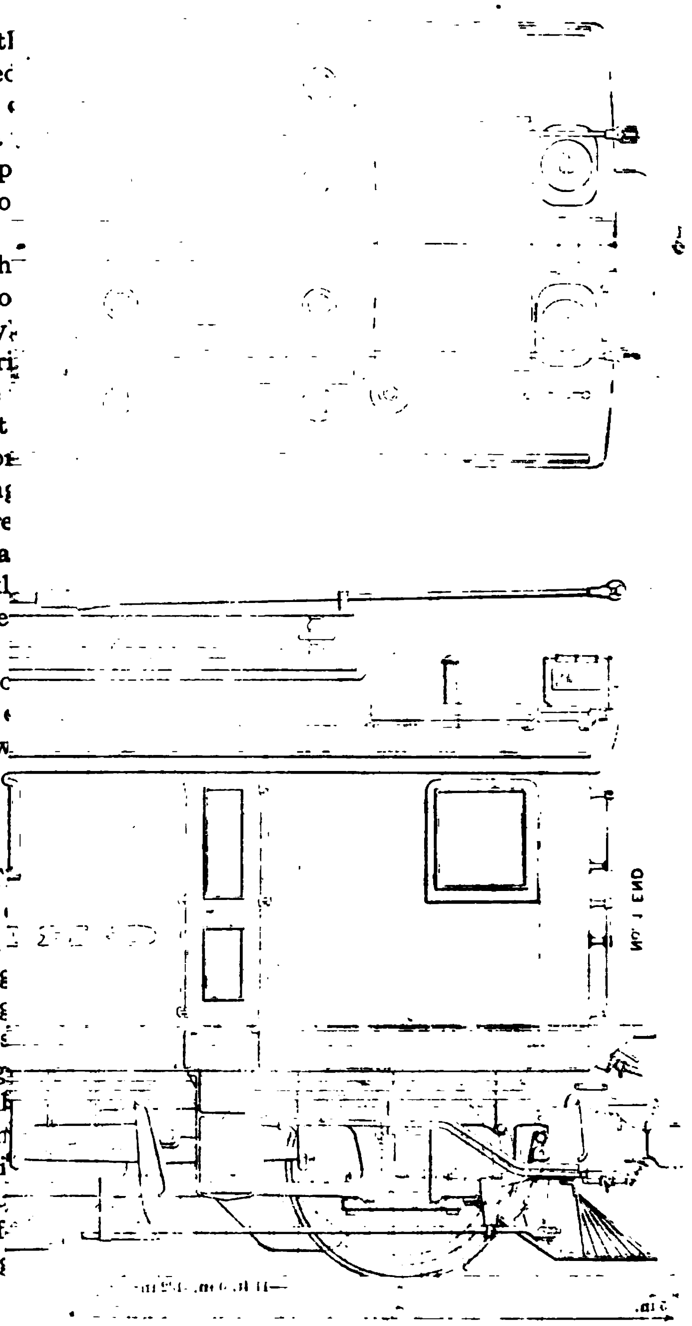


2 Trucks	81,500 lb.
1 Cab	30,000 "
4 Motors	48,800 "
8 Gears and gear cases	11,000 "
2 Transformers	20,800 "
2 Air compressors	5,800 "
1 Blower	1,300 "
40 Rheostats	10,200 "
56 Contactors	3,200 "
Miscellaneous	17,400 "
Total	230,000 lb.
That is,	
Total weight per axle	57,500 "
Dead weight per axle	18,500 "

The specification of the motor required an output of 250 h.p. continuously for three hours with 75 deg. cent. temperature elevation, when supplied with not more than 2000 cu. ft. of air per minute. The test results of the motor show a continuous output of 375 h.p. at 500 volts with 1500 cu. ft. and 400 h.p. at 625 volts, with the same air; the one-hour rating of the motor at 500 volts with 1500 cu. ft. of air per minute is 475 h.p.; the ratio of continuous output to the hour-rating with 1500 cu. ft. of air is therefore 79 per cent. The continuous output at 500 volts corresponds to a tractive effort of 9350 lb. per motor and the one-hour output to a tractive effort of 11,900 lb. per motor; the locomotive will, therefore, give 37,400 lb. tractive effort in continuous duty, or 47,600 lb. tractive effort for one hour. Fig. 3 shows the characteristic curves of the motor, at 500 volts.

Calculations from the profile of this section give:

Westbound, Leavenworth-Cascade	
Average up-grade	1.37 per cent
Distance	32.4 miles
Work per ton at the wheel rim	2.15 kw-hr.
Average power per ton at the wheel at 15 miles per hour	1.00 kw.
Eastbound, Skykomish-Cascade	
Average up-grade	1.88 per cent
Distance	24.8 miles
Work per ton at wheel rim	2.16 kw-hr.
Average power per ton at wheel rim at 15 miles per hour	1.31 kw.
Average power per ton at wheel at 15 miles per hour for round trip	1.12 kw.
Maximum power per ton accelerating on 2.2 per cent grade	1.8 kw.

These figures assume the train to be moving continuously and are based on 6 lb. per ton train resistance, as are all calculations herein unless otherwise stated.

The average power of the locomotive when pulling will then be 1.12 kw. per ton, and therefore each motor can carry 250 tons in continuous service on this mountain division, assuming there are no stops and no opportunity for cooling; or each locomotive could haul (4 × 250 − 115) = 885 tons trailing load, if the power requirements were continous; as there are necessarily stops, the rating as determined by heating is somewhat greater than this.

The locomotive has been tested to a maximum tractive effort of nearly 80,000 lb., corresponding to a coefficient of adhesion of nearly 35 per cent; with 60,000 lb. or 26 per cent, each locomotive can accelerate the train of 885 tons trailing on a 2.2 per cent grade, using 60 lb. per ton as the total tractive effort; or, in other words, the train that a locomotive can haul, as determined by the average duty and safe heating limits, is just about equal to the train that it can accelerate on the maximum grade; that is, the average capacity of the locomotive and its maximum capacity are in the same proportion as the average duty and maximum duty. The design is well balanced.

Making some allowance for these figures for the sake of conservatism, the rating of the locomotive on this division can be put at 750 tons trailing load.

ELECTRIC EQUIPMENT OF LOCOMOTIVE

Each locomotive is equipped with four three-phase induction motors, wound for 500 volts at the primary or stator; the motors are completely enclosed and are cooled by forced air circulation from a large blower. They are suspended from the axles in the standard manner, except that they are geared at both ends of the armature shaft; this was made necessary by the low speed and high torque required, as it was not considered safe to use a single pair of gears. The gear had 81 teeth, the pinion 19 teeth, giving a gear ratio of 4.26. The gears are of specially hardened steel; in order to secure perfect alignment the two pinions on each shaft were cut simultaneously. At first it was the intention to use some form of spring connection between motor and driving wheel, but this was subsequently abandoned, as it seemed that there would be sufficient flexibility in the armature shaft to take out any small differences between the two sets of gears. As far as can be told at present, this assumption appears to be correct, for there has been no difficulty with the gears and no unequal wear. The gears run with little noise and the construction seems satisfactory.

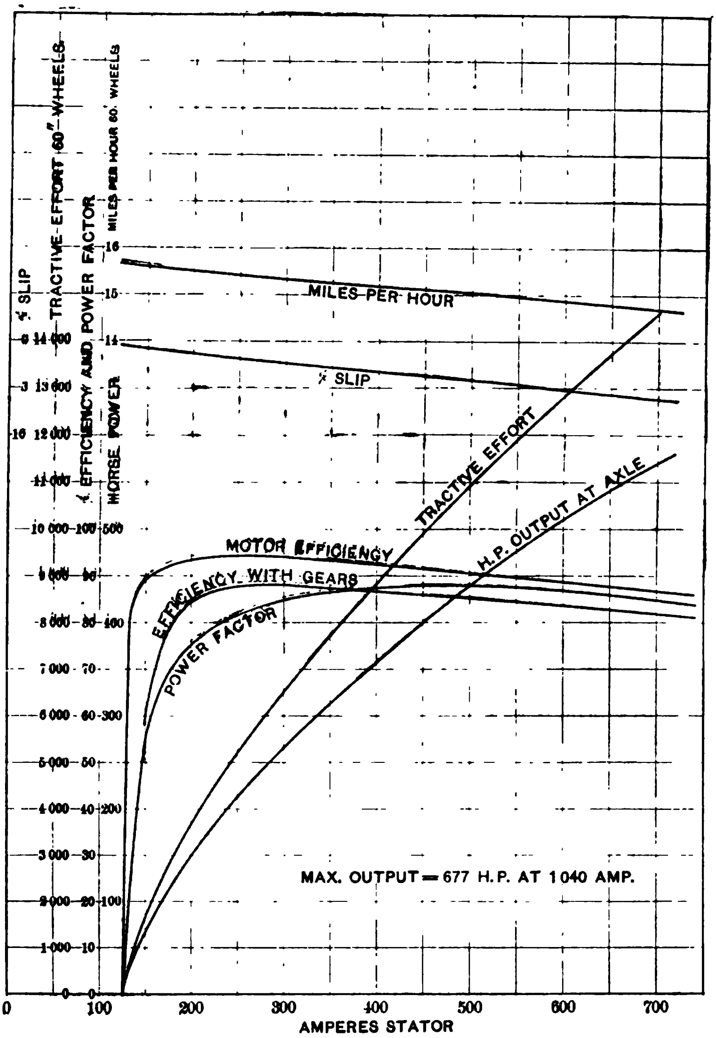


Fig. 3.—Characteristic curves of Great Northern three-phase 475-h.p. 25-cycle, 500-volt motor—gear ratio 4.26; 60-in. wheel

The locomotive carries two three-phase air-blast transformers, having a nominal rating of 400 kw. each, transforming from 6000 volts to 500 volts normally, or to 625 volts by the use of taps. The continuous capacity of the transformer is not as great as that of the motors, although it is fully up to the specification, and it may be that the quantity of air to the transformer will have to be increased when the locomotives are put in continuous service.

Compressed air for the brakes is supplied by two 100-cu. ft.

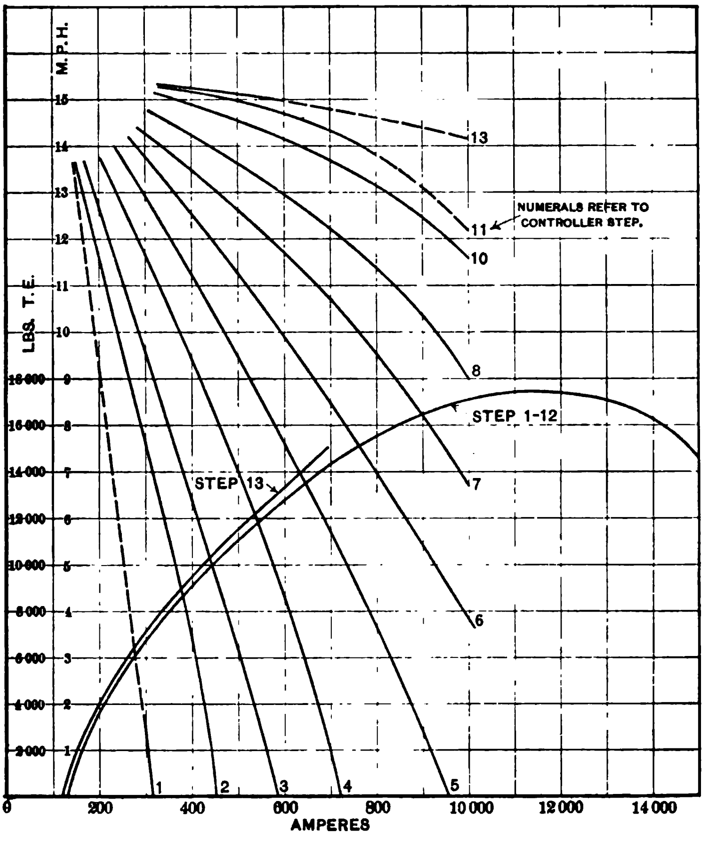


Fig. 4.—Speed-torque curves of Great Northern three-phase motor on the various control steps

induction-motor-driven compressors; the cooling air is supplied by a 9400-cu. ft. motor-driven blower. The locomotive is equipped with a combined straight and automatic air-brake system.

Control system. The control system of each motor is separate; the circuits branch from the transformer and are independent through the resistances. There are 14 contactors in each motor circuit, 56 in all. The pilot control is in duplicate, one switch at each end of the locomotive. There is a clear aisle on each side of the locomotive from end to end, all of the apparatus being assembled in the center of the cab.

At first I intended to have two running speeds by changing the number of motor poles, but this led to many complications; every effort was made to keep the equipment as simple as possible, and I finally decided to use resistance control in the rotor of the motors and to have a single-speed unit.

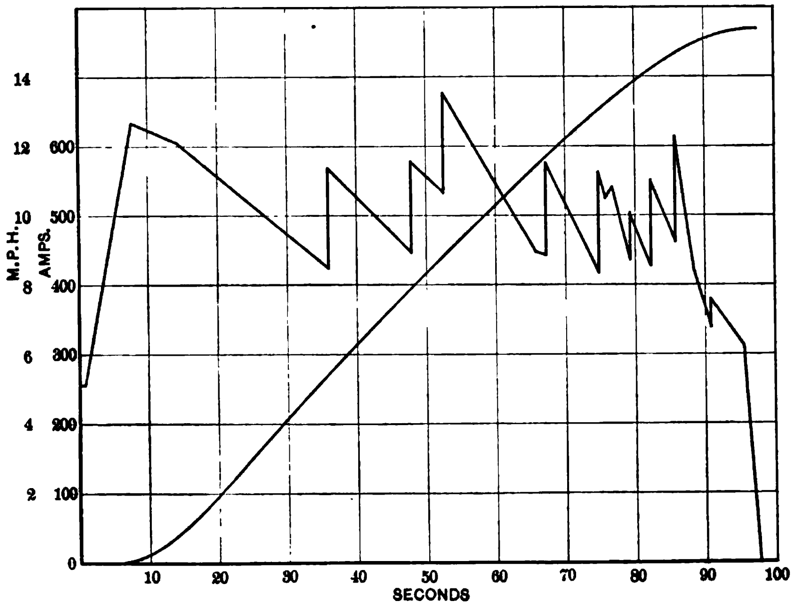


Fig. 5.—Acceleration curves
Tractive effort for locomotive—44,400 lb.
Acceleration—0.177 miles per hr. per sec.
Equivalent to a trailing load of 555 tons on a 2.2 per cent grade

Iron grid resistances are provided for each motor; there are thirteen steps in the control, but in order to reduce the number of contactors to the lowest possible point an unsymmetrical system is used. A change is made in the resistance of one phase only, in passing from step to step. This arrangement in effect treats the three-phase circuit as a single-phase circuit; on each step of the control the torque is the average of the three values of the torque of the separate circuits. The principal advantage of this is that 56 contactors do the work that would otherwise require 128, thus effecting a great gain in the simplicity of the control apparatus.

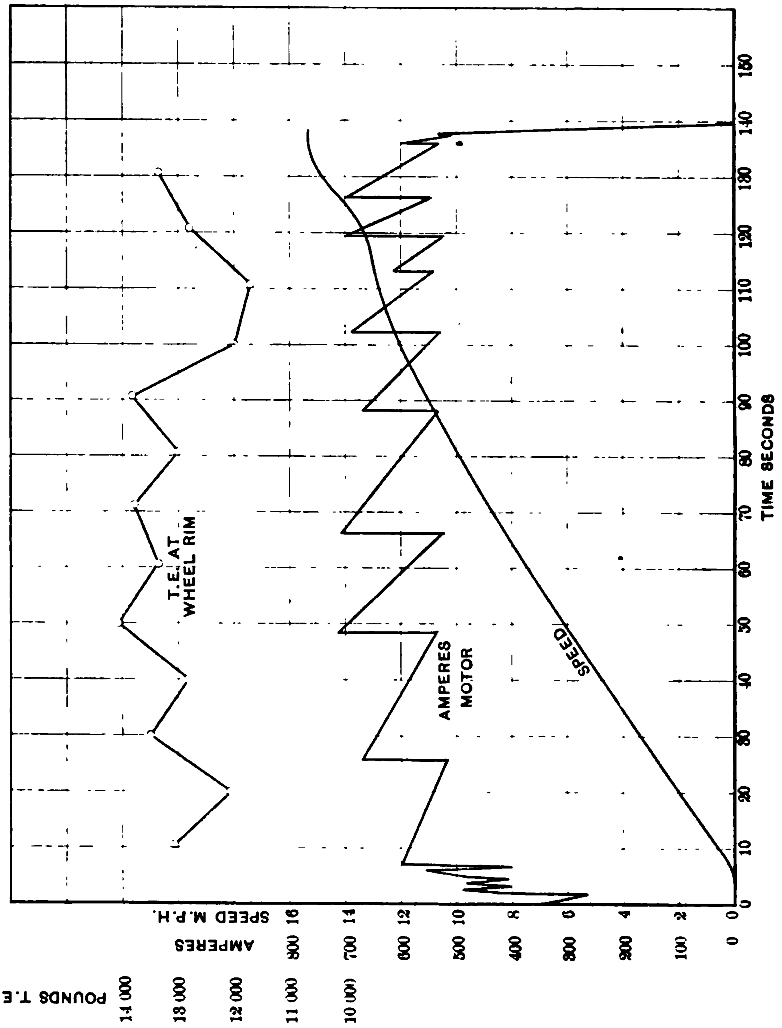


FIG. 6.—Acceleration curves
Tractive effort for locomotive 52,000 lb.
Acceleration 0.12 miles per hr. per sec.
Equivalent to a trailing load of 735 tons on a 2.2 per cent grade

Experience with the locomotive in service indicates that the initial torque, which is approximately 20,000 lb., is somewhat high, and I am now having the control changed so that on the first step two motors only will be thrown in circuit, and on the second step all four motors. This change is readily made by eliminating step 12, which tests have shown to be of little or no value. Fig. 4 shows the speed and tractive effort of the motor on the different control steps, with unbalanced circuits, and on the final step, without resistance.

Many acceleration tests were made at Schenectady, generally using one motor. Fig. 5 shows the result of one of these tests, in which the average tractive effort was 11,100 lb. per motor, corresponding to 44,400 lb. for the locomotive. Fig. 6 shows a similar test in which the average tractive effort was 13,000 lb. per motor, corresponding to 52,000 lb. for a locomotive. Fig. 5 is equivalent to accelerating a train of 555 tons on a 2.2 per cent grade at the rate shown on the curve; that is, 0.177 miles per hr. per sec. Fig. 6 represents the acceleration of a train of 735 tons on a 2.2 per cent grade at the rate there shown, that is, 0.12 miles per hr. per sec.

MECHANICAL DESIGN OF LOCOMOTIVE

The locomotive is of the articulated or hinged type, having four driving wheels on each half of the running gear and is without guiding wheels. The running gear is not two independent trucks coupled together, but is more nearly comparable to the Mallet type of steam locomotive, in that the hinged sections are so rigidly connected that they tend to support each other vertically and guide each other in taking the curves, although the hinges are designed to offer minimum resistance to lateral flexure. There are no springs to prevent this flexure, and the wheel base is free to accommodate itself to any curvature; the effect of this guiding action is to minimize the flange wear, as in the Mallet locomotive.

The equalization system takes advantage of the vertical rigidity of the truck to distribute the spring stresses over groups of springs instead of concentrating them on single springs; the truck section on the one end is side equalized, but the section on the other end is carried on a three-point suspension. The springs are thereby equalized in groups and the groups are so arranged as to eliminate all skew or twisting stresses in the truck frame.

The framing of the running gear is of substantial steel castings annealed and held together by body-bound taper bolts in reamed holes. Side-frames are castings of truss pattern; end-frames and bolsters are steel castings of box-girder type; the end-frames and all parts are designed for buffing stresses of 500,000 lb. Bolsters are hollow castings and form part of the air reservoir for the motor ventilation; the air is supplied to the motors through a hollow center pin. The wheels are 60 in. in diameter with removable steel tires 3.5 in. thick. The wheel-centers are steel castings. The gears are shrunk on an extension of the wheel-hub, thus eliminating the torsional stresses from the locomotive-axles. The motors are connected through gears at both ends; that is, they are twin-geared to the driving wheels; this has the advantage of maintaining accurate alignment between axles and armature shaft.

The cab is carried on the trucks through center pins on each bolster, the center pin on one end having a slight longitudinal sliding motion to allow for variation in the distances between truck center-pins in taking curves. The cab extends the entire length of the platform and is made of No. 10 steel plates which carry a monitor that supports the trolley base and has a ventilated opening running through the center and perforated side plates to permit the escape of air from the interior of the cab. The greater part of the control apparatus, the rheostat, the transformers, contactors, etc., is placed in a separate compartment 60 in. wide and 22 ft. long, enclosed by steel partitions extending directly up to the monitor roof. This leaves two open operating spaces at the ends of the locomotive, connected together by two side aisles 30 in. in width. This center compartment is divided into three parts by steel-plate partitions, the middle part contains the high-tension apparatus, including switchboard; the end parts are duplicates, each containing one transformer and the contactors for two of the motors. The rheostats are placed in the monitor at the top of the cab. The air for ventilation, after passing through the transformers, cools the rheostats and then escapes to the atmosphere. Placing these rheostats at the top of the cab has also the advantage of raising the center of gravity of the locomotive, which is nearly 60 in. above the rail head, higher than is usual with electric locomotives.

GENERATING SYSTEM

The energy supply for the locomotive is derived from the Wenatchie River, which flows along the line of the railway for a distance of some 20 miles. The power house is located about 2.5 miles west of Leavenworth. There is a low concrete diverting dam in the river at a point about 12,000 ft. west of the power house, and from this dam a wood-stave pipe of 8.5 ft. interior diameter runs for a distance of 10,908 ft. and continuing this stave-pipe line is a steel-pipe line for a distance of 962 ft. The pipe line has substantially the same gradient as the railway line, and gives a static head at low water of 203 ft. and in ordinary water of about 200 ft. The operating head at rated load is 180 ft.

The crest of the diverting dam is 400 ft. long; it has three head gates, a log sluice, and a fishway. The pipe line ends in a surge tank at the corner of the power house, having a total height of 183 ft. above its foundation. The tank proper is 30 ft. in diameter, and with a storage height of 54 ft. above its hemispherical bottom gives a storage capacity of approximately 38,000 cu. ft.

The pipe line leads directly into the upright pipe of the surge tank, which is 8 ft. in diameter; within the upright pipe is a waste pipe having a diameter of 3 ft. 2 in., extending 7 ft. above the level of the crest of the dam; in the tank the waste pipe is expanded uniformly to a diameter of 7 ft. 6. in, thus affording a circular weir of 23.5 ft. in length.

The power house is designed for three main units and two exciter units. There are now installed in the power house two main units, each turbine rated at 4000 h.p., directly connected to a three-phase alternating-current generator.

The two main units now erected, with the exciter, require approximately 500 cu. ft. of water per second when operating at full load of 8,000 h.p., giving a velocity of flow in the penstock of 8.7 ft. per sec.

The extreme low flow of the river at the dam is estimated to be 380 sec-ft. The small pond formed by the dam has a storage capacity equivalent to 8000 h.p-hr., for a depth of one foot; it is possible to draw the water in the dam down three feet. There are two other power sites in the canyon, each affording a head of 200 ft., available for subsequent developments.

The entire hydraulic installation was designed and constructed under the direction of J. T. Fanning, of Minneapolis.

ELECTRIC EQUIPMENT OF POWER HOUSE

The electric equipment in the power house at present consists of two main generating units, each for a nominal capacity of 2500 kilovolt-amperes at 375 rev. per min., 6600 volts and

25 cycles; these machines are designed to have very large overload capacity, and operate at a low flux density.

There are two exciter units, each having a nominal capacity of 100 kw. at 750 rev. per min. These units also have a large overload capacity; they frequently carry 150 per cent overload, on account of the very poor regulation of the water wheels. A third unit, identical with the first two, has been ordered.

The power house also contains four transformers for raising the pressure to 33,000 volts, each of a nominal capacity of 833 kw. but guaranteed to operate 100 per cent overload for one hour, with a low rise in temperature. Three of these units are in service, the fourth is kept as a spare.

The switchboard apparatus is of the usual type, having panels for the generators and the feeders, and is provided with the usual measuring instruments.

One reason leading to the use of the three-phase system was the possibility of regeneration; that is, of returning energy to the system on down grades. With the present installation it is obviously not possible to make any use of the energy so returned, but in order to prove this practically an automatic rheostat controlled by the speed of generator was installed in the power house; when a train on the down grade reaches a little more than the synchronous speed, the electrodes of the water rheostat are automatically lowered by an amount proportional to the difference between synchronous speed and the speed of the generator; this throws a load on the system and acts as a brake to the train. The operation of this apparatus is entirely effectual.

The nominal capacity of parts of this equipment, in particular of the transformers, may seem unusual; but it must be remembered that the plant is intended to operate on a load having extreme fluctuations, the entire load being on for, say, 15 minutes and then off for two or three hours, and consequently the transformers can be made small.

This plant has operated satisfactorily with the exception of certain troubles with the water wheels; in particular, the generators have shown ability to hold their rated pressure under extreme variations of speed, due to the effective control of the Tirrill regulators. The generator fields, designed for 125 amperes, have frequently carried 300 to 350 amperes, and the regulators have held the pressure normal, in spite of fluctuations of 35 to 40 per cent in speed.

TRANSMISSION LINE

The transmission line extends from the power house at Leavenworth to the sub-station at Cascade, a length of approximately 30 miles, following the railroad all the way; part of the distance it is on the same side of the river as the railroad and part on the opposite side. Figs. 7 and 8 show the general appearances and the details of the construction of the line.

FIG. 7.—General view of transmission line

The line carries two circuits each of No. 2 B. & S. gage stranded hard-drawn copper wire; each circuit is in a vertical plane at one side of the pole, thus permitting the use of short cross-arms; the upper cross-arm was placed some distance below the top of the pole in order to leave room for a ground wire, which has not as yet been installed. The poles are 40 ft. long, placed 6 or 7 ft. in the ground, the tops being 10 in. to 12 in. in diameter; these poles

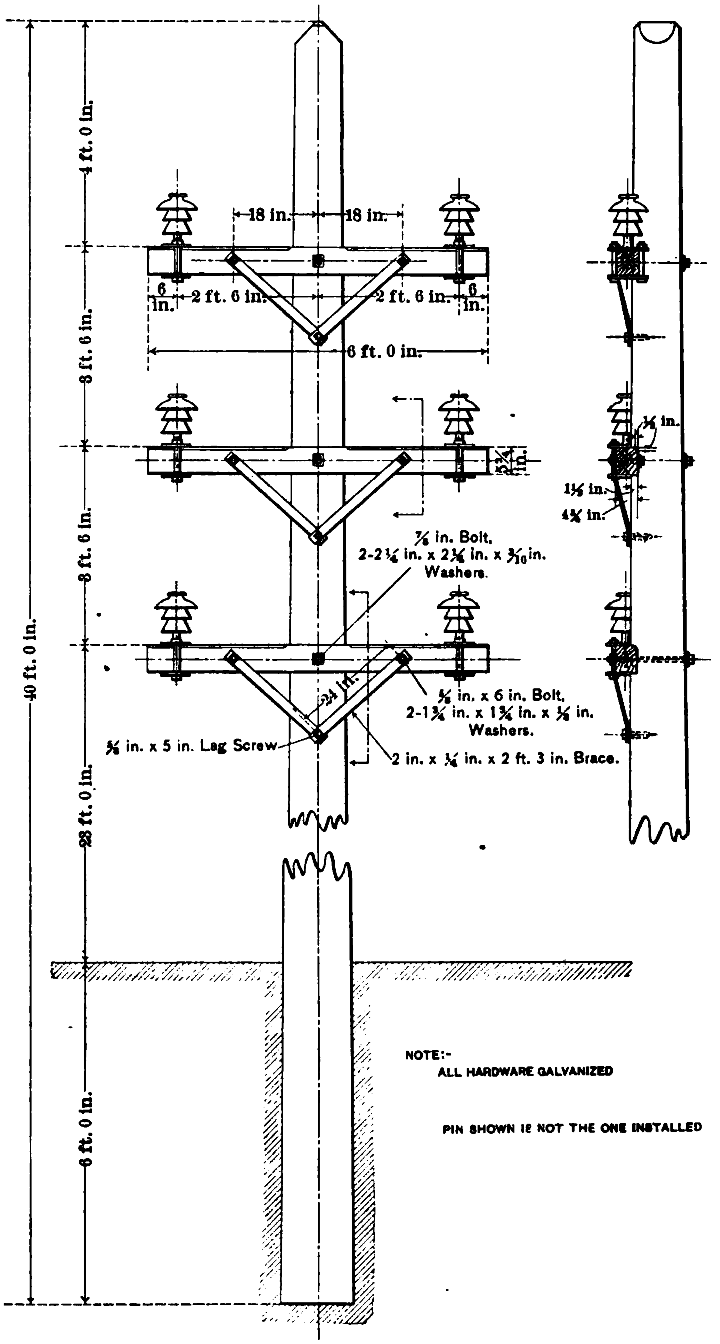
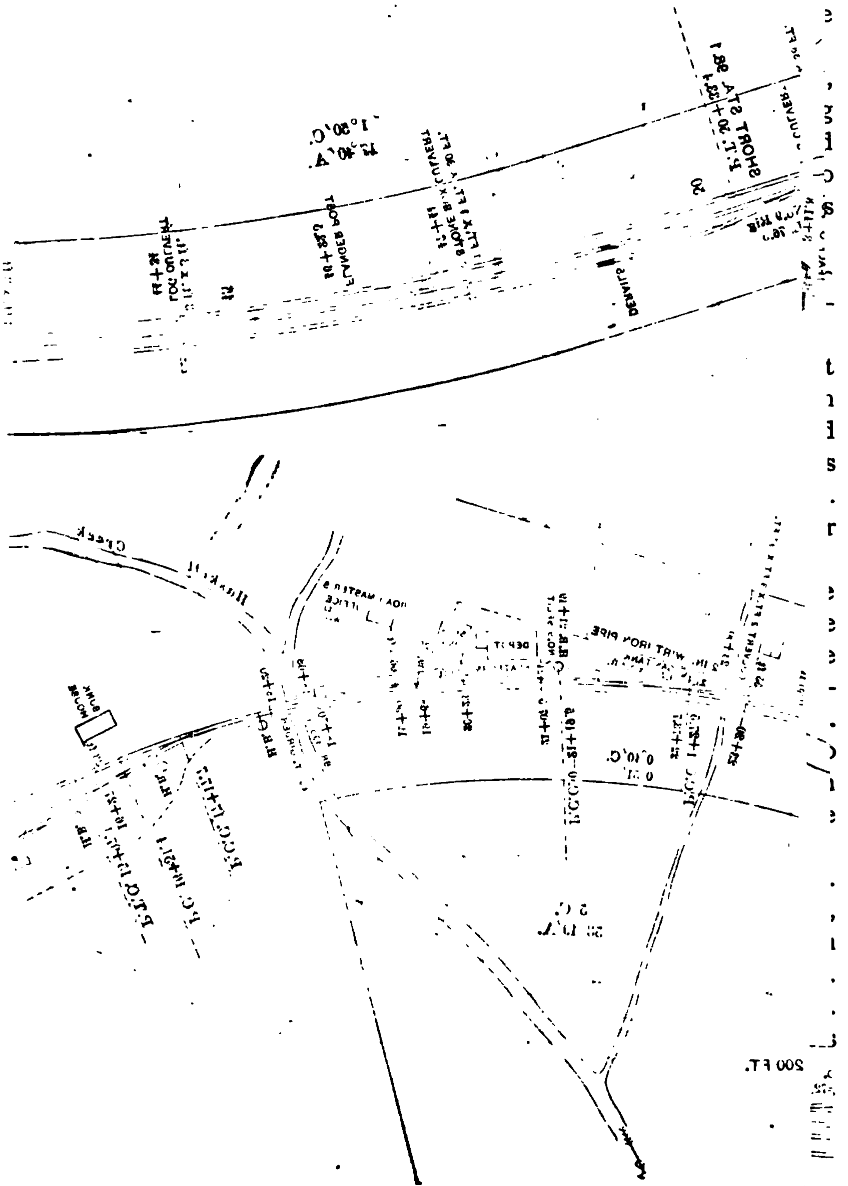


FIG. 8.—Standard pole of transmission line: two 33,000-volt circuits of No. 2 B. & S. gage wire



lington yard showing tracks. The main track through the snow shed a

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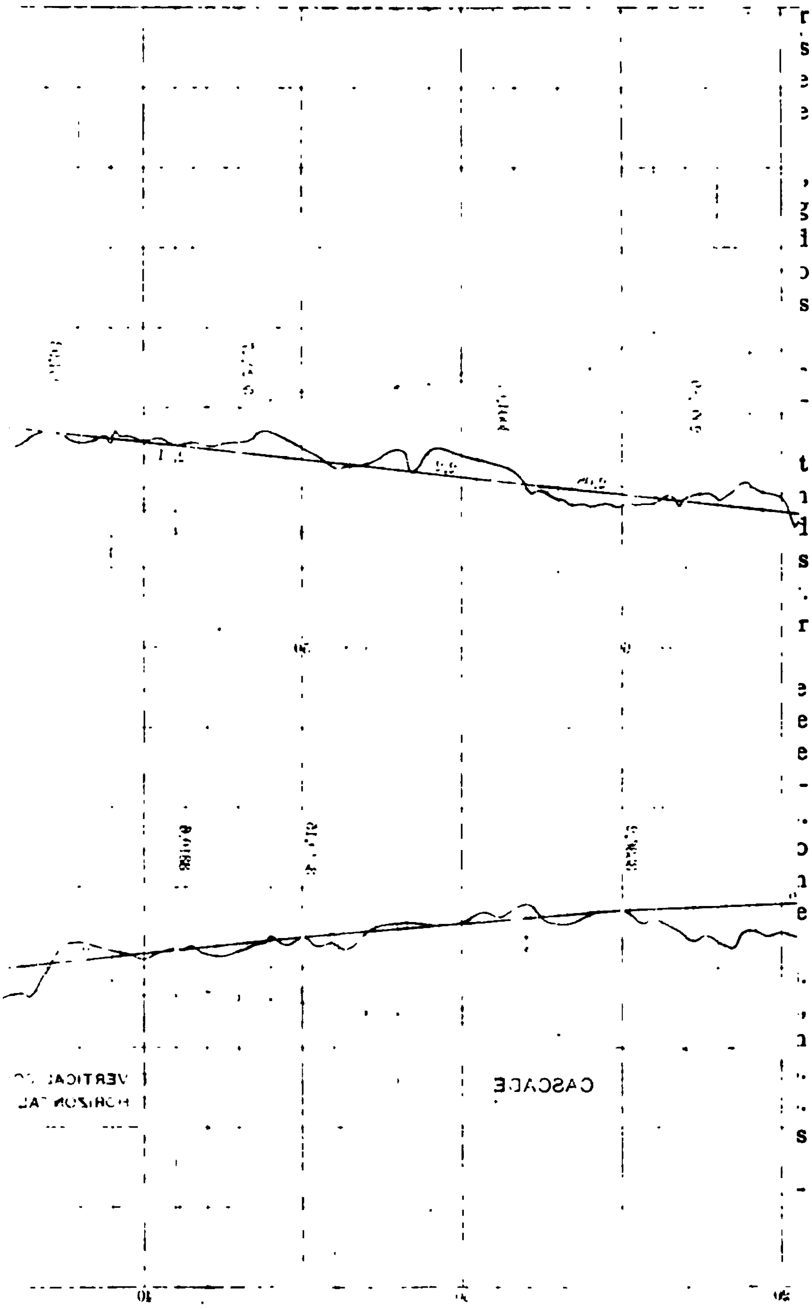
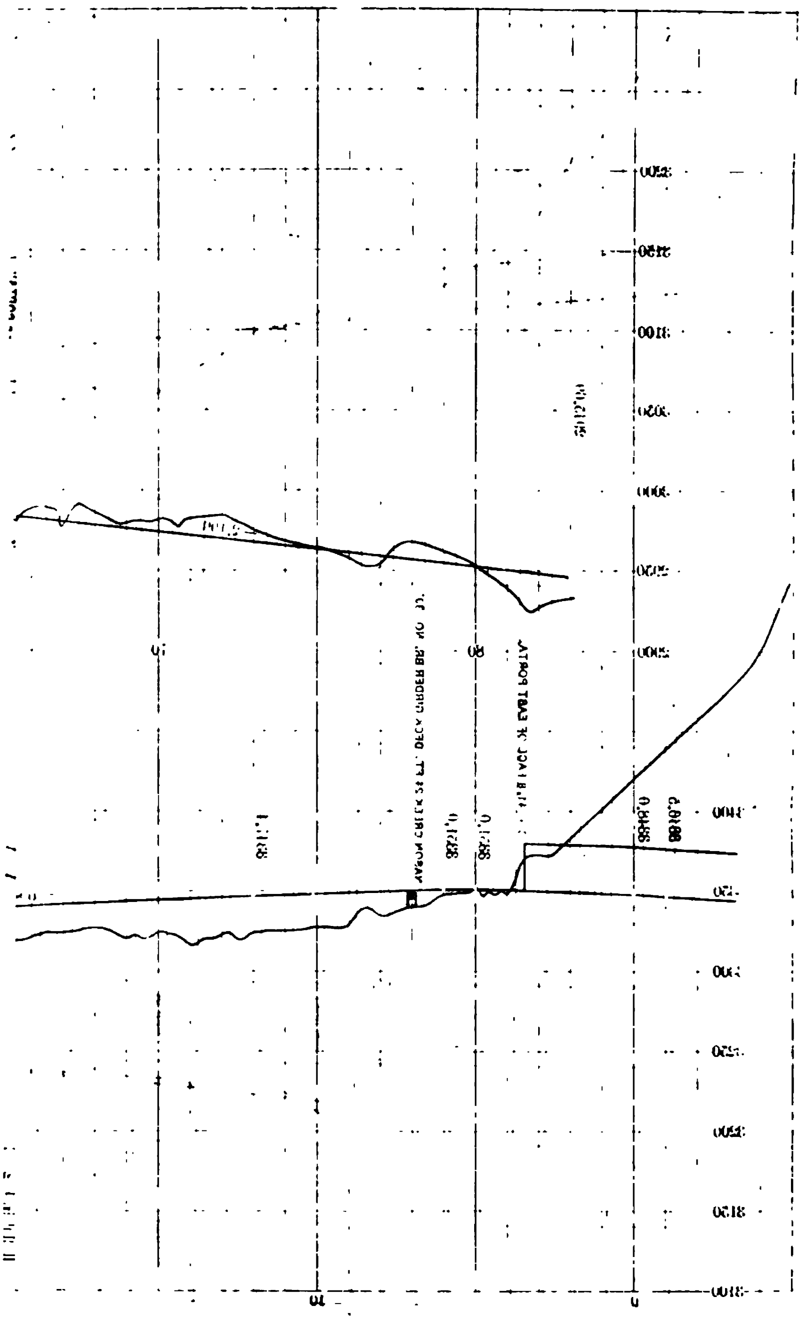


FIG. 11. Profile of Wellington



are unusually sturdy, and it was owing to the fact that timber of this kind could be obtained cheaply in the West that this type of construction was adopted. The line is divided into three sections by two out-of-door switches operated by means of a pole deposited with a station agent; each switch is near a station.

In the design of the line, as in all other features of the work, the aim was to secure apparatus and types of construction giving promise of the greatest reliability, in order that there should be as few links as possible in the chain from the power house to the locomotive that would be liable to derangement; for this reason a comparatively low line pressure is used.

The telephone line is carried on the same poles; the transmission line is not transposed, but the telephone line is transposed at every fifth pole.

The construction of this line was completed a year ago, and it has stood through one winter, during which there were more than thirty snow and rock slides; only one of these slides caused damage to the line, and in this case only one of the two circuits was interrupted; it could have been repaired within an hour. The same slide interrupted the operation of the railroad for eight to ten hours.

Substation. The substation is at Cascade, practically at the east portal of the tunnel. Three single-phase transformers are in service and a fourth in reserve; these transformers are duplicates of those in the power house. The equipment of the substation is along the usual lines and calls for no special comment. The low-pressure bus-bars at the substation are connected to the overhead wires in the Cascade yard and also to the Wellington feeder, which runs through the tunnel to the extreme end of the Wellington yard.

Tracks electrified. Fig. 9 and 10 show plans of the two yards. In both yards the main track and two side tracks are electrified, together with the necessary crossovers, etc. The total length of the track equipped, including the tunnel, is about six miles. Fig. 11 shows profile of the yards; the tunnel grade is 1.7 per cent.

The length of the several parts of the overhead structure is as follows:

Substation to east portal of tunnel	200	ft.
East portal to west portal	13,900	"
West portal to end of electrified track	6,960	"
Total, substation to rear electric locomotive	21,060	"
or, practically 4 miles.		

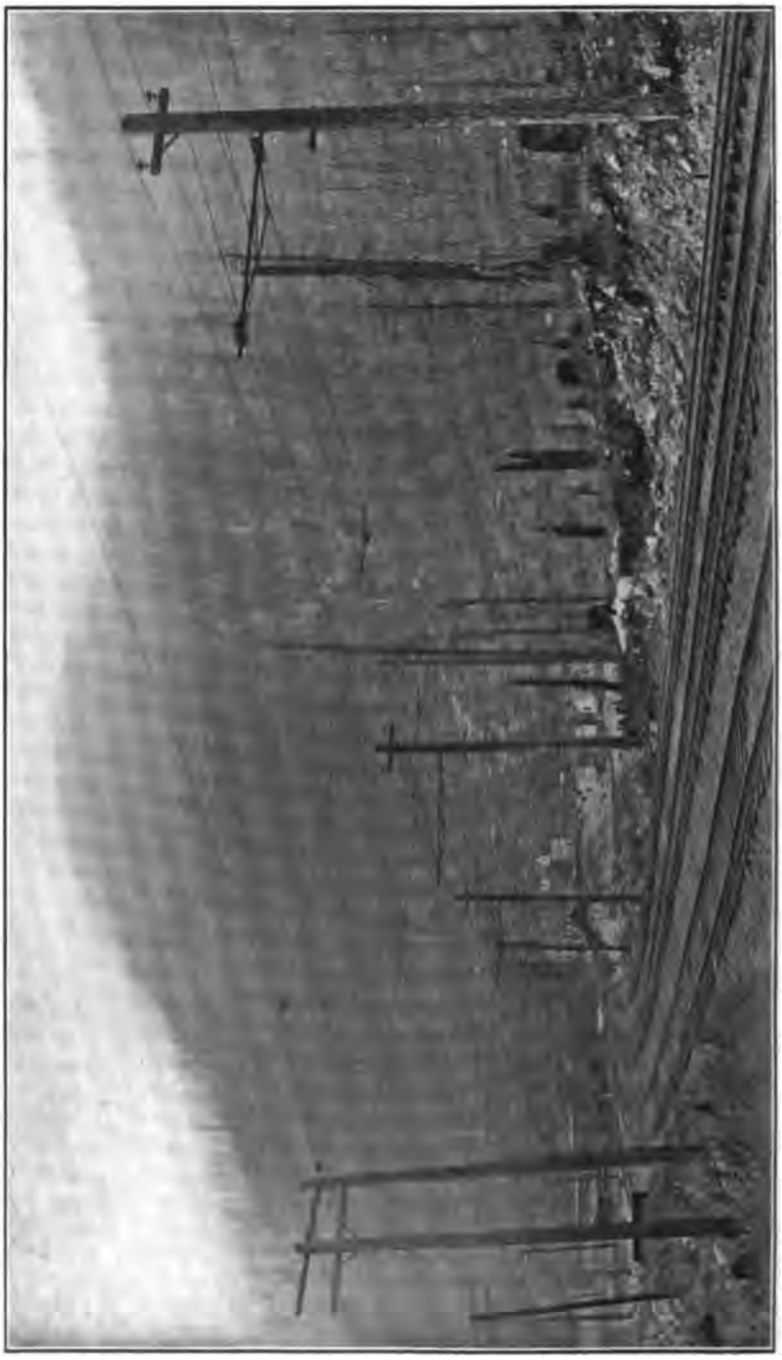


FIG. 12.—Overhead construction in Cascade yard, showing bracket construction at curve

Overhead Construction in Yards

Figs. 12, 13, 14, 15 and 16 show the general type of bracket and cross-catenary construction used in the yards. Figs. 17, 18 and 19 show details of the cross-catenary suspension. Fig. 20 shows details of the bracket construction. The wires are 24 ft. above top of rail and 5 ft. apart; for single tracks a bracket type of construction is used, and for multiple tracks a cross-catenary type, supported by very heavy wooden poles located about 8 ft. from center-line of outer tracks, thus leaving unobstructed the space between adjacent tracks. The wires are supported at intervals of 100 ft.

Multiple track supports consist, for each phase, of a steady span supported by and insulated from a cross-catenary span, both spans being secured to cross-arms on the poles by means of porcelain petticoat strain insulators; the spans for the two respective phases are three feet apart. The wires of the same phase, for the different tracks, are insulated from each other by means of wood breaks and porcelain link insulators, in series.

In the case of brackets, each phase is insulated from ground by means of a wood break in series with a porcelain petticoat strain insulator.

Where wires of opposite phases cross at turn-outs, they are insulated from each other by section insulators made of wood and about five feet in length; four insulators are used, each connected at one end to a special 8-deg. crossing pan and at the other end to one of the four wires converging toward the crossing. Except for one track whose wires are cut straight through the crossing pans without section insulators, it is necessary to switch the controller to the off position when the trolley wheel passes under the insulators; methods of avoiding this have been considered and are being tried out.

Heavy steel bridges, Fig. 14, forming anchorages for the trolley wires are located in both yards at intervals of 1000 ft. Lightning protection, though thunder storms are rare, is afforded by arresters connected to the wires at the ends of the tunnel and yards.

Both rails in the tunnel and one rail in the yards are bonded, with cross-bonding at frequent intervals. A single 4/0 exposed bond is used at each joint, having a length of 36 in. in the tunnel, and 36 and 50 in. in the yards.

In my opinion the use of double insulation everywhere is the reason for the almost total freedom from troubles of any

FIG. 13.—Cross-catenary construction in Wellington yard at switch point

kind originating on the overhead structures; two separate pieces of insulation of any given strength are much better than one piece of four times that strength. The only troubles experienced up to the present have been at the section breaks and turn-outs, and have been caused by the trolley wheel leaving the wire. There has been no failure of the wires at any point of the overhead structure nor any breakdown of insulation.

OVERHEAD CONSTRUCTION IN TUNNEL

This construction is shown in Fig. 21, 22 and 23. Fig. 21 gives a cross-section of the tunnel and shows the location of the trolley wires, trolley feeder, the wires for the lighting circuits, and the telegraph and telephone cable. Fig. 22 shows a cross-section of the method of supporting the trolley wires, and Fig. 23 shows a longitudinal view of the trolley suspension scheme; this, however, does not show the swiveled connection of the stud to the clamp holding the trolley wire at the lower end. The necessity for adding this swivel connection was shown by the breakage of several studs.

In the tunnel the wires are 17 ft. 4 in., above the top of the rail and 8 ft. apart; the latter spacing enables train-men to operate the hand-brakes, or walk on the tops of freight cars, the construction being such that head-room in not interfered with. Each wire is supported every 50 ft. by means of a 14-in. Detroit clamp attached by swiveled connection to a stud which is in turn swiveled to the middle point of a turnbuckle. The two eyes of the latter, by means of strand wire, connect each to a link and petticoat strain insulator arranged in series, the two petticoat insulators being secured to the roof of the tunnel by means of two expansion bolts, about 5 ft. 6 in. apart. Anchors and side-braces for the wires in the tunnel are located at intervals of 3000 ft.

Practically all metal work in the tunnel supports is copper or bronze, but experience has shown that galvanized iron, soon becoming protected by a slight coating of soot, would have been satisfactory. The insulators, when first put in service, were covered by a very thick coating of wet soot, but, even under these conditions, it was found possible gradually to bring the voltage up to normal without breakdown. Volumes of smoke and steam issuing from steam locomotives caused only a slight surface leakage, and one rough cleaning sufficed to put the insulators in reliable working condition.

FIG. 14.—Anchor bridge in Wellington yard, showing three tracks electrified.

Spacing the wires 8 ft. in the tunnel was necessitated by the requirement of the railroad company that there should be no construction in the roof of the tunnel which could possibly interfere with a brakeman's walking on the top of a freight car. This change in the location of the wires complicated the construction somewhat and was one of the principal reasons leading to the use of a trolley wheel in place of a bow collector. It has, however, caused no material inconvenience and is satisfactory as long as the trolley wheels are in use, but if a change is made to a bow collector, which is not impossible, there may be difficulty in adapting the bow to this location of the wires.

FIG. 15.—Construction at switch point, Wellington yard

Electric lighting. It is intended ultimately to clean and whitewash the tunnel and light it electrically, and for this purpose a lighting system has been installed. Five transformers of 4 kw. capacity each are placed in refuge chambers; incandescent lights are spaced 50 ft. apart and are connected four in series of a 500-volt system. Several plans were worked out for this lighting system, but taking into account maintenance costs, it seemed best to use a standard 110-volt carbon filament lamp.

Telegraph lines. The telegraph wires, ten in number, as shown in Fig. 21 run through the tunnel in a cable; this service was thrown entirely out of commission when the electric locomotives began running. There is no interference with the telegraph wires due to the transmission lines paralleling them for thirty miles; the entire interference seems to originate in the tunnel. In order to eliminate this interference, a neutralizing transformer has been installed and adjustments are now in progress. There has been little difficulty in making the ordinary single-wire telegraph service satisfactory, but considerable difficulty has been experienced in

FIG. 16.—Bracket construction at curve Wellington yard

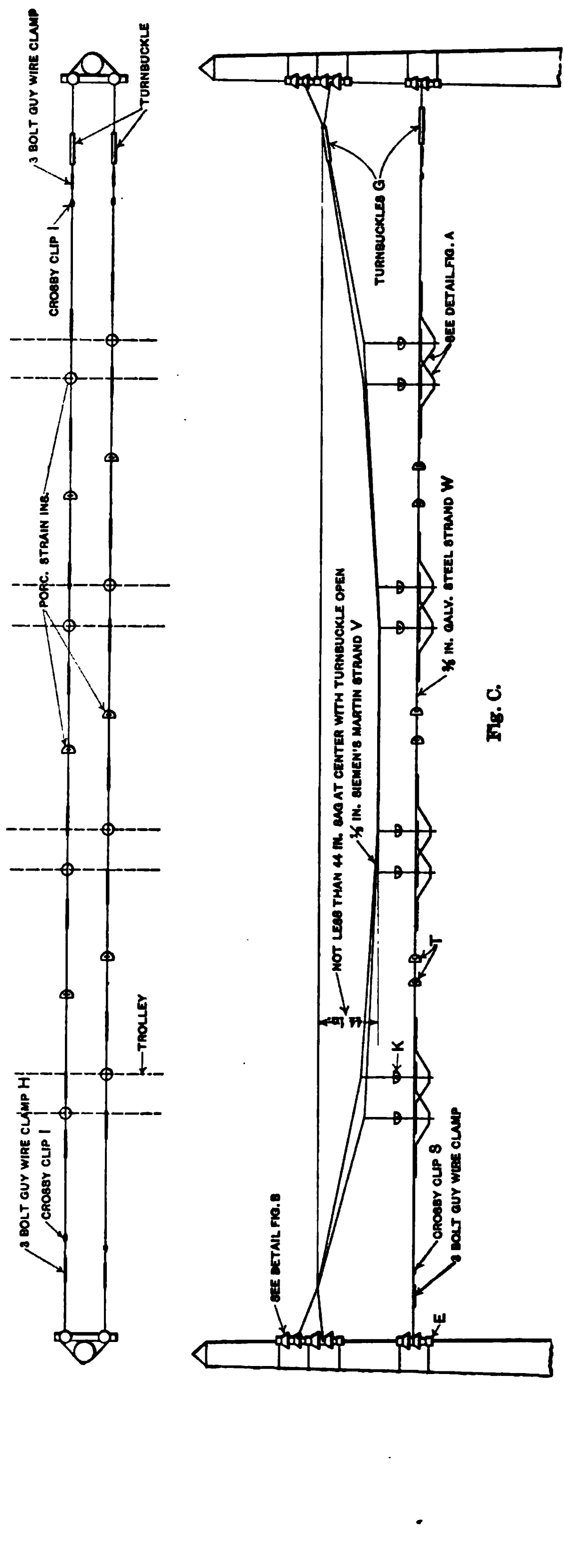


Fig. C.

FIG. 17.—Cross-catenary suspension, general scheme]

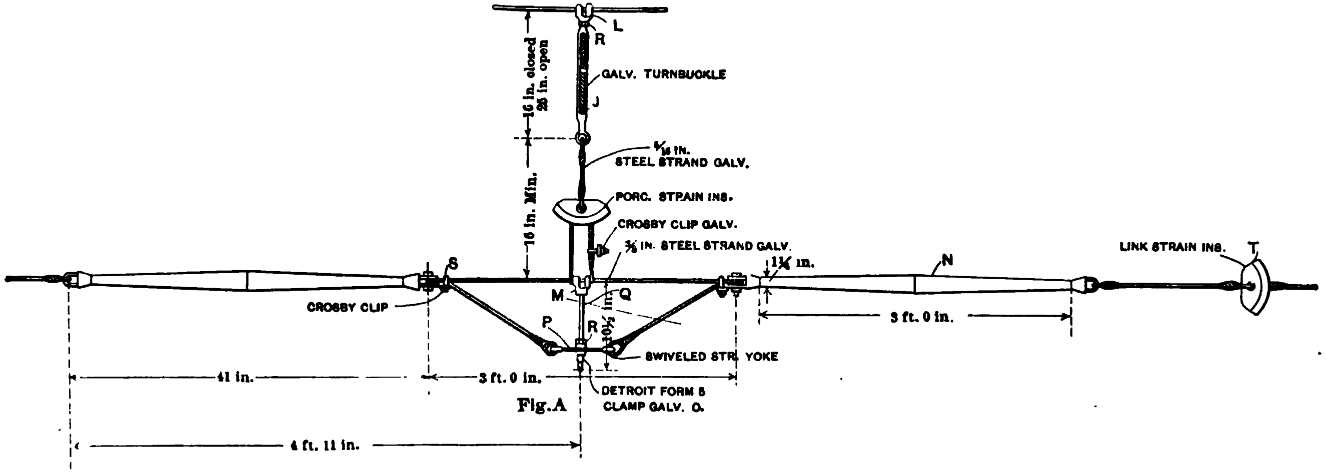


FIG. 18.—Detail *A* of Fig. 17 showing method of holding trolley wire.

getting the quadruplex to work satisfactorily; this matter is still unfinished.

OPERATION OF THE SYSTEM

The electric service was started on July 10, although one or two trains had been handled previously. From that time to August 11, practically the entire eastbound service of the company has been handled by electric locomotives.

During this period of 33 days there have been 212 train movements of which 82 were freight, 98 passenger, and 32 special. In each case the steam locomotive was hauled through with the train. The tonnage handled was as follows:

Freight tonnage	171,000 tons
Passenger "	88,500 "
Special "	15,500 "
Total	275,000 tons

This is an average of 8350 tons per day, all eastbound.

The average freight train weight has been as follows:

Cars	1480 tons
One Mallet locomotive	250 "
Three electric locomotives	345 "
Total train weight	2075 "

The maximum weight of cars was 1600 tons; the minimum 1200 tons.

The representative passenger train handled is made up as follows:

Coaches	426 tons
Two steam locomotives	347 "
Two electric locomotives	230 "
Total train weight	1,003 tons

The maximum was about 125 tons greater.

Frictional resistance of steam locomotives. The power required to haul these trains seemed greater than it should be; investigation showed that the difference was accounted for by the unexpectedly high frictional resistance of the steam locomotves, as a trailing load; tests were made on several engines with the following results:

TABLE III

1 Test No.	2 Engine classification	3 Total weight with tender Tons	4 Weight on drivers Tons	5 Total resistance on 1.7 per cent grade lb.	6 Equivalent weight of freight cars Tons
1	Mallet No. 1904.2-6-6-2	250	158	19,340	482
2	" No. 1911.2-6-6-2	250	158	17,500	432
3	" No. 1905.2-6-6-2	250	158	24,200	602
4	Consolidation....2-8-0	159	90	10,080	255
5	Pacific..........4-6-0	188	70	10,270	257

The tests were made by towing an engine through the tunnel behind an electric; the electric was fitted up with test instruments and the total tractive effort was thereby obtained. An allowance of 6 lb. per ton was made for the resistance of the electric and the difference is the draw-bar pull in column 5. Column 6 is the equivalent load in cars, taking car resistance as 6 lb. per ton. Each test given is the average from six to twelve separate readings. The average for the three Mallets is more than 20,000 lb.

If the grade resistance be deducted from the total pull, and the difference lumped as "lb. per ton" for the locomotive and tender, there results:

TABLE IV

1 Engine classification	2 Frictional resistance of locomotive	3 lb. per ton
Mallet No. 1904.......	10,840 lb.	43.0
Mallet No. 1911.......	9,000 "	36.0
Mallet No. 1905.......	15,700 "	63.0
Consolidation..........	5,480 "	34.5
Pacific................	3,870 "	20.7
Electric...............	1,500 "	13.0

The average for the three Mallets is 47.0 lb. per ton for the frictional resistance on a straight level track.

The figure for the electric was obtained from tests made by

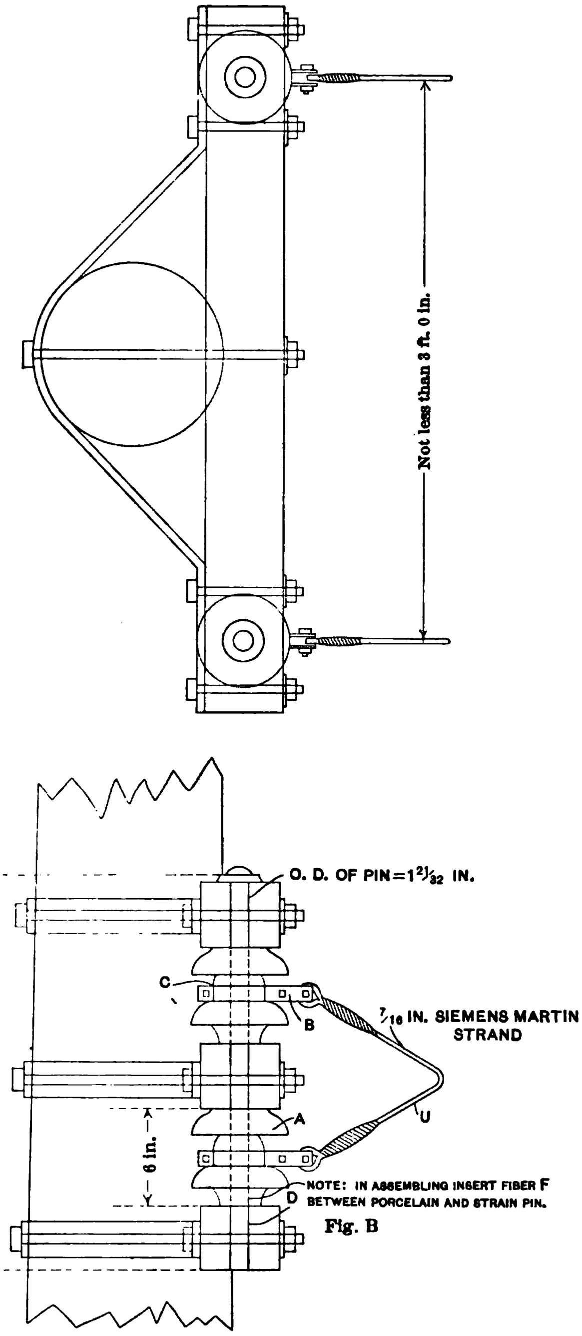


FIG. 19.—Detail *B* of Fig. 17 showing method of attachment of cross-catenary to pole

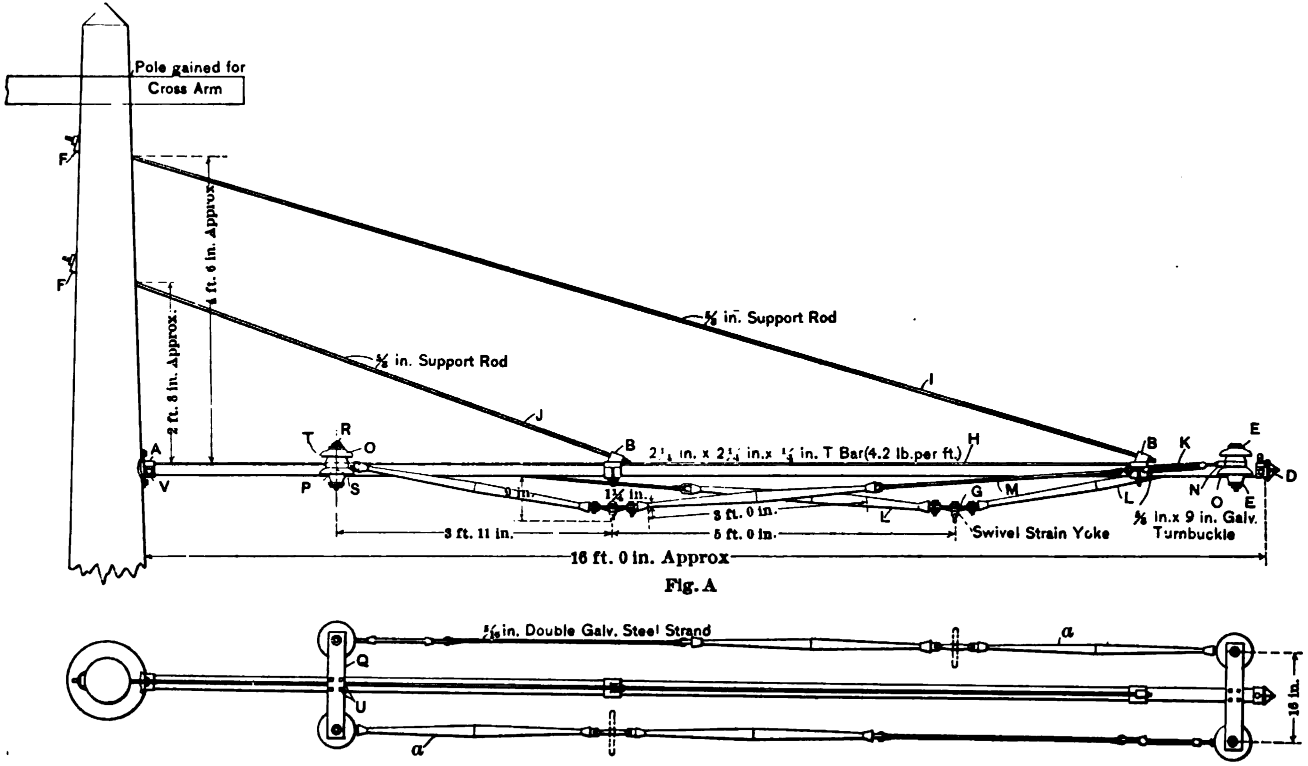


Fig. 20.—Bracket construction in yards

towing it by a motor car on straight level track; this test was made at Schenectady. Included in it is the resistance of gears and bearings of motors.

Using 20,000 lb. as the pull required for a Mallet on the 1.7 per cent grade, the approximate average from Table III, the total tractive effort for the average freight train, is:

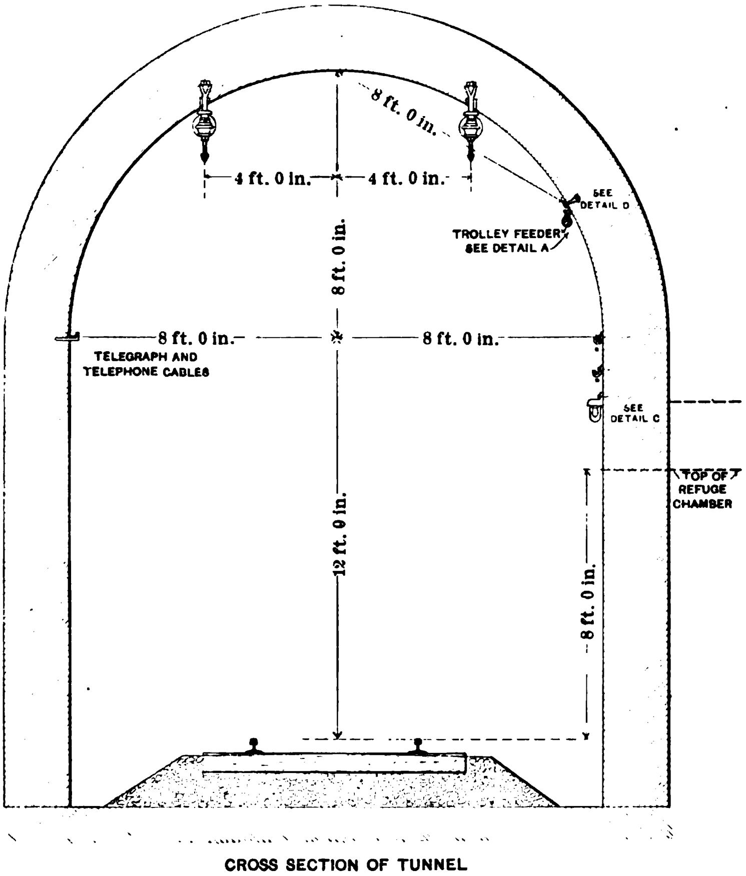


FIG. 21.—Cross-section of Cascade tunnel, showing location of trolley wires, trolley feeder, lighting and telegraph cable

Cars	1480 tons × 40 =	59,200 lb.
One Mallet	250 tons × 80 =	20,000 lb.
Three Electrics	345 tons × 40 =	13,800 lb.
Total tractive effort		93,000 lb.

This is equal to 31,000 lb. for each electric locomotive.

On account of the very high frictional resistance of the Mallet engine as a towing load, this representative train is equivalent to 1980 tons, excluding the three electric locomotives, or a total of 2325 tons, on the 1.7 per cent grade. This is on the assumption that the draw-bar pull required for the Mallet is replaced by freight cars at 6 lb. to the ton; this represents the average freight train handled.

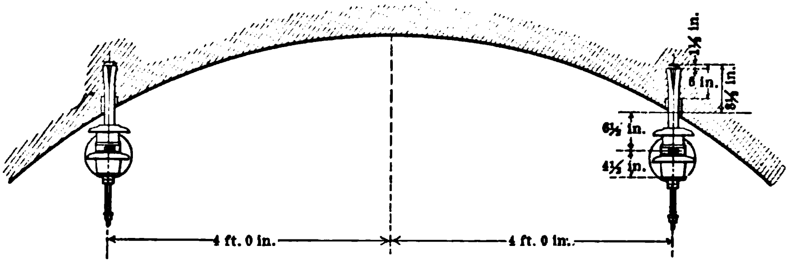


FIG. 22.—Cross-section showing trolley wires in tunnel

The tractive effort for the passenger trains varies from 40,000 to 50,000 lb., depending on the number of steam locomotives taken through; two electrics are ordinarily used, although one would answer in nearly all cases.

During this period there have been no delays due to failure of the electric locomotives, and but two trifling delays due to failures of the electric plant, both chargeable to the transmission line and both caused by accidents beyond the control of the operating force.

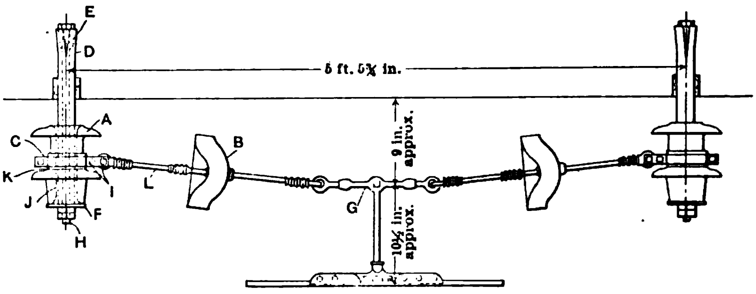


FIG. 23.—Longitudinal view of the tunnel suspension scheme—these supports are spaced 50 ft.

On August 11 the electric service was discontinued, owing to failure of both water wheels. Service was resumed on Sept. 9 and has been continued regularly since. The plant was taken over by the operating department of the railroad late in September.

The westbound service was not at first handled by the electrics regularly, as there is nothing in particular gained by braking the trains electrically on this short stretch, but now westbound passenger trains are so handled, for the benefit of the passengers.

Regenerating. A number of tests have been made to determine the power returned when regenerating; the following is typical:

TABLE V
TRAIN: MALLET ENGINE, 1550 TONS CAR WEIGHT, TWO ELECTRICS ON 1.7 PER CENT GRADE

	Force due to grade	Frictional Resistance	Remainder for acceleration
Mallet	8,500 lb.	11,500 lb.	- 3,000 lb.
1550 tons in cars	52,500 "	9,300 "	+43,200 "
Three electrics	11,700 "	2,070 "	9,630 "
Total for acceleration			49,830 "

This is equivalent to 1495 kw. delivered to the gears of the motors at 15 miles per hour.

The efficiency of the locomotive is approximately 80 per cent—hence the power returned to the line, should be 1200 kw. The test of this train gave 950 kw.; this difference is due to the standard practice, not yet abandoned, of keeping a certain number of car pressure retainers set on down grade.

The Mallet, instead of adding to the delivered power is an additional load that has to be carried by the train.

A similar test on a ten-car passenger train weighing 950 tons gave

Delivered power, calculated	590 kw.
" " measured	597 "

In this case there was no added resistance of pressure retainers.

These tests merely confirm the calculations, as they should. On a 1.7 per cent grade, then, one ton, descending at 15 miles per hr., will deliver 0.67 kw. to the system; on a 2.2 per cent grade it will deliver 0.91 kw.

Efficiency. The losses in the system when delivering 4000 kw. to the locomotive, at the west end of the Wellington yard are:

Place	Power Kilowatts	Per cent.
Power house low-tension bus-bars	4740	100
Substation " " "	4250	89.8
Trolley wheel of the locomotive	4000	84.5
Driving axles " " "	3320	70.

The average efficiency is somewhat higher than 70 per cent.

HANDLING OF TRAINS

The maximum duty was imposed upon this equipment from the outset. On account of very poor regulation of water wheels, steam has been used in one of the Mallet engines in starting the freight trains in the Wellington yard; an attempt has been made to use just sufficient steam to enable the Mallet engine to turn itself over. Steam is shut off at the portal of the tunnel; in addition to this, in order to provide smoother starting, a slight air pressure has been maintained on the locomotive at starting, which is gradually reduced.

On several occasions trains have broken in two, due to the trolley wheel on the rear locomotive leaving the wire and thus cutting off part or all of the power supply to the rear locomotives. This throws a greatly increased draw-bar pull on the front locomotive, and the consequence is that the train is jerked apart. This happened in the early stages of the work, and was due to the fact that the turn-outs were not in the best order, and also that the engineers had not sufficient experience in handling trains. Another means taken to avoid the broken draw-bars was to use the rear Mallet engine to assist the train over the trolley crossings in the Wellington yard; this was a temporary measure and has been discontinued.

Economy of Mallets. It is interesting to compare the performance of a Mallet compound locomotive under the same operating conditions as this system. The data for this are given by Mr. Emerson, superintendent of locomotive power of the Great Northern Railway Company, in a discussion before the American Society of Mechanical Engineers on locomotives of this type;* as an excellent performance he gives these data:

> Recent performance shows that on a round trip over this division the L-1 engines handled 1600 tons with a total of 43$\frac{5}{8}$ tons of coal, or equivalent to 25.13 lb. of coal per 100 ton-mile.

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* Transactions of the American Society of Mechanical Engineers Vol. 30, page 1031.

The division referred to is from Leavenworth to Everett, 108.7 miles. The work done per ton for a round trip over this run is readily calculated; from the profile I find,

Total rise, westbound	2212 ft.
" " eastbound	3440 "
	5652 ft.

and $5652 \times 2000/2.65 \times 10^6 = 4.26$ kw-hr., at the rail; this is the work done per ton in lifting the train; the work done against train resistance, assuming resistance to be 6 lb. to the ton, for 108.7 miles, is 1.3 kw-hr; the total work done in round trip per ton 5.56 kw-hr. There should be a negligible addition to this for starting the train.

The average train weight is:

Cars	1600 tons
One engine, 109 miles Second " 58 " Equivalent engine weight	380 "
Total	1980 tons

The coal used was $43\frac{5}{6}$ tons, equal to 87,660 lb.

Coal per ton	44.3 lb.
Coal per killowatt-hour	8.0 lb.

A modern steam station can deliver one kilowatt-hour for 3 lb. of coal, at the bus-bar, which, with an efficiency of 70 per cent to the rail, gives a consumption of 4.28 lb. per kilowatt-hour at the rail; in other words, the Mallet compound requires nearly twice as much coal per kilowatt-hour at the rail as would be used in a modern steam station in the place of the hydroelectric station at Leavenworth.

ADVANTAGES OF THREE-PHASE SYSTEM

This plant has demonstrated, in my opinion, that the three-phase induction motor has certain very marked advantages over any other form of motor for heavy traction on mountain grades; these advantages may be stated somewhat approximately.

1. *Maximum electrical and mechanical simplicity.* This point is of great importance and was one of the principal reasons for using three-phase system; the motors will stand any amount of abuse and rough use.

2. *Greater continuous output within a given space than can be obtained from any other form of motor.* This, I believe, is

shown by comparison with other electric locomotives; it is due to the fact that the losses can be kept lower in a three-phase motor than in any other type. As Fig. 3 shows, the electrical efficiency of the motor is high for a wide range of load.

3. *Uniform torque.* This is important, particularly at starting. I believe that a three-phase motor will work to a three or four per cent greater coefficient of adhesion than a single-phase motor at 15 cycles.

4. *The possibility of using* 25 *cycles.* This is important, as it leads to a less cost and a better performance of power station apparatus; moreover, it is standard and the power supply can readily be used for other purposes, as well as for traction; a commercial supply can be provided.

5. *Constant speed.* This is ordinarily stated as a disadvantage of the three-phase motor; but in my opinion it is a distinct advantage in mountain service, particularly the limitation of the speed on down grades. It has also the advantage on up grades that meeting points can be arranged with greater definiteness. There is a general notion that the impossibility of making up lost time with the three-phase motor will be a decided drawback to its use. This would be true if there were the same liability to lose time with three-phase motors; but when a train can be counted on to make a definite speed, without regard to conditions of tracks or of its load, there is less liability to lose time. Although I am not prepared to state that a three-phase motor is suitable for cases where the profile is very variable, yet it is by no means certain that it would not work out well; the question is merely one of making a given schedule between two points with greatest regularity.

6. *Regeneration on down grades.* This matter has been discussed since the earliest days of electric traction, but, as far as I know, has not been, up to the present, put into practice. Although this result can be attained with other forms of motors, yet it is most perfectly attained by three-phase motors, there being no complications involved. This is of importance in reducing the power-house capacity required for a given service; although, no doubt, the saving in power-house capacity will not be as great as indicated by theory, owing to the various emergencies that must be provided for, nevertheless there will be a material saving. A 2500-ton train on the average down grade of 1.5 per cent will deliver about 1400 kw. to the system. The equivalent power house capacity would cost at least

$200,000; hence if only 20 per cent of this can be utilized the saving will equal the cost of one locomotive.

7. *Excessive short-circuit current is impossible* and consequently destructive torque on the gears and driving rigging is eliminated. There will be no necessity for the complication of a friction connection between the armature and driving wheels, as in the design of recent large direct-current electric locomotives.

8. *Impossibility of excessive speeds.* Even when the wheel slips the speed remains constant. Therefore, the maximum stresses put on the motor are less and are more accurately known than with any other form of motor.

DISADVANTAGES OF THREE-PHASE

On the other hand, the principal disadvantages of three-phase motor, for traction use, are commonly stated to be:

1. *The constant speed.* This is rather an advantage for this class of service.

2. *Constant power.* The fact that the motor is a constant-power motor and therefore requires the same power at starting and while accelerating as at full speed. While this is true, it is not a matter of any particular consequence in a service where the stops are very few, and consequently the proportion of total time spent in acceleration is small, and where the additional power required to accelerate the train is a small percentage of the power used by the train at full speed. In this particular case on the 2.2 per cent grade, when accelerating at the rate of 10 lb. to the ton, the power required during acceleration is only 20 per cent greater than that required at full speed; this is not a serious matter.

3. *Small mechanical clearance.* In this particular motor the clearance is ⅛ in., which is ample for all practical purposes.

4. *Inequality of load on several motors of a locomotive due to differences in diameter of driving wheels.* To meet this an adjustable resistance is included in the rotor of each motor, the motors are then balanced up and no further attention is required as long as the wear on the driving wheels is approximately the same. If, at any time, the load becomes badly unbalanced it is a simple matter to readjust the resistances.

5. *Low power-factor of the system.* This does not seem to be borne out by practice. The power-factor, as shown by the switchboard instruments in the power house, is 85 per cent. This is a good result and is much higher than the power-factor

of a well-known single-phase system that I recently had occasion to visit.

6. *Two overhead wires.* There is no doubt that two wires will cause more trouble than one, and in case of complicated yard structure it might not be practicable to use two overhead wires; but where the problem is that of a single track with an occasional turn-out or crossing there is, practically speaking, no more difficulty in maintaining two wires than one.

In brief, in service, of this character the three-phase motor has marked advantages in capacity, reliability, simplicity, and general trustworthiness, when compared with any other motor.

Some Minor Advantages of Electric Traction

In the many discussions of electric traction which have recently taken place, I do not find several minor advantages sufficiently emphasized. One of these advantages lies in the fact that with electric traction the exact performance and condition of the locomotives and of all elements of the system is accurately known at each moment; on the other hand, with steam locomotives neither the engineer nor the motive power man can have any clear knowledge of the conditions of operation at the moment; he can only ascertain the performance of the locomotive by elaborate tests, which, as a matter of fact, are seldom made. The ratings and performance of steam locomotives are made up largely by " authority " based on a few tests from time to time, and take no cognizance of the actual condition of the locomotives. The importance of this, I think, is clearly brought out by the tests of the steam locomotive cited herein.

With electric locomotives the operation on a heavy grade becomes as simple as on the level; the engineers and train men feel much greater confidence in the electric locomotives and consequently the mountain division ceases to be a terror to them.

Electric traction will permit the use of very long tunnels, which are not now possible on account of difficulty of ventilation. There is no particular reasons why tunnels of ten or twelve miles should not be operated as easily as those of one mile.

The great increase possible in the speed of trains with electric traction and the consequent increase in the capacity of a single track will operate to postpone for a long time the necessity for double tracking. This double tracking on a mountain is a very expensive piece of business and this saving alone will, in some cases, more than offset the cost of electrical equipment.

A word in closing: the construction work in the tunnel and yards was carried out under great difficulties, owing to the necessity of not interfering with the regular service of the road. At times it was not possible to work in the tunnel for more than one hour a day, and for days at a time two or three hours was all that could be allowed, but in spite of this the work was carried out with very satisfactory speed, due particularly to the skill and ability of my assistants, R. Beeuwkes and W. S. Skinner, and the unstinted assistance of the engineering department of the road.

DISCUSSION ON "THE ELECTRIC SYSTEM OF THE GREAT NORTHERN RAILWAY COMPANY AT CASCADE TUNNEL."

NEW YORK, NOVEMBER 12, 1909

President Stillwell: We are to have the pleasure this evening of listening to the presentation of a paper by Cary T. Hutchinson on "The Electric System of the Great Northern Railway Company at Cascade Tunnel." It is certainly a fact of great interest that in this year, 1909, a three-phase railway installation of magnitude has been completed and put in commercial operation in the United States. Polyphase motors were brought to this country in 1888. Those which arrived in that year were rated about one-quarter horse power, but none of them, I think, ever succeeded in developing that output. At that time serious efforts were made by American engineers associated with one of our manufacturing companies to adapt this type of motor to railway purposes, but they reached the conclusion that the constant-speed characteristic of the motor rendered it unsuitable for such service. A number of years later DeKando, in Europe, undertook to adapt polyphase motors to traction purposes, and it is a pleasure to have an opportunity to record the admiration that I feel, that I think all American engineers feel, for DeKando's exceptionally able and original work in that development.

The three-phase system has been in use in Italy, and in Switzerland, for a number of years, and, since 1904, on what may be called a large scale on the Valtellina line. From 1890 until recently but little attention was paid in the United States to the practical application of the polyphase motor to railway purposes. It received during that period, it is true, careful study; but the conclusions reached were negative, so it was not introduced in commercial service in this country.

In the United States there are to-day three different systems operating electric traction of the heaviest kind; namely, the direct-current system, the single-phase alternating-, and the three-phase alternating-current systems. All of these systems, I think it may fairly be said, are doing their work not only successfully, but in a manner that shows a marked improvement over the steam locomotive operation that they have superseded.

The steam railroad managements of the country are beginning to awaken. They are asking which is the best system for general railway work, and that question must be answered by the electrical engineer. A member of the committee of the American Railway Association said to me this morning that he felt the art was not sufficiently advanced to justify his railroad in considering seriously the application of electric motors. Now, the fact is that we have a variety of methods, and it is important to accelerate the process that ultimately is to result in the survival of the fittest.

It is here, I think, that one of the functions of this

Institute comes in. In this country there is no government commission to decide general standard specifications and to pass on the claims of various systems before adoption, as is done, for example, in Germany. With us, the evolution of a system is not directed, except so far as commercial interests may influence it, or the consensus of opinion of the members of this Institute affects it. I am always glad, therefore, to have this subject presented, because there is nothing within the scope of the American Institute of Electrical Engineers that is of greater technical interest, or that compares with it in commercial importance.

Cary T. Hutchinson: I shall not attempt to cover the entire scope of the paper, but shall merely emphasize a few of the features of the work. The first is that this system was installed with the expectation that it will form part of a larger system, having a length of from 60 to 100 miles. At present it is merely a shuttle service through a tunnel from a yard on one side to a yard on the other, the distance being about 4.5 miles.

If nothing further than this were contemplated, it would seem that such electrification would constitute a very serious additional expense, and this doubtless would be true, although owing to the peculiar conditions under which the steam service has been handled there is an actual saving in operating expenses over this stretch of about $100 a day. The fundamental reason, however, was increase in capacity. This tunnel formed the congested point of the railroad system; under some conditions it was almost impossible to get the tonnage through the tunnel.

A short description of the method of handling the traffic under steam will indicate the difficulties that were encountered. Trains east-bound from the Pacific coast were from 1400 to 1500 tons trailing load with two Mallet compound engines. At the west end of the tunnel, at the foot of the grade, all trains were stopped, fires were hauled and cleaned, the engines took on a special high-grade coal, new fires were built and the engines remained in the yard for an hour or more, coking these fires in order to get rid of superfluous gas. In addition, a helper engine was kept in the yard, which used the same grade of coal and with the same precautions. The train was divided into two parts, the helper engine taking about 400 tons through and the two Mallet engines afterwards taking the remainder of the train, say 1000 tons.

When weather conditions were bad it was almost impossible to get trains through the tunnel; sometimes it was necessary to wait two or three hours after the passage of one train before it was safe to send a second train through. Frequently the steam pressure in the rear Mallet engine would fall from 200 lb. to 70 lb. or less, owing to the impossibility of maintaining fires on account of the exhausted condition of the air in the tunnel. The train would then have to stop and be split into two sections, and it would be necessary to back the rear engine out with part of the train.

These conditions also had a very bad effect on the train crews. Good engineers would not stay on the division; it was considered dangerous service.

Under these conditions Mr. James J. Hill, finally determined, after several years' consideration, to try out an equipment at the tunnel with the express intention of using it on the entire mountain division, if it proved to be satisfactory. These were the conditions that led to the adoption of this particular system.

W. S. Murray: As a single-phase man in other fields I wish to say that as far as the Cascade Tunnel *per se* is concerned, I am heartily in agreement with Dr. Hutchinson's chosen method of electrification. It is my belief that the physical conditions call for this method. Assume any piece of trackage, either one mile or 300 miles in length, at constant grade, whether zero or such a percentage that admits of adhesion of the locomotive driving wheels, and with no stops in the schedule (or if inclusive of stops then with exceedingly low train acceleration). Under these conditions, particularly where single track is involved, thus eliminating any complication of overhead construction, it is my belief that the three-phase system would be correctly applied.

Dr. Hutchinson says that traction developed by motors of the three-phase type admits of 3 per cent or 4 per cent greater adhesion than in the case where single-phase motors are used. Now, the single-phase motor is admittedly heavier than the three-phase motor of the same capacity, and, therefore, if it lack adhesion in its torque developing characteristic—which statement is by no means accepted by all—the deficiency is taken care of by its excess weight, thus illustrating the old adage, " It is an ill wind that bloweth no man good."

Though the subject treats of a three-phase installation, I am sure that Dr. Hutchinson will not object to an effort at drawing the line between the application of three-phase and single-phase apparatus. Dr. Hutchinson speaks of the advantage of a frequency of 25-cycles. This frequency is also applicable to single-phase installations, but it is true that the use of three-phase apparatus assures less costly generators. This saving, however, is offset in the case of single-phase installations by less costly switchboards. It is interesting to note that it is not much more expensive to use three-phase generators for single-phase distribution, as the new type of dampened field cuts down the rising voltage on the idle phase, making it possible to develop and use three-phase current for commercial requirements.

Concerning the speed of trains propelled by three-phase or single-phase motors. Infrequently it is said that a train under three-phase propulsion is more certain of making its schedule, on account of its constant-speed characteristics. Now, there is no desire on the part of the single-phase motor not to go. If we should place impress 500 volts on the terminals of one of Dr. Hutchinson's three-phase motors, and on one of the New

Haven locomotive single-phase motors, subjecting neither to any load, the former, if a frequency of 25-cycles were used, would arrive at 300 revolutions and go no higher, while the single-phase motor would, in a very short interval of time, arrive at a speed far in excess of that of the three-phase motor. The speed of the single-phase motor depends simply on the balancing resistance of the train, at the voltage applied to the motor. If the required balancing speed is 60 miles an hour, there is a voltage that corresponds to this on the transformer; it is simply for the engineer to see that the controller is on the right notch to supply it. Speed is a direct function of voltage, and the single-phase motor receives its voltage without the interception of resistance. Resistance, both within and without the circuits of the motor, means loss. In the case of the three-phase motor, except cascade connection, resistance has to be inserted for all speeds below the normal slip-speed of the motor.

The true speed-torque traction curves for railway motors were given by the direct-current series motor long before the alternating-current motor, either of the induction or the single-phase type, put in an appearance. In general it may be said that this type of motor conserves the apparent necessity of a service having a motive power which, at high efficiency, will take care of variable-speed requirements made necessary by accelerations, slow-downs, and stops. Horse power is directly proportional to speed and torque. On a grade the series motor admits of a lower speed, which, taken with the increased torque requirements, tends to keep the horse power constant; in the case of the polyphase motor, the speed remaining constant with the increase of torque required, due to grade, the horse power rises. It is thus clear that the single-phase motor, with speed characteristics similar to those of the direct-current series motor, admits of maintaining nearly constant load upon it under varying conditions of grade: with the three-phase motor, the load, for the reasons stated, must vary over exceedingly wide limits. For example, Dr. Hutchinson's locomotive, when hauling a train up a 2.2 per cent grade, has to develop six or seven times as much power as when hauling the same train on a level. A constant load-factor cannot fail its appreciation, be it in a power house or an electric locomotive, and the illustration previously made is an attempt to bring out the just reason for Dr. Hutchinson's application of the three-phase motor to special conditions of constant grade, no stops or low acceleration, and that of the single-phase motor in the field which admits of great variation in grades and higher acceleration.

To exemplify more concretely the point made in the previous paragraph, Dr. Hutchinson says that the Cascade Tunnel electric locomotive requires only 20 per cent more power in accelerating a train in the tunnel grade than in running the same train on the same grade at full speed. This is interesting, and convincing as to the ability of an electric locomotive of this design to take care of the concrete conditions cited.

It is also interesting to analyze this conclusion. To accelerate a train on grade it is necessary to overcome three classes of resisting forces:

1. The inertia of mass.
2. The resistance of frictional parts.
3. The resistance of gravity.

At an acceleration at the rate of 0.1 of a mile per hour per second, the resisting force due to inertia of mass is 10 lb. per ton. The friction per ton in a freight train, inclusive of the locomotive, may be estimated at 8 lb. per ton, though this is high. The grade is stated to be 2.2 per cent. Gravity offers, therefore, at 20 lb. per ton, a total of 44 lb. Thus, the total resistance per ton to accelerating on the grade in question is 62 lb. After the train has been accelerated to speed, 10 lb. of this 62 lb. drops out, due to the disappearance of mass inertia. The ratio of 62 to 52 is practically 20 per cent, as Dr. Hutchinson points out. Under this analysis it is not difficult to see, however, why the ratio is so small. If we drop the acceleration to 0.05 of a mile per hour per second, then the difference would have been only 10 per cent. The two things that cause this ratio to be so small is the low acceleration and the high grade.

Exactly opposite conditions exist in high-speed suburban passenger service, where the acceleration is exceedingly high and grade is practically eliminated. As an example, under the conditions of no grade, a passenger train being accelerated at 0.7 of a mile per hour per second will require 70 lb. to the ton, and assuming the average friction per ton up to 60 miles an hour to be 10 lb., the total pounds per ton required is 80. After the train has arrived at the balancing speed of 60 miles per hour, mass inertia disappears; the remaining resistance, train friction, may be 15 lb. per ton. Now, it is seen that the ratio of the torque required to accelerate this train to the torque required to keep it at 60 miles an hour is 80 to 15, or the increase instead of being 20 per cent is 530 per cent. An acceleration of 0.7 mile per hour per second is not unduly high for a suburban service on trunk lines, and this analysis is an attempt to bring out the great difference between the case cited and the duty requirements of the Cascade Tunnel locomotives.

I agree with Dr. Hutchinson that in regard to mechanical clearance, ⅛ in. is ample for all practical purposes. The method suggested for dividing up the load uniformly on the motors by the insertion of resistance would seem to be practical. As these resistances must be continually in series it would be interesting to know what percentage of loss is incurred; doubtless it is low.

The single-phase system, such as, for example, that of the New York, New Haven & Hartford Railroad Company cannot claim any higher power-factor than that mentioned by Dr. Hutchinson in the case of the Cascade electrification. Power-factor in a system is an interesting detail. It is possible to be misleading. The New Haven road is a large user of single-phase power, and its power-factor seldom rises above 85 per cent. Indeed, it is more frequently below 80 per cent. It is well to know, however, exactly what power-factor stands for. A high-voltage system primarily stands for very low transmission losses. Let us assume, for example, that the actual transmission losses of the New Haven systems are between 5 and 10 per cent at unity power-factor. Even should the power-factor sink as low as 75 per cent, this would mean that the line loss, instead of being from 5 to 10 per cent, would be from 6.7 to 13.3 per cent. Remembering that many systems have a normal loss of 25 per cent, it would seem that the fluctuation of power-factor, even within wide limits, is not serious.

I am in agreement with Dr. Hutchinson that the yard proposition on two overhead wires is not practicable, and I also believe that this is true of main-line tracks where high speeds and many switches are involved. I wish to support Dr. Hutchinson's views in regard to simplicity, capacity, and reliability of the induction motor. I have always had the greatest respect for this kind of motor. It is my great regret that its electrical characteristics do not, in my belief, conform to those required by the general traction problem. It is to the alternating-current series motor what the direct-current shunt motor is to the direct-current series motor. The direct-current shunt motor has disappeared forever on all traction lines, and I do not believe that it can reappear under the cloak of alternating current.

E. B. Katte: Sometime ago I had the privilege of seeing one of the electric locomotives in the works of the manufacturing company and believe it will be hard to improve upon either the electrical or mechanical design for the speeds for which the engines are intended.

The reasons for adopting a three-phase system over the whole mountain division are quite obvious, but I am surprised to note that this same system would probably have been used if only a four-mile tunnel section was to have been considered. Without going into figures, it would seem that a direct-current system with storage batteries would have made unnecessary the use of steam locomotives in starting electric trains, and at the same time would have relieved the power station from the sudden inrush of current, thus securing better regulation at the water wheels. And further, by adopting multiple-unit control for the locomotives, two or more at the head end of a train could have been operated with one-half the number of men.

Dr. Hutchinson describes the ground-wire, provision for which has been made on the top of the transmission-line poles, but states that it has not yet been installed. I wish he would explain why the ground-wire was finally omitted. When the transmission line of the New York Central was designed, similar provision was made for a ground-wire, but after further consideration it was left out; for the reason that the poles were of steel and each carefully grounded to a large copper place set in permanently wet ground, and it was believed that each pole would act as a lightning rod and thus protect the line. However, on the Great Northern line the poles are wooden and the insulator pins do not seem to have been grounded, consequently if a ground-wire is ever necessary, these would appear to be conditions under which it would be most valuable.

The fact that wooden poles are used through forests leads me to ask if any special protection against destruction by fire was adopted. Last year when estimates were made for the information of the " up-state " Public Service Commission, covering the cost of electrifying railroads through the state forest lands, it was considered necessary to use steel poles because of the danger due to forest fires.

The experience with insulators covered with soot from steam locomotives is similar to that on the New York Central system. At first we were much perturbed because of the soot which was accumulated upon the 11,000-volt insulators in yards used by steam locomotives through which the transmission line passed, but after careful tests on several insulators which were well covered with soot it was found that the flashing-over point was several times the normal voltage even when the soot was well saturated with water.

Among the minor advantages to be derived from electric traction, brought out in this paper, is the possibility of knowing at any instant, by the direct reading of meters, the exact operating condition of any element of the system. I believe this to be more than a minor advantage and think it of very great importance and help to those charged with the safe and reliable operation of trains.

Bion J. Arnold. During the last summer I rode through the Cascade tunnel several times on the electric locomotives described by Dr. Hutchinson. I was interested in the operation of the system. It seemed to perform its work as satisfactorily as any direct-current or single-phase installation I have ever seen. It had the objectionable double overhead conductor, and the yard was necessarily somewhat complicated on that account. I agree with Mr. Murray that for a railroad with many yards—and many yards are the rule with steam railroads if an overhead conductor is to be used—the single-phase installation is preferable. That is one of the principal reasons why the single-phase system was used for the tunnel of the Grand Trunk Railway system between Detroit, Michigan, and Sarnia, Ontario—a tunnel installation similar to this, terminating at each end in a vast yard with a number of tracks, and located in a climate where snow and ice were likely to cover tracks—over which the train movements were infrequent. I concluded that under such conditions a third-rail might become iced or covered with snow, making it difficult at times to move trains. These and other conditions impelled me to adopt the single-phase system, and at a time when such a system had not been tried on heavy traction work. The Grand Trunk installation has been in successful operation for some years, and so far as I know there is no desire to adopt any other system.

We all know that both the direct-current system on the New York Central and the single-phase system on the New York, New Haven and Hartford are operating successfully. Mr. Sprague and others are advocating a high-potential, direct-current system, and I have no doubt that within moderate limits that system will be equally successful. All of this tends to show that while we may individually believe in some particular system, none of us can prove conclusively that his is the ideal system—and that when conditions arise which call for the development of a new system, such a system will be properly developed and applied.

I am surprised at the excessive friction of the Mallet compound locomotives. Dr. Hutchinson gives it as an average of 46 lb. per ton. Ordinarily the friction load for steam railway trains is estimated at 6 lb. per ton on level straight track. This excessive friction is probably due to the greater number of cylinders, reciprocating parts, and extra weight of the valve motion of these engines; and it indicates that some of the advantages of these immense engines are offset largely by this excessive friction, especially when they become a trailing load. What is the friction of these engines when running under steam? I assume that this table gives the friction when the engines are being pulled as trailers by the electric locomotive.

Dr. Hutchinson says he adopted a method which gave him a single speed, for his electric locomotives and that resistance was used when starting. He also says that one of the reasons for doing this was to obtain simplicity, giving as an additional reason that the power cost was nothing, being developed by water power, consequently he could afford to waste it in starting the locomotives. But such practice would not do in case the power were produced by a steam power plant on a railroad of any great magnitude. I think, therefore, that a different conclusion would have to be drawn as to the method of control to be adopted, in case the three-phase system were made applicable to a large railway system. In this respect Mr. Murray has pointed out the superiority of the single-phase system, as far as economy of operation and securing of variable speed is concerned.

F. N. Waterman: As one who has advocated the consideration of three-phase motors for railway work, I am particularly gratified by the evidence of its advantageous application as set forth in the paper of the evening. There is one interesting property of induction motors which is not exhibited in the present instance, because only one train is operated; namely, the action of moving trains as fly-wheels to keep down the peaks or to minimize the fluctuations of output of the central station. This was illustrated by the operation of one of the electrified divisions of the Italian state railways, known as the Valtellina line. The traffic comprised freight and passenger service, with an average of from four to six trains running simultaneously. With only one train running, as occurred at the extremes of the day, the ratio of maximum to average ordinate of the output curve was about 3.5 to 1. The average run was short, requiring frequent acceleration. With a number of trains on the line, the ratio of maximum to average output fell to 1.7 or 1.8 to 1, giving a load-factor of 55 to 60 per cent. The reason why the ratio of maximum to average was as favorable as 3.5 to 1 with single train operation, was the employment of the cascade control for most of the trains. The freight was handled at that time, in the manner adopted by Dr. Hutchinson, by rheostatic control with a low rate of acceleration. The remarkably favorable results on the Italian state railways was unquestionably due to the peculiarity of induction motors, that they cease taking current if the frequency falls by the amount of their slip, and return current if it falls to a greater extent. The water wheels driving these generators fell off in speed some five per cent, as full load came on, while the average slip of synchronously running trains was less than one per cent. Hence, as the shock of starting a train came upon the power house, the frequency fell, and it had to fall only one per cent entirely to relieve the station of other loads. A further fall would cause the moving trains to return energy to the line and help supply the starting current. This momentary relief of the station resulted in the high load-factor noted. It would appear that this property of induction motors should be of great value where a small number of trains is operated.

Of course, relief of the power house by this means is only momentary. Whether it would be of consequence at all in such a proposition as Dr. Hutchinson is dealing with is perhaps problematical. The starting of a 1600-ton freight train is a very different matter from the acceleration of a 125- or 150-ton passenger train, and the time-interval during which the fly-wheel action is effective might very readily be so small that the advantage would not be realized to anything like the same extent, but it is a property resulting from the constant speed characteristic of the motor, which in many cases is of large consequence, and in any case is extremely interesting, as being not merely a theoretical deduction, but as proved out in the practice of the Italian State Railways. The tandem control, which has been spoken of as " messy ", is employed by the Italian state railway, even on a recent installation, which is like this Cascade installation in being a through haul on a constant grade.

I had some calculations made a short time ago showing the effects of tandem control of three-phase motors in comparison with the series-parallel control of the New York Central locomotives. It was impossible to include a computation for the single-phase locomotive, because sufficiently accurate information regarding the performance of single-phase locomotives was not available. Table I shows that the tandem control with two speeds—a method that leaves the entire equipment available for either kind of running—is at least not inferior to the New York Central locomotives, employing four motors and their three groupings, in respect of maximum draught on power house or total energy consumption, but is rather better. If handled on the basis of constant-current input, which is not the custom in direct-current practice in this country, I believe the three-phase locomotive will show rather a noticeable advantage when the application of the three-phase motor to railroad work has received the same thorough study and development as given to the direct current motor. If experience abroad may be taken as a criterion it will be found superior for many purposes, to any other form of motor.

COMPARISON OF THREE-PHASE AND DIRECT CURRENT LOCOMOTIVES.

Type of locomotive	Total train weight tons	Net train weight tons	Distance in feet	Time in sec.	Speed maximum miles per hour	Kilowatt maximum	Kilowatt hours	Watt-hours per ton-mile	
								gross	useful
New York Central (weight 95 tons)..	435	340	27300	426	58.4	1920	110	49.4	62.8
Valtellina 2 speed type (weight 68 tons)	408	340	27300	426	58.5	1660	104	49.1	59.4
Valtellina 3 speed type (weight 68 tons)	408	340	27300	425	58.5	1660	91.5	43.5	52.3
New York Central..	265	170	29800	403	60.5	1800	82	54.9	85.5
Valtellina two-speed type............	238	170	29800	404	59.5	1660	71	52.8	74
Valtellina three speed type............	238	170	29800	402	59.5	1660	60	44.7	62.5

Notwithstanding the use of cascade control on the Valtellina locomotives, the control apparatus is much more free from complicated or messy apparatus than that of any electric locomotive in use here. This results from the use of liquid rheostats with compressed-air control. A limit relay is used to maintain the rotor current constant, and the rate of acceleration is determined merely by the notch in which the handle of the controller is set. In the simplicity and small space requirements of the control apparatus there is a great contrast in the appearance of these Valtellina three-phase locomotives and that of the large locomotives in use in this country.

From a mechanical point of view I was much interested in the motors of the Italian state railways. The clearance used there between rotor and stator is 2 mm., about

$\frac{1}{16}$ in., and the wear of the bearings, in some 60,000 miles of operation on these locomotive motors, was about 0.3 mm. The reason for such a result is that the collector rings are outside the bearings, leaving it only necessary properly to proportion the spiders to have virtually the entire interior of the rotor for bearings and lubricating means. While the three-phase motor, particularly if arranged for cascade operation, requires an air-gap as small as $\frac{1}{12}$ in. the remedy is present in ample bearing space. Dr. Hutchinson points out some of the advantages of the three-phase motor; the foregoing seem to me to be further advantages.

J. H. Davis: The system described marks an epoch in the history of heavy railroad electrification in the United States. It is the first attempt in this country to use the three-phase induction motor for handling heavy passenger and freight trains on a trunk line railroad.

I am especially impressed with the importance of the electrical engineer's decision in recommending the adoption of a certain system of electrification. His decision is second in importance only to that of the engineer locating the railroad. A decision to use this or that system of electrification for a certain purpose, as, for instance, handling heavy traffic over a mountain division, will, of necessity, have great weight in determining the system of electrification to be used when other divisions of the road are electrified. The system thus adopted may or may not be that which is best suited for the desired extension. If the entire road is eventually electrified, one system of electrification should be used throughout, although this system may not be best adapted to all of the various conditions to be met. Therefore the system adopted should be that which is best adapted to the requirements of the road as a whole. The necessity for interchange of equipment from one division to another is well known, and in meeting this requirement the electrical engineer can best obtain simplicity of equipment by confining himself to one system of electrification. The gain in this direction will be more than sufficient to offset the loss due to the adopted system not meeting in the best way some of the conditions.

Inasmuch as the conditions at Cascade Tunnel are very similar to those encountered on the Belt Line Railroad of the Baltimore & Ohio, where direct-current electric traction has been used for 14 years—this being the first installation of electric locomotives for heavy traction purposes in the United States—a comparison of the physical conditions, train weights, tonnage handled, equipment used, etc., may be of interest. This comparison I give in the subjoined Table I.

It might be added that the working conductor on the electrified section of the Baltimore & Ohio was originally placed overhead, its design, however, being very different from that used at the Cascade tunnel. The low working voltage on the Baltimore & Ohio necessitated the collection of a large amount of current, and a rather complicated overhead construction was necessary. Serious trouble was experienced in maintaining this overhead structure, and for this reason it was abandoned and the third-rail installed.

TABLE I.

Physical conditions:	B. & O. R.R.		G. N. Ry.	
Length of electrified section	3.7 miles		4.0 miles	
Ruling grade	1.5%		2.2%	
Average grade	1.0%		1.7%	
Length of longest tunnel	7,400 ft.		13.873 ft.	
Train weights:				
Freight, including steam and electric locomotives	1928		2075	
Passenger " " " " "	990		906	
Tonnage handled per day:	B. & O. R.R.		G. N. Railway	
	No. of train	weight	No. of train	weight
Passenger	21	6,630	3	2,690
Freight	28	29,600	2.5	5,290
Special	0		1	470
Totals	49	36,230	6½	8,350
Equipment:	B. & O. R.R.		G. N. Ry.	
	Pass.	Freight	Freight	
Number of locomotives	5	2.5	4	
Weight, tons	90	160 (2 units)	115	
Number of motors	4	8	4	
Rated horse power	1,100	1,600	1,900	
Tractive effect, rated load	26,000	70,000	47,600	
Speed at rated load, miles per hour	16	8.5	15	

NOTE:—Data on B. & O. equipment based on natural ventilation: Great Northern on forced ventilation.

L. R. Pomeroy: About seven years ago I made an examination of the Cascade Tunnel to determine the possibilities of electrification. At that time it was very difficult to arrive at the actual cost of steam operation, on account of the fact that the motive power statistics furnished were for average and general conditions, complicated by the addition of constructive switching and arbitrary mileage.

Since then I have been furnished with a road test of a Mallet locomotive over the section described in the paper, namely from Leavenworth to the Cascade Tunnel summit, a distance of 32.4 miles, with an average grade of 1.35 per cent and a limiting grade of 2.2 per cent. Also from a neighboring road, having similar physical conditions, an actual coal record; that is, tons of coal used for a period of six months, of individual classes of locomotives, representing 156 locomotives making 1,382,092 miles, and consuming 174,121 tons of coal, as follows:

No.	Class	Engine-miles	Tons of coal	Pounds per 1000 ton-miles	Pounds per engine-mile
55	2-8-2 simple.	291,070	33,418	191	230
6	2-8-2 compound.	81,150	10,275	175	251
24	2-8-0 simple.	299,036	33,931	345	227
71	2-8-0 compound.	710,836	96,479	306	271
156		1,382,092	174,121		

Some figures of the test referred to are as follows:

Distance	32.4	miles.
Running time	4 hr. 0	min.
Time lost in stops	3 " 4	"
Total time	7 " 4	"
Average speed (miles per hour)	8.1	miles.
Pounds of coal used per trip	23,100	lb.
" " " " " square foot of grate, per hour	74.03	"
" " " " " mile	717	"
" " " " " 1000 ton-miles	896	"
Average tonnage hauled	810	
Average number of cars per train (all loaded)	21	
Average grade	1.35%	
Maximum or ruling grade	2.2 %	
Indicated tractive force	60,000	lb.
Type of locomotive 2-6-6-2 (L2)	Mallet	
Total weight of locomotive	225	tons.

From the foregoing data the writer desires to present a few deductions.

A train with a trailing load of 2500 tons over the section of road on which the test was made will require about 5750 kw-hr. at the rail per trip.

Assuming a modern steam generating station, the coal used per trip at 15 miles per hour would be about 5 lb. per kw-hr. (at the rail) or a total of 28,750 lb. With the same tonnage per train under steam conditions at 15 miles per hour, three steam locomotives would be necessary.

Increasing the speed of the steam train from 8.1 miles per hr. to 15 miles per hr., reduces the tonnage about 30 per cent per locomotive. 810 tons trailing load plus 225 tons, the weight of the locomotive, times 70 per cent, equals 725 tons per locomotive. The coal consumption of the steam train then becomes 32 miles times 717 lb. per mile times three locomotives, equals 68,832 lb. Percentage of difference in favor of electricity:

$$1 - \frac{28,750}{68\,832} = 58 \text{ per cent.}$$

Going back to the coal used by the 156 steam locomotives—these locomotives are used on two mountain divisions—for six months; namely, 174,121 tons. For a year the amount would equal 348,242 tons. At the rate of $2.00 per ton for Crow's Nest coal, the cost of coal equals $696,484. Also the cost for water used would be about $25,000. It has been shown that the coal saving amounts to 58 per cent. Calling this one half or 50 per cent, the saving would equal $348,242. It is claimed that the Mallet type of locomotive is 30 per cent better than the types composing the 156 locomotives referred to. We will, therefore, reduce this amount to correspond. $348,242 times 70 per cent equals $243,769; add the saving in water, $25,000, and the net saving then becomes $268,769. This amount capitalized at 5 per cent represents $5,375,380. This amount alone, not figuring on other savings, such as train crews, reduction in train-mileage with the same tonnage, and the advantage of a great increase in capacity, would go to show that such a mountain section comes very near being a situation where we can accomplish by electrification what is now impossible under steam conditions.

In the table of test data it will be seen that the time to make the run was 7 hr. and 4 min.; time consumed in stops or laying in side tracks, 3 hr. and 4 min.; time in motion, performing useful work, 4 hr.

Approximate figures from four railroads which give separately in the annual reports the coal per locomotive-mile for freight and passenger service, based on the total coal charged to engines for the year, the consumption per horse-power-hour is as follows:

	Passenger	Passenger and Freight	Freight
Road A	12.30		9.64
" B	12.86		11.20
" C	14.00		10.00
" D		10.63	

while from individual road tests we find the coal consumption frequently is from 4 to 8 lb. per horse-power-hour.

The point that I desire to make is that it is not quite fair to the electric side to base the comparative costs on a road test without adding a liberal amount to cover this "contingent" feature.

In Tables III and IV the resistance of the Mallet locomotives is shown to be in the neighborhood of 50 lb. per ton exclusive of the resistance due to gravity. This is not to be wondered at when the sizes of the pistons are taken into consideration. The L-1 locomotive has cylinders 21.5 in. and 33 in. by 32 in. stroke and the combined area of the four pistons is 2436 sq. in. If atmospheric pressure of 15 lb. per square inch is figured against the low-pressure pistons only, the thrust equals 25,659 lb. A large share of this piston resistance is by-passed, but the fact that these locomotives cannot drift freely down a hill without a slight opening of the throttle, and from the tests shown in the paper, it would seem that the by-pass valves should be supplemented by some form of drifting valve which would result in materially reducing the resistance found in towing the locomotive with closed throttle. It is customary with some railroads to base the value of saving due to elimination of curves and grade reduction, not on the increased capacity, but on the money value of a reduction in train-miles. For example, on a division of 225 miles having seven freight trains per day the value of each one per cent in reduction of train-miles is about $3000 per annum, the capitalized value of this amount at 5 per cent per annum equals $60,000 for each one per cent of saving. The rate per train-mile being 50 cents, which represents the costs directly affected; that is, transportation expense not general expenses. This being the case, figures representing costs of electric service on this basis will directly appeal to railroad managers; whereas figures based on increased capacity are more or less problematical and open to doubt.

W. N. Smith: Although for a dozen years or more the three-phase system has been firmly established as the standard for general power transmission, certain disadvantages incident to its use have until now deterred engineers in this country from undertaking to avail themselves of some of its inherent advantages in heavy electric traction. It has been reserved for the author of the paper to be the first in the United States to reduce theory to practice and to place before us a general description of the construction and performance of a type of electric locomotive which, so far as this country is concerned, has never before emerged from text books and technical papers.

It seems to me that in the case here treated, operating conditions are such that the advantages of the three-phase system are of maximum importance, and the disadvantages of minimum importance. The relative advantages are clearly stated by the author and need no further comment. On the other hand, the chief disadvantages of the three-phase system, reduced to their lowest terms, are the harnessing of the inherently constant-speed motor to variable-speed duty, and the necessity of two trolley wires instead of one.

The first objection is largely minimized in this electrification by the nature of the train service and the character of the railroad line itself, both of which favor maintaining a constant speed. Whether or not there is any valid objection to maintaining a constant speed on a long railway line on the surface, there can certainly be none to doing so in a tunnel; and the speed is so moderate that the relatively inefficient performance during acceleration is not of long duration in proportion to the entire length of the run. In this case the acceleration seems to last about 1.5 min. out of the 12 to 14 min. that would be required to make the tunnel run.

The objection to two trolley wires is partly obviated in this case by the slow speed of 15 miles per hr. In my opinion this is the salvation of the wheel-trolley contact system here adopted. But even slow speed cannot mitigate all the disadvantages of two trolley wires of opposite polarity.

I have somehow received the impression that our European friends operate their railroads under some conditions that seem inapplicable to our roads. They appear to have a somewhat different view-point, to which both the employes and the public are accustomed: they pay strict attention to methodical detail all down the line, and subordinate the results thereto; while in this country the aim is more toward the final result and all possible time-consuming details are regarded as secondary to that result. This is the only way I can account for the favor with which the Europeans apparently regard the use of two trolley wires. They seem to have tackled this phase of the problem with remarkable freedom from the prejudice against it that has always existed in this country.

In a long straight tunnel taken by itself the double-trolley construction adopted by the author does not seem to present any unusual difficulties in maintenance. It seems to have been experienced in long-tunnel electrifications that the transition period from steam to electric power is the time when insulation is most likely to fail. The worst difficulty with the double-trolley wire seems to me to be at track intersections where moving contact must be made at will, upon intersecting wires of opposite polarity, without risk of short-circuit, and without danger of temporarily checking headway and injuring draft-gear by losing power for a few seconds when accelerating a heavy train at slow speed. The first of these considerations is all-important. The second depends on how many chances it is safe to take by temporarily cutting off or reducing the locomotive torque while starting a heavy train. Under the conditions of the Cascade Tunnel electrification, with main and side tracks at tunnel portals on a two per cent grade, it would seem necessary to have two sets of trolleys in contact, one set at each end of the locomotive when passing switches, at least whenever conditions make steady acceleration difficult, as with snow on the rails and journals stiffened by frost, and excessive train weight.

The paper betrays some dissatisfaction on the part of the author as to results so far accomplished with the double-trolley system as here developed. In working out improvements he will have the sympathy and encouragement of all who realize that, after all, the mechanical reliability of the moving contact system is the very foundation of successful electric railway operation, regardless of the kind of current employed. It is this feature that appeals to me as being susceptible of the greatest improvement. It is in respect to the trolley problem that the single-phase system is likely to be regarded as superior for some time to come.

It seems to me that future development in the perfection of the moving contact will be in the way of the wide roller type with pantagraph mounting, as distinct from the narrow trolley wheel or the sliding shoe; for the sliding shoe, widely used for high-speed work at the present time, seems susceptible of further betterments, if wear and tear at high speeds and heavy currents are to be overcome.

It is quite conceivable that ultimate speeds of 20 to 30 miles per hour may sometimes be thought advisable for some classes of train service on a mountain-grade line of this type instead of the 15-mile speed chosen for the heavy freight service of this installation. This refers more particularly to fast passenger and light freight trains. Train-speeds that operating economy may demand in the future ought not to be rendered impossible by the limited reliability of the time honored trolley wheel for high speed in such heavy service, particularly when passing switches.

The same considerations of speed prompt the opinion that the next locomotives to be built for this electrified section, or a similar one, will be fitted either with pony wheels or with side-rods for coupling to motors placed on top of the frames, or possibly with both of these contrivances. There seems to be no mistaking the tendency that has set in during the last two or three years, for electric locomotive construction to be guided more and more by the experience gathered during the two generations of steam locomotive practice. The boasted simplicity of the geared or gearless motor hung directly on the locomotive axle has proved disadvantageous in some other respects. The increased flexibility of locomotive design from the mechanical standpoint, which is consequent upon placing the motor on top of the frame and using side-rods and jack-shafts, and the general mechanical uniformity with the frames and running gear of existing steam locomotives, will make an electric locomotive appear more like a standard piece of machinery to the railroad operating man than has hitherto been the case. The great advantages will be the raising of the center of gravity, the ready standardizing of mechanical parts independently of electrical equipment, and the ability to use the same arrangement of frames and running gear for either direct-current, single-phase, or three-phase motors. With such construction safe speeds are not limited to 15 miles per hour. Without it, track maintenance and liability to derailment would likely continue to be as disadvantageous to the electric locomotive at high speeds as they have in the past.

One feature of the author's description of the performance and rating of the locomotive motors which is of particular interest is that emphasis is put upon the continuous capacity, as well as the one-hour rating and the maximum tractive effort. In spite of the objections that have been urged against the term " continuous capacity " as applied to railway motor specifications, the author apparently takes it for granted that it is bound to survive; and it is to be hoped that its evident applicability to the specification of locomotive motors will lead to a more universal recognition of its appropriateness in specifying the smaller sizes of railway motors.

The author's estimate of the power station fuel consumption of these electric locomotives as compared with the Mallet compound steam locomotives, while interesting, would be more convincing from an economic standpoint if submitted in greater detail. The chief advantage of electric traction, demonstrated by the paper, is the increase of the capacity of the tunnel and adjacent mountain section, by doubling the speed possible with steam locomotives of the most economical type. Moreover, there are still other operating features, such as the location of passing sidings, and the signalling and train-dispatching system governing the physical possibilities of getting the trains past each other at the increased speed, which have need of full consideration in order to determine the economic value of the increased speed made possible by the electric system.

F. S. Denneen: The chief reason for selecting the direct-suspension type instead of the more elaborate catenary type, now so popular, was the greater mechanical and electrical simplicity of the former. It is at once evident that with two wires over each track, with 6600 volts between them and between either wire and the ground, the problem of insulating the catenary type of construction would be a difficult one. With several tracks having numerous switches and intersections the problem would be greatly complicated. Within the tunnel the available head-room and side-wall clearance were so small that the catenary suspension was not desirable. With the speed limited to 15 miles per hour, many of the advantages of catenary construction over the direct-suspension type would be lost. A careful study of the entire situation then led to the conclusion that the direct-suspension type would fully meet all operating requirements, and, at the same time, because of greater simplicity, repairs could be much more quickly made, thereby reducing the danger of appreciable delays in the service.

The overhead structure in the yards on single track consists of the bracket shown in Fig. 20. It will be seen that each phase is supported by an independent span, and that auxiliary insulation is provided in every case; that is, the major insulation may be said to consist of the two heavy porcelain strain insulators marked *E* and the auxiliary insulation, the wood break strains marked *A*. The porcelain strains are rated for 10,000 volts, while the wood break strains might be rated at 3300 volts, or more. If I remember rightly in certain parts of the yards it was necessary to provide overhead construction for as many as six tracks; the details of the design work have somewhat slipped away from me, because it is more than a year and a half since I had anything to do with it. It was not possible to place any supporting means between the tracks and the entire overhead structure had to be carried on cross-span construction, which, because of its flexibility, made the insulation a difficult matter.

Fig. 17 shows that wires of the same phase are carried upon one cross-catenary, while those of the opposite phase are carried upon another one, also that there is insulation between the wires of the same phase over different tracks. This was done in order to make the tracks entirely independent, and to make it possible to cut out any one track or any set of tracks. Fig. 18 shows a unit system, that is, it is arranged so that by removing one or two bolts a new piece or a new unit can be quickly inserted without serious interruption to service. Adjustment by means of suitable turn-buckles is provided at every point where necessary.

Within the tunnel, the end-section of which appears as Fig. 21, the details of the overhead construction appearing as Fig. 22 and 23, bronze fittings were used in most cases. There was a great deal of moisture and drip, but it was not known how much of the moisture was due to the steam from the locomotives and how much from the drip through the tunnel roof. To provide against corrosion, bronze was largely used. Dr. Hutchinson says it is possible that malleable iron and steel properly galvanized would have done as well.

Dr. Hutchinson refers to the trouble experienced at the intersection of lines due to the trolley leaving the wire, this trouble occurring as the trolley wheel crossed the pan-casting. At the time the layout was originally made, a scheme was considered for automatically turning the tongue portion in the pan so as to carry the wheel across in the proper direction, but this scheme complicated the arrangement and was not used.

When the original tunnel layout was made, the trolley wires were set 5 ft. apart, but after the designs had been worked out and approved by the railway engineers, the officials of the road decided that they wanted the entire central part of the tunnel clear, so it was necessary to set the trolley wires out to a separation of 8 ft. within the tunnel, which added a number of difficulties. The clearance between the side walls and the trolley on either side was only approximately 14 in., and as it was necessary to prevent the trolley from swinging, it was somewhat difficult to put in steady members with double insulation. The steady device used consists of two porcelain insulators of the ordinary skirt type of about 22,000 volts rated capacity, placed in series; the insulators are fastened together in a vertical position by means of a U-shaped casting with the ends cemented into the insulator pin holes. Each insulator carries a malleable iron cap, one of which is attached to the trolley wire and the other to the side wall of the tunnel. The connecting U casting is provided with a flanged portion all round, to protect the porcelain from blows from the trolley wheel. The large strain insulators used in the tunnel are capable of working at 20,000 volts, and the porcelain links at 10,000 volts; either could be broken,therefore, without interrupting the service.

It was the aim to provide against the likelihood of failure due to electrical or mechanical trouble with the insulation; for this reason heavier insulation was used than heretofore, for lines of this voltage.

W. I. Slichter: It is to some of the minor features and problems of the designing engineer, that I would like to call especial attention. The principal characteristic which differentiates American from European railway installations is size. Our trains are about three times as heavy as the European trains, and our heavy traffic over single-track roads requires that every operation must be performed with the utmost reliability to prevent costly blockades.

In the locomotives under consideration it was necessary that there should be developed a tractive effort about three times as great as that developed by the foreign locomotives, and the practice of pushing a 2000-ton train up a 2 per cent grade required that this tractive effort should be applied gradually, steadily, and continuously, as any sudden variations in a tractive effort of this large value would almost certainly result in breaking a train in two and possibly in causing a wreck. Thus the control system of such a locomotive is a most vital feature. There can be no reduction in the tractive effort after it is once applied, and there must be sufficient control-steps so that successive increments of tractive effort are not so great as to slip the wheels or strain the draw-bars to a dangerous extent.

These conditions rendered any scheme of double-speed connection, such as concatenation or changeable poles, undesirable, as in these it is necessary to cut out at least a portion of the motors while the change is being made. In this particular case the character of the service and the low speed of the locomotive eliminated the necessity of having more than one running speed. The problem was then to provide a control system which would give a steady acceleration and yet provide for running at fractional speeds for short intervals of time such as 15 min., as contrasted with continuous running.

This is accomplished by using plain rheostatic control in the secondaries of the motors, varying the resistance by contactors and providing sufficient capacity in the rheostats to permit of running for 15 min. at full load. Of course this means that the locomotive takes full rated power from the instant of starting; but the percentage of power wasted in this way is not great, as the running time is long compared with the time occupied in starting.

The control system consists of fourteen contactors per motor, five of which are in the primary, there being one contactor on one phase and two on each of the other two phases to provide for reversing the motors. This leaves nine contactors in the secondary to give thirteen steps, which is accomplished by a scheme of dividing the resistances into two or three groups, each having its contactor; and these groups are brought into different combinations so that each group is used over and over again, some times in series, some times in multiple with the others, and not left idle after being used once.

Of course this involves increasing the resistances unequally in the three phases, but this unbalancing has been kept within such limits that the torque per ampere is never less than 90 per cent of that with balanced resistances on all steps, and this loss is of far less importance than the inconvenience that would result either from increasing the number of contactors or decreasing the number of steps. As Dr. Hutchinson has said, an additional step has been obtained by closing the circuit at starting on two of the four motors before the circuit of the remaining motors is closed, thus the tractive effort on the first step is about 10,000 lb. and on the second 20,000 lb. and while accelerating at an average tractive effort of 37,500 lb. the tractive effort may be kept within the limits of 41,000 lb. maximum and 35,000 lb. minimum.

A separate and independent set of resistances is provided for the secondary of each motor to avoid the tendency of the motors to exchange current and " buck " when they are all connected in multiple to one set of resistances. If the driving-wheels were of exactly the same diameter, this multiple connection would act as a side-rod and tie the motors together; but as there are apt to be inequalities in the diameters of the different driving-wheels, a considerable load might be put on the motors in merely slipping the wheels to make them revolve at the same speed. As it is, the only effect of the existence of driving-wheels of different diameters is to cause a slightly unequal division in the load on the motors, which may be cared for by the auxiliary resistance referred to by Dr. Hutchinson. At the same time the natural tendency of the wear is corrective, tending to wear most on the larger wheel.

The advantage of the induction motor, due to its peculiar adaptability to regeneration, is best illustrated in this instance by considering the amount of energy which is regenerated and which would otherwise have to be dissipated in rheostats. To hold a train having a gross weight of 600 tons on a 2.2 per cent grade would require a resistance capable of absorbing 650 kw. per locomotive for the time during which the braking occurred. This corresponds, in size of rheostats, to the condition of running continuously at a speed of 4 miles per hr. with an input of 460 amperes per motor and a tractive effort per locomotive of 37,500 lb.

A very prominent feature of regeneration with the polyphase induction motor is the simplicity of its operation. As the greater part of the train gradually passes the summit and comes upon the down grade the speed gradually increases from 15 miles per hr., to 16.5 miles per hr., and without any attention on the part of the motorman the locomotives change their function from motoring to generating and from taking 1000 kw. from the line to giving back approximately 600 kw. Meantime there has been a tendency on the part of the generators in the power house and the water wheels to increase in speed with the speed of the motors on the locomotive.

This tendency is made use of by means of a centrifugal device to throw in circuit the water rheostat mentioned by Dr. Hutchinson, and located just outside of the power house. This rheostat takes the energy generated by the motors and holds the speed and frequency of the system down to normal. The water box is controlled in such a way that with a very slight increase in speed of the water wheels or generators the resistance is thrown across the generator bus-bars. When the speed has become constant the resistance in circuit remains constant, and, conversely, as the speed decreases the resistance is drawn out of circuit. With a growth of the system and increase in the number of locomotives operating at once, this rheostat in the power station would be used less and less and more of the regenerated energy would be usefully employed.

E. F. W. Alexanderson: Looking at the design of the motors on the Great Northern locomotive as an induction motor, nothing new is to be found except in the proportions. In order to meet practical railroad requirements the mechanical clearance is three times as large as is usually made in a stationary motor of the same type, and twice as large as it has been made in certain well known three-phase European locomotives. As illustrating that the predetermination of the characteristics of induction motors has become almost an exact science, even when the proportions do not allow their derivation from other existing machines, it may be mentioned that the characteristic curves and overload capacity of the motor from test agree within the errors of measurement with the data submitted with the contract.

The interesting part of the problem in this case is the adaptation of the induction motor to railway requirements. The motor, as mentioned in the paper, considerably exceeds the specifications of capacity in continuous operation for a given temperature rise. In the case of a stationary motor of the ordinary kind, such a result would be a criticism of the design. With a locomotive motor it only emphasizes a fact borne out by experience in several instances, that the success of an electric locomotive depends more upon a certain balance of design than the ability to meet a definite service requirement; in other words, the maximum tractive effort of the motor must have a certain relation to the weight on drivers, and a locomotive motor that lacks overload capacity would be unsuitable even if it should meet the specified requirements in the most creditable way. Railway motors of the ordinary type are in most cases limited in capacity by the temperature-rise in service; this is substantiated by the fact that there is allowed a higher temperature than that found economical with stationary machinery.

The continuous capacity of such motors of the closed type is usually about one-third of the capacity for one hour, whereas, the continuous capacity of the Great Northern motors with forced ventilation is 79 per cent or 74 per cent of the hourly capacity at 500 volts and 625 volts respectively. In attempting to meet the Great Northern requirements, it was immediately apparent that a motor of any reasonable size would run too hot unless forced ventilation were used. It was naturally attempted to make the artificial cooling as efficient as possible by taking advantage of the structure of an alternating-current motor with distributed windings, thus bringing the air into intimate relation with the active parts. In order not to waste space in the length-direction of the motor—which had already been encroached upon by the double gearing—the air is led through holes or channels running longitudinally through the core. This system of ventilation proved successful, and the tests show that the continuous capacity with forced ventilation is practically the same as the hourly rating on a standard basis without ventilation. It is most gratifying to see in Dr. Hutchinson's analysis of operating conditions that the design is well balanced, and that the continuous capacity is in proportion to the maximum work the locomotive may be called upon to do with a given weight on the drivers.

The weight-efficiency of the three-phase railway motor is often referred to. It might, therefore, be of interest to compare the Great Northern motor with two other well known locomotive-motors—the Detroit River tunnel locomotive (a freight locomotive of the same weight and mechanical design provided with four motors of the double geared type), and the Simplon, a well known three-phase locomotive. In the same table is shown the comparative figures for a stationary three-phase motor of the same dimensions. All three induction motors have practically the same armature peripheral speed, and the weight per horse-power is favorable. The Simplon motor is favored by a small air-gap, but handicapped by being wound for high voltage. No data are available for another three-phase railway motor with forced ventilation, but the capacity at 40 degrees rise of the Great Northern and the stationary motor gives a sufficiently good comparison. As might be expected, the weight per horse power in this case is somewhat greater for the railway type of motor on account of the air-gap being more than twice as large. The comparison of the four-motor types shows a relative consistency and also indicates the great possibilities of the inductive motor for high continuous output.

	Detroit River tunnel 600-volt direct current	Great Northern 625-volt three-phase	Simplon 3000-volt three-phase	Stationary motor 550-volt three-phase
Weight	8330	12200	22000	11500
Air-gap		0.125	0.059	0.050
Peripheral speed in feet per minute	2450	3440	3250	3550
Horse-power hourly—75 degree rise	300	550	1100	—
Weight per horse-power	29.5	22	20	—
Horse-power continuous—75 degree rise	—	400	—	—
Weight per horse-power	—	30.5	—	—
Horse-power continuous—40 degree rise	—	260	—	330
Weight per horse-power	—	47	—	35

C. L. de Muralt: I am one of those who desire that each system shall have a fair show. I do not propose to advocate that any one system shall be used exclusively. The three-phase system has advantages which have already been thoroughly appreciated, and which will be more appreciated the more it is used, and I think it will be used extensively. But the other systems have also their advantages, and these systems will no doubt be continued to be used. It is for the broad-minded man to understand and realize and appreciate the advantages and disadvantages of each system. Engineers, in considering the electrification of steam railroads, must decide which system presents the greatest number of advantages and the least number of disadvantages in each particular case. There is no such thing as a universal system. There is no universal steam locomotive now. We might as well put forward one type of steam locomotive to haul all of our steam trains, as to put forward any one electrical system for hauling all our electric trains.

What Dr. Hutchinson brings out principally, to my mind, is that the efficiency of the three-phase system is extremely high. I have claimed that for some time, but have met many doubters. We have now an American example which shows conclusively that I actually underestimated the efficiency of the three-phase system. There is no other system that will show the same efficiency under the same conditions.

The recuperative feature has also been rather underestimated by me. Dr. Hutchinson's paper shows conclusively that the regeneration of the trains on the down grade is fully up to the calculated results. There is, of course, no reason why actual experience should disagree with calculations on this subject. But the full commercial value of recuperation has not been brought out. It cannot, because this is too limited an application of electricity. When the road is extended and operates over a longer distance it will show this also. In Europe, where roads are operating over long distances, with several trains on the line at one time, good use is made of the recuperative feature. Many mountain roads in Switzerland do not need any thing like the amount of energy that would ordinarily be required to propel the trains up-grade, because the power returned by the trains descending the grade helps out the power station.

Some engineers claim it is not good practice to use two trolleys. Unquestionably, one would be preferable; but two are used, and have been used for years, under conditions where switches are placed as close together as the tracks will permit, and these trolleys have been operated successfully. It is not an operating feature at all; it is a matter of suitable design, and proper location of overhead line. Once these are taken care of, the road will operate with two overhead wires just as well as with one. There is hardly any difference in maintenance either, because the maintenance cost is made up of labor rather than of material, and the same track-gang that must be kept waiting to take care of an occasional break on a one-trolley line will also take care of an occasional break on a two-trolley line.

The constant-speed characteristic is of course an engineering question, a question that needs to be carefully investigated in each particular case. It will not do simply to say that the series characteristic is advantageous. It may be so in many cases but not always. Sometimes it is disadvantageous, and for main trunk line operation I think it generally is disadvantageous. It is all very well to say that the constant-speed characteristic means increased power when the train runs at full speed up-grade. But those who have ridden up hill in an automobile, and watched the automobile slow down until it stopped, will want a constant-speed machine for grade work, and not a variable-speed machine. Of course when the locomotive does not do its work, it does not use any power. But the amount of energy consumed by a train running at slow speed and using small power, is not one whit smaller than the energy consumed by a train running at high speed and using big power, because the big power will be used for a shorter period only.

Calvert Townley: One point has not had as much emphasis as its importance deserves. The advantages of electric over steam traction and the possibilities of using mountain streams to supply electric power to the Western railroads have been much discussed on paper. Here is a case where the installation has actually been made. A large steam railroad, backed by abundant capital, and officered by men of high professional standing has electrified a section of its line at heavy expense. The type of apparatus selected, its performance, and characteristics, in which we, as electrical engineers, are natually much interested, important though it may be, is really secondary. The greatest importance attaches to the adoption of electricity to replace steam in this sort of service for the first time. It means more than any mere question of the electric system selected. We hope that this installation will be successful; that it will be extended; that the road will find the substitution of electricity for steam has been to its advantage; and that not only because of operating economies but also on other and broader grounds the value of this installation will prove to be so great that a distinct advance toward the electrification of important trunk lines will have been made.

I am personally pleased that we have at last in this country a three-phase installation for heavy railroad service, and from which we get such an encouraging report of early performances. The service requirements are well selected to favor this system, which certainly should do well here, if anywhere. It would be extremely unfortunate, both for those immediately concerned, as well as for every one else interested in the electrification of steam roads, if such an installation should partly or wholly fail. The railroad world is quick to note success or failure, but slow to differentiate between systems or to accept explanations from interested parties.

Some matters in the paper are not entirely clear. First, what is the actual capacity of this locomotive? I note that the guaranteed performance of the motors before they were built was 250 h.p. each under continuous load, while after construction the tested capacity was 375 h.p., an increase of 50 per cent. In making this statement the author permits us to infer that there is a corresponding increased locomotive capacity. In another part of the paper, however, the transformer capacity is said to be smaller than that of the motors. The transformer rating is given at 400 kw. each, there being two supplied. If the transformer is limited to its rating, the continuous output of the motors cannot exceed 200 h.p. each, due allowance being made for losses; that is to say, 7.64 h.p. per ton total weight of locomotive. Even if the transformers can be made to carry 25 per cent overload continuously, and thereby permit the motors to be rated at their guaranteed capacity of 250 h.p. each, the horse power per ton becomes only 8.7, not as great as can be obtained with, for example, 25-cycle, single-phase motors. In view of this fact the author's second advantage of a greater continuous output than with any other type of motor would fail of demonstration. Further, if the tested capacity of the motors, 375 h.p. each, is to be made available, apparently the transformer capacity must be very materially increased. Additional or larger transformers probably mean a larger cab, heavier framing, and so on, and this of course changes the weight and upsets any direct comparison. It is not stated that the control apparatus, switches, and resistance are large enough to handle the current for motors rated at 375 h.p. each, or that the blowers have sufficient capacity to furnish additional air to the transformers. If these matters have been covered by tests, a statement regarding them would afford a better understanding of the claim for great power per small weight.

The claim for maximum electrical and mechanical simplicity is valid as applied to the induction motor, which should receive full recognition. However, the control apparatus, compared with that required by direct-current or by single-phase motors, is much more complicated. It is necessary to break twice as many circuits as with direct-current or single-phase motors. Instead of being more simple, therefore, the control part of the three-phase equipment would naturally be somewhat more complicated.

With reference to uniform torque, I ought perhaps to say that our observations on single-phase locomotive performances do not support the view that the so-called pulsating torque of that motor is practically in evidence.

Since practically all the single-phase installations in this country use the 25-cycle current, the author's claim that the three-phase system has an advantage because it alone can use this frequency is somewhat puzzling.

The comment of a prominent steam railroad engineer on the question of constant speed was that the conditions which affect the operation of trains on schedules and which cause delays are many of them entirely foreign to any question of traction. Various and diverse influences cause delays, requiring trains to make up time if they are to be maintained on schedule. Therefore, an inflexible and a uniform speed is undoubtedly somewhat of a disadvantage even though the running time and operating conditions indicate that ordinarily it is desirable to maintain a uniform speed when the trains are running.

Ability to regenerate current by the three-phase system is of an undoubted advantage, and, naturally, will be used to produce a saving as the system is extended beyond its present limitations.

Charles P. Steinmetz: More than 15 years have elapsed since three-phase induction motors were first applied to railway work. Some years previously the single-phase commutator motor had been designed for railway work, but had not been used in practice, because there was no frequency low enough to make that type of motor suitable. A great deal of work was done on three-phase induction motors, a number of equipments were built, and high hopes were entertained that we were at the beginning of important developments in electric railroading. At the same time the synchronous converter was successfully developed and applied, its use enabling the operation of direct-current railway systems over such distances that the direct-current railway motor took care of all railway work for many years. For this reason the three-phase induction motor railway development did not progress in this country as it was hoped it would. The three-phase motor was used only to a limited extent, in mining locomotives, etc. Abroad, where prejudice retarded the introduction of the synchronous converter, considerable work was done in three-phase railroading.

Ten years after the early work the alternating-current railway motor was taken up again and the old single-phase compensated commutator motor was introduced industrially. Meantime it has developed so that to-day the single-phase motor is successfully applied to the solving of electric railway problems. At the same time most of us have begun to understand its limitations; it is not a universal motor, as its application is seriously circumscribed. The need of a frequency lower than the present standard as claimed by many designing engineers, limits the use of this type of motor. If it requires a system that differs from standard in all its parts—generators, transformers, etc.—this motor will be handicapped, because the economic development of the electrical industry must be towards uniformity in methods of generation, transmission, and distribution of power.

It seems now that the three-phase induction motor also has reappeared and found successful application. The advantage of this type of motor is its simplicity and reliability, its uniform torque, and greater output for its weight. These are the characteristics of polyphase machinery. The main characteristic of the three-phase induction motor, however, is that it is a constant-speed motor. From this feature follow most of the other characteristics: the relatively low efficiency of acceleration; that it consumes the same power in turning round slowly as when running at full speed at the same torque. A result of the constant-speed feature is the automatic regeneration of power above synchronism. We can improve the acceleration by concatenation, or, as it is called abroad, cascade connection, or by changing the number of poles. The repulsion motor or any alternating-current commutator motor can be made regenerative, but this means additional complication, which to my mind is undesirable in railway work.

The constant-speed feature limits somewhat the general application of the three-phase motor to railway work. It is well suited for mountain divisions, for running continuously with heavy torque, positive or negative. The successful application described by Dr. Hutchinson is on a mountain division. Another application would be for very high speed passenger service. At speeds of 50 or 60 miles an hour, or more, the air friction produces a considerable part of the train resistance; there is a decrease of the difference between the power required to run on a level track at a constant speed and the power of acceleration, and, therefore, an approach to the same conditions as running on a mountain division.

For general railway work, however, as at present carried out in this country, the three-phase locomotive is not as well suited as the direct-current locomotive or the single-phase locomotive, for the reason that the direct-current series motor or the alternating-current commutator motor can directly replace the steam locomotive in present railway operation, while the three-phase induction motor locomotive is not at its highest efficiency, when operating on a railway system under existing conditions. The method of operation must be rearranged to a constant-speed service. Whether the constant-speed operation of the railway would be disadvantageous, or advantageous, over the present variable-speed method, requires further consideration. At present we are inclined to consider it as a disadvantage; the present varying speed method as preferable. If the steam locomotive slows down on an up-grade, or loses time at a station, it can make it up on the level track by speeding. At the same time, if the traffic is unusually heavy, the steam locomotives cannot make schedule and all schedules are upset, and just when we need the full capacity of the railroad system most, the operation of the railroad is at its worst, as we have seen more than once.

In a broad study of the railway problem we have to investigate whether the method now in use is really inherent in the problem, a necessary requirement of the desired results, or whether it is an incidental feature of the particular apparatus we use. The steam locomotive is a constant-power motor. It gives approximately the same power irrespective of the speed, the power as limited by the steaming capacity of the boiler. Whether there is a heavy grade or a run on a level, there is a definite power limit, and this condition has brought about the present method of railway operation. It was the necessity of making up for lost time, as the locomotive has to slow down on up-grade, because it can not keep up steam when running as fast on a grade, as on a level track. With a different type of motive power, however, it would be well to investigate whether there would not be an advantage in rearranging the method of operation to suit the characteristic of the new motive power. It is quite likely that the capacity of any railway system could be greatly increased if we could get really constant-speed operation irrespective of grades, loads, etc. Possibly at constant speed much greater passenger traffic and much greater freight traffic could be handled. All these problems require impartial investigation by engineers that are not in favor of any one type of motor, or of the steam locomotive; engineers that would consider the entire railway problem, and find a solution for increasing the capacity of existing steam roads.

As regards the limitation of the shunt motor, I wish to draw attention to one particular feature: when we speak of the shunt motor, or the induction motor, we always exclude the rapid transit service, from its field of use. We consider rapid transit as that class of service where the series characteristic is especially necessary and to which the shunt motor is especially unsuited. The most extreme case of this intermittent service, acceleration at heavy torque and no constant speed running—the most extreme case of rapid transit—is the high-speed passenger elevator. This service is now always operated by the induction motor and the shunt motor, with or without compound field. It is rather interesting to see that where no precedent limited the character of operation, in the extremest case of rapid transit, motors of shunt characteristic have been chosen for the sake of service capacity, reliability, and safety.

Carl Schwartz (by letter): The operating conditions as presented by Dr. Hutchinson seem to indicate that the three-phase system is well adapted to the service, its few inherent disadvantages being overbalanced by its advantages.

In previous considerations of various systems of electric traction considerable attention was given to the design of the locomotive, the characteristics of the motors, and comparatively less to transmission and generating systems. While the locomotive is a very important part of the whole, both the weak and the strong features of an electric traction system are only in part determined by the characteristics of the locomotive. The decision as to which system is best to adopt may be influenced very much by other considerations.

One of the first advantages of the three-phase system in common with the direct-current system is that the generators are not subjected to such extremely heavy strains as are incidental to single-phase operation. In case of the Great Northern Railway Company's electrification current is generated at 6600 volts, transformed at the power house to 33,000 volts, this pressure is reduced at the substation to 6000 volts, and fed to the trolleys and the track rails. The intermediate transformers are a very important element in the system, and, together with the fact that the system is three-phase and not single-phase, explain the freedom from generator troubles.

Under present conditions we understand that one important feature of the three-phase system, the recuperation of energy from trains going down-grade, cannot be taken advantage of. This advantage, of course, exists only if trains are in service simultaneously up- and down-grade, so that there is load to carry at the switchboards for the train going down grade and returning power back to the station. This condition can ordinarily only be met by an installation of sufficient size, unless the schedule is so arranged that trains will travel up- and down-grade simultaneously. If this is not the case the power returned by a train running down-grade will have to be absorbed by automatically regulated rheostats which thus simply replace the mechanical brakes on the locomotive and dissipate the energy.

I investigated in detail sometime ago the merits of the three-phase system for a tunnel electrification in the Middle West where no water power was available. I found that the same conditions eliminated the feature of power recuperation, and, in this case, the only reason remaining for possible selection of the three-phase system. The result was the selection of direct current with a storage battery to equalize the load.

The operating conditions in the generating stations are stated to be very irregular. The generators may carry full load for, say 15 minutes and then run idle for several hours. Outside of bad regulation the objections against such intermittent operation are not great, but the operation would become extremely wasteful in case of a steam generating station and would show results on the coal pile that would exceed the consumption of the Mallet type locomotive.

Dr. Hutchinson calculates the equivalent consumption of a Mallet compound locomotive at 8 lb. of coal per kilowatt-hour. In case of the three-phase system he assumes 3 lb. of coal per kilowatt-hour at the bus-bars, or 4.28 lb. at the rail, taking the total efficiency from the station bus-bars to the rail at 70 per cent. The consumption in a modern steam station is two or three pounds per kilowatt-hour for a load-factor of, say, between 60 per cent and 40 per cent, but not for operating conditions similar to the Cascade Tunnel electrification. I do not desire to predict any figure for coal consumption in this case, but it will be above 8 lb. per kilowatt-hour, as in the case of the steam locomotive, and not below.

Any other system than the three-phase would under the same conditions not show better results, as the question of coal consumption is influenced more by the load characteristics than by the few per cent difference in efficiency between rails and station bus-bars. The traffic will have to be materially greater to approach a consumption of, say 3 lb. of coal per kilowatt-hour or one-half that of the Mallet compound locomotive.

Dr. Hutchinson has enumerated under the disadvantages " the constant speed of the locomotive " but he himself sees this characteristic rather as an advantage. Constant-speed characteristics of the locomotive motor on a mountain division is apt to accomplish one thing which other systems than the three-phase will not do; that is, allow close adherence to the schedule, which can be made more uniform than for steam service. While there is no possibility of making up lost time there is less possibility of losing time. As the speed is limited by the amount of traffic possible to handle up-grade on the division, the average speed will be increased. This means a proportionate increase in the capacity of the road and may in some cases eliminate the necessity of double-tracking.

Some of our Western roads may find this feature a sufficiently strong impetus to induce them to electrify, even if the power house should not show one-half the coal consumption of the Mallet type of locomotive. Furthermore, this item of energy consumption, as far as station economy is concerned, disappears more or less if water power is used. The only feature remaining is some possible increase in capacity of the power and transmission system, which may not be too expensive on account of the short duration of the peaks.

The three-phase system installed for the Great Northern railway by Dr. Hutchinson is the first three-phase railroad electrification in America, and there seems good reason to believe that this example will go far to secure for the three-phase system in this country the place it deserves.

Frank J. Sprague (by letter): The present is no time for arbitrary statements as to the supremacy of any one electrical system, but rather for that catholicity of view which admits of a variety of effective solutions for many problems, even if for others some one system may offer a preponderance of advantages. I shall, therefore, express no special views on the relative merits of different systems, except that I am glad to note that my efforts in behalf of the adoption of interpole motors and 1200-volt, direct-current operation, with both overhead and third-rail conductors as one of the possible alternatives, have received the practical endorsement of adoption and a rapidly widening application, thus giving the electrical engineer an additional lever for attacking the electrical transportation problem on a large scale.

Without discussing earlier installations, it is of interest to note that so far as at present developed this Cascade Tunnel installation is one of three in this country of almost identical requirements; that is, operation through a tunnel of heavy freight and passenger trains on severe grades at moderate speeds. Each of these is characterized by a different electrical system. Two , the Sarnia single-phase and the Cascade three-phase, are in operation, while the Detroit Tunnel direct-current locomotives have been fully tested. In each case the steam locomotive could only be used under the maximum disadvantages, the very worst possible conditions. Adoption of electrical operation by almost any method offered an effective remedy, and it is an encouraging fact that each of these installations overcomes many difficulties incident to steam operation under certain limitations, and that we have as a result higher speeds, greater capacity, and increased safety and cleanliness.

But none of these installations represents trunk line requirements under conditions which exist on many of our roads. It has been my fortune to have for nearly three years made a study of such a trunk line, presenting what I consider perhaps the most difficult operating problem I have ever encountered. I refer to a stretch of nearly 140 miles on the Sacramento Division of the Central Pacific Railroad, over the Sierra Nevada Mountains. There is much about the investigation of this which it would not be proper for me to touch upon, and I will only refer to it in a brief way.

The section in question is normally single tracked, with sidings every few miles which raise the aggregate trackage to something over 200 miles. The physical conditions are such as to present extreme difficulties to double tracking, although second tracking is being added for a part of the distance. There are nearly 32 miles of snowsheds and tunnels, and in winter the snow sheds form practically continuous tunnels. The grades are severe, there being a rise of about 7000 ft. in 83 miles in one direction, with a ruling grade of 2.4 per cent, and the amount of curvature is startling.

Over this division practically the entire freight and passenger traffic from the Union Pacific Railroad for Central California passes. Freight trains, often over a third of a mile in length, and with 2000 to 2500 tons trailing load, are operated in both directions. These trains require as many as four consolidated locomotives, or two of the heaviest Mallet compounds. The running speed is sometimes as low as seven miles an hour, and the schedule speed for the division is seriously interfered with by opposing traffic. Coupled with this freight operation is passenger operation in both directions, in trains up to nearly 400 tons trailing load, way trains, " limited," Pullmans, and fast-mail trains, operating at double the freight speeds, and with coasting speeds as high as 50 miles an hour.

This division is approaching the limit of steam capacity, especially when considered in relation to the balance of the system, and the question is whether such a division can be operated electrically, and if so, what can be gained thereby. Would the object be economy in fuel? Such alone would not warrant electrification, although the general line of investigation of railroads operated by electricity will show about 50 per cent in coal economy. If carried out, electrification will be primarily for the purpose of increasing capacity, and thereby effecting ultimate economy.

The specifications already issued require operation on this road of 2000-ton trains at 15 miles an hour on a 2.4 per cent grade, and 400-ton passenger trains at twice this speed. This last condition involves a much larger motor capacity at the head of a passenger train than the gratifyingly large capacity exhibited by the locomotives of the Cascade Tunnel, not in tractive effort, but in the product of tractive effort and speed.

The investigation of the possibilities of electrification on this road have been conducted on a plan somewhat different from that ordinarily taken. It was not deemed wise first to decide upon a system, but rather to ascertain the costs of locomotives by various systems which could perform a service determined as essential to effective operation, and then to collate all the facts, advantageous and otherwise, affecting capital cost and cost of operation, after which the best system to meet the existing conditions could be determined.

If asked what system would probably be indicated, I must frankly say that I do not know. That electrification is possible I do know, and that such can be successfully carried out I do not doubt, with increased capacity and general economic results. That it will be so done I also firmly hope and believe, but I am impressed with the absolute necessity that in considering a problem of this character, as well as all problems which are continually confronting the electrical engineer, there is no development which can be reasonably undertaken which should be curtailed, and none which should be disregarded.

We are passing through that inevitable stage of development and elimination essential to final correct decisions and permanency of results. However critical, therefore, I may sometimes feel as to the inadequacy of any system in some particular application, I welcome every installation which promises to further the effective and economic application of electricity to trunk-line operation.

DISCUSSION AT MINNESOTA SECTION, NOVEMBER 18, 1909.

Edward P. Burch (by letter): The writer made a study of the Cascade Division of the Great Northern Railway, including the Cascade Tunnel, and reported on its electrification to the Great Northern Railway Company, in January, 1904. The report was on the power problem, the mechanics involved, the available water power, the advantages of electric traction to prevent congestion of traffic, and finally on the net saving which was possible. The latter was corroborated by the record made by the general manager. It was recommended that a commission be appointed to study the subject as the responsibility for selecting a definite electric system for the whole division was large. The only precedent for the work was at the Baltimore and Ohio Railroad tunnel, where there were hauled many more freight and passenger trains per day up heavy grades and with great satisfaction, after the third-rail was installed.

The electrification of the Cascade tunnel itself was an exceedingly simple piece of work, but the electrification of the Cascade Division from Leavenworth to Everett, 109 miles, involved many problems not yet solved. The electric system and the locomotives were to be suitable for, and interchangeable on, the entire division, not for the tunnel only.

It was well known that no electric system was offered by American manufacturers for real railroading on these mountain grades; and experimental work was not welcomed on so large a scale. President Hill's decision was that the new Mallet compounds should be tried out.

The great objection to the use of three-phase power for railroad work is due to the necessity of carrying two overhead conductors; nor is this a minor matter in railroading. The delivery of power from a contact line to the locomotive is of vital importance and must be made absolutely perfect. Two overhead conductors in railroading, around freight yards and terminals, do not promote simplicity. It is not possible to carry two overhead wires with a difference of potential of 6,000 to 11,000 volts, above the many switches at yards and sidings which are most common in railroading, and make a rugged construction. Long, expensive, and complicated section-breaks are not desirable.

In practice the alignment of American track is not good. Further, the distance between the rail and the trolley of American roads will be from 22 to 24 ft. as a minimum, where European practice shows from 14 to 18 ft. Track irregularities cause the deflecting force at the upper end of the pantograph or trolley wheel to vary about as the square of the height. In railroading it will not do to have the trolley flop off, partly because it will be dangerous in ordinary operation. When there are two or three locomotive units to a train it is absurd to think that locomotive men will give attention to four trolley poles, turning them when the direction is reversed. A pantagraph is necessary, but it is not possible to run a pantagraph over rough switchwork at good speed without danger of short-circuiting the two trolley wires. A difference of potential of 6,000 to 11,000 volts will be used in heavy electric traction.

Modified systems may be used for mountain grades; namely:

1. The use of two trolleys for slow, three-phase freight locomotives; and the single-phase system, using one of the two overhead trolleys, for passenger service, for simplicity, variable speed, and rapid, efficient acceleration.
2. A single-phase, 11,000-volt trolley line and a rectifier on the

locomotive delivering 600-1200 volts direct current for motors. This would make an interchangeable system.

3. Three-phase generation, single-phase utilization from a single contact line, and the H. Ward Leonard scheme with the high-voltage, high-speed, light-weight, single-phase motor-generator which will drive the axles through intermediate low-voltage motors.

4. The use of the three-phase system with two trolleys for heavy grades, and the use of three-phase motor as a single-phase motor from one trolley at all sidings, yards, terminals, shops, etc., in slow speed and light switching work, for simplicity and safety.

Max Toltz (non-member): In regard to the details of the electric locomotive. Transmitting the power by gears from the motor to the axle is street railway practice and is not as good as side-rod construction. The gear transmission with which the Great Northern electric locomotive is equipped makes it unhandy to inspect the apparatus, or to repair motors or to inspect accessories, because it will be necessary to lift the cab and pull the truck from under and then raise the motor, etc. With the side-rod construction smaller wheels can be used, and, instead of four motors, two motors need only be installed above the locomotive frame. This has also the advantage of locating the collector rings where they can easily be inspected and repaired.

The motors should be wound for at least 3000 volts, instead of 500 volts and the former voltage should be also carried by the trolley wires. In that case the transformers on the locomotive between the trolley wires and the motors would be eliminated—a step towards simplification—and at the same time the electrical losses due to transformers will be cut out.

Instead of trolley poles with wheels, bow trolleys with roller contact for each wire could be used having the advantage of overcoming the present trouble of the trolley wheel jumping trolley wires when going in either direction.

An automatic device similar to the one used on the Valtallina electric three-phase locomotives should control the current supply to the motor instead of the common step-down rheostat.

A single speed in the motors is satisfactory for the tunnel operation, but if the whole Cascade division is to be electrified two speeds will be necessary, so that trains going down grade may run at a higher speed.

The transmission lines between the power house and the sub-station would be more reliable if each circuit had its own pole line, one on each side of the railway, for a slide or a falling tree would not put the line completely out of commission.

Trolley wires suspended from messenger cables would withstand harder usage in heavy operation.

In regard to some of the data given in Dr. Hutchinson's paper, exceptions should be taken. The rail resistance is given at 6 lb. per ton, which under the very best of conditions of rail and equipment is 6.5 lb. Dynamometer tests give 6.5 to 14.25 lb. per ton. In the tunnel with its soot and wet rails the resistance used to be over 10 lb. per ton.

The rail resistance of the Mallet locomotive is stated to be 47 lb. per ton, computed from ammeter readings. This figure is much too high, and is probably due to the air pump action of the pistons in the cylinder. It is assumed, of course, that the throttle valve was closed with the reverse lever being in the forward corner notch. It should be borne in mind the cylinders of the Great Northern Mallet locomotive have no by-pass connection, but are equipped with valves, one at each end of the cylinder.

The following results were obtained from tests in which indicator cards were taken simultaneously on all four cylinders of the Mallet, on a level track:

Type of locomotive	Locomotive weight	Miles per hour	Horse power absorbed	Resistance lb. per ton
Mallet	250 tons	8	57 h.p.	10.8 lb.
"	250 "	10	74 "	11.2 "
"	250 "	12	95 "	12.7 "

If Mr. Emerson had given the coal consumption per 100 ton-mile-hours instead of 100 ton-miles the results would have been somewhat different. The writer assumes, therefore, that Dr. Hutchinson's calculations are based upon a speed of 7 to 8 miles per hour, but calls attention to the fact that the most economical work of the Great Northern Mallet is performed at about 11 miles per hour.

The minor advantages of electrification as explained should be called " major " advantages but to these should be added:

1. The saving in locomotive ton-miles due to the elimination of the tender of the steam locomotive.
2. The mileage of the electrical locomotive will also exceed that of the steam locomotive, because the engine need not go to the round house for boiler repairs and need not be turned.
3. The best showing of the electric locomotive as compared with the steam locomotive will be made during the extreme cold weather when the latter will fail in generating the usual quantity of steam, while the former will not be hampered by any temperature prevailing in this country.
4. Also the elimination of all water and coal stations should not be overlooked.

The steam locomotive cannot expect to equal the record made by the New York Central locomotives of only 14 minutes delay in 80,000 train miles.

E. Marshall (non-member): On down-grade through the tunnel the crews were at first afraid to trust to regeneration by the induction motors to do the braking, but a few trips were sufficient to reassure them. The trip through the tunnel is now entirely devoid of danger from this source.

There have been only a few failures due to the electric locomotives. In one case some of the resistance grids were burned out, but the locomotive could be operated. In several cases of overloaded motors the secondary leads of the motors were melted from the rings. Due to inaccessibility the repair of these motors is a difficult task.

The system of current collection by means of a wheel trolley and overhead wires strung similar to street railway lines is not satisfactory. Trolleys leave the wire, tear down the overhead work, and sometimes are the cause of a train breaking in two, due to relieving the load on the locomotive. In case of change of direction the trolleys must be changed; this is sometimes forgotten and the overhead construction suffers in nearly every case. On account of the 5 ft. spacing of the wires in the open, and 8 ft. in the tunnel, the pantagraph cannot be used. It is probable that the overhead work will be changed to catenary construction and bow collectors used, as there is no question about that design being more satisfactory.

On the whole the operation of this system is most satisfactory. The above remarks are not made as criticisms but are mentioned to show that the defects are no greater than one has a right to expect in a system where precedents are so few. Everyone connected with the operation of this system is anxious to see it extended to take in at least all of the track having the 2.2 per cent grade.

Cary T. Hutchinson: I am gratified to see that there seems to be a very general agreement with me that the three-phase system was well adapted for use in this particular place. I believe nearly all of the speakers have assented to this.

I find in the discussion a number of points in which the various speakers differ from me in regard to details, and it is very probable that they may be right and I wrong. I do not think it necessary to discuss these points, but wish merely to answer the questions that have been asked.

In reply to Mr. Katté. The ground wire was omitted as there is no lightning on this side of the mountain. My reasons for saying that probably a three-phase system would have been used even though only the tunnel were under consideration, was because of the far greater capacity of three-phase motors as compared with direct-current motors in the same space, and the lesser cost of construction and operation. Wooden poles were used, as they could be obtained very cheaply and of extremely good quality.

Mr. Arnold and others question the high frictional resistance of the Mallet locomotives. I can only say that these tests were carefully made by competent observers, and I am sure are accurate expressions of the conditions that existed. I of course do not pretend that the internal losses of the Mallet, when operating under its own steam, are represented by these figures; there is no direct comparison between the two conditions.

I do not think that the method of control used on the Italian State Railways referred to by Mr. Waterman would be satisfactory under the conditions of a Western railroad in this country where it would be fatal to install any apparatus requiring careful supervision of operation and maintenance. Everything must be of the sturdiest character, and as nearly as possible "fool-proof."

Mr. Pomeroy gives some very interesting results of coal consumption of heavy locomotives on mountain grades. It should be noted that Mr. Pomeroy shows the coal consumption to be nearly twice as great as I deduced from Mr. Emerson's statements, amounting to from 13 to 19 lb. per kilowatt-hour as compared with 8 lb. Mr. Pomeroy also brings out the very interesting fact that the coal consumption in operation is just double that deduced from test results. I had also arrived at the same figure by the comparison of records of operation with special test runs made on hills—such runs are practically of no value in determining coal consumption.

I agree with Mr. Smith and with others who state that the collection of the current is a very important factor in deciding the type of machinery to be used. The use of the trolley wheel in this particular case was forced upon me, and was not my deliberate choice, as the officers of the road would not permit encroachment upon the overhead space in the centre of the tunnel. It is not at all improbable that some change may be made in this, particularly if the system is extended, and a pantograph may be used.

I am also glad to see that Mr. Smith, in common with others, approves the rating of an electric locomotive by its continuous duty. This seems to be the only sensible way to rate any piece of electrical apparatus, even though it is used in intermittent service. There will of course be all sorts of intermittent service, and the ratio between the actual service and the continuous capacity must be determined for each particular case. A motor, however, having a greater continuous capacity will, other things being equal, be the better motor for any service. Other methods of rating railway motors serves principally to conceal the facts.

Mr. Denneen has emphasized some of the reasons for the use of special features of the overhead construction. In this, as in other matters, I can only say that all the details of this subject were carefully considered.

Mr. Townley questions the continuous capacity of locomotives on the ground of the lower rated capacity of the transformers. It is true that the rating of the transformers is only 800 kw., continuous, with the quantity of air specified but the transformers have an overload rating of 100 per cent for one hour. For the service that the locomotives are now employed in, the transformers have ample capacity, and there is space enough either to install larger transformers in case they are needed for the extended service under contemplation; or what would be simpler, increase the quantity of air to these transformers. This has been done on test. There would be no difficulty by one or the other of these methods in making the transformers equal in continuous capacity to the motors and rating the locomotive at something over 1100 kw. continuous. The control apparatus has been operating regularly at much greater power, and there will be no difficulty at this point. The motors themselves are the limitation to the capacity of the locomotive—not the transformers, nor the subsidiary apparatus.

Mr. Schwartz is of course correct in stating that the coal consumption of a steam station, operating as the Tumwater station is now operating, would be much greater than 3 lb. per kilowatt-hour and might be almost anything. My comparison was not intended to refer to existing conditions but to the service as it would be when handling the entire traffic of this mountain division, and the traffic so arranged as to secure a reasonably good load-factor at the power station, which I regard as an essential to the electrical handling of any train service. In other words, when a division is electrified, the train dispatching must be conducted in accordance with the exigencies of the power station; the cost of any other method of dispatching will be so great that railroad officials will readily agree to this limitation.

If, however, Mr. Pomeroy's figures represent more nearly the coal used in steam service, as I believe they do, then it is not at all certain that a steam station would not give better coal economy, even if operating under as disadvantageous conditions as now exist at the Tumwater station.

Mr. Toltz gives some interesting figures for the frictional resistance of Mallet locomotives based on the indicated power in the engine cylinder. As I have said above, there is no necessary connection between the power so used and the power required to tow the same locomotive. I do not, however, think that much reliance can be placed on indicator cards, taken under the conditions described by Mr. Toltz. It is to be noted that the figure he gives for the total resistance of the locomotives, of say 11 lb. to the ton, is about the same as he states the rail resistance should be, which he gives at from 6.5 to 14.25 lb. per ton. The 6 lb. to the ton that I used was given me by the chief engineer of the railroad.

Mr. Marshall has referred to some accidents to the overhead structure, due to trolleys leaving the wire. This has been due largely to the impossibility of keeping this overhead structure in proper alignment, owing to the fact that little or no time can be found for working on this structure, on account of the exigencies of the train service.

Parker H. Kemble (by letter): The handling of traffic on railroads has now been a business and a study for some eighty years. Certain broad principles have been laid down and methods developed which are worthy of attention in discussing or selecting a method of electric operation. A change of motive power does not imply an overturn in methods. Electric power does mean larger loads, greater speed possibilities, and greater range in grades without change in weight of train or type of locomotive; in other words, improved tools for the use of the traffic manager. The broad principles remain as before. On a railroad system of varying profile, the present system provides locomotives of moderate weight and high speed for levels, heavier and slower engines (or else lighter trains for the same engine) for the moderate grades, and Mallet specials and pushers for the steepest ridges of the divides.

To handle this traffic, what does electricity offer? In the alternating-current division there are two main systems at present —single-phase and three-phase. These are of essentially opposite characteristics. Neither will fulfil all the requirements of railroad traffic over varying profile. Each is perfectly adapted to handle a particular grade or condition. In combination they fill all requisites.

As regards power stations they are identical; both generate three-phase, 25-cycle current at about 11,000 volts pressure; as regards transmission line, even where all the power would ordinarily be taken from one phase, the combination would require but one more transmission wire with the added advantage of a possible balancing of load. As regards contact line, the extra wire shown in the paper under discussion can be easily installed.

A modification of the single-phase pantagraph would be necessary, but that would be about all the change. On the levels and slight grades the single-phase motor with its high acceleration variable speed, and variable torque, complies with the traffic requirements. On the heavier grades another wire is strung over the track and the three-phase motor comes in to add its valuable grade-climbing abilities and safe down-grade speed control to the other.

It does not seem beyond the possibilities of multiple-unit control to imagine these two motors working together. At any rate, were the three-phase motor to be restricted to the role of pusher, the single-phase motor could surely carry its own weight. With the rapid progress in alternating-current motor design, a combination of types for certain profiles might be available.

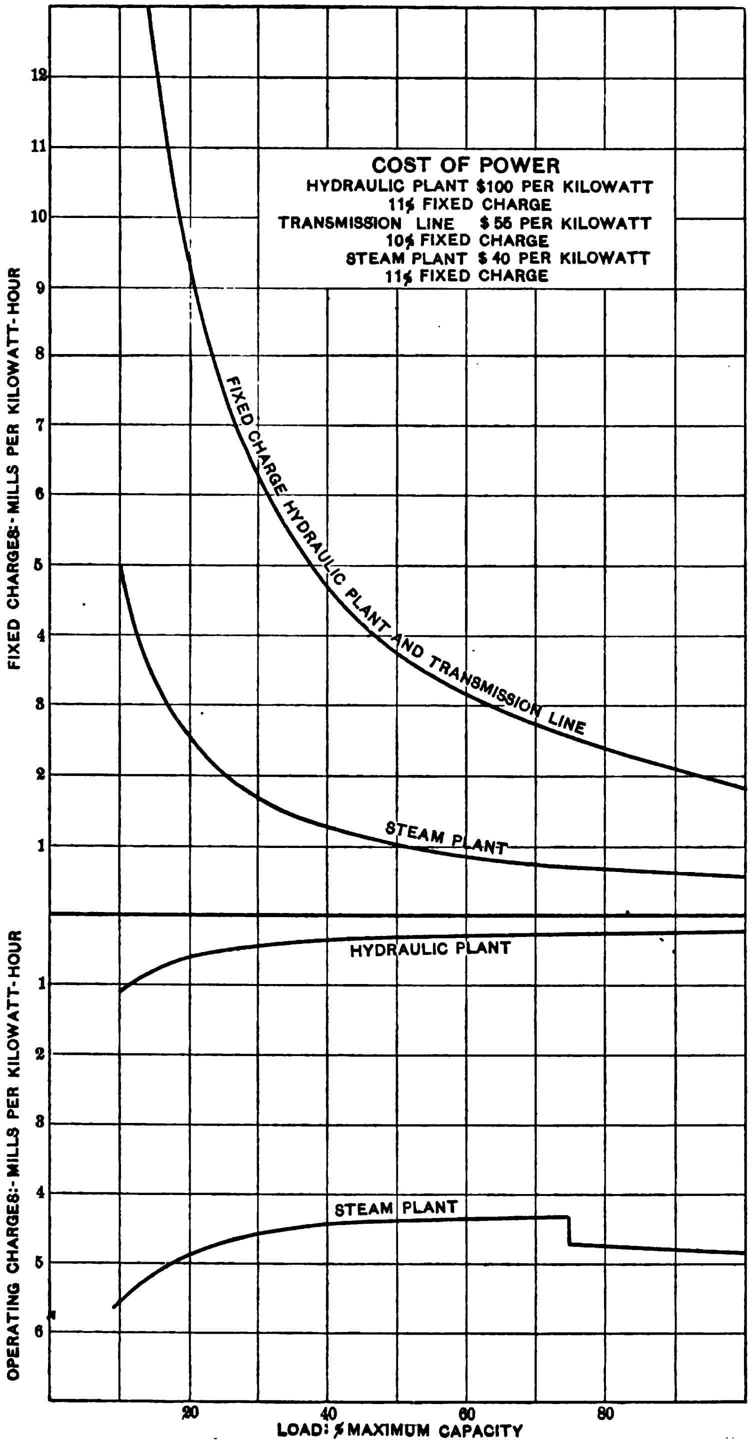
COST OF POWER
HYDRAULIC PLANT $100 PER KILOWATT
11% FIXED CHARGE
TRANSMISSION LINE $55 PER KILOWATT
10% FIXED CHARGE
STEAM PLANT $40 PER KILOWATT
11% FIXED CHARGE
FIXED CHARGE HYDRAULIC PLANT AND TRANSMISSION LINE
STEAM PLANT
HYDRAULIC PLANT
STEAM PLANT
FIXED CHARGES:- MILLS PER KILOWATT-HOUR
OPERATING CHARGES:- MILLS PER KILOWATT-HOUR
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
20
40
60
80
LOAD: % MAXIMUM CAPACITY

Fig. 1

mercial reasons may prove to be more important. I think it will be found if we could take an ideal condition, such as the lighting of a large city, and get a load curve put before us, that we would probably not end by wanting all our power from a hydraulic plant. We would find it desirable to generate part of that power (and for many reasons) from a steam power plant. I have gone over that part of the subject very thoroughly, and agree that there is only one type of steam plant to consider, and that is the steam-turbine plant; that type can be modified so as to cut the investment charges in two. I will refer to a few curves which I think will bring out the fact that in considering a reserve plant, there is only one problem we have in hand —the fixed charges. The operating charges are almost negligible as compared to the fixed charges.

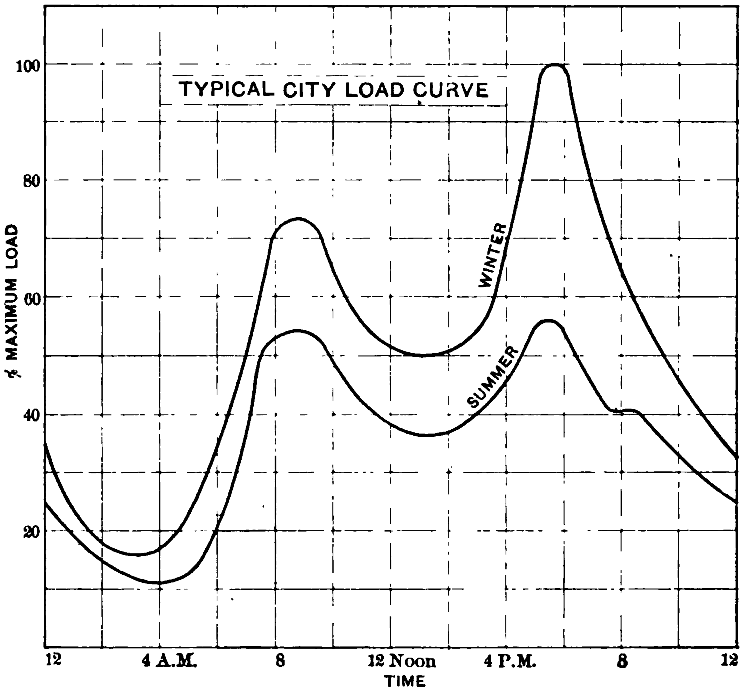

Fig. 2

Mr. Doherty referred to the efficiency of boilers. The question before us is how the reserve plant shall be operated as a reserve on the hydraulic plant? The suggestion is here made that powdered fuel should be used, but no furnace has been found so far that will stand powdered fuel. The heat generated is so intense that no brick work can stand it. The other alternative to holding the steam plant in reserve, is to operate it every day during peak loads. That is another point I will show in these curves. In order to bring something definite before you, I built up a load curve which may be representative of any

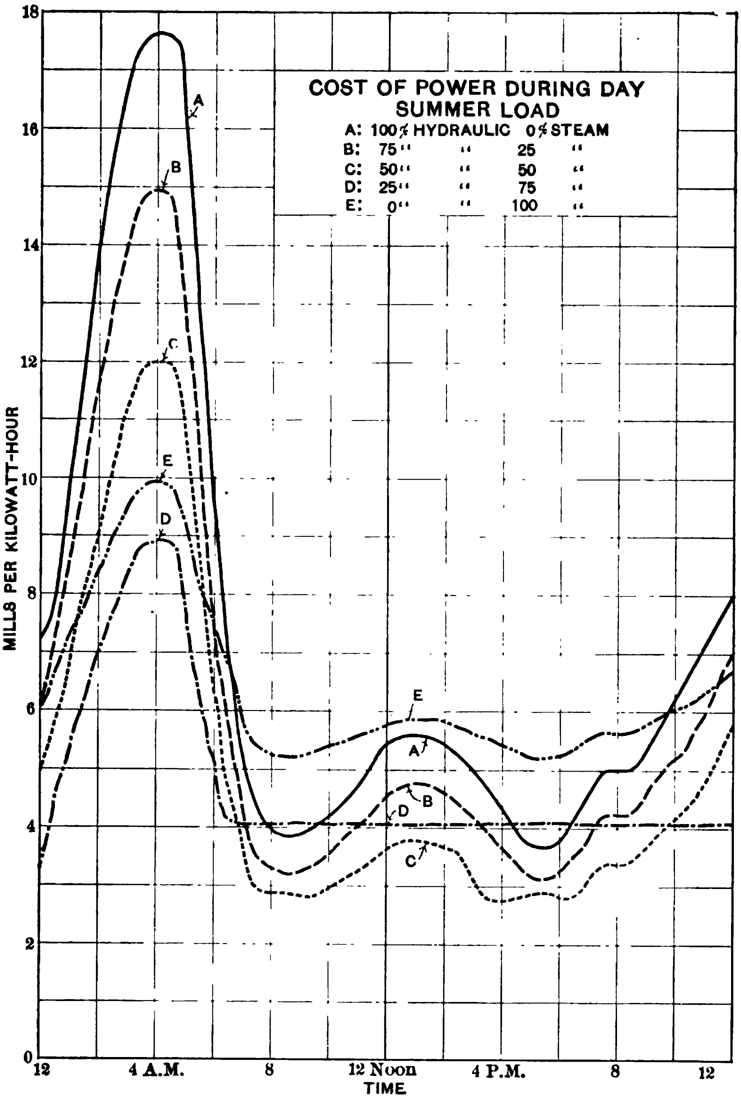

FIG. 3

large city: it is made up of a lighting load, a railroad load, and industrial-power load. In making these curves and calculations it has been necessary to make a number of assumptions. I cannot think in arbitrary units, as Mr. Doherty has done, so have used dollars and cents, and have therefore assumed certain costs.

Fig. 2 is a load curve which is typical of that obtained in our large cities, the lower curve being the summer load, and the upper being the winter load. These are both shown, and for a good reason. I have taken the ordinary hydraulic plant and assumed a cost of $100 per kilowatt, and $55 per kilowatt for a double transmission line of 100 miles. That makes a total investment per kilowatt of power delivered, including the step-up and step-down transformers, of $155. The total fixed charges are assumed to be 11 per cent on the plant and 10 per cent on

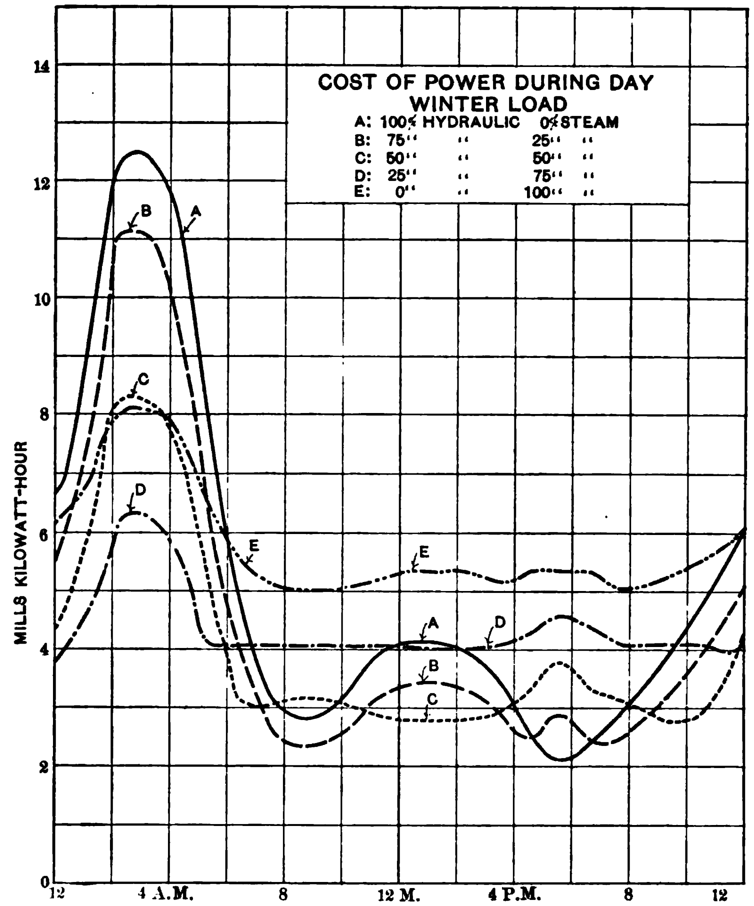

FIG. 4

the transmission line, annually. You will notice that the steam plant investment is $40 per kilowatt. That cost was arrived at in this way: a first-class steam-turbine plant will cost in the neighborhood of $80 per kilowatt. Supposing we order a 5,000-kw. unit, and stipulate that the generator shall have a rated capacity of 7,500 kw., and we also stipulate that there shall be a by-pass connection on the turbine, permitting high-pressure steam to be admitted to the second or third stages. This at

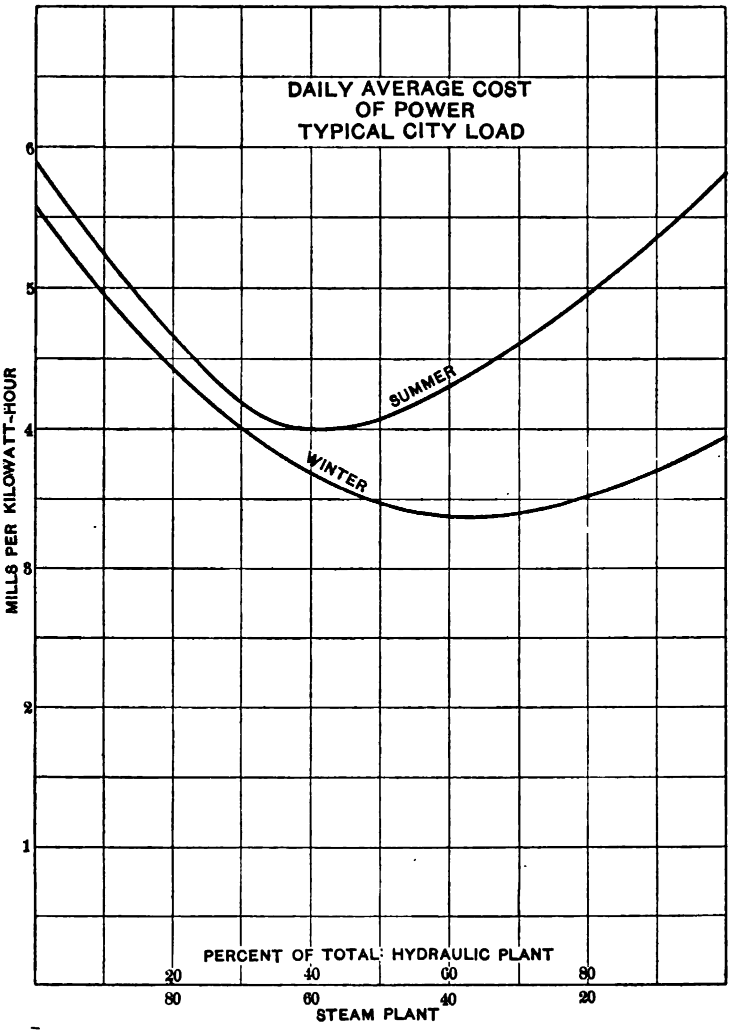

FIG. 5

once enables us to generate 100 per cent above the rating of the plant during peak loads, at a very small reduction of efficiency. The boilers should have a ratio of grate area to heating surface of 1 to 30, thus enabling us to drive them at 200 per cent of rating when necessary. The fixed charges at 10 per cent load-factor on the steam plant are 5 mills, whereas on the hydraulic plant and transmission line they are 15 mills.

Fig. 3 represents the results obtained from a combination of hydraulic and steam plants as applied to the summer load curve in Fig. 2. The curve *A* is a hydraulic plant. The costs shown are not operating and maintenance costs alone, but also fixed charges; in other words, they represent the sum of the ordinates in Fig 1. The total costs between 1 a.m. and 6 a.m. are very high, due to the fixed charges, as shown in Fig. 1. The hydraulic plant at no point of the load curve is the best. Curve *B* is 75 per cent hydraulic and 25 per cent steam. That you will notice is also practically all the way above the others, the lowest average cost being reached in curve *C*, which is 50 per cent steam and 50 per cent hydraulic. It is, of course, impossible to generalize from these statements, as I have had to assume certain fixed conditions, and every load curve must be studied by itself.

I do not wish to say that this is a general solution of the power question but it simply illustrates how it can be solved in one particular type of load curve.

Fig. 4 gives the series of curves for winter. Here you find that the conditions have changed, for the one giving the best average is not curve *C*, 50 per cent of each, but is now *B*, 75 per cent hydraulic and 25 per cent steam, and illustrates very clearly how these proportions vary at different times of the day. Not only the load-factor, but what might be called the diversity-factor should be considered; that is, the time and the shape of the load curve.

Fig. 5 is practically a summary of the other curves and shows, when applied to these two particular load curves for summer and winter, which combination gives the best average results. These curves clearly illustrate the average cost of power with different combinations of hydraulic and steam. The best combination for winter is 60 per cent hydraulic and 40 per cent steam. In the summer curve we find that 40 per cent hydraulic and 60 per cent steam gives the best results.

S. E. Doane: The discussional tone of Mr. Doherty's paper tends to conceal or render less conspicuous many of the statements he makes. In a paper on "Rates" read before the National Electric Light Association in 1900, Mr. Doherty advocated a single service charge made up of two charges for two classes of service, as well as another charge for each kilowatt-hour. The purpose sought was to make the cost to the consumer depend upon the cost of supplying such consumer.

To his advice I think we will now universally agree, although there is some discussion as to whether the embodiment of this theory in the particular system he described is one which will be universally adopted, if any one system can be universally adopted. We should remember that Mr. Doherty's paper particularly disclaimed any advocacy of any universal system of rates, but that he did advocate the universal application of a principle. Recalling the discussion occurring at that time, it seems to me it was very largely overlooked that the paper really was in support of a theory and the embodiment of the theory in some comprehensive system was advocated on the ground that if it was right then there was nothing to lose and everything to gain at some later time, when the inevitable improvement in efficiency of incandescent electric lamps would find many systems of rates insufficient to meet the changed conditions. In other words, Mr. Doherty advocated that even though the weather were fair we should embark in a ship that could weather a storm. Since the introduction of the tungsten lamp many engineers have recalled his position on this matter.

Mr. Doherty speaks specifically of the effect of increase in efficiency of heat engines upon the value of hydroelectric plants. In round numbers let us say that the highest practical efficiency from the coal pile to the steam-driven fly-wheel is now about 10 per cent, and that for a gas engine the efficiency is about 20 per cent. This leaves a wide margin for improvement, and is a situation similar to that existing in the lighting industry at the time of his paper on rates.

His qualifications of the value of hydroelectric plants due to the possibility of increased efficiency of heat engines is most interesting. Mr. Doherty may only see possibilities for improvement, but it is a fair question to inquire specifically if he has any knowledge of any work of this character of special significance at this time.

He points out that every undeveloped water power represents a constant source of unnecessary fuel consumption. He testifies to the importance of the movement to conserve our natural resources. He states, further, that in this movement the most important feature is the conservation of our various fuel supplies. These statements are made in a simple and commonplace style, but their importance is worth serious attention. We can replant our forests—there is an enormous margin of increase possible to the fertility of our soil—but already certain districts have found their fuel supply exhausted and other districts face fuel famine in the immediate future. The mild language used in stating the importance of the speedy development of our water powers as a means of conserving our natural resources is entirely inadequate.

I do not pretend to see this problem more adequately than the author of this paper, but I regret that he did not confine his whole paper to this single subject. There is much of value and importance in this paper under other subjects, but there is no discrimination between the knowledge imparted which is of great importance and that which is of only minor importance.

Had the author cared to, he could have pointed out that nitrogen is the important element in maintaining the fertility of the soil, and that at present we largely depend upon our coal to supply this nitrogen. The coal burned under our boilers yields no nitrogen for fertilization, while the coal distilled for gas-making, and the coal carbonized for coke in modern ovens, yields appreciable amounts of nitrogen in the form of ammonia. So the fuel saved by the development of water powers means not only a direct fuel-saving but also the conservation of the material from which fertilizer may be produced. Few people to-day look upon our coal beds as immense deposits of fertilizer. Aside from our beds of natural fertilizing material, we depend almost entirely upon the nitrogen of our coals. Another method of nitrogenous production in form for fertilization is by means of electricity. The known processes for the fixation of nitrogen for the purpose of fertilization depend upon a production of power at a cost far below that price realized by the use of heat engines. This means the utilization of cheap water powers.

The products now used are either difficult of transportation or are bulky and mean much weight and much expense for freight transportation. The author has already pointed out that electricity may be transported to other localities at a lesser investment cost and with greater economy for irrigation purposes than for any other purpose. He might have pointed out that power could be generated at one point and transmitted to a point many miles distant for the creation of fertilization products at their point of application, thus necessitating the transportation of only one element of the product necessary for fertilization—transporting this by means of electric energy at a much less cost than matter which is acted upon by gravity can be transported by the usual means.

Mr. Doherty speaks of the failure to realize the predictions made by the investigating engineers in construction of hydroelectric properties and a reader might be led to believe that the investigating engineer is entirely to blame. This is certainly not always the case. Many of these disappointments have been due to mismanagement and tardy action on the part of others. The investigating engineer can only say what can be done, assuming reasonably competent management in every branch of the undertaking. In permitting his readers to believe that the investigating engineer is solely to blame, Mr. Doherty has in this one instance done a grave injustice to his erstwhile professional associates. I venture to maintain that even with the same investigating engineers, and no difference in the original report, few of these disappointments would have been realized had the execution of the entire enterprise been in the hands of any experienced and competent organization. Without wish to shirk responsibility, it is the duty of the engineer to place the blame where it belongs. It is an easy matter, but often unfair, to place the blame upon the investigating engineer. Were I doing this class of work, I should qualify my report by saying that I was unwilling to take the responsibility for the results promised, unless the financial, legal, organization, construction, contracting, and operation work were placed—if possible without divided authority—in the hands of people considered competent by me.

Strained financial ability, inexperienced direction, inharmonious relations between the various financial interests, unreliable contractors, incompetent construction superintendence, ignorant management of market development, ill-considered changes from original plans, and incomplete operation of the plant after completion—all have played an important part in the disappointments which have been realized. How unjust it is to blame the investigating engineer for the incompetency of every element which enters into the various divisions which go to make up the sum of the successful going plant, starting with simply a prospective stream development!

Financial means sufficient to control a corporation does not insure competency in any of these numerous branches. Mr. Doherty can well say that the proper investigation of a water power proposition is an expensive matter; and he might have added that the ordinary promotion house is loathe to spend its own funds beyond the extent required for writing an attractive prospectus.

Mr. Doherty says that the less known about a prospective development the greater attractiveness can be given to the enterprise, and he further states that " we are apt to have the condition that only the poorer projects will be developed." I do not deny the correctness of this statement, but why speak of it wholly in the future tense? Is this not in a large measure the condition which has existed for at least the past three years?

If my remarks are seemingly a criticism of Mr. Doherty's statements, or his method of statement, it will be a matter of much regret to me. His statement of the relative increased valuations of quasi-public and other properties, in his presidential address before the Northwestern Electrical Association in 1899, his paper on " Rates " at the Chicago Convention of the National Electric Light Association, his extension and amplification of Thomson's Law for determining the selection of transformers, his work on the proper selection of lamp efficiencies, have all been stated in a manner which made little impression at the time, but appear of vast importance in looking back over the several intervening years. I venture the opinion that his paper on " Organization ", read at the Chicago Convention of the National Electric Light Association in 1908, and this present paper, either for their contents or their results, will ten years from now seem of much greater importance than they do now.

Mr. Doherty speaks of the retardation of electrical development owing to the confusion of methods of charging for current and misunderstanding of terms. This point is of sufficient importance to be worth consideration, but it seems to me the importance of this matter is almost completely eclipsed by the bad effects resulting from the use of systems of charging which are both irrational and inequitable.

All electric energy supply companies are furnishing not simply energy but service as well. The expense to provide service to each consumer bears no universal relation to the energy furnished to each consumer. To charge purely upon the basis of the energy supplied, without regard to the service supplied, or vice versa, means inability completely to develop the profitable market, and results in unjust inequalities between consumers and an aggregate charge for electrical employment beyond that which would be necessary if a rational system of charging was used.

No one can successfully deny that even within the profession an unwarranted difference of opinion exists regarding rates. This, therefore, seems to me to be a proper subject for comprehensive treatment by this Institute. The reference to rates and methods of charging in Mr Doherty's paper makes this a suitable time to consider the advisability of appointing a committee to handle this subject in much the same way as the High-Tension Transmission Committee has handled its subject. It is difficult for me to refrain from entering upon a discussion of this subject, but the time is too limited to do more than urge its complete treatment at some future time.

Under the heading of " Methods to insure against interruptions or to lessen the harmful effects of interruptions " Mr. Doherty speaks of rotating a steam or water turbine at full speed by using the generator as a motor, with a governor which will operate by a drop in voltage or frequency, opening the steam or water valve and immediately placing the unit in service as a generator. The expense for this will be partly offset by the use that could be made of the generator under such conditions to regulate the power-factor of the system. So far as I know this has never been done. I am endeavoring to emphasize this suggestion so it will not be overlooked if it has merit.

Under the next heading there is much that seems to have deserved more extended treatment. The suggestion that we do not know as much about boilers as we should is probably true. More knowledge is needed regarding not only their efficiency from no load to maximum load but also the maintenance of this initial efficiency.

The suggestion regarding the ultimate capacity of boilers and the various features which fix the limit should not be allowed to drop without further discussion, either by the author or other members of extended experience in boiler work. I cannot concur in the belief that the Scotch type of boiler promises greatest economy for this work. It seems to me its relative large water-content would alone be a serious objection. My opposition on this point to the views expressed in the paper are prompted solely by a desire to bring out the reasons behind this statement.

The writer refers to the starting of boilers by the use of oil as an auxiliary to coal-firing. Natural gas is not infrequently used where natural gas and coal equipment are used somewhat indiscriminately for firing, but I did not know that natural gas or oil were ever installed deliberately for the purpose the author suggests. If this method is in use and is not a new suggestion it would have benefited many readers had some examples or some literature on the subject been cited. The suggested use of powdered coal is also valuable, but it is open to the same comment; namely, that additional information would have greatly benefited the readers of this paper. My present information prompts me to say that except for cement burning, powdered coal is rarely used, and while we have the author's statement that " it is ideal for the class of service under consideration " and are willing to accept his opinion, yet we would appreciate his opinion as to how to study the problem to determine whether we can adopt it.

The method of " insurance against interruptions " is certainly both ingenuous and novel. It would not be difficult for any reader to identify the inventor of this method. Whether this method is generally applicable or not I am not competent to say. It seems to me that the time of day or night when the interruption occurs is a factor that should be considered in fixing the time of running the steam plant to insure against future interruptions. I do not consider myself competent to add any information of value to this subject, but I do think that lack of knowledge on this point, and lack of knowledge regarding rates and the factors which go to make up the cost and value of service, has prevented many supply companies from selling their service and many prospective purchasers from availing themselves of a service advantageous to them. Simply the inability of the purchaser and seller to understand how to buy and sell has played an important part in the retardation of electrical development. Not only this but it has probably been the foundation for unnecessary competition.

It seems to me that Mr. Doherty touches upon a fundamental reason for the slow development of a market which will apply not only to the case of hydroelectric plants, but more widely and with just as great force to all central station work. The public must be made to understand the value of cost of service as well as the value of the electrical energy. Illogical and unjust methods of charging have served greatly to retard the fullest and most complete utilization of the capital invested in central station securities. As Mr. Doherty says, the fault in this matter lies to some extent with the electrical fraternity itself which it seems has not yet fully realized the importance of this question, so vital to the commercial success of its efforts. The engineer may make the physical plant as perfect from the purely engineering standpoint as anything on this world of ours can be. With this task complete, however, his duty is not done. He must do all he can to enable the plant to be used to the greatest advantage, and in doing so must become commercial enough to apply his engineering principles to the construction of a rate system which must not only be equitable but which will allow the greatest opportunity for future healthful development. The engineers and commercial men must work together. Engineering dictates must be accepted by the commercial man as the basis of operation. He must build on a solid foundation, otherwise his commercial structure will probably be seriously injured by some future and perhaps unforeseen development.

Systematic and logical cost-keeping methods have served to demonstrate that there are some principles of rate-making which cannot be disputed. A few years ago the idea of embodying them in a rate system was scoffed at. Some stations, however, with sufficient faith in their convictions, have demonstrated the entire feasibility of such procedure with satisfaction to their customers and profit to themselves. The complicated nature of the cost of the production of electrical energy and the comparatively slow progress in its understanding, should be a challenge to the Institute to investigate and establish correct principles, thereby placing the entire matter of rates upon a sound and logical basis. I think that this Institute should be a forum for the consideration and solution of such problems. These comments are prompted by the belief that the importance of proper methods of paying for or insuring against interruptions of service, together with a better understanding of matters pertaining to the method and rate of charge and the value of service, are not properly recognized. It seems to me that the method of insurance proposed by Mr. Doherty would be very expensive; for this reason I should like to see specific figures of the cost of this method.

That the investment and maintenance cost for meters alone for large groups of central station consumers is greater than the investment and maintenance cost of the generating equipment needed for their supply is a startling but probably true statement. It illustrates the fact that we are furnishing an expensive service entirely aside from the energy supplied. This fact also seems to sustain the position taken by Mr. Doherty in his paper entitled " Equitable, Uniform and Competitive Rates ", in which he maintained that a uniform charge to each customer in addition to the capacity and energy charge was essential if equity were to be maintained as between all consumers.

In illustrating the usual characteristic difference between the elements of the cost of supply for a steam plant in comparison with a hydroelectric plant, Mr. Doherty's method is, I think, a valuable addition to the proper understanding of the problem. Under usual conditions there will always be some certain load-factor where the total costs are equal.

Mr. Doherty speaks of the need of maximum development of a stream in relation to the conservation of our natural resources. He also speaks of the advisability of giving hydroelectric companies the right of condemnation. It is hard to see how the maximum development of a stream can be secured without the right of condemnation, although this right alone will not insure the result which is sought. It seems to me that Mr. Doherty's position regarding the right of condemnation must be conceded by all as correct.

This brings us to the question of " how can maximum stream development be assured, even given the right of condemnation." It is an easy matter to see how hasty or unintelligent planning may bring about developments at the wrong locations, or of a character that will permanently limit the power yielded by the stream to a small fraction of the total power available.

It is also easy to see how inadequacy of funds may necessitate a 30-ft. development at the wrong location while a 100-ft. development was possible at the right location. It is also easy to see how this inadequacy of funds may forbid the purchase of land for reservoirs which would enable the flood waters to be stored and used for power purposes. I have no adequate solution to offer to this problem, and can only make one minor suggestion. It occurs to me, however, that by restating this problem it would perhaps insure not only greater interest in the solution of the problem but would also call the attention of a greater number of people to the problem. The obvious suggestion is that complete surveys of every stream capable of yielding power be undertaken by the Federal or State Governments, and that these surveys be directed to determining the nature of the development necessary to secure the maximum power from each stream. Since many states have spent large sums of money in their geological surveys, to locate coal, clay, cement rock, and other natural resources, it does not seem unreasonable for these same states to investigate their streams as a means of conserving their natural resources.

There remains now but one more point; namely, the maximum hydraulic development which commercial economy will warrant. When Mr. Doherty says that this development can be increased until the available water will permit some of the generating units to be used but four days in the year, it cannot be designated as other than a startling statement. It is so contrary to general methods now in vogue that it should not be allowed to stand without discussion as to its accuracy. Mr. Doherty gives an example in which the cost for steam power is cheaper for any load-factor less than 38 per cent, and then he says that " the operation of a water turbine for 100 hours per year will, in some cases, warrant its installation ". It will be noted that 100 hours would represent a load-factor of only 1.14 per cent while the example given represents a use of equipment for 3328 hours, or 33 times as long.

I do not assume that the author of the paper is in error, in fact I believe he is right, but I do think that these two statements will seem contradictory or confusing to some of his readers unless further explanation is made. No doubt Mr. Doherty has long ago formulated some law for the determination of the maximum power which can be developed with commercial economy, and the statement of this law by him would add much to the value of the information contained in his paper.

I wish to give a word of explanation regarding my reason for presenting such a lengthy discussion. It is simply this—a paper merely presented before an engineering society is very often read in a cursory manner without the careful study it deserves. If the discussion serves to bring out various views upon the important principles involved it not only makes us think more carefully about what the author has said but it shows us new ways of looking at a subject that may at least be interesting.

Those of us who are interested in central station work have learned that what Mr. Doherty says, or writes deserves careful study, and I hope that by touching upon the points in his paper which seem of the most importance to me I may have helped to concentrate the interest of the reader upon them and perhaps caused thereby a second and more careful reading of the original article.

Cary T. Hutchinson: Mr. Doherty's paper offers a number of opportunities for comment, among them the matter of depreciation of hydroelectric plants. This is probably one of the most important matters touched on, and there is comparatively little regarding it in the literature of engineering.

Much data have been made public recently concerning depreciation of steam generating plants by the various public authorities, particularly the public service and railroad commissions, and the testimony of well known engineers is accessible. There seems to be a general consensus of opinion that the depreciation from " wear and tear " of a steam electric generating plant will vary from 5 to 7.5 per cent, and that in addition to this there is an entirely independent depreciation due to " obsolescence "; this also is put at from 5 to 7.5 per cent.

The heavy depreciation on such plants is due to the fact that all the machinery used is subject to very great wear and tear, and further that the type of steam generating plants changes rapidly. One has to go back only a few years to recall the gradual progression from small high- and low-speed engines belted to generators, to high- and low-speed engines direct connected; then to the marine type of engine, either compound, triple, or quadruple expansion direct-connected to generators —finishing with the most advanced type of reciprocating engines, as seen for instance in the Interborough plant in New York. But we all know that this type of plant is now considered in great part obsolete, and that new plants are building almost exclusively with steam-turbines in very large units, such as shown by the new Waterside plant in New York and the Quarry Street plant in Chicago. It is probably safe to say that the average life of any type of steam generating apparatus has been less than 10 years, although of course many plants have been in operation for a longer period of time. New York affords an excellent instance of obsolescence; it was only 25 years ago that the old Pearl Street Station of the Edison Company began operation. Since then that company has built and abandoned at least four distinct types of station, and would probably now consider as obsolescent the Waterside No. 1 completed only eight years ago.

Nor is there much reason to think that the end of this period of change has been reached. There is in sight the development of the internal combustion engine, the possibility of gas-turbines, and, for all we can say, of other means of converting the energy of coal into mechanical energy, which at present have not even been suggested. The fundamental reason for this is found in the very low efficiency of the process of converting the heat energy of coal into mechanical energy, 12 per cent being about the best figure for steam plants and, say, 25 per cent for gas-engine plants. There is obviously a wide margin between these figures and the best that may be imagined, and on this account a liberal allowance must always be made for depreciation due to obsolescence of plants of this kind.

With a modern hydroelectric generating station the matter is quite different: first, because the kind of construction is much less subject to depreciation through wear and tear; secondly, because the efficiency of conversion is much higher, and therefore there is not the wide margin for improvements. The efficiency of conversion in a modern hydroelectric plant from the theoretical energy of the water to the output at the bus-bars of the power house will be about 75 per cent, leaving a theoretical margin of only 25 per cent for all improvements. The efficiency of large electric generators and transformers is so high that there is no reason ever to expect material improvement in this direction; probably the cost of such betterment would exceed the advantages to be derived. There remains only the efficiency of the water wheels, and although this will undoubtedly be increased from the conventional figure of 80 per cent to 90 per cent, possibly this improvement would result in an increased output of only about 10 per cent, whereas with the steam plant the theoretical improvement may be put at from 200 per cent to 500 per cent.

The history of existing water power plants, as at Lowell, Lawrence, and other places, shows that they have a good long life; they are relatively stable in comparison with steam plants. These facts and consideration of the character of the machinery leads to the conclusion that depreciation due to "obsolescence" in a modern hydroelectric plant will be small.

An analysis of the depreciation of such a plant is given in Tables I and II. Table I covers the cost of construction of a modern, medium head, hydroelectric plant of large capacity, delivering energy at comparatively short distances in large blocks. While this table does not pretend to be exact for any one plant, yet I believe it to be fairly typical of construction of this character. It of course does not apply to the high-head plants in the West with flumes or ditches or steel pipe lines.

TABLE I

Cost of modern medium head hydroelectric generating and transmission plant

Item	Proportional cost
1. Riparian rights for dam and flowage basin, real estate, franchises, organization expenses, preliminary legal expenses, cost of financing, removal of railroads, highways, bridges, and all expenses preliminary to actual construction work	20
2. Permanent construction, dam, power house, and waterways, etc.	30
3. Equipment of power house	14
4. Transmission system	13
a. Right-of-way 4.50	
b. Copper 1.50	
c. All else 7.00	
Sum	77
5. General expense, engineering, administration, legal, etc.	11
6. Interest during construction	12
Total	100

Item I of Table I covers the many costs that must be met, exclusive of the actual construction costs. Item 2 is principally made up of rock excavation and concrete. Item 3 is for the usual equipment, comprising water wheels, generators, switchboard apparatus, transformers, and the various small parts of the power-house equipment. Item 4 covers the transmission system, including sub-stations. Items 5 and 6 are self-explanatory. Of these items only 2, 3, and 4, comprising in all 57 per cent of the total, are subject to depreciation; and of these the greater portion of Item 2 is not subject to depreciation, as it covers rock excavation and concrete almost entirely.

Table II gives an estimate of the depreciation of the plant based on the cost given in Table I.

TABLE II

Depreciation of system

Items of Table I	Proportional cost	Assumed life	Annual amount for depreciation, in per cent of total cost
1	20%		—
2	30	50	0.168
3	14	20	0.458
4	13	20	0.415
5	11	—	—
6	12	—	—
			1.041%

Equivalent to an average life of about 39 years.

This table is calculated on the basis of the assumed life given for the different parts of the plant, the annual charges being compounded at the rate of 4.5 per cent.

Table III shows in detail the proportional parts of the total cost of the various elements going to make up Items 3 of Table I, and the life assumed for the different parts, together with the annual depreciation. This gives the total annual depreciation charge of 3.4 per cent, making the equivalent life of the power house as a whole 19 years; in Table II this is taken at 20 years.

TABLE III

Depreciation of equipment of power house

Item	Proportional cost	Life years	Annual amount for depreciation in per cent of total cost
1. Stop logs, gates, and other wood exposed to air and water..........	0.80	5	0.146
2. Flooring, roofing and hardware, and miscellaneous fixtures...........	9.80	15	0.472
3. Tile wainscoting, sewage, plumbing system, and metal window frames, etc............................	2.45	15	0.118
4. Electric light and telephone........	0.80	10	0.065
5. Switchboard equipment...........	4.35	10	0.355
6. Cables and heavy wiring...........	3.90	10	0.318
7. Cranes..........................	1.25	15	0.060
8. Water wheels....................	33.75	25	0.757
9 Water-wheel governors............	2.90	10	0.235
10. Generators and transformers.......	40.00	25	0.898
	100.00		3.423

3.423%—Equivalent to average life of 19 years

Tables IV and V show similarly the details of the cost of the transmission line, and of the sub-stations which taken together make up Item 4 of Table I. The equivalent life of the transmission line is 26 years and of the sub-station 20 years. In Table II both are taken at 20 years.

The reason for the low depreciation on the transmission line is the comparatively high cost of the right-of-way, 45 per cent of the total. This together with nearly 25 per cent for copper makes the depreciation on the whole system low. The total depreciation due to wear and tear on a hydroelectric system of this character may then be placed at approximately 1 per cent, equivalent as a whole to a life of about 39 years, approximately the life of the bonds usually issued for the construction of plants of this character.

TABLE IV

Depreciation ot transmission line

Item	Proportional Cost	Life years	Annual Amount for depreciation in per cent of total cost
1. Right of way	45.	—	—
2. Towers	18.4	15	0.885
3. Special structures	5.1	10	0.415
4. Insulators	2.1	10	0.170
5. Copper	23.7	25	0.530
6. Installation	5.7	—	—
	100.0		2.000

Equivalent to about 26 years life

TABLE V

Depreciation of sub station

Item	Proportional cost	Life years	Annual amount for depreciation in per cent of total cost
1. Land	6.0	—	—
2. Buildings	30.	25	0.67
3. Transformers	40	20	1.28
4. Switches, etc	16	10	1.29
5. Installation	8.	—	—
	100.		3.24

Equivalent to 20 years

It is difficult to see why in plants of this character there should be any charge for obsolescence; once in operation there is no sufficient inducement to change the principal features of its construction; in fact, these features cannot well be changed, as they are fixed in the original design. It is understood that switching apparatus may change, transformers, may change to some extent, and the minor appliances change, but the depreciation charge for wear and tear should cover all these features. The water wheels can only become antiquated by the introduction of something very much better, and the possibilities are not great. With these facts in mind, I believe that an additional depreciation charge of 1.5 per cent for obsolescence is certainly a very liberal estimate.

The fixed charges on the two classes of plants can then be taken somewhat approximately as given in Table VI.

TABLE VI

Fixed charges of steam and water-power generating plants

	Steam	Water
Interest	6.00%	6.00%
Insurance	0.50	——
Taxes	0.50	0.50
Depreciation	5.00	1.00
Obsolescence	5.00	1.50
	17.00%	9.00%

The total annual charge on a steam plant will be about 17 per cent, and on a water-power plant of the character under consideration about 9 per cent on the investment; if the investment were even approximately equal, the water-power plant would be able to deliver energy at a much lower price than the steam plant, but this is far from the case. A modern steam-turbine plant of large size can be built for $80 per kilowatt of rated turbine capacity. There are very few hydroelectric plants that have cost as little as $150 per kilowatt of rated capacity; generally the cost will run up from $200 to $300 per kilowatt of power delivered at the sub-station bus-bars, including all costs of the generating and transmitting system. For the purpose of determining the relative cost of energy supply by the two systems, $200 per kilowatt of delivered power will be a fair price for the hydroelectric plant, rather favorable than otherwise. The operating cost of the steam plant may be taken at say 0.5 cents per kilowatt-hour and of the hydroelectric plant at $2 per kilowatt per year of plant capacity, irrespective of output. The annual charge on the steam plant then becomes $13.60 per year and on the hydroelectric plant, including the operating cost, $20.00.

Table VII based on these figures then gives the cost of energy for the two plants for various annual load-factors; the cost for the hydroelectric plant is seen to be much lower, under all conditions of practical operation.

It is, however, ordinarily not the cost but the selling price of the energy from a hydroelectric plant that has to be considered. Ordinarily a hydroelectric plant is built to supply a market already supplied by steam plants, and the hydroelectric company is expected to sell to the steam company at a price less than the bare operating cost of the steam plant, the argument being that the operating company would have to carry fixed charges on its steam plant whether or not it is operating. The hydroelectric plant at the same time is expected to make a profit. Taking this profit at 6 per cent on the investment, or $12 per kilowatt of plant capacity, Table VIII shows the selling price the hydroelectric plant must obtain for various load-factors.

TABLE VII

Cost of energy per kilowatt-hour at various annual load-factors

Basis: $13.60 plus 0.5 cents for steam plant
$20 for water plant

Load-factor	Steam plant	Water plant	Ratio water to steam
15	1.54 cents	1.52 cents	100%
25	1.12 "	0.91 "	82
33	0.97 "	0.69 "	72
40	0.89 "	0.57 "	65
50	0.81 "	0.46 "	57
60	0.76 "	0.38 "	51
75	0.71 "	0.31 "	43

TABLE VIII

Selling price of energy from water plant with 6% on the investment or $12 per annum added to cost for profit

Load-factor	Selling price
15%	2.44 cents
25	1.46 "
33	1.10 "
40	0.92 "
50	0.73 "
60	0.61 "
75	0.49 "

If the steam company is willing to pay as much as 0.5 cents per kilowatt-hour, it is evident that the hydroelectric plant can supply only a very small proportion of the load of the steam company; that is to say, that portion of the load having a load-factor of 75 per cent. If the steam plant expects to get energy at less than its own cost, the hydroelectric plant cannot possibly sell to it.

This analysis shows clearly the preponderating part that the charges on capital bear to the total cost in a plant of this kind. Of the total revenue of $32.00 per kilowatt per annum, forming the basis of Table VIII, no less than $24, equal to 75 per cent, is a direct charge on the investment. If this plant were built as a part of the general system by a corporation which could get its money at 5 per cent, the total annual cost would be reduced to $18.00 per kilowatt per annum, and the selling price for energy at a 50 per cent load-factor would be 0.41 instead of 0.73 cents.

There are other important disadvantages that hydroelectric plants usually labor under; of these one of the most important is lack of flexibility. The rating of such plants is usually fixed by the output of the turbines at 80 per cent gate opening. This leaves just sufficient margin for governing and possibly sufficient spare capacity to operate at its rating in case of one unit being disabled. A steam-turbine plant will, on the other hand, carry very heavy loads in excess of its rating, the exact amount varying with the conditions; but its overload rating can be taken conservatively at 50 per cent for one hour. Hence, if costs are estimated on the basis of the one-hour capacity of the steam turbine plant they will be materially less than given in Table VII: for a 50 per cent load-factor, for instance, the cost per kilowatt-hour would become 0.58 cents instead of 0.81 cents, as given in the table; in other words, the cost would not be much greater than that of the hydroelectric plant.

That this point of view is correct is proved by several important contracts for the supply of steam energy recently executed, notably that of the Chicago Edison Company, with the Chicago Railways, in which the provisions for determining the maximum demand on which the charge of $15 per annum is based are such that no hydroelectric plant could possibly compete. The maximum demand in the case of a hydroelectric plant when selling to a big customer must be taken equal to the capacity of the machinery employed in supplying it, which is, practically speaking, the rated capacity. In other words, the maximum demand must be based on say the five-minute maximum, and little leeway can be allowed to the customer above the hard and fast maximum fixed by this consideration.

A further disadvantage that hydroelectric plants labor under, which leads to a high cost of the supply, is the necessity of ensuring continuity, against interruptions of the supply due both to the low-water period that exists on practically all the rivers in the country, and to the possible failure of transmission lines. As Mr. Doherty points out, the only certain way to ensure this continuity is the establishment of a steam plant at the point of consumption. This steam plant may be owned either by the customer or by the hydroelectric company, depending upon the contract arrangements that can be made for its use. But whatever these may be, it means an additional burden on the hydroelectric plant, which may amount to as much as $5 or $6 per kilowatt per annum in extreme cases, but which on the other hand may become as little as 0.75 cents to $1 per kilowatt if favorable arrangements can be made.

A consideration of these various elements indicates, I think, the reason why so many hydroelectric plants have been total failures from the point of view of a financial operation. In a word, they are so burdened with capital charges and costs that do not enter directly into the productive capacity of the plant, that competition with a modern steam plant is in many cases rendered impossible. The remedy would seem to be a total change in the methods of financing such propositions, by which they will be handled in the same way as the construction of a railroad or the establishment of a steel mill, or any other commercial enterprise.

H. W. Buck: Mr. Doherty has brought up one important matter, and that is the attitude of the Federal Government toward water-power development. I think that this Institute can do much toward educating the popular mind in this regard. There has been a great deal of literature circulated during the past year which has given false impressions about the fabulous value of water powers as they exist in nature. As a matter of fact, a mountain stream in the wilderness has practically no value whatever in itself. It is only when it is combined with a very large expenditure of money, ranging perhaps from $100 to $200 per horse power, together with the expenditure of a great deal of brain power in management, financing, and engineering, that this natural geographical situation, called a water power, derives a value. This value is contributed to only in a small degree by the water in its natural state. In this respect the people have a false idea about the value of those properties which the Government has lately refused to give over to private enterprise for development.

Furthermore, when a water power is developed and is successful, it is profitable only in a reasonable degree. At the present time active competition exists between water power and power from various forms of heat engine, and this condition is likely to continue for many years. Even good water powers cannot compete with power generated from steam at low load-factor in parts of the country where coal costs less than, say, $2.00 per ton. People have been led to believe that a water power is an absolute power monopoly, but such we all know is far from the fact. The Government also apparently assumes that water powers will, for all time, continue to be the only source of power. This hardly seems to be justified. The most efficient heat engine to-day has perhaps a commercial efficiency of 20 per cent, and there is therefore a large margin for possible improvement and economy in this form of engine. A slight improvement would still further increase competition with water power. Furthermore, the energy of water power is merely converted energy of the sum. It is quite possible that other means for the utilization of the sun's energy may develop in future generations. The attention of the Government is directed toward the preservation of water powers for the sake of posterity. It may be that when posterity arrives the energy of water powers will not be required at all, other sources of energy having superseded its use; and in the meantime the prevention of water power development represents a sacrifice for present generations and the loss of a great industrial opportunity.

The Government also seems to have adopted a discriminating attitude against water powers as distinguished from other natural resources. Economically there is no difference between a water power and any other form of natural resource. It is a situation in nature which can be developed for reasonable profit. So can timber lands, mines, farm lands, and all other property be developed and their potential value liberated for the benefit of mankind; but the agitation against the private development of water power as the one natural and injurious monopoly, without reference to all other forms of natural resources, seems to be a very one-sided form of socialism and an unjust discrimination against those who are interested in the development of water power.

This Institute can undoubtedly do a great deal toward correcting the wrong impressions which people have at the present time, with reference to the real situation respecting water powers and water-power development.

W. N. Ryerson: In speaking of collateral enterprises, Mr. Doherty says, rightly, that they should receive our careful attention. I have in mind one contract which provides that the customer is entitled to power generated by the water which would otherwise flow over the spillway of the hydroelectric plant. This contract is with an electrochemical company whose process enables them to reduce their consumption of power from time to time without serious interference; and the contract expressly provides that no interference shall take place with the continuous supply of power to other customers. Naturally, power is sold to this customer at a low rate, and a guaranteed minimum amount of power is provided, below which the customer cannot be asked to reduce his demand.

In saying

> Non-coincidence of maximum demands is, however, a legitimate source of profit to any supplying company, and this non-coincidence of maximum demands is generally a primary source of profit to the supplying company.

I take it Mr. Doherty does not mean that it is not legitimate for a supplying company to offer special rates for " off-peak " business, which I think every such company does.

The additional statement that,

> The capacity the consumer should pay for should generally be based upon this absolute maximum peak experienced at any period throughout the year.

Experience prompts me to say that I would prefer this should be based on the maximum peak during the term of his contract.

Mention has been made by various speakers of the subject of "Depreciation." In the state of Wisconsin there is a public service commission composed of able men, and not very long ago a certain town in the state, through its citizens, petitioned for a reduction in electric rates. The commission held hearings, and after finding that the company was not setting aside a depreciation fund, ordered it to raise its rates, in order that such a fund might be provided.

There is a recommendation in the paper that all terms of expression be standardized. I should like to see the term "load-factor" made more definite as to the time-interval covered by the maximum peak upon which it is determined.

Calvert Townley: I agree with the author of this paper that the Institute can perform a distinct service to the country at large by educating the public to a better understanding of the basic facts governing hydroelectric developments. Although my experience is limited, I can say that the more I operate and investigate water powers the greater respect I have for steam. It is unquestionably true that in New England there are comparatively few water powers than can be commercially considered for hydroelectric development, because they cannot compete with steam on the basis of cost. In the face of these facts, I am, naturally, reluctant to hear advocated the enactment of any laws by Federal or State governments which will put additional burdens on the present expense of developing or operating New England water powers. I believe that such development is of greater benefit to the communities supplied with power than it is to the capitalists who invest in the development itself, and that any additional burdens placed on such investment will tend to prevent all hydroelectric development wherever the margin of prospective profit is close, thus retarding by just that much the progress of any community which would have been served.

Compared with a steam-driven power station, a hydraulic plant is admittedly inferior in every particular except its cost of operation. Therefore, there must be a sufficient saving in such cost to warrant accepting other disabilities. The general public, and not a few engineers, seem to believe that because it does not consume fuel, water power costs nothing to produce. We seldom see the facts analyzed, but it may be interesting to inquire: what is the possible margin of saving in the total cost supplying power from water over the cost of performing similar service by steam?

Consider first the station itself. We see that it costs to operate a hydroelectric station about the same amount that it does to operate a modern steam-turbine station, omitting all boiler room expenses—fuel, boiler water, ash-handling, maintenance, and repairs. The largest of these items is of course fuel. At a New England seaport a high grade of anthracite coal would average to cost about $3.00 per long ton, and, therefore, a fuel consumption of minimum 2.5 lb. to maximum 3.5 lb. per kilowatt-hour results in the corresponding fuel cost per kilowatt-hour of minimum 0.334c. to maximum 0.466c.

To translate these figures into annual costs we must next consider the load-factor. If the yearly output of a station equal an average continuous load of 20 per cent of its rated generator capacity there will be 1752 kw-hr. annual output for each kilowatt of machinery installed. Similarly, an average output of 40 per cent produces 3504 kw-hr. annually for each kilowatt installed. Multiplying these two sets of figures together, we see that with the minimum coal consumption and the lower load-factor, the annual fuel cost per rated generator kilowatt installed will be $5.85. With the maximum assumed coal consumption and the higher load-factor, this cost becomes $16.32. I have taken the load-factors of 20 per cent and 40 per cent for the reason that these factors are not far from the limits found in hydroelectric developments in New England; that is to say, it is unlikely that a station will produce annually more than 40 per cent of the theoretical possible output, assuming every unit to be operated 24 hours a day, 365 days a year, at full rated load, while it is quite possible that under any but favorable conditions a 20 per cent output may be the best obtainable. These assumed conditions are, therefore, not theoretical, but practical. They must be reckoned with.

The other boiler-room expenses—mainly labor and repairs—may be partly, wholly, or more than wholly offset in a hydraulic station by the repairs to hydraulic structures, reservoirs, flume, forebay, tail-race, etc., and also by the cost of patrolling and repairs to the transmission line. The wide variation between hydraulic structures, and between the length, type, and voltage of transmission lines, makes impossible any concrete comparison of these cost items. We have to admit, however, that not infrequently in a hydraulic plant the items named will annually equal or exceed those of the corresponding steam station, leaving the net annual operating margin in favor of the water power no more than the saving in fuel.

The next item of cost, and one which many of us would like to forget when we wish to develop a hydraulic property, is the fixed charge. Here is the worst stumbling block. The average flow of New England streams is 40 per cent of their maximum flow, omitting freshets, while the minimum flow in years like the current year, and last year, may almost reach the vanishing point. The engineer who undertakes to develop a water power is, therefore, confronted at the outset with the question: What per cent of this maximum flow shall I develop? If the development be for the minimum flow only, the cost per unit of capacity may, become, and probably will become, so abnormally high as to be at once prohibitive. Per contra, if, in order to reduce the unit cost, a large percentage of the maximum flow be developed, it can all be used for but a part of each year, and a correspondingly large relay supplemental power must be provided. The usual decision is a compromise. Enough flow is developed to make the unit cost seem not too abnormal, and the disability of a shortage of water during, perhaps, two months of each year is accepted. During that time a relay steam plant must be operated. Many New England water powers cost to develop considerably more than would steam plants of equivalent rated capacities. In addition, transmission lines and relay steam plants of no inconsiderable size have to be paid for. It must not be forgotten, further, that whereas steam turbines are now commonly designed with large overload capacity, a water wheel has no overload capacity, and the rated capacity of a hydraulic development must, therefore, equal the peak load which it may be expected to carry. The ordinary commercial peak load is of such short duration that the overload capacity of a steam turbine is nearly as available as is the rated capacity; consequently the rated capacity of a steam plant may be from a quarter to a third less than that of the hydraulic station built to perform exactly the same service. The capacity and the cost of the hydraulic development must be further increased on account of the transmission losses, which reduces by just so much the power available at the point of utilization. Let me illustrate what I have said by applying some average conditions and working out a concrete case. Let us compare the total cost of producing current by water and by steam under the following conditions:

TABLE I

Hydraulic Development—5000 kw. capacity	
Cost of same, not including transmission lines	$125 per kw.
Duplicate pole lines for transmitting power to point of utilization	$50,000
Sub-stations at distributing points, capacity 4500 kw.; cost of sub-station	$8.00 per kw.
Peak load at power station	4000 kw.
Average load the year round on station—that is, 30 per cent load-factor	1500 kw.
Average loss in line and sub-stations	10%
Minimum flow of water for two months	1000 kw.
Steam relay at distribution center, rated capacity with 50 per cent overload guarantee	2500 kw.
Cost of steam relay per kilowatt rated capacity	$100
Annual labor and material cost to operate the hydraulic power station, sub-station and to maintain the property	$25,000
Cost to operate steam relay plant and supply the insufficiency of power during two months, also to keep it on call for the remainder of the year	$3,000
Interest, depreciation, taxes, etc., on total cost of hydraulic plant	10%

From these assumptions we at once deduce the following figures:

TABLE II

Capital Invested.	
5000 kw. at $125	$625,000
Pole line	50,000
Sub-station, 4500 kw. at $8.00	36,000
Steam relay, 2500 kw. at $100	250,000
Total investment	$961,000
Fixed charges, 10 per cent	$96,100
Operating and maintenance cost of hydraulic plant	25,000
Operating and maintenance cost of the steam plant	3,000
Total annual cost	$124,100

Output 1500 kw-hr. 24 hours per day, 365 days = 13,140,000 kw.; less 10 per cent loss in transmission = 11,826,000 kw-hr. net power delivered at point of utilization, making the cost per kilowatt-hour delivered—10.5 mills.

Had this power been produced by a steam turbine plant located at the point of utilization we may assume the following conditions:

TABLE III

Capacity steam plant, to deliver a peak load of 4500 kw., corresponding to that required for the hydraulic plant, less transmission losses, the steam plant to have an overload capacity of 50 per cent; that is, 6000 kw., or if four 1000 kw. units be selected, the overload capacity with one unit out of service will be 4500 kw., equivalent to the peak load. Cost of steam plant rated capacity	$100 per kilowatt
Coal consumption	3 lb. per kilowatt-hour output
Cost of coal	$3.00 per long ton
Labor and maintenance charges same as for the hydraulic plant	$25,000 per year
Fixed charges and depreciation, capital invested as against 10 per cent for the hydraulic plant	12 per cent

On the basis of these assumptions we at once deduce the following figures:

TABLE IV

Investment necessary.	
4,000 kw. at $100	$400,000
Fixed charges at 12 per cent	48,000
11,826,000 kw-hr., fuel cost	47,304
Other operation and maintenance charges	25,000
Total operating and fixed charges for the year	$120,304

or a cost per kilowatt-hour produced of 10.1 mills, slightly under that of the corresponding hydraulic cost.

It is clear from these figures that, although the operating cost of the hydraulic plant is very much lower than that of the steam plant, its fixed charges are so much higher that the saving is more than offset. Therefore, if its construction can be justified, a reasonably low cost of a hydraulic plant must be assured beyond any reasonable doubt, or a high load-factor must be secured, or both.

On these two points there is a vast amount of current misinformation. Not a few hydraulic projects, some of them very large ones, have put their investors badly " in the hole " because the enthusiasm of their promoters had underestimated the cost of their construction, and overestimated, very much overestimated, the average load to be secured.

I am operating a 6000-kw. water power which is developed for only 60 per cent of the 10 months' stream-flow instead of 100 per cent, as in the example taken, and it should, therefore, have a greater per cent of minimum flow to draw upon. This power is further supplemented by three steam relay plants. We apply all of the power generated to our own service, and we have a heavy demand for it. We are, therefore, able to operate under favorable load-factor conditions. Notwithstanding this fact, the best average annual load-factor I have been able to obtain is 38 per cent. The figure of $125 per kilowatt for hydraulic development is under the average estimated cost of those New England powers that have come under my own observation. Many powers would materially exceed this cost. The steam plant cost of $100 per kilowatt is a fair average cost, as most of you know, although it can be frequently lowered, as also can the coal consumption of 3 lb. used in my example. These conditions, then, are practical, present conditions, with which we are confronted; and in the case of which I have spoken no one would consider the installation of the hydraulic plant, because in addition to costing more to produce this power the possibility of interruption by ice, freshets, damage to the reservoirs or other hydraulic structures, breakdown of pole line, etc., render the service less desirable, and, consequently, add an additional element of expense.

It is doubtless, true that the nation's visible coal supply is decreasing, and that the cost of that fuel may, therefore, be expected ultimately to advance. The predictions of such an advance, however, are not new. The same prediction has been repeated continually for several years, in the face of which prediction the cost of coal consumed in our plants per kilowatt-hour has continued to steadily decline. If, therefore, we invest in New England water powers, expecting that our profits are to come from the expected shortage of coal supply and the consequent higher comparative value of water power, we should first decide whether or not we wish to reap the benefit of that profit ourselves or allow posterity to do so.

I have limited my remarks to New England because I am more familiar with the conditions which are prevalent there. I have no desire to reflect by implication on any hydroelectric development past or prospective which any member of this Institute may have investigated and approved. But I wish to point out that the majority of men with whom I have talked regarding the general hydroelectric proposition seem to have in mind Niagara Falls, or some one of the few very large water powers in the country, and to bear but little in mind the very large number of moderate sized powers in our hundreds of streams. I have regarded this fact as unfortunate, and from information furnished to me I am led to believe that our governmental authorities have an entire misconception of the value and importance of water powers. If there is any prospect of the so-called gigantic water power trust that has been exploited more or less in the press, I believe our government should go slow in discouraging such an organization, not that I am in favor of trusts or monopolies, but because in the formation of any large syndicate competent advice and assistance is at once sought, and there is a much smaller chance of blundering in estimated cost of construction, operating expenses, fixed charges or receipts, with consequent inevitable financial disaster, and if the justifiable development of the really useful water powers of the country is retarded by arbitrary restricting laws, the country, not the investor, will suffer.

Julian C. Smith: I have only a few facts to bring before the members of the Institute, but before giving the results of several years' operation, I would like to indicate briefly the conditions of operation. We have a large power station, two separate pole lines about 100 miles long, a large receiving station, where almost all of the power, about 95 per cent, is taken. The pressure is 50,000 volts.

I have tabulated the results of seven years' operation of the Shawinigan system in two classifications: first, what might be termed a geographical one; the second deals chiefly with the causes of interruption. I have called an interruption of service, any actual interruption to the service delivered. As all of this service is delivered through synchronous motor sets, this classification includes many interruptions which might on other systems be classed merely as disturbances.

TABLE I

Transmission lines 27 per cent.
Lightning 21 per cent.
Sub-stations 11 per cent.
Power house 24 per cent.
Terminal stations 13 per cent.
Unknown 3 per cent.

TABLE II

Elements 8 per cent.
Interference 7 per cent.

Operators 20 per cent.
Lightning 21 per cent.
Breakdown of machinery 21 per. cent.
Breakdown of insulators 11 per cent.
Bad construction 11 per cent.

The first table requires no explanation. The second, however, may be elucidated as follows:

By " Elements " I mean such interruptions of service as were caused by exceptional and extraordinary conditions—forest fires, hurricanes, floods far beyond the average, or ice movements of exceptional severity.

By " Interference " I mean interruptions caused by persons not employed by our company. This includes such causes as farmers blasting stumps near the lines, malicious interference, shooting at insulators, moving houses under the transmission line, etc.

By " Operators " I mean all those interruptions caused by the company's men, either through carelessness or ignorance.

By " Lightning " I mean the interruptions caused at the time of the storms—doubtless some of the interruptions under breakdown of insulators should be put under this classification. Under classification " Breakdown of machinery," I have put all interruptions caused by generator troubles, exciters, transformer burn-outs, switch failures, etc. Under " Breakdown of insulators " I have put all shutdowns caused, or apparently caused, by insulator troubles. This includes burned or broken pins, burned poles, and cross-arms. Under " Bad construction " I have tabulated the interruptions caused by the immediate failure in service of new apparatus or interruption caused to the operation by reason of construction in the neighborhood.

It will be observed from Table II that the three main causes of troubles are operators, lightning, and machinery.

The number of troubles caused by lightning and machinery is becoming less every year. By the use of better lightning arresters, protective relays, etc., the lightning disturbances are being reduced. By the more rigid testing of machinery, the making of trial runs, lasting some days, the use of much heavier and better oil switches, and the use of machinery better adapted for the purpose, the trouble from this cause is also being reduced.

The troubles caused by operators is a different story. There are two sorts of errors made by our men, one due to ignorance and the other to carelessness. We endeavor to give the men a thorough training and limit the number of men who actually handle the switching operations. There is a large personal element involved, however, as the operation of a large station calls for men who are content to perform monotonous duties for long periods of time, and yet find these same men keen, self-reliant, cool-headed and active in case of emergency. I wish that other members of the Institute who have had operating experience would state how they have met this problem.

Henry L. Doherty: Mr. Doane calls attention to the fact that our fuel beds were not only fuel beds, but immense beds of fertilization products. That subject was in my mind when I wrote the paper, but it was not included. Coal distilled in an ordinary gas-house retort will yield about 5 lb. of ammonia per ton of coal distilled; I say this in the absence of reliable data, but my recollection is that it requires the equivalent of about 30 lb. of ammonia to fertilize an acre of ground, in the form of ammonia sulphate. Such fertilization would provide double the average production of the wheat lands of the United States. I think it can safely be assumed if all of our coal were gassified in coke ovens or retorts, it would add at least $500,000,000 to the fertility of our soil. Considerably over one billion dollars would be added to our farm products if the bituminous coal now burned in our boilers was gassified by the Mond system and the resultant ammonia used for fertilization. From this it will be seen that enormous farm-product wealth lies in our fuel beds, if it can be made commercially available.

Mr. Doane, Dr. Hutchinson and Mr. Stott called attention to the feature which I attempted to bring out in my paper, that at 38 per cent load-factor the steam and the hydraulic plant can be operated at equal cost, below that the steam plant at lesser cost and above that the water-power plant at a lesser cost. Mr. Doane specifically brought out the point that I was seemingly contradicting myself when I stated that it was possible to install water turbines, even though they were only run 100 hours each year. It must be remembered that we cannot take our average investment cost for a hydroelectric company in figuring what we can do in the way of additional installation equipment, because the main preparation expense is often work on the river, perhaps producing no physical property, or which cannot be seen, like the blasting out of a channel or something of that sort. Then there are other preparation expenses, which are enormous. With the type of simple development mentioned, however namely, simply a dam across the river and the water flowing directly to the turbine, and flowing from the turbine to the river below, while the total cost for the water power and transmission lines might be as much as $400 per horse power, perhaps the additional cost of adding water-power units might not be over $35 per horse power. We would then have only to figure fixed charges on an additional $35 as the investment for each additional horse power, thus verifying Mr. Stott's curves, where the steam plant and hydraulic plant, by virtue of the lesser fixed charges, show higher economy on a low load-factor. An additional installation of water wheels for carrying the flood flow of the river works out in the same way. But these cannot be depended on to furnish capacity; they furnish current only, because there is not both water and capacity to keep them running all the time.

The country is influenced by the belief that an attempt is being made to control these water powers by a so-called trust.

I have no doubt that the public can be induced to abuse anything that they believe is going to result in trust control. That is an awful bugaboo to them. The same opinion exists regarding the so-called watering of stock. The public has been taught to believe that the capitalization beyond the actual cost of any property means the watering of stock. I do not see why the cost of a property need represent its capitalization. Let us assume there is a water power, possibly in the northern part of this state, and let us assume that we can buy the necessary land and riparian rights, etc., for $50,000. Let us assume further that we can take another $950,000, and complete a plant having a hydroelectric capacity of 10,000 kw. That means an investment of $1,000,000 of real money. We must take all the risks, and if it is not a success we are the losers. We would be very deficient in mental ability if we were willing to invest $1,000,000 in a plant which might be worth $1,000.000 and no more. We certainly would be foolish to put money into it unless we had the possibility of making the plant worth $2,000,000. If we believe it is going to be worth $2,000.000, and if we put our money in it, believing that it will be worth $2,000,000, we are not doing any one any injustice if we capitalize it at $2,000,000, provided there is no misrepresentation of the facts. If things are worth only what they cost, then that must end the revaluing of our real estate, because there is a remarkable example of a value away beyond the original cost. Assume that a plant which cost $1,000,000, had proved a failure, had proved its inability to earn interest on a single dollar; surely it could not be contended that that plant is worth $1,000,000, because it cost that much. In other words, the cost of a thing does not represent its real value.

Mr. Buck does good service in calling attention to the fact that the public have a well-developed case of hysterics—although he did not put it so strong as that—over water powers as one of our natural resources, and the growing fear that some one would develop these and reap a profit, while very little has been said about the other natural resources, all of which have proved equally, or even more profitable than water powers. That point was brought out by Mr. Townley, who remarked that the one to benefit primarily by the development of the water powers of the country is the public, and not the capitalist. The capitalist can find other places to put his money.

Mr. Martin says that an interruption of service, under the plan suggested in my paper, might produce a very long period of the operation of the steam plant. I did not attempt, purposely, to give full details as to the plan of insuring service. It was not intended that insurance should be required beyond the time necessary to put the steam plant in operation, which we would assume would be done under different conditions all the way from one half hour to two hours.

Mr. Stott stated powdered fuel could not be used in any type of furnace. I have had some experience in using powdered fuel and do not hesitate to say it can be applied to any class of service, although I agree with him that powdered fuel cannot be applied to ordinary furnace practice developed for producer gas, or other gases of much lower flame temperature, which contributes heat to the bounding surface.

Mr. Ryerson spoke of a contract that had been made for the utilization of waste water. As a favor to the other engineers who are interested in this class of work, Mr. Ryerson might contribute a written discussion telling us more about that contract. I have no doubt that such a contract would make money and make a slightly profitable water-power plant more profitable to its owners. Mr. Ryerson also spoke about special rates for off-peak business, and rather drew the inference, from my paper, that I held that non-coincidence of simultaneous peaks is a legitimate profit for the central station, and that they should charge the same, whether the consumers' peak occurs at the time of their simultaneous peak or not. I did not mean that inference to be drawn, although I think it is warranted. It is my opinion that the consumer should pay for what he would be compelled to furnish himself, but if the company sees fit to make any certain rate for the sake of getting business, which is extremely favorable to them, due to the fact that the peak occurs at some time when it is not a tax on them, they certainly should have the right to do so. I believe we should be allowed, even where we are strictly quasi-public corporations, to take any business that creates more revenue than its specific cost, on the assumption that it still leaves something as a contribution toward our overhead burden that will lessen the burden on other consumers. In other words, we should not be forced to figure against all business, whether the traffic can bear it or not, its proportion of the unavoidable overhead expense.

Mr. Ryerson also called attention to the point that the peak of the consumer should not be taken simply for the year, but for the term of the contract. In that respect I think Mr. Ryerson is right. We are not simply interested in that year, and if it is possible to do that we ought to put it on the basis, as nearly as possible, of what the consumer would have to do if he were to furnish his own plant, for there he must not only pay for the peak he uses, but he must anticipate, provide, and pay for the peak he expected before his actual demand was experienced.

Carl Schwartz (by letter): One of the best features of the paper presented is that it touches upon almost every problem in connection with hydroelectric development. There is one question particularly that seems to be in a rather unsettled condition—the amount and most economical kind of auxiliary power to insure against interruption and to improve the load factor.

If the first costs of a hydroelectric development are high, the fixed charges will frequently exceed those of small heat power plants of prospective consumers; taking their business then, usually means relying on the diversity-factor of the load and on an auxiliary power plant to carry the peaks. The investment for auxiliary power will depend for instance, among numerous other questions, on the cost of the hydroelectric development itself. If its cost per kilowatt is large, to be a paying investment it should allow operation with a high load-factor. On the other hand, the installation of auxiliary power increases the investment still more so. The question of auxiliary power capacity will always be a matter of detail calculation for each particular case.

The merits of steam or gas power, however, for auxiliary plants can generally be compared and the following comparison is submitted.

Taking the steam turbine station at, say, $90 per kilowatt, and the cost of coal at $3 per ton, we find that between 25 per cent and 30 per cent station load-factor fixed charges and running charges balance each other. If, therefore, the station load-factor is lower than, say, 25 per cent, the station should be built at low first cost. If higher, say 30 per cent, it will pay to install refinements that may slightly raise the first cost but improve the economy. The same reasoning applies to a gas-power plant, except that if we take the first cost at about $140, the fixed charges will overbalance the running charges until the load-factor exceeds 60 per cent.

It is thus clear that if a gas-power station were to be given preference over a steam-turbine station, the auxiliary power plant should operate under a good load-factor. As this is ordinarily not possible, the steam-turbine station should be the best type of auxiliary plant. Its lower first cost and high overload capacity compared with the gas plant makes it serviceable for low load-factors and allows the bulk of the load to be supplied from the water-power plant where the operating expense is an insignificant item. The design of such a steam turbine plant and its method of operation will depend on the conditions to be met; and there is no difficulty in making, if desired, the design most economical for a certain load-factor and intermittent operating conditions.

An ingenious plan for insurance against interruptions of service is outlined in the paper, but it supposes the use of a steam station of the full capacity of the hydroelectric plant. This must considerably increase the fixed charges and thus the costs of the service to consumers. This amount of insurance may be required, for instance, for light and power service for a city, but it would be prohibitive for purposes where only a low price of current can successfully compete against or replace other service or create new industries.

The financial standpoint is probably the most important feature to be considered, for the reason that all engineering calculations, whether they concern the amount of power advisable to develop, the methods to do it, whether duplicate lines or auxiliary power are advisable to install, etc., are based upon financial considerations. Inasmuch as in hydroelectric plants over 80 per cent of the cost of current is made up of fixed charges, it is easy to realize the importance of the correct valuation of depreciation. The depreciation period should not be too long, say not more than 15 years, because of possible changes in the art of engineering. For instance, the generation of current by heat is still very inefficient, and we may some day see great improvements which might affect in some cases the valuation of hydroelectric properties were the depreciation period too long.

C. P. Fowler (by letter):

THE VALUE OF WATER-POWER SECURITIES

1. *Labor.* Hydroelectric plants differ from other enterprises in that the number of wage-earning employes is comparatively few and of a highly intelligent kind, the probability of differences between employer and employe, and of strikes, are thereby minimized. Furthermore, freedom from difficulties of fuel supply incident to strikes on railroad and at coal mines, freight congestion, etc., tends to stability of earning power for this class of security.

2. *Raw material.* Large investments in raw material and fuel are unnecessary with hydroelectric plants as with industrial enterprises and steam plants.

3. *Depreciation.* The amount that is necessary to set aside annually to cover depreciation for hydroelectric plants is probably not more than from one-third to one-half of that necessary with an equivalent steam plant. This amount even bears a relatively smaller ratio to the depreciation rate of industrial plants where, in addition to the depreciation of machinery, a certain amount must be set aside to cover goods that have become unsalable.

4. *Operating expense.* Another feature, peculiar to hydroelectric plants is the possible large increase in gross earnings without a proportionate increase in operating expenses. To illustrate this point, I give below a tabulated statement of the ratio of operating expenses to gross earnings of a hydroelectric development of which I have knowledge, covering a period of five years of operation.

First year	53.5	per cent
Second year	32.4	"
Third year	30.0	"
Fourth year	23.0	"
Fifth year	23.0	"

During the five-year period referred to above, the gross earnings increased over four times while the operating expenses for the fifth year of the same interval were less than twice those of the first year of operation.

5. *General.* These conditions indicate the small demands made by hydroelectric plants for working capital compared with other undertakings. This is of great importance in times of financial stringency such as were experienced in 1907.

THE RELATION OF WATER-POWER DEVELOPMENT TO THE CONSERVATION OF OUR NATURAL RESOURCES

Mr. Doherty very properly points out the interrelation of water-power development and the conservation of our various sources of fuel supply. Our chief fuels are wood, oil, and coal. Wood fuel is now almost a thing of the past, oil although used extensively in some parts of the country is of limited supply, and before long may cease to be an important factor in the problem. Coal, therefore, is the chief remaining fuel; but when it is remembered that the increase in coal consumption in the United States has doubled during each decade—a greater rate than the increase in population—the necessity for prompt measures to reduce the drain upon our coal deposits at once becomes apparent. This may be largely accomplished by a more complete harnessing of the large number of our water powers now going to waste. Recently I have estimated the value of coal saved yearly by only four hydroelectric developments located along the Canadian boundary to be in the neighborhood of $3,000,000.

CALCULATIONS ON DEPRECIATION

In reference to estimates concerning depreciation of plant, I agree with Mr. Doherty that in order to arrive at a reasonable figure covering the entire property, it is essential that the useful life of each element composing it be taken up in detail, rather than resorting to the frequent practice of using a blanket depreciation rate covering the complete plant. It is also properly conservative to use a depreciation rate which is the result of the investment of the annual depreciation fund at prevailing savings bank interest rates during the period of the estimated useful life of the portion of plant under consideration.

J. Lester Woodbridge (by letter): I cannot permit to pass unchallenged Mr. Doherty's brief reference to the use of storage batteries as a protection against interruptions of service in hydroelectric systems. I hardly feel that a sufficiently thorough investigation of this subject has been made to warrant so sweeping a conclusion; in fact statements in other parts of the paper indicate that this conclusion could not have been based upon very complete data.

The author practically admits the necessity of providing some means for insuring continuity of service in the class of systems discussed, and the problem resolves itself into a determination of what character of apparatus will give the desired insurance at the least annual cost including operating expenses, depreciation, and fixed charges. In order to solve this problem it is of course necessary to have accurate data as to the annual cost of the different schemes proposed. The author appears to favor an auxiliary steam plant for this purpose, but in stating that he has never seen an efficiency curve on boilers, showing their economy from no load to full load, he has apparently admitted that he lacks at least one factor necessary to a complete solution of the problem. In cases where the cost of fuel is high and the character of service to be rendered requires that a steam plant shall be kept constantly ready to take an emergency load, this factor may be a most important one.

It is, however, the figures on the other side of the equation; that is, the annual cost of a stand-by battery, that I would particularly discuss, as I fear that Mr. Doherty's statement has been based on more or less misleading information.

The use of a storage battery for purely stand-by service is, in this country at least, of comparatively recent origin. In the early days of storage battery history there was no such thing as a purely stand-by battery. The man who made a considerable investment for a storage battery plant was not satisfied unless the battery was kept constantly at work. He was satisfied to install three generating units in his power plant and permit one of these to lie idle as a spare unit from January 1 to December 31; but not so with the storage battery. That must be worked or he was not getting the return for his money. A large part of this work was of course legitimate and was work which a storage battery could be called upon to do economically, using the word in the broadest sense of the term; but a very considerable part of this work was in many cases absolutely unnecessary and could have been handled much more economically by the generating units. In either case, however, the work done was far in excess of that required from a stand-by battery. On this account the first cost and maintenance charges for a battery which is limited to strictly stand-by service will be considerably less than past experience would indicate, and the great bulk of the data on which we might draw for information as to the commercial results of the operation of a storage battery is therefore quite useless in the present problem.

Within the last year or two there have been put into service several large storage battery plants especially adapted for this class of service. The plates are of a type designed to give the maximum capacity, particularly at high rates of discharge, with minimum weight, floor space, and first cost. These batteries are not designed to handle heavy peak discharges every day, and are not so used, but are held strictly in reserve ready to take up the load in case of any failure in the generated power. Such discharges occur only at comparatively infrequent intervals and although the question of maximum durability under heavy work has been subordinated to other considerations in the design of the plate, the depreciation and maintenance of these plants will undoubtedly be exceedingly low. Information on investment cost for this type of battery is, ofcourse, available and shows an appreciable reduction from that for the standard types.

I feel, therefore, that so far as the question of dollars and cents is concerned, the comparison between the storage battery and other means for insuring continuity of service should hardly be dismissed with so brief and sweeping a statement as the author has made. There are, however, other aspects in which this problem must be considered. The conditions to be met vary widely in different cases. There are, of course, situations in which the storage battery is not the proper solution of the problem, but the conditions, as shown by Mr. Doherty's paper, vary over so wide a range that conclusions arrived at in one particular case can rarely, if ever, be applied to another. In some cases it is possible that a combination of both storage battery and steam- or gas-engine-driven generating machinery may be successfully employed. The character of service required will also have an important bearing upon the problem. To quote Mr. Doherty's own words:

> The importance of continuity of service varies in degree with almost every customer served. To some industries a mishap which causes even a fall in voltage or a change in frequency may be a serious matter.

I believe that many cases will arise in which the storage battery will be found the only means for producing the desired results and will be adopted even in the face of increased financial outlay.

The above remarks apply to the application of a storage battery for strictly stand-by service. There is, however, a wider field than this for the storage battery in connection with hydroelectric developments, for carrying occasional peak loads beyond the capacity of the generating machinery. So long as the power marketed does not tax this capacity at any time, there will be no excuse for such service from a battery; but as soon as the limit of the power development is reached, there will in many cases be profitable situations for storage battery installations for increasing the station capacity where further increase in the water power development would be impossible or prohibitively expensive, and the length of the peak so short as to render steam generation highly inefficient.

W. E. Winship (by letter): That portion of Mr. Doherty's paper dealing with methods and equipment to insure continuous service is of special interest to me, but I wish to take exception to the statements that the investment and cost of maintaining storage batteries practically preclude their use for this purpose. If absolutely continuous service is required their use is necessary, as they offer the only practical instantaneously available source of electric power.

The entire storage battery situation has radically changed during the last few years. Experience has taught what constitutes proper operating conditions in order to obtain a long life of plates and other parts. Progress has been made in the direction of design for the different service conditions. Costs of manufacture have been considerably reduced. In particular, batteries for stand-by service have been made considerably cheaper, and their cost of maintenance is extremely small.

In my opinion it is almost impossible to make general deductions that will hold good for even the majority of water-power situations. The available water-flow may be ample in some cases; it may be insufficient in others at least during a portion of the time. It is probable that in all cases the latter condition will be true eventually, though this may be far removed and a temporary solution will often be the only justifiable one. There is at least one storage-battery plant—probably there are many others—installed in connection with a water power, whose entire cost was saved during its first year of operation, by shutting down the steam plant which had been used to take the peaks. This particular battery has been in service over six years, with no renewals and with little prospect that any will be required for several years more. I have intimate knowledge of a number of battery plants of from seven to nine years old without plate renewals and with none being required for several years. I have strong grounds for asserting that the pure lead Planté type of positive plate is good for from seven to nine years of life in hard service, and that under stand-by conditions it will last much longer. Planté negative plates properly made will have conservatively at least double the life of positive plates. It may be admitted that many engineers have the opinion of battery maintenance cost expressed in the paper, but they should inform themselves in regard to the performance of some of the makes of batteries with which they may be unfamiliar.

A comparatively recent development is the use of regulating storage batteries whose duty is controlled by the variation of the alternating-current load. This function, in addition to their available discharge capacity for a limited time, makes them an extremely valuable adjunct to a plant if the load is variable. Incidentally, both voltage and water-wheel regulation are obtained; these are not small points in themselves, while the plant and line capacity are both increased.

I am surprised at the apparent lack of faith in the reliability of transmission lines shown in the oral discussion of Mr. Doherty's paper. Numerous transmissions of moderate length and voltage are satisfactorily serving public utilities all over the country; and with the better insulation and lightning protection now available, it would seem that the proper step, in those cases where trouble is experienced, would be to improve the lines. With duplicate lines and facilities for rapid testing and switching, it should be practically possible to reëstablish service in a very short time. The investment corresponding to the duplicate lines need not be prohibitive, as the duplicate lines could be designed to carry the load at maximum economy with both lines in service, but with a greater drop in voltage when but a single line is operated.

Holding either a steam or water power plant in reserve but ready for instantaneous service seems to me an extremely inefficient way to utilize apparatus; furthermore, it would not under any condition insure against a short interruption of power. Instantaneous readiness for service could scarcely be obtained with a steam plant, as there would necessarily be an appreciable interval before the boiler could respond to the sudden demand. Water wheels might respond more quickly, but their governors are notoriously sluggish, especially with low heads. Some instantaneously available source of power is necessary if momentary interruptions are to be avoided, and storage batteries form the only practical apparatus for the purpose. If the water power is insufficient to carry the total load, necessitating reinforcement by another generating plant, it would of course be much simpler to throw an additional load on the operating steam plant than on such a plant standing idle; even in this case, however, there would be grave danger of a short interruption of power without a storage battery.

Francis Blossom (by letter): Many engineers will not concur in Mr. Doherty's statement that

> The problem of reliable service on long transmission lines is much further from solution than all of the other problems that have done so much to contribute obstacles to rapid development.

The use of a long transmission line does not necessarily entail interruptions exceeding in frequency those occurring on the multiplicity of feeders frequently served from a steam station located nearer the point of power consumption.

The continuity and reliability of service supplied over a transmission line is largely a question of the mechanical and electrical strengths of the line. Assuming proper design, mechanical strength is a function of purchased safety-factors, and the same is true—but to a lesser extent—of electrical strength, which, however, is more subject to stresses of unknown magnitude.

Mr. Martin has stated that some performance figures would be given with respect to the 15,000 kw. power supply furnished to the Pacific Gas & Electric Corporation over the transmission line of the Stanislaus Company. These show an uninterrupted line delivery over a ten months' period—from February 1, 1909, to December 1, 1909—of a 100-mile transmission line of the Sierra & San Francisco Power Company, supplying a maximum demand of some 15,000 kw. from the hydroelectric station of about 20,000 kw., on the Stanislaus River, in the Sierra Mountains, to a sub-station of the purchasing corporation at Mission San Jose. The conductors are of 2/0 copper, six-strand, hemp center, spaced about 9 ft. minimum vertical and 16 ft. horizontal distances apart on an unsymmetrical triangle, supported by suspension insulators of five elements on single-circuit, pyramidal, galvanized steel towers, averaging six and two-thirds towers per mile.

The operating performance is tabulated as follows:

TABLE I

	Hours	Minutes	Percentage
Total period of delivery of power to purchaser	6709	22	92.26
Total period of non-delivery of power due to cessation of purchaser's demand	539	21	7.42
Total period of non-delivery of power due to interruptions caused by troubles of any nature in the generation of power	23	17	.32
Total period of non-delivery of power due to interruptions caused by troubles of any nature in transmission line	0	0	0.00
Total elapsed period (10 months)	7272	0	100.00

Philip P. Barton (by letter):

METHODS TO INSURE AGAINST INTERRUPTIONS OR TO LESSEN THE HARMFUL EFFECT OF INTERRUPTIONS

In a general manner, the transmission system by means of which Buffalo and Tonawanda are supplied with electrical energy from the plants of The Niagara Falls Power Company and Canadian Niagara Power Company is indicated herewith, in Fig. 1. The installation may be described as consisting practically of a closed-loop arrangement of transmission lines passing through three great hydroelectric generating stations and through three sub-stations—two in Buffalo and one in Tonawanda—in such a way that any or all of the sub-stations may be supplied in either direction from any one or all of the three generating stations. The system as shown was completed substantially in 1907, although the third Canadian circuit was not constructed until 1908. In the 30 months during which this system has been fully in operation, there have been two interruptions to the entire power service to Buffalo, each caused by lightning. On one of these occasions, all of the American and Canadian transmission lines were short-circuited almost simultaneously by a wide-spread lightning storm. On the other occasion, the entire service would not have been interrupted except for the fact that the American plant was completely shut down for repairs to the tunnel at the time when the lightning short-circuit occurred. From July 24, 1908, to this date (January 3, 1910), the continuity of Niagara power service to Buffalo has not been broken.

The following is a statement in detail of the complete interruptions to the Buffalo service since January 1, 1905:

TABLE I

1905	
Jan. 25,	Short-circuit in transformer in customer's sub-station.
Feb. 23,	Short-circuit due to mistake of electrical fitter at generating station.
June 5,	Wire thrown across transmission line by telephone lineman.
June 5,	Transmission line short-circuited by lightning.
July 17,	Transmission line short-circuited by lightning.
July 19,	Transmission line short-circuited by lightning.
July 27,	Short-circuit in step-up transformer at generating plant.
Aug. 3,	Transmission line short-circuited by lightning.
Aug. 10,	Bale wire thrown across transmission lines.
Aug. 30,	Transmission line short-circuited by lightning.
	Total...10
1906	
Jan. 4,	Short-circuit on transmission line caused by wind storm.
Jan. 5,	Defect in cable insulation at generating plant.
Apl. 14,	Mistake in switching at generating plant.
Apr. 29,	Transmission line short-circuited by lightning.
May 4,	Transmission line short-circuited by lightning.
June 8,	Transmission line short-circuited by lightning.
Aug. 3,	Transmission line short-circuited by lightning.
Aug. 3,	Mistake of attendant at customer's sub-station.
Oct. 10,	Tree broken down across line by heavy snow storm.
	Total...9
1907	
Jan. 20,	Short-circuit on transmission line caused by wind storm.
Apl. 24,	Mistake of attendant at customer's sub-station.
June 4,	Tape line thrown across transmission line by civil engineer of a railroad company for purpose of measuring elevation of conductors.
	Total...3
1908	
June 22,	Transmission line short-circuited by lightning.
July 24,	Transmission line short-circuited by lightning.
	Total...2
1909	None
	Total...0

Few of the above interruptions lasted more than 5 min. In many cases the service was resumed within 2 or 3 min.

While the experience of The Niagara Falls Power Company may not be especially helpful to those who are endeavoring to transmit energy to great distances at very high voltages, members of the Institute may be interested in the statement that the central station lighting companies in Buffalo and Tonawanda scrapped their steam plants more than 11 years ago and have not burned a pound of coal for power purposes since 1898; and that the railway company operating substantially all of the urban and interurban trolley service within 30 miles of Buffalo keeps its steam plants shut down and closed up except during the winter months, when its peak load requirements cannot be supplied economically from a hydroelectric plant.

In dealing with the subject of safeguards against interruptions to service, I think that in many cases too little consideration is given to the necessity of building up an efficient operating organization. One of the important ways in which insurance of continuity of power service is sought is by connecting up into a common network several generating plants with a number of inter-connected sub-stations. Operating complications and opportunities for mistakes multiply very rapidly with this process, and the problems of selecting and organizing and training operating forces to handle successfully such plants are often of far greater importance than the problems of design and construction. The variety of possible emergencies in a modern power installation is very large. To prevent these emergencies, to predetermine and carry out correct methods for dealing with those that cannot be prevented, and to meet with prompt resourcefulness and coöperative team work those that cannot be foreseen, require the same kind of preparedness and discipline in an operating organization that are exhibited by a successful army in the field, and these qualities are to be acquired by similar methods in each case. I think that many engineers would be surprised, were they to make a critical analysis of the operating records of some large power installations, to find what a large percentage of accidents must be charged directly or indirectly to defective organization.

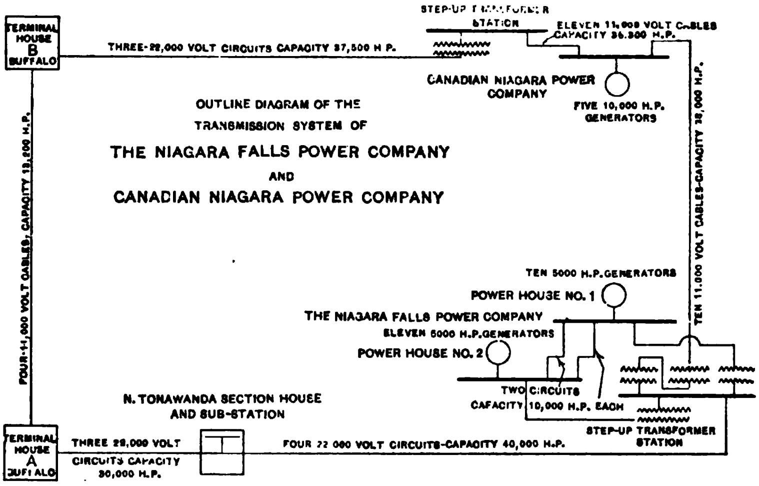

FIG. 1

PENALTIES FOR INTERRUPTIONS OF SERVICE OR INSURANCE AGAINST INTERRUPTIONS

The only point I wish to make on this subject is the desirability of keeping contractual relations between a power company and its customers as simple as possible. I doubt whether any penalty that it is practicable to get into a contract will have any appreciable effect on the continuity of service from a hydroelectric power plant. In most cases, the service will be the best that the ability and resources of its management can produce, irrespective of the question of penalties. I think that the common expedient of a rebate of charge during periods of interruption, and perhaps for an agreed period in addition thereto, will meet the requirements of nearly every ordinary case. The plan described by Mr. Doherty seems to be ingeniously complicated. As I understand it, it simply means that the parties have agreed that to insure continuity of service a steam plant must be operated at times, and that the cost of such operation is to be divided between the parties in a certain arbitrary manner. If the method of dividing the cost is to be arbitrary, perhaps it might be simplified to advantage.

CALCULATIONS ON DEPRECIATION

Depreciation appears to be regarded by many persons as something whose magnitude can be calculated in figures of percentage accurate to the third decimal place. Two elements must be known before such a calculation can be made. The first is precisely how long a thing will last; the second is the exact cost of replacing it at the end of the period. Each of these elements is a subject for intelligent guessing rather than for refined calculation, and the best guess based on knowledge and experience of wear and tear may be upset by the uncertain factor of obsolescence. Nevertheless, some provision for depreciation must be made in every well-considered enterprise. I am inclined to think that the best results will be obtained if rules and percentages are abandoned. No two cases are alike. Each must be treated by itself. I am of the opinion that the amount to be set aside annually for depreciation should be determined somewhat arbitrarily by the application of common-sense to conclusions reached after a free and thorough discussion by the engineering and accounting and financial representatives of the enterprise. In a prospective development any figure for depreciation is necessarily a guess. In a going concern the financial situation must be considered quite as much as the physical situation in setting up reserves for depreciation.

I have been asked to give some figures on depreciation based on the actual experience of The Niagara Falls Power Company, and have had prepared a statement of the actual expenditures for maintenance and repairs and betterments for the electric generating plant and for the hydraulic motive power plant covering the period from January 1, 1900, to December 31, 1909.

The electric generating plant consists of twenty-one 5000-h.p. generators with switchboard equipment, etc. The plant is now apparently in about as good condition as when it was new. About 40 per cent of the switch gear may be described as obsolescent, although for practical purposes it is more efficient than when it was installed. At a convenient time, however, it doubtless will be replaced with modern equipment. The actual annual expenditures on this plant for maintenance and repairs and betterments have been slightly under three-fourths of one per cent of its original cost. This includes complete new windings of improved design for the armatures of seven of the generators. It is interesting to note, in this connection, that generator No. 1 put in commercial service in 1895, has required practically no repairs and exhibits no visible signs of depreciation.

The motive power plant consists of twenty-one 5000-h.p. turbines with shafting, governors, headgates, oil pumps, oiling system, etc. The actual annual expenditures for maintenance and repairs and betterments have been slightly under two per cent of the first cost of the installation. The entire plant has been kept in the best possible physical condition, but it is probable that ten of the turbines will be rebuilt within the next few years in accordance with improved designs.

C. H. Baker (by letter): I have always felt that a power engineer leans, unconsciously, toward particular kinds of power and particular types of apparatus, from which he is not likely to be weaned. Mr. Doherty, I assume leans towards steam as a motive power, while my leaning is decidedly toward the power derived from falling water. His experience undoubtedly has been most satisfactory with steam; mine has been decidedly so with water power. I am not disposed to admit that a water-power plant properly designed and constructed requires any steam adjunct at all in the sense of reserve power, although it may be well to have a considerable capacity in steam to carry either the daily fluctuating peak in a mixed service or to carry the winter peak if the service produces such a condition.

I do not recall a properly designed water-power plant where a steam plant has been introduced as a reserve. It is very common to find auxiliary steam plants in connection with water-power plants, but they owe their existence to the fact that they preceded the water-power plant, the steam plant being retained as an auxiliary either to carry the peaks or as a protection against uncertain service, as a wiser measure than to reduce it to scrap and practically get nothing for it. My belief is that a water-power plant can be so simply designed and so well constructed that even with a long transmission the interruptions to service and the fluctuation in voltage will compare favorably with the service rendered by any steam plant.

I believe that the Snoqualmie Falls plant which supplies Seattle, Tacoma and Everett in the state of Washington, has no equal from any point of view in the shape of any steam power plant in operation on the Pacific Coast. The Snoqualmie plant operates year in and year out with scarcely a second of interruption, and although the transmission lines carry the railway circuits as well as miscellaneous power and lighting circuits, the variations in the voltage curve are almost limited to the thickness of the curve itself. The success of the Snoqualmie plant as a reliable power agency is due: first, to the absence of a flume which the river itself takes the place of; secondly, to simplicity of wiring and switching arrangements, both at the primary and terminals; and, thirdly, to a well built duplicate transmission line following a right-of-way cleared beyond peradventure of all trees and other features which might challenge the continuity of the service.

It is particularly important that the transmission conductors whether of copper or of aluminum, should be stranded cables. I prefer aluminum, principally because of its lightness. My judgment is that the extra investment necessary to incorporate an auxiliary steam plant—if incorporated in the water-power plant itself—in the shape of duplicate pole lines, extra conductors, concrete or steel towers, a spare unit at the generating station, the best type of insulators and lightning protection, and spare transformer units at both the primary and subsidiary end will lay a foundation for a service as reliable as that offered by any steam plant. I also believe that flumes should be replaced by excavated canals or tunnels wherever possible.

I concede, of course, that no two water-power situations are alike. Among them all there will be a few conspicuous for desirable features with which nature has endowed them. There will be others which by their very nature will be almost impossible situations. Then there will be a large number having only average merit. If one could design his own water power he would avoid extremely low heads, meaning that an unusually large volume of water per horse power would have to be handled for power production; and he would avoid extreme high heads where great pressures and high velocities would be encountered, requiring great and unusual strength of apparatus, and developing features inimicable to good regulation. The ideal head would neither be 10 ft. nor 3000 ft. but about 500 to 600 ft., thus calling for impulse wheels in place of turbine wheels.

A word with reference to the relation of power companies in general to the public. An asset item of as great value to a power company as its boilers or its water wheels is that of popularity. This item affects very materially the earnings of a company and the value of its franchise rights, which emanate from the people. A good plant and a poor and short-sighted management may not be as good an investment for the bondholders as a poor plant presided over by an able and courteous management which is ever ready to doff its hat to the public. The company must have public confidence, and the eye of suspicion must not rest upon it in regard to any of its measures or actions. If the public knows that the company is in league with corrupt councilmen for the purpose of gaining lasting and unreasonable privileges, then every person in the community will disparage it at every opportunity.

The disposition quickly to repair troubles, to adjust complaints as to bills, and to not ask too much of the public in way of franchise privileges is in line with Mr. Doherty's remarks, and my reference is simply to emphasize what he has said upon the subject. I have witnessed the situation of a water-power company being out of commission due to a fire, and the opposition company endeavoring to take advantage of the situation by offering its service at once, coupled, however, with the condition that long-time contracts be entered into. The afflicted company was so popular, however, that stores, residences, etc., burned candles for about 36 hours rather than entertain any propositions for relief whatsoever coming from either electric or gas light opponents.

The ideal situation in a water-power business is a water power company serving large industries like flour mills, steel works, etc. Mr. Doherty's optimism makes it clear that most water-power companies may be able in the future to select their own business. This is the kind of business that such companies would naturally prefer, for the reason, as he stated, that the service may be for some purposes less refined than where lighting and street car services are involved. Besides thus developing an uncomplaining class of customers, the situation is simplified by having fewer circuits, fewer meters, fewer accounts to keep and fewer although larger collections to make. A mutuality of interest may at the same time be developed by the power company investing in the securities of this class of customer which it may serve.

If a central station handling mixed business of the community exists, the power company may furnish it a certain allotment of power covering its base load, and not exceeding say one half the average peak. If there is an interruption in service under this condition it would only be partial, as the central station would have its steam plant in operation, and the patrons of the company during the period of affliction could get along with half their necessary lighting, and the street car service could be reduced temporarily one half. The power thus sold by the hydroelectric company to the central station should be accepted by the central station company, subject to the conditions which experience teaches are likely to obtain, and the price should be made accordingly. There should be no penalties, which only promote friction and bad feeling. The hydroelectric company will maintain no better behavior due to any code of penalties. In such an event it is the greater sufferer by virtue of losing reputation and revenue.

If the hydroelectric company desires to handle the mixed business of the central station, it should preferably have its own central station do its own distributing as well as generating, and deal directly with the members of the public without the intervention of another company. In this way the consumer feels that he is getting his power first hand, and at more nearly its reasonable value, and he is also in a position to know whom to commend for a good service and whom to censure and have recourse upon for bad service.

H. F. Parshall (by letter): I have been called upon to carry out or report on very many power installations, the majority of which have been founded on more or less sound commercial lines. In many cases, however, the rate of growth of demand for power has been overestimated. In the design of a central power installation it is necessary to take into consideration in the original arrangements the character the installation may ultimately assume. In the case of hydroelectric undertakings it frequently happens that a good deal of the initial investment has to be on a scale to provide for the size the installation may be expected finally to grow to. The same remark applies in certain details, but to a lesser extent, to steam installations. In both cases it has been found as a matter of practical experience that the demand does not arise before the ability to supply it and growth is frequently very slow, even after the supply has been demonstrated to be both advantageous and reliable. It follows, therefore, that any type of power installation is likely to be subject to heavy initial interest charges. In some instances engineers have been over-sanguine as to the time required for completion, over-sanguine as to the prices that could be realized with any reasonable rate of growth, and over-sanguine as to the time such growth would be sufficient to earn fixed charges.

Looked at from a financial point of view, the time-element is the principal deterrent. Any hydroelectric installation sensibly located, is, in the long run, likely to become a valuable property, although the original projectors may not be the ones to reap the benefits of the undertaking. Owing to many engineers having overestimated the possible earnings of power installations, many financial houses have become extremely pessimistic on the subject. At the present moment I think it may be fairly stated that, from a financial point of view, many of the hydroelectric power installations in the United States are of the future rather than of the present. But there can be no doubt as to the ultimate value of this class of undertaking. A paper of the character of Mr. Doherty's is of especial value in that it should tend to restore an equitable balance between the optimism of the engineer and the pessimism of the banker.

I recently heard the opinion expressed by a banker who is associated with the development of hydroelectric power schemes in Switzerland, that eventually such installations had won out, and that hydroelectric undertakings were a good class of security to have on a banker's shelf, since they were constantly appreciating in value. This opinion is based on installations that have been working for some time, and on the smaller class of installation where the initial capital required for future development was comparatively small.

In building a railway it is frequently possible to install a structure more or less temporary, so that the capital charges are small, until such time as the traffic justifies something more permanent, so that " scrapping " at the opportune moment is of less importance than the interest charges that would have been incurred on a permanent class of installation. Unfortunately, this course cannot be followed out in a hydroelectric installation, and, as stated in the beginning, this introduces the all-important factor as to time.

I think most of the hydroelectric installations have been well designed, although in some cases greater attention should have been given to the duplication and stability of lines. Here again, time-element and capital have to be considered.

In many installations the question of a stand-by plant has to be seriously considered, and I do not know that there is any general solution in view. Both gas engines and oil engines are extremely expensive to install but are efficient in the matter of fuel consumption. The steam-turbine station is the cheapest to install and maintain, but in some cases the stand-by charges are considerable.

Generally speaking, I do not suppose that my opinion differs at all from that of all other engineers; namely, the less the extent of stand-by plant, the less the likelihood of its being called into commission, and the more attractive the hydroelectric installation. Once the supplementary stand-by power stations become a necessary part of a water-power scheme, the commercial result becomes problematical and often evanescent.

Having regard for the natural conservatism of the banking fraternity, my advice is that engineers should be especially careful to catalogue the risks as fully and as explicitly as the prospective and possible advantages, so that a useful field is not needlessly handicapped by preliminary mistakes.

J. F. Vaughan (by letter): A feature too often slighted in hydroelectric plant design, but essential to the best economy of operation, is some adequate provision for recording the flow of the stream. The usual method of determining flow by guage heights taken once or twice a day without reference to the rise or fall of the river at the time of observation or the possible changing of the cross-section of the river is often inaccurate or a wholly unreliable indication of the power of the stream, or of capacity for further development by storage, steam supplement, or otherwise.

Wherever possible, measuring weirs should be provided and where too costly, otherwise impracticable, every other available means of determining the stream-flow or of checking other measurements should be taken; as for instance by:

1. Calibration of the dam-crest as a weir, using a continuously

recording gauge to determine the height of water above the crest and the variation of the pond-level.

2. Calibration of sluice gates, fishways, etc., in the same manner.

3. Calibration of the water wheels themselves to determine the flow through them at different gate openings, and recording of backwater level.

4. Calibration of flume or canal at a given section by current meter or weir, and use of a recording water-level indicator.

5. Measurement of pipe line or penstock flow by pitot tubes (preferably recording).

6. Indication of flow by venturi tubes, or even by friction head losses measured at sufficiently remote points in the pipe, etc.

These should be supplemented by meteorological observations wherever there are insufficient government stations.

Not only should designers provide every reasonable facility for keeping the most accurate records of the power available and used, but operators should see that the records are properly kept and the accuracy of the methods maintained; for without such records, neither can the owners get the maximum return from their equipment, nor can they properly determine the true value of the power nor the extent to which it may be further developed.

E. C. Brown (by letter): The impression generally prevails that the Federal Government is unfavorable to the liberal development of water powers. This, perhaps, is taking an extreme view of the attitude of the authorities at Washington. But, be this as it may, the effort now making by Government officials and an association devoting itself to the conservation of the country's natural resources cannot but exert a favorable influence on our water courses, since the devastation in recent years of vast tracts of woodland has very appreciably affected the constancy of developed water powers. Let us hope that any retardation, by reason of the general policy of the Federal Government against development of water powers, may be counterbalanced by the efforts now making for husbanding woodlands so essential to the permanency of streams.

Calculations on Depreciation

Under Calculations on Depreciation the writer would submit that hydroelectric plants should be built with at least three views always in mind:

1. Thoroughness to insure stability of dam and all work connected therewith. Inferior construction in this field of operation, probably more than any other, might lead to most disastrous consequences, as well as loss of considerable investment.

2. Construction with a view of obtaining every foot of available head, even though initial investment may be increased.

3. A factor of safety is generally a wise policy, when estima-

ting on water power development, by making a liberal allowance for cost of construction on the plant and figuring the dependable stream-flow a fair percentage below that which seems warranted by the measurements and statements made to the engineer by " old inhabitants of the region."

With respect to 2. About 10 years ago I was associated with a hydroelectric development that suffered a loss of nearly 15 per cent in possible power development because of the unfortunate decision to save a matter of $200,000 in flume construction instead of tunnel development which should have been made.

J. H. Wilson (by letter): In my opinion the investing public's distrust of hydroelectric projects is more fully justified than we might like to admit. The arbitrary deductions on the engineer's estimate made by those who have had experience with these investments is, I think, a serious matter. It shows that in many cases the engineers who make these estimates are professionally incompetent or do not realize their moral responsibility.

To be specific, large sums of money have been invested on engineers' reports in which the minimum stream-flow was given at from three to five times the amount justified by the available reliable data. While the lengthy prospectuses might have some merit as works of fiction, as a basis for investing money with the expectation of getting a fair return, they were absolutely valueless.

Only under exceptional conditions as to market and cost of development is it commercially feasible to develop for more than the minimum flow of water, as the cost of auxiliary equipment which ordinarily must be provided renders the commercial success of the enterprise questionable.

Most streams in their normal condition do not provide a minimum flow that justifies very extensive development. We are thus brought face to face with the problem of artificial storage, which is absolutely necessary in order to conserve our water power. As to whether this should be done by public or private enterprise we may differ, but that it should be done admits of no question.

James Lyman (by letter): Public attention was first directed to the commercial possibilities of utilizing the water powers of the Country in 1895 when the Niagara Falls Power Company started its great power house. Since that time many water powers have been developed, and what was then a new and unexplored field of engineering has now been thoroughly worked out.

Water wheels of either the turbine or impulse type have been designed with a capacity up to 15,000 h.p. and for heads up to 1500 ft. and giving a brake horse-power efficiency in the largest size up to 90 per cent. The design and construction of masonry dams to withstand extreme flood water and all conditions of weather and climate is now as well understood as bridge building and other lines of civil and mechanical engineering.

Electric generators and step-up transformers with voltages suitable for transmission of many thousands of horse-power 150 to 200 miles with comparatively small energy losses, are of standard and reliable design.

The substantial steel towers well set on private right of way, the suspension link porcelain insulators of great mechanical strength and high insulating qualities, and the heavy stranded, hard-drawn copper cable ensure reliable service for long distance power transmission.

Before proceeding with any proposed hydroelectric development the following data should be obtained:

1. The fullest information should be obtained of the water flow throughout the year and over as many years as possible. The drainage area of the stream, the vegetation, timber lands, and character of the soil should be determined.
2. The available market for the power should be carefully canvassed, prices obtained, and actual or possible competition recorded.
3. To ensure the best returns on the investment, the hydroelectric company should control the lighting, electric railway or other power companies, using the water power developed. In other words, it should sell direct to the consumer instead of to a local company. A water power should not be developed until a good market is assured.

The majority of the water powers throughout the country are subject to a wide range of stream-flow. For two or three months of the year the flow may not be more than one-half the minimum flow during the balance of the year. To provide for this low-water season, a steam-turbine power house should be installed at the receiving end of the transmission line. The capacity of such power house should be, say, the difference between the power corresponding to the minimum flow during the year and the minimum flow during the nine or ten full months.

Such a power house would serve three important functions:

1. It would bring the capacity of power developed up to that corresponding to the minimum flow through nine or ten months of the year.
2. It would act as an insurance reserve on the system in case of possible interruption to the water-power service.
3. In long-distance transmission especially, one or more of the steam generator units could be kept running on the system, with very little energy loss, as a synchronous rotary condenser. By means of a Tirrill regulator in connection with its exciter, it could automatically maintain constant voltage at the receiving end of the line through a wide range of load and power-factor, the voltage at the water power house being kept constant regardless of the load conditions.

R. A. Ross (by letter): Until the engineer is willing to recognize that his services are only valued by the public according to the returns they give either in dividends or benefits, he will not fulfil his whole duty to the public, nor will he obtain that recognition which he deserves. Most engineers are too much wrapped up in the technical aspect of their profession, to the neglect of the commercial point of view, which has to do with the dollar. As a result, it is frequently remarked by financial men that engineers' estimates are notoriously too low. This is exemplified in the quotation given in the paper:

> We will not consider a water-power project unless, after doubling the cost, cutting the available power in two, and reducing the market price by 40 per cent it will show interest on the bonds necessary to issue.

This remark is a purposed exaggeration, designed to call attention to a situation. It is pertinent, therefore, to inquire wherein engineers' estimates have failed in this regard, and why. A number of reasons may be given, among others the following:

1. Estimates may be based on insufficient information, information which it is impossible to get, varying from that furnished by the oldest inhabitant as to the height of the water in a stream, up to reliable information by gaugings which have been carried out for a number of years. There is here a wide unavoidable margin for discrepancy.
2. The cost of certain parts of the construction, such as foundations, may be unknown and perhaps unknowable until " unwatering " takes place.
3. Estimates may be made during a period of depressed prices, and the project may be held over by the monied interests until prices have risen, when the financing is done on the old estimate.
4. Additions may be made to the enterprise which were not previously considered. It would appear that the cost of such additions would be allowed for in the mind of the financial man as extras, but it will almost invariably be found that he remembers nothing but the total amount of money originally extended or required and makes no allowance for extensions to the scheme. In fact he seems constitutionally unable and unwilling to recognize any other figure than that placed before him by the engineer for a stated case, whereas the development in its final form is entirely different.
5. Insufficient consideration to expenses other than those involved in the physical construction.

In the development of any project, the costs group themselves into two divisions:

a. Those purely engineering costs which cover the construction and equipment.

b. Those financial or business costs which cover the working capital, financing, deficits during the initial period of business, etc.

To illustrate this point, consider the following table which has been derived from an actual case of hydroelectric development under three schemes producing progressively larger amounts of power:

TABLE I

Data	Development		
	A	B	C
Construction			
1. Estimated cost of hydroelectric plant	$1,895,225	$2,618,715	$3,694,386
2. Estimated cost of transmission lines and equipment	1,393,287	2,009,668	2,693,299
3. Estimated cost of sub-stations and equipment.	636,488	1,051,617	1,304,315
4. Total estimated cost of plant from items at market value	3,925,000	5,680,000	7,692,000
5. Shortages, construction plant unavoidable extras, and mistakes, etc	275,000	350,000	500,000
6. Total cost of physical equipment	4,200,000	6,030,000	8,192,000
7. Engineering, with plans, supervision, and preliminary operation, say 5 per cent on Item 6	210,000	301,500	409,600
8. Business, legal, insurance, and accident costs, allow	75,000	100,000	150,000
9. Total cost of enterprise apart from financing.	4,485,000	6,413,500	8,751,600
Organization and Financing.			
10. Organization and promotion, charter, printing, brokerage, etc	75,000	100,000	150,000
11. Interest during construction, on Items 1 to 10 at 5 per cent on face value of bonds issued below par	329,979	480,706	649,267
12. Normal operating costs and bond interest in excess of gross earnings say for one year after operation commences	55,000	70,000	100,000
13. Securing business, extra advertising, canvassing, etc., during development period as above, allow	22,000	30,000	40,000
14. Interest on Items 12 and 13 for say 1 year	3,750	5,000	7,000
15. Total estimated cash expended until earnings equal operating costs plus bond interest	4,968,729	7,117,206	9,697,867
16. Allowance for working capital	200,000	300,000	400,000
17. Total cash required	$5,168,729	7,417,206	10,097,867
18. Additional costs of Items 1 to 9 if development *A* is increased at different times instead of the larger developments being made at once	——	$500,000	750,000

The engineering estimate will include Items 1 to 9, while the financial or business estimate should cover those from 10 to 17 inclusive.

The question then arises, in whose province is the estimating of such additional costs for which money must inevitably be raised? If left to the financial man, does he do his duty; or, failing this, does he not frequently take refuge in the statement that the engineering estimates are too low? I think that most engineers who have had to deal with these matters will recognize that the latter occasionally happens. It becomes a question, therefore, whether the engineer should not in self-defence consider these financial and business items in every case to the best of his ability, which if not corroborated by the financier with his wider experience, would at least serve notice upon him that they demand consideration.

The results in the illustration given may be summed up as follows, for equipment (*a*)

Total cost of physical equipment	$4,200,000.00
Total cash required for enterprise	5,168,729.00
Indebtedness to bondholders for above cash. bonds being sold under par	6,500,000.00

In this case it will be noticed that the indebtedness incurred exceeds the cost of the physical equipment by 55 per cent.

As stated by Mr. Doherty, financiers do apply the pruning hook to engineers' estimates, but of course not to the extent indicated in the quotation. The question arises whether this does not tend to the acceptance of schemes that have not been soundly estimated upon in preference to those which have? Where a careful conservative estimate is made the costs will be high, and the application of any arbitrary rule tends to eliminate it from favorable consideration on the part of the financier, and to give the preference to an ill-considered, ill-estimated proposition showing a lower cost. In other words, the whole matter hinges on whether the engineer is to be considered as a technical man dealing with the cost of the physical equipment only, or whether he is to be considered a business man competent to deal with the enterprise as a whole?

The education of the engineer has been neglected in his relation to business. It is about time this was recognized, and his responsibilities extended to the scheme as a whole. It is only when this education has been acquired and acted upon, that he will receive that respect from the business public and financial men that his profession warrants.

M. H. Collbohm (by letter): The combination of water power and irrigation projects mentioned by Mr. Doherty is interesting and new. For a number of years electrical power has been utilized in irrigation schemes, demanding, however, only a moderate amount of the total station capacity plants. Only recently have hydroelectric plants been built mainly for the purpose of supplying electrical energy for irrigation. Plants of such order are building with considerable station capacity, making it worth while to study the special conditions met with in this new line of work. In one of the developments of this nature with which I am associated, the generating station will be designed for a final equipment of 100,000 h.p. capacity.

The power for irrigation only is used for a certain period in the year comprising about 6 months. The new problem is, to find a market for the electrical power during the rest of the year. If commercial conditions would allow the use of the surplus energy for electrochemical purposes, such as fixation of atmospheric nitrogen, production of calcium carbide, etc., the question would be solved. However where such is not the case a market may be created by selling the power cheap enough to compete with coal or oil for heating purposes. This kind of market does not interfere with that for irrigation, as their respective seasons do not overlap. The sale of power for such a purpose would probably not bring any profitable returns, but it might cover the running expenses and fixed charges.

The problem of reliable service from long transmission lines is indeed not yet completely solved. However, with duplicate lines on modern steel towers and designed with due regard to the severest conditions likely to arise, with the suspension-type insulator, and frequently grounded guard-wires of copper-clad steel of proper size instead of ordinary galvanized steel, (as recently discussed by the writer) the reliability of a transmission line would be considerably higher than that heretofore obtained.*

The equipment outlined in the paper to provide against interruptions serves as an emergency arrangement to help out in case where an interruption has already taken place at some point in the system rather than a means to provide against such interruption. The usual cause of interruption to service in a station comes from lightning, atmospheric and internal, as produced by arcing grounds etc., entering over the transmission line. To provide against interruptions from this cause the electrolytic lightning arrester in connection with choke-coils is used satisfactorily. As a further protection to station apparatus, iron wires of high permeability can be substituted for the copper wires commonly used for high-tension leads in the power house. The protective action of the iron wires is based upon the skin effect produced by the very high frequency of lightning, thereby increasing the resistance of the iron wire enormously.†

It appears doubtful whether financial aid can be obtained to install equipments that are kept running only for immediate help in case of emergency. The fixed charges and operating expenses for such an equipment would tend materially to reduce the net income of the plant, because its operation is almost entirely unproductive. The money that would be required for such an equipment could possibly be spent to greater advantage on the transmission line, by running each line (in case of a duplicate circuit) on a separate right-of-way—which is very seldom done on account of high cost—and by providing more

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* See *Electrical World*, May 20, 1909.

† See article by the writer in the *Electrical World*, Dec. 2, 1909.

guard-wires of non-magnetic material and large cross-sections above the lines, grounded at every tower, to take care of the heavy currents inherent in atmospheric lightning. Lightning arresters at various points along the line would also materially reduce the danger to insulators and station apparatus.

H. A. Storrs (by letter): Mr. Doherty's comments must appeal to all engineers in the West, who are in a position to know the effect of the present conservation movement on hydroelectric enterprises. His remarks are specially opportune just now, when the Government, through its officials, is calling for legislation and shaping policies looking to better control of our natural resources. It is true that in the past the Government's efforts to exercise control over water-power developments have been "largely misdirected or very generally misunderstood." Especially does this seem to be the case from the point of view of those who have found the former untrammelled conditions conducive to large gains on small speculative investments. It is not so much a matter of inducing public officials to take the "proper attitude" toward the development of our water powers, as of bringing about proper legislation to enable public officials to have some definite basis of authority on which to act. Our government officers, if given definite, comprehensive laws under which to work, and sufficient funds to enable them to perform the required work, can furnish a basis for future development of the water-power possibilities of the country that will give a stability to hydroelectric enterprises not possible under the present chaotic conditions.

As intimated by Mr. Doherty, there is need of "intelligent planning and engineering" to supplant the haphazard methods now in vogue, by which a partial development of the power possibilities of a stream is governed by a policy so ill-advised and short-sighted as to preclude, for a long time, any further utilization of the remaining power latent in the stream. If given proper authority and means, the states and nation, through their technical bureaus, could determine for each stream its ultimate power possibilities, including the approximate normal flow of the stream the opportunities for creating storage of flood flow, the sites for hydroelectric plants, etc. Estimates of cost and output of installations, based on such definite and reliable data, would be accepted by the men who have money to put into such enterprises, without the excessive "discounting" referred to in the paper. This discounting of the promoters' and engineers' statements has heretofore been somewhat warranted by the uncertainties on which many an attractive proposition has been based.

That an enterprise of the character under discussion may be undertaken on a very narrow margin of profit, if a proper examination has been made of the proposed water plant provided "the behavior of the stream is a matter of reliable record for several years", is, as implied by Mr. Doherty, worthy of notice.

It directs attention to the requirement that somebody should, for several years prior to the inaugurating of a new project, have been keeping a reliable record of the stream-flow. The systematic gauging of streams, in advance of any proposed commercial developments of power, will, of course, not be undertaken except by the state or national Government.

Engineers interested in hydroelectric and irrigation projects, should be the first to urge upon the Congress the making of adequate appropriations to enable the hydrographic branch of the Geological Survey to continue its stream measurements on all streams where a partial record has already been secured, and to extend its work to all the remaining streams as rapidly as new gauging stations can be installed. The topographic branch should also be provided with funds to enable it to continue its valuable work. Its contour maps furnish at once the basis for determining the profiles of streams and probable location of power plants, as well as possible reservoir sites. Not until complete data have been obtained can the Government intelligently determine the extent of the power possibilities of its streams, or make comprehensive plans for their utilization.

Referring to Mr. Doherty's statement to the effect that the efforts of the Government to exercise some control over water-power developments seem to be obstructing rather than encouraging such enterprises, the particular case presented below will serve to show what results may be expected if the present Government policy is enforced. The National Government can not, however, under the present laws, exercise general control over the waters of non-navigable streams, since this authority is vested in the separate states. But, under the Act of June 4, 1897, the Secretary of Agriculture has full power to regulate the occupancy and use of the natural forests. Through the Forestry Service, therefore, the Government deals with prospective power plants, storage reservoirs, conduits and transmission lines, so far as they may be located within the limits of the forest reserves. The essential features of the Governments policy as stated recently by the Chief Forester in a letter published in *The Outlook*, December 4, 1909, are: first, that the right to develop water power on the forest reserves shall be granted for a limited term of years and not for all time; secondly, that a reasonable charge shall be made for the privilege granted. The application of these principles is illustrated by the following case.

Under date of November 24, 1909, permission was granted by the Forestry Service, covering the occupancy and use of certain lands in one of the national forests in Colorado, for the storage reservoir of a power generating plant. The principal features of the terms under which the permit was granted are as follows:

1. Payment to the United States, annually in advance from September 1, 1909 until the beginning of use of the waters for

which permit is granted, at the approximate rate of one dollar per acre of reservoir area and five dollars per mile of conduit for the land occupied by such works.

2. Payment to the United States of a gross operating charge, based on the total electrical output of the plant per year, at the following rates per 1000 kilowatt-hours.

For the	1st year	2	cents
" "	2nd "	4	"
" "	3rd "	6	"
" "	4th "	8	"
" "	5th "	10	"
" "	6th to 10th years inclusive	12½	"
" "	11th " 15th " "	15	"
" "	16th " 20th " "	17½	"
" "	21st " 25th " "	20	"
" "	26th " 30th " "	22½	"
" "	31st " 35th " "	25	"
" "	36th " 40th " "	27½	"
" "	41st " 45th " "	30	"
" "	46th " 50th " "	32½	"

Certain deductions are allowed from the "gross" charge in case; (*a*), the title to part of the watershed has passed out of the United States; (*b*), the conduit is not wholly on government lands; (*c*), the power is derived in part from water stored in a reservoir constructed or owned by the permittee.

The following table shows the gross charges as determined for the project under consideration:

TABLE I.

Year	Output			Rate per 1,000 kilo-watt-hours·	Annual charge
	Average kilowatt per day	Average kilowatt hours per day	1,000 kilowatt hours per year		
1912	3,000	72,000	26,380	2 cts.	$525.60
1913	5,000	120,000	43,800	4 "	1,752.00
1914	7,000	168,000	61,320	6 "	3,679.20
1915	10,000	240,000	87,600	8 "	7,008.00
1916	12,000	288,000	105,120	10 "	10,512.00
1917 to 1921	12,000	288,000	105,120	12.5 "	13,140.00
1922 " 1926	12,000	288,000	105,120	15 "	15,768.00
1927 " 1931	12,000	288,000	105,120	17.5 "	18,396.00
1932 " 1936	12,000	288,000	105,120	20 "	21,024.00
1937 " 1941	12,000	288,000	105,120	22.5 "	23,652.00
1942 " 1946	12,000	288,000	105,120	25 "	26,280.00
1947 " 1951	12,000	288,000	105,120	27.5 "	28,908.00
1952 " 1956	12,000	288,000	105,120	30 "	31,536.00
1957 " 1961	12,000	288,000	105,120	32.5 "	34,164,00.

3. Payment for all timber destroyed in the forest reserve.

4. Construction of the works to begin within 18 months from date of approval of the permit; construction to be completed

and operation of the works for the purpose intended to begin within 3 years from date of approval of permit.

5. The United States reserves, conditionally, the right to purchase power at as low a price as that allowed to any other purchaser.

6. The permit is not transferable.

7. The permit shall be forfeited to the United States, if the works be controlled by an unlawful trust, or if they be used in restraint of trade in the sale of electric energy.

8. The permit shall cease and be void at the end of 50 years but is renewable upon conditions not yet fixed.

For the purpose of comparing the Government charge to be paid for the water-power privilege with the annual income of the plant, the following table has been prepared showing what per cent of total gross receipts must be paid to the Government.

TABLE II.

RATIO (IN PER CENT) OF GROSS ANNUAL CHARGE TO GROSS ANNUAL INCOME

	Sale price of delivered power per kilowatt-hour				
	1 cent	2 cents	3 cents	4 cents	5 cents
1912	0.2	0.1	0.07	0.05	0.04
1913	0.4	0.2	0.13	0.10	0.08
1914	0.6	0.3	0.2	0.15	0.12
1915	0.8	0.4	0.27	0.20	0.15
1916	1.0	0.5	0.33	0.25	0.20
1917 " 1921	1.25	0.625	0.42	0.31	0.25
1922 " 1926	1.5	0.75	0.5	0.38	0.30
1927 " 1931	1.75	0.875	0.58	0.44	0.35
1932 " 1936	2.0	1.0	0.67	0.50	0.40
1937 " 1941	2.25	1.125	0.75	0.56	0.45
1942 " 1946	2.5	1.25	0.83	0.63	0.50
1947 " 1951	2.75	1.375	0.92	0.69	0.55
1952 " 1956	3.0	1.5	1.0	0.75	0.60
1957 " 1961	3.25	1.625	1.08	0.81	0.65
Average.........	2.085	1.0425	0.695	0.52	0.417

The table shows that for the 50-year period the average payment to the Government is about 2 per cent of the gross receipts, at a sale price or valuation of 1 cent for each kilowatt-hour, delivered by the plant, and about 1 per cent at a valuation of 2 cents per kilowatt-hour.

Applying these figures to the case in hand, assuming the average value of the electric power during the 50-year period to be 1 cent per kilowatt-hour, the gross annual receipts would be about $1,000,000 and the average annual payment to the United States would be $20,000.

In response to inquiry, asking what privileges and benefits were secured by paying to the United States the above " conservation " charge, the Forest Service replied as follows:

> The conservation charge is based on the value of the land occupied for the particular use to which the land is to be put, and on the special benefits the permitee received by reason of the care and administration of the natural forest including the protection of the watershed from fire and destructive cutting which materially affect the water sources.

The permit in hand was secured for the benefit of a project comprising a storage reservoir of 10,000 acres superficial area, of which 260 acres only were within the boundaries of a forest reserve. It follows that the annual payment of $1.00 per acre for the three years allowed for construction amounts, in this case, to only $260; whereas, if the entire reservoir had been in the reserve, a payment of $10,000 per year would have been required. It is presumed that the object of this heavy initial tax on the enterprise is to compel immediate construction of the works, thus preventing the power possibility from being held, undeveloped, for speculative purposes. Speculation in undeveloped water powers on forest reserves is still further guarded against by making the permits non-transferable.

The recommendations of the Secretary of the Interior, in his recent annual report, are generally in line with the present practice of the Forest Service, except that he would limit the life of the permit, or " easement ", to 30 years, allow 4 years for accomplishing the first quarter of the proposed development, and require that transfer be made to the United States of the water rights necessary to provide for the estimated power development.

In view of the probability that, during the next decade electrical power will be applied extensively to the operation of railroads in the West, the policy and methods of the Government in exercising control over water powers located on government lands are subjects of great practical moment to the country at large. They deserve the careful consideration of engineers who are in a position to influence the trend of legislation and of public opinion.

Mr. Doherty's remarks under " collateral enterprises " are timely and specially applicable to present conditions in Colorado. Here the extensions of present irrigation systems, depending on gravity for conveyance of water, are becoming relatively more expensive each year, the earlier developments having taken advantage of the easier propositions. It is now more economical, in many cases, to resort to pumping. Electric motors driving centrifugal pumps are the ideal arrangement for such purposes, and pumping service affords a desirable load for a commercial generating station during the three or four months comprising the irrigation season. During the rest of the year, the generating capacity can often be used to advantage in meeting the extra demands for lighting and railway service. Rather than purchase power for operating the pumping plants, it is sometimes profitable to build generating stations using the power available at some of the " drops " which frequently occur in main canals of the gravity system. Or, if cheap fuel is at hand, steam generating plants may be warranted. A complete power and pumping system using the lowest grade of lignite was recently built by the United States Reclamation Service, the writer being responsible for its design and construction. The system is located near the North Dakota-Montana line, on the Missouri River, from which water will ultimately be pumped for irrigating about 25,000 acres. The generating station is close to the portal of the mine which was opened and is operated by the United States to supply fuel to this plant. The machinery installed comprises eight 250-h.p. boilers, three turbine generating sets aggregating 1100 kw. and two 225-h.p. steam-turbine pumping units. The main canal brings water to the plant from the pumping station located on the Missouri River and the water is lifted, at this point, to higher canals, thus providing abundant water for condensing purposes. The power is transmitted to five pumping stations, two of which are distant 28 miles from the generating plant. The boiler furnaces are designed especially for burning lignite containing 40 per cent moisture, 25 per cent fixed carbon and 25 per cent of volatile hydrocarbons, and show, under usual working conditions, an evaporation better than 6.5 lb. per pound of dry coal. The plant is out of commission about 8 months each year, but it is hoped that manufacturing establishments, such as flour mills, alfalfa mills, and paper factories, can be induced to locate where power can be furnished cheaply during the non-irrigating season. A beet-sugar factory, if built adjacent to the power house, so as to take steam directly from the installed boilers, would make a desirable combination.

Irrigation systems can hardly be developed on streams having as flat a slope as the Missouri River, namely, 0.8 of 1 ft. per mile, without resorting to pumping. Where the flood rise, occurring during the irrigation season, is as great as on the Missouri River, namely, 19 ft., and the banks very unstable, it is considered advisable to mount the pumps and motors on floating barges. These are rendered free to rise and fall with the river level, by conveying the water from the barge to the shore by means of steel pipes and flexible joints. Electrically driven pumps are, of course, best suited to installations of this kind, but in some cases it has been found desirable to place the entire steam plant on board a boat. The delivery of fuel to the floating plant is expensive compared with the delivery of electric power.

Fuel-consuming pumping plants and generating stations on irrigation projects will not ordinarily be resorted to, if electric energy can be had from a water-power plant located within reasonable distance.

The above description of a pumping system depending on fuel merely serves to emphasize the fact that irrigation requirements have already opened up a new field for the disposal of electric power from hydraulic plants in competition with power obtained from more expensive sources.

E. P. Roberts (by letter):

THE VALUE OF WATER POWER SECURITIES

The value of a water power is not intrinsic. As Mr. Doherty points out, it is affected not only by the present or the near future cost of furnishing energy in the desired form to the consumer, as compared with the cost from some other source, but, from the standpoint of the investor, by the probable future comparative cost.

THE RELATION OF WATER POWER DEVELOPMENT TO THE CONSERVATION OF OUR NATURAL RESOURCES

Although the work of the Federal Government and of some of the states relative to the conservation of natural resources, including potential water powers, is proving exceedingly beneficial and the data recorded by the Federal and State Engineers are of great value to the water power engineer, nevertheless the development of water powers has, in the writer's opinion, been hampered by law and by the rulings of federal and state authorities, the result being detrimental to the development of water powers and an economic waste. Federal or State control is necessary, and, in some cases, construction and operation by the Federal Government is advisable. Undoubtedly the benefit to the community resulting from the increased interest in the conservation of natural resources will be very great, but it seems as if there were a tendency to define the verb "to conserve" as meaning "to bury."

The conservation of large areas of timber land may be advisable, and in some cases undoubtedly is so; but in other cases it is a question whether throwing such land open to settlement is not more advisable from the standpoint of economics. Where land is used for forests only, the annual value per acre of the growth on such land is very small as compared with the possible value of farm products, provided the land is suitable for farming and there are transportation facilities. In most locations, if the land is suitable, transportation facilities will follow, if they do not precede, the development of farms. The cost of supervising, developing, and safeguarding forests is very considerable, and sometimes losses by fire are great. The number of persons employed for any given area is of course far greater when it is thrown open to settlement than when it is used solely as a forest. The above is not intended as an argument against conservation of forests, but merely against unwise conservation.*

COLLATERAL ENTERPRISES

Occasionally irrigation and boat canals must be considered. In a report made in 1905 by Mr. W. H. Abbott, relative to a

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*See article by R. C. Beardsley, *Southern Engineer*, June, 1909.

proposed power development in the Northwest, it was proposed to irrigate considerable tracts by electric pumping. The power was to be used for general purposes, so the pumping could be done at hours when other loads were at a minimum, thereby improving load-factor; in other words, provision for pumping for irrigation purposes was not to increase the cost of the water-power development. In some cases pumping could be done directly into the ditches, and in some places storage reservoirs would be obtainable at slight expense. A considerable amount of land along the bottom of the valleys was already irrigated, but there were many square miles at a slightly higher elevation which could not be irrigated except by pumping. Of course, anything which tends to improve the load-factor is beneficial, though the degree of benefit and consequently the rates which can be obtained depend upon storage capacity as well as upon other factors affecting each individual case.

THE UNFAVORABLE FEATURES OF WATER-POWER ENTERPRISES AND THEIR OPERATION

There are few proposed enterprises which require a more careful detailed investigation than a proposed water-power development. This investigation can only be made by spending considerable money. Unfortunately, many of those interested in such proposed developments are not willing, or are unable, to have such investigation made, with the inevitable result that many water powers have been financial failures. In some cases the first cost was far greater than that anticipated; in other cases the income was much less than the amount estimated.

In some cases there are legitimate reasons why the construction cost proves to be either greater or less than the estimated cost. For example, the estimate may be based on construction at times of average flow, work being done in the months that are shown by the records to be months of minimum flow, and especially least liable to floods. If the flow conditions are different from those anticipated, even though provision be made for deflecting the water to avoid damaging existing structures, nevertheless construction may be delayed, and often at considerable expense. On the other hand, if the season is unusually dry the cost may be materially decreased. In some cases the owners may postpone construction until the season advised by the engineer has passed and then insist, perhaps wisely, that construction be commenced. The changed conditions may, however, increase the cost, causing the engineers' reputation for accurate estimating to suffer.

Even when the first cost has been accurately predetermined, and possibly also the water-flow; minimum, average, and maximum considered by weeks, months, and years, and the possible and also the advisable storage capacity carefully investigated—nevertheless in many instances the market has not been accurately predetermined, and the result may be a failure.

Rating of Water Powers

The mere statement that a water power has a specified rating is indefinite, and may be misleading, although comparisons are frequently based on statements of total horse power and cost per horse power, generally on the total rated horse power of the wheels installed. The following example indicates the fallacy of considering the value of a water power as based on the rating of the wheels installed

The proposed general development is to include three water powers to operate in conjunction. One power to have materially greater fall and also greater storage capacity at its site than the others, but the other two to be located lower down the stream and consequently to be benefited by the storage capacity of the upper power. Estimates were based either on first constructing and operating the greatest power, or on simultaneously constructing and operating all three. The output was estimated to be used as follows:

1. To operate an interurban electric road. The requirements of such a road can be predetermined with a fair degree of approximation, and the nature of such load is one having great momentary fluctuations.
2. *Lighting load.* The general nature of this can also be predetermined, the characteristic being a peak load during the early evening, the peak being greatly in excess of the load at other times.
3. *Factory power load.* The general characteristics of this are a fairly constant load and mainly day load.
4. *Pumping for town and village water works.* The greater amount consists of pumping into reservoirs, and consequently furnishes an ideal load both as to constancy and as to the practicability of such load operating only or mainly at times of minimum general load. The lesser amount consists of pumping into mains, but even such load is of excellent character.

The estimated resulting general-load curve has of course its maximum at the time of the overlapping of the factory-power load and the lighting load, which would occur early during winter evenings, especially during the Christmas holidays. Although the pumping load would presumably be off at such times, nevertheless safety required an allowance for a certain portion of such load. Also, although the interurban road would operate less cars then than on holidays during the summer, nevertheless it might also be operating under unfavorable weather conditions; this might not only bring up the average requirement but also, because of bucking snow, might result in excessive momentary fluctuations. The resulting general load curve would evidently be materially affected by any considerable modification as to any one character of load.

One estimate was based on the development of the greatest power operating alone, which evidently required that the installation in such power should take care of all conditions, and as electric generators have far greater overload capacity than turbines, therefore on account of the momentary fluctuating demand caused by the interurban road, the rated horse power of the turbines was estimated as being much greater as compared with the kilowatt capacity of the generators than would be required for constant generator load.

Another consideration was the probable result of installing storage batteries in the sub-stations of the interurban road. This would result in a power-house load having very slight momentary fluctuations, thereby decreasing the rated capacity of the generators, especially of the turbines, as the turbine rating would be approximately that required to operate the generators at constant load.

Another result would be that the capacity of the machinery in the sub-stations of the interurban road could be lessened, and the reliability of operation of the road somewhat increased; also the size of the transmission wires could be decreased, provided the size previously estimated was not already as small as the strength required would permit.

Another plan estimated was based on the use of storage batteries in the power house.

The plans above mentioned were made without reference to the operation of the other two powers referred to.

It will be noted that the useful output, and consequently the income, was practically the same in each case, but the rated horse power of the turbines was about in the ratio of two to three for the plan with storage batteries in the power house as compared with no storage batteries.

It might also be noted that the case was further complicated by the question whether the railway company, or the water-power company, should install storage batteries; and if the former installed them, then the water power company could afford to make the railway company a lower rate. It is evident that the decision as to what kilowatt capacity rates, and what comparative kilowatt-hour rates would be properly comparative, or equivalent, for each of such conditions, would require considerable study.

Estimates were also based on the development of the two smaller powers, considering whether either or both would take the peak load only, or would operate continuously; and whether they were to be placed in operation at the same time as the greatest power, or at some future date. This would obviously affect the horse power capacity of the turbine to be installed at the greatest power, but, nevertheless, the annual output of such principal power would not be affected except as the smaller powers might allow the operation of the largest power mechanism at rated rather than at part load.

Any specific case is complicated by such questions as the following: Will there be a market for secondary output, or such output as may be available at times, but is not expected, or guaranteed as being always available?

The question may also arise whether by increasing the water storage capacity, or by installation of steam power, or by making arrangements with existing steam powers, it may not be financially advisable further to guarantee the primary power or to take at least a portion of the secondary power out of such class and place it in the primary. Such changes may, or may not, materially affect the rated horse-power of the turbines installed, but may materially affect the gross and net income.

MATTERS WORTHY OF DETAILED CONSIDERATION

Methods to insure against interruptions, or to lessen the harmful effect of interruptions. In most cases approximately reliable service is imperative. Assurance is impossible and how much less than absolute reliability is imperative depends upon conditions. As Mr. Doherty points out, it is frequently possible not only to tie hydraulic plants together, but also to operate in conjunction with central station plants operated by steam or gas engines. An example of such tieing together is illustrated by the plants described in the *Electrical World* of September 2, 1909, where three water-power plants, a gas-engine plant, and a central station are tied together, and in addition are connected with the plant of a manufacturing company having considerable electric output capacity, normally used for testing electrical apparatus, but which testing can stop in case of emergency.

Equipment to insure against interruptions, or to lessen the harmful effect of interruptions. If steam or other power is to be used for emergencies only, and only for comparatively few hours annually, then the financial cost is the prime consideration, and the hourly expense of operation only a minor factor; but if it is to be used as an auxiliary plant, then the importance of operating expense increases.

Another consideration is the character of labor available. And such reserve plant should be of as simple a character as possible, as in such case it is most likely to be properly handled by the force operating the water powers, and will not require the employment of a high grade stationary engineer.

Penalties for interruptions of service or insurance against interruptions. The prime object of providing a penalty is not to enforce it but rather to make such provisions as to assure the customer that he will receive the service required, which if not received will result in loss to the producer. There is, however, always the danger that by making the penalty too high the producer must materially increase the charge and the customer may pay too high for his insurance. The method described by Mr. Doherty may be applicable to some cases, but I do not understand that he suggests it as a general basis.

Methods of charging. As Mr. Doherty states, there are many methods, but the fundamentally correct one is that the customer should pay:

First, an amount depending upon the maximum demand of the customer at the time of maximum demand on the producer. Unfortunately such basis is not always practicable and the charge must be based on the customers maximum demand.

Second, for the actual energy furnished to the customer.

Whether the maximum demand shall be based on the maximum between certain hours of the day, or whether on the maximum demand whenever it may occur during the 24 hours, and how often it shall be ascertained, will vary with the conditions. The rate at which the actual energy shall be paid for varies with the character of the load curve, including the degree of variableness of the load and the momentary fluctuations. In other words the entire character of the load affects the cost to the producer, and therefore the proper charge to the consumer.

Classes of services which can be advantageously supplied. Mr. Doherty says that " no general and complete rules can be laid down whereby the maximum load-factor can be secured to a hydroelectric company ". The writer at this point suggests, as Mr. Doherty does later, that it is not the maximum load-factor which is the important item, but the maximum net income, and that there are cases where a better net income is obtainable from a low load-factor than from a higher one. If, for instance, an existing steam power plant furnishes general supply for a city, and a water power auxiliary is possible, the question will arise whether to increase the capacity of the steam plant or to develop the water power. The probabilities are that the first cost per kilowatt of capacity delivered at the steam power plant will be greater for the water power than for an equivalent addition to the steam plant, but the stand-by losses for such portion of the steam plant as are required to handle peak load may be so great as to more than offset the difference, including interest, maintenance, and depreciation charges. Under such conditions it might be preferable to have the water-power plant take care of the peak load and to operate the steam plant under approximately steady load, or at least an exceptionally good load factor. Under such conditions the load-factor of the water power would be comparatively low. Of course, other things being equal, the better the load-factor, for either steam or water power, the better the net result, but it is seldom that all things are equal.

How to develop the market selected. The points made by Mr. Doherty are, in the writer's opinion, well taken.

How to figure the amount of power which it would pay to develop. This evidently requires a comprehensive study of all the conditions. Under the above heading Mr. Doherty refers to the possible advisability of water power taking the peak load and the inequalities of load when operating in conjunction with a steam plant, and the writer has touched upon this point in connection with a previous sub-heading. It might be well, however, to add that it is important to ascertain at what time of the year the maximum peak will result, and to be sure that there will be water available at such time.

It might also be noted that the amount which can be economically expended for storage capacity can only be ascertained by comparing the estimated result with that obtainable from steam or other power auxiliaries. At the same time consideration should be given to the risk of break-down of transmission lines, and to other features affecting reliabilitiy. The possible benefit of greater reliability cannot be exactly expressed in dollars and cents, but may be a deciding factor, especially when the comparative values otherwise obtained are approximately equal.

Calculations on depreciation. Unfortunately depreciation frequently is not estimated, and the statement is sometimes made by promoters that the appreciation of the property will more than offset the depreciation, and although this may be true, the result, not infrequently, is that money is not available for replacement.

Methods to determine the accuracy of engineers' estimates. Allowing and providing for freedom of discussion and criticism by all the engineers of a corps, or several heads of an engineering force, will frequently disclose errors and also opportunities for betterment, and this can be accomplished without loss of discipline.

P. W. Sothman (by letter): I agree with Mr. Doherty that it is to the best interest of all that projects for the development of water powers should be undertaken and encouraged, which would be in accordance with the movement to conserve our natural resources. These projects should be carried on under one head with well developed plans to insure the greatest possible development of the total energy available from our streams, rather than by numerous interests with no concerted plan of action. With this object in view it is my opinion that governmental control and regulation of all water-power developments would greatly reduce the immense amount of waste power, by bringing under its direction not only one development but all such developments in any territory. It would serve judiciously to carry out plans for uniform supply, thereby assuring the most efficient use of the water powers, including under their control projects for irrigation, forest preservation, storage for the prevention of floods, etc.

It is difficult to estimate the annual earning capacity of the energy wasted in floods, and the direct damage done by them. The proper storing of water will not only permit of development at the site of the dams but will also increase the power of every user down-stream. With well-designed storage systems it would be possible to more than double the horse power available without storage.

The relation of forests to water-power development is of great importance in the uniformity of flow. In Europe large sums of money are spent to forestize large tracts of land and, in recent years, water-power developments have been encouraged and assisted.

It is only by such a system of intelligent government control that advantage can be taken of all the conditions which go to obtain the maximum amount of energy from the available sources.

O. S. Lyford, Jr. (by letter): Engineers are looked upon as experts in money saving, but seldom as authorities on methods of money getting. Market development, contract making, conservation of earnings, and other strictly commercial problems are seldom discussed by this Institute. Most of our attention is given to the creation of facilities for existing enterprises, but in the field of electric railroading, power development, and other public service utilities, as well as occasional industrial enterprises dependent upon electric power or electric processes, the electrical engineer is being called upon more and more to extend the scope of his investigations and include commercial as well as constructive and operative matters. This requires a thorough knowledge of the essential elements of existing business of the kind under consideration, and ability to form a clear conception of the problems affecting the sales, costs, capital charges, net profits, and even the strategy involved in putting the new enterprise in its proper place in the world's business.

In the matter of costs the engineer must be able to foretell, within reasonable limits, not only the construction cost over which he may have more or less control, but the expense of organization, financing, legal work, interest during construction, etc., which are outside of the sphere of engineering. The fundamental question is: "what will be the return on the investment." The "return" is the net profit dependent upon astute management, as well as the potentiality of the market; the "investment" includes all the money spent in getting the enterprise on an earning basis.

One unfortunate feature of this branch of engineering is that there is never money enough in advance of construction to pay for an extended study of the local conditions. The promoter of a new enterprise faces the prospect of losing all the time and money he puts into it, in the event that the construction funds are not underwritten. In consequence, he allows only a few days for engineerng investigations and restricts the expenditure to a nominal sum. The result, as shown in many of the engineering reports presented to financiers, is an insufficient grasp of the essential facts and improper conclusions as to the warrant of the project. The colossal commercial mistakes in water-power developments in the last few years indicate that even the largest enterprises are subject to the risks involved in this lack of digestion of the governing conditions.

It is obvious that the responsibilities involved in engineering of this character require that only engineers with thorough knowledge of the construction and operation of such properties should be employed. This Institute should aid in the development of this knowledge by giving its members the benefit of as much experience of this character as possible.

Referring to the various subjects suggested in Mr. Doherty's paper, the following comments are submitted:

Interruptions and penalties. The striking feature of the plan of "penalties and insurance" is that it starts out with the statement that "the central station company is not desirous of collecting any penalties," and yet the result of what must have been extended negotiations is the most complex and burdensome method of penalizing the power company which has come within the writer's knowledge. The general theory of the scheme looks reasonable at first, but the practical application is a wide departure from the original proposition.

The apparent intent in this case was to obtain insurance by placing heavy financial burdens on the power company. Penalties are not insurance, however, and even these provisions for operation of the steam plant can be only partially successful in limiting the number and duration of the interruptions, because it is necessary to limit the waste involved in the stand-by losses and therefore the length of time that the steam plant is to be held ready for immediate service.

Thus far the only practical way found to positively insure against power house or trunk line interruptions is with storage batteries large enough to instantly take the load. Aside from the lighting and power systems of heavily congested business centers and a few railroad and industrial plants, this extent of insurance has not been found necessary. For all remaining purposes the service which can be given by a well designed and carefully operated prime mover and transmission system has been found adequate and satisfactory. Where a long distance transmission line is introduced between the prime mover and the consumer, the line is the cause of most of the troubles, but the general experience with *first class* installations throughout the country has been that disturbances due to transmission lines decrease in frequency and magnitude as the system becomes adjusted to the local conditions and the operating force becomes skilled in its duties, so that it is commercially practicable to either depend entirely on the distant power house or at best to have available a relay prime mover plant close to the center of distribution, which plant is not held in readiness to fully and immediately relay the transmitted power, but can be prepared for service in a short time. In some instances the load may be divided between the local steam plant and the distant water power plant so that the overload capacity of the steam plant is available as relay for the water power. This works out commercially only when the load is largely in excess of the water power used.

One great difficulty in attempting to protect the power user against the cost of interruption is that penalties cannot in equity be made to apply in the case of strikes, fires and other major catastrophes without a corresponding provision that the power user shall continue to pay for the power in the event of similar casualties in his own business. Therefore, these causes are usually excluded from the penalty provisions, except possibly interruptions due to lightning. Inasmuch as interruptions to the service usually occur more frequently because of accidents beyond the control of the power company than because of negligence or inadequacy, it is at once apparent that penalty provisions do not insure.

The art of generating and transmitting power has now reached a state where a user contemplating the purchase of power may predetermine within reasonable limits what degree of continuity of service may be expected from the plant of the company tendering its power. He should first satisfy himself that the power company has the power to deliver and that its plant is complete, first class and up to date (or will be when his service is inaugurated), and that the operating force is adequate to provide the best service practicable for such a plant. He should next satisfy himself that the service possible with such a plant and organization is such that he can afford to become dependent upon it. Unless these conditions obtain, the deal is impracticable at any price, but if they are found satisfactory, the question of price is next in importance and should be determined by comparison with the cost of alternative methods of obtaining power, taking into account the greater or less reliability. Finally it is proper to introduce into the power agreement such conditions as shall insure that the power company's plant and organization are kept up to the highest practicable state of efficiency. Experience has demonstrated that penalty provisions will have this effect, but simple and moderate penalty provisions have been found adequate. It is not practicable to make up in the penalties for any lack in the inherent possibilities of the power company or for a price that is too high.

The writer has been involved in the making of a number of these power contracts, representing in some instances the purchaser and in others the seller. He has in mind four cases of long-term contracts where the penalty imposed upon the power company is either a fixed sum for each interruption or a provision that the power company shall pay to the consumer for the interruption a sum equivalent to twice that which the producer would have paid during the period of the interruption; or that the power company shall pay the cost of temporary operation of the purchaser's plant during the period of interruption or deficiency. In each case there was more or less difficulty between the two organizations during the first months of operation, but the service of the power company improved until the results had been eminently satisfactory to both parties to the agreement.

The making of a long-term contract is often a matter of weeks or months, because each party is trying to anticipate all the contingencies which may develop during the period of the agreement, and it is well for the engineer not to introduce any complex provisions which can be safely avoided.

Verification of engineers' estimates. It is customary to state in the report of a proposed power development the cost of development per horse power or kilowatt of capacity, and if, for instance, the cost is less than $100 per horse power of generator capacity, or $133 per kilowatt, the general impression is that it is a cheap power. In other words, we have become more or less accustomed to put a measure on the feasibility of the development by determining the unit cost on a capacity basis. This has led to false impressions. The writer suggests two factors for convenience in sizing up these enterprises: One that may be called the " Capacity Unit Cost," which is the cost per unit of capacity above referred to. The other may be called the " Output Unit Cost," which is the first cost per kilowatt-hour of estimated possible annual output *deliverable to the customer* in an average year. The annual output to be assumed for the determination of this factor is the maximum which may be delivered at the customer's premises, as limited by the stream flow, the capacity of the equipment and the efficiency of conversion and transmission, assuming a market sufficient to absorb this maximum.

To illustrate the point, the following table is submitted, giving the cost (estimated or actual) of seven separate water powers in the same general district in our Southeastern states, these powers being developed with heads varying from 30 to 120 feet, and with generator capacity varying from 10,000 to 30,000 kw.

A comparison of plant *D* and plant *E* for instance shows that whereas the first cost per kilowatt of generator capacity is in one case $118.13 and in the other $160.14, the output unit cost (first cost per kilowatt-hour deliverable), for primary power only, is lower with plant *E* than with plant *D*. Therefore, unless a large market for secondary power at a good price can be developed, plant *E* is more feasible commercially than plant *D*, in spite of its larger capacity unit cost.

The capacity unit cost of a proposed development may be made to look low by providing an abnormal amount of equipment, but the output unit cost would thereby be raised and the enterprise be thus handicapped. One factor is a check against the other.

The output unit cost is important as giving an immediate measure of the rate at which the power must be sold to make the enterprise commercially practicable. The project will not be attractive to investors unless it promises, within the near future, net earnings at least equal to 10 per cent of the cash cost of development.

Referring to plant *E* in the following table, the output unit cost is 7.15 cents per kilowatt-hour. The minimum net earnings should be, at least, 10 per cent of this, or 0.715 cents per kilowatt-hour. The cost of operation including labor, supplies, maintenance, insurance and taxes for delivering power to the consumers for plants of the size covered by this table varies between 0.1 and

TABLE I

UNIT COSTS OF HYDROELECTRIC DEVELOPMENTS.

Plant	A	B	C	D	E	F	G
Land and water rights	Cash $14.10	cost $12.86	per $8.89	kilowatt $14.20	of $22.22	generator $13.07	capacity. $15.00
Hydraulic construction (dam, canals, flumes, head gates, etc.)	35.00	43.41	49.50	44.53	51.30	62.42	56.71
Power house building and substructure							
Hydraulic equipment	14.00	13.95	13.00	9.05	7.76	7.84	7.56
Power house electrical equipment	21.00	22.73	19.20	13.85	14.50	13.53	12.50
Transmission line, including right of way	17.20	6.26	18.30	9.00	20.70	17.50	28.50
Substation buildings and equipment	5.72	6.51	9.75	7.55	6.82	8.40	8.40
Distribution system	10.00	6.94	4.58	4.45	15.67	14.58	12.00
Interest during construction	6.30	7.36	5.54	4.75	8.40	6.18	6.16
Engineering	5.90		6.14	6.30	7.00	6.87	6.84
General and legal exp.	3.70		6.20	4.45	5.77	7.48	6.84
Capacity unit cost (total cash cost per generator kilowatt	$132.92	$120.02	$141.10	$118.13	$160.14	$157.87	$160.51
Output unit cost, (first cost per kilowatt hour of annual output deliverable to customer) Primary	0.0825	0.0717	0.0743	0.0815	0.0715	0.1137	0.0985
Primary and secondary	0.058	0.05	0.0625	0.067	No secondary	0.078	0.0820

0.2 cents; say for this case 0.15 cents. The entire output of this plant (all primary in this case) must be disposed of for an average price of 0.715 plus 0.15 or 0.865 cents per kilowatt-hour, or better, to satisfy the investor. If only half the output can be marketed in the near future, the amount of initial development must be diminished or the average price realized must be twice this figure.

In passing, it is suggested that all estimates of cost of hydroelectric projects be subdivided under the general headings of Table I, in order that convenient comparisons can be made. These headings indicate the general groups which vary independently of each other.

Amount of water it will pay to develop. Mr. Doherty makes the rather startling statement that " the operation of a water turbine for 100 hours per year would in some cases warrant its installation." This must be for very unusual conditions and must relate only to a case where the power can be delivered direct from the turbine to the device driven. In the case of electric generation, transmission and distribution, the investment in hydraulic machinery, generators, transformers and transmission copper varies with the peak load, and it has not been found practicable to provide for service of less than six to eight months duration per annum. The possible condition which Mr. Doherty quotes, however, emphasizes the advisability of considering in each case the provision which should be made for extension of plant to take care of short-term power which may later become commercially practicable.

Under this heading, Mr. Doherty makes the statement that " In this character of developemnt (a hydroelectric development having simply a dam from which the water immediately enters the turbine and is immediately discharged to the river below the dam, without any expensive canals, flumes, etc.), all inequalities of load should be taken care of in the hydraulic plant and if it is necessary to run steam, the steam load should be run for such time, and at such uniform rate, as will secure the most economic generation of steam power."

Usually, the lowest annual cost of operation will not be obtained by operating as Mr. Doherty suggests. It will be found that this will result from generating as few kilowatt-hours per annum with coal as practicable. This will mean a high cost of generation from coal per kilowatt-hour, but this is not the principal feature which concerns the stockholder. With combined coal power and water power equipment, the only items of expense which vary materially with the annual output are coal, maintenance and a part of the labor. The variable elements in the two latter items are small and the principal variable is therefore the coal. As a general proposition, then, the operation which requires the least coal per annum will be found the most economical.

Calculations of depreciation. The writer agrees with Mr.

Doherty that practically all the present assumptions for depreciation on hydroelectric plants are too high. These assumptions, however, usually appear only in the preliminary engineering reports. In the reports of actual operation and earnings they are generally noticeable by their absence. A wrong impression of earning power is often made in the early years of operation of a hydroelectric plant by not providing any sum for depreciation in excess of the actual cost of running repairs. In a recent case under consideration the bankers have proposed that the hydroelectric company set aside each year for maintenance and depreciation a sum equivalent to 10 per cent of the gross earnings from operations, the actual cost of running repairs to be paid out of this fund and the balance to be kept in the treasury as reserve for depreciation. There is no direct relation between depreciation and gross earnings, and therefore no absolute consistency in this plan, but if a depreciation fund is built up on this basis, it will insure against misconception of the earning power of the enterprise, and by being inaugurated in the first years of operation, when the apparatus is new and in good order, an adequate fund will be obtained with a much lower burden on the enterprise than would result from the depreciaton rates usually assumed in advance by the engineers reporting such projects.

In this connection " appreciation " should be taken into account as well as depreciation. The probable increase in the cost of steam power and consequently in the market price for water power is sufficient to counterbalance the elements of depreciation known as " inadequacy " and " obsolescence," so that the only element which need be taken into this consideration is the wear and tear, and possible major accidents due to flood, fire, etc.

Government policy relative to water power developments. In view of the widespread interest in this subject, it may be helpful to the members of the Institute to read into this record the substance of an article published in the " Outlook " of December 4, 1909, in which Mr. Gifford Pinchot outlines the " A, B, C of Conservation." This briefly describes what may be taken as the basis of the policy of the Forestry Service under Mr Pinchot.

Answering the question, " Why is it important to protect the water powers? " Mr. Pinchot states in part as follows:

> It is of the first importance to prevent our water powers from passing into private ownership as they have been doing, because the greatest source of power we know is falling water.* * *Under our form of civilization. if a few men ever succeed in controlling the sources of power, they will eventually control all industry as well. If they succeed in controlling all industry, they will necessarily control the country.

Answering the question, " How must it (the protection of the water powers) be done?" He states as follows:

> The essential things that must be done to protect the water powers for the people are few and simple. First, the granting of water powers forever, either on non-navigable or navigable streams, must absolutely

stop. * * * Water powers must and should be developed mainly by private capital and they must be developed under conditions which make investment in them profitable and safe, but neither profit nor safety requires perpetual rights, as many of the best water power men now freely acknowledge. Second, the men to whom the people grant the right to use water power should pay for what they get.* * *There are other ways in which the public control of water powers must be exercised, but these two are the most important.

Answering the question, " Does the same principle apply to navigable streams as to non-navigable?" the following statement is made:

Every stream is a unit from its source to its mouth, and the people have the same stake in the control of water power in one part of it as in another. Under the constitution, the United States exercises direct control over navigable streams. It exercises control over non-navigable and source streams only through its ownership of the lands through which they pass as in the public domain of National Forests.

Summing up the subject, Mr. Pinchot states:

It (the conservation idea) asserts that the people have the right and the duty, and that it is their duty no less than their right, to protect themselves against the uncontrolled monopoly of the natural resources which yield the necessaries of life.

It is not my purpose to discuss this policy in detail, but to show how it works out in a practical application.

The practice of the Government based upon the theory quoted is best illustrated in the form of permit which the Forestry Service is willing to issue. The following extracts are taken from a permit issued in April 1909. These extracts indicate the principal restrictions placed upon the power company:

The gross operation charge for any year shall be calculated by the Forester upon the basis of the quantity of electric energy generated in such year at a maximum rate which shall not exceed the following amounts per thousand kilowatt-hours.

For the 1st year	2 cents
" " 2nd "	4 "
" " 3rd "	6 "
" " 4th "	8 "
" " 5th "	10 "
" " 6th to 10th years inclusive	12½ "
" " 11th " 15th " "	15 "
" " 16th " 20th " "	17½ "
" " 21st " 25th " "	20 "
" " 26th " 30th " "	22½ "
" " 31st " 35th " "	25 "
" " 36th " 40th " "	27½ "
" " 41st " 45th " "	30 "
" " 46th " 50th " "	32½ "

From the gross operation charges for any year, calculated as aforesaid, deduction shall be made as follows:

(*a*) A sum bearing approximately the same ratio to one-half such gross operation charge as the area of unreserved lands and patented lands on the watershed furnishing the water stored, conducted, and/or used in the works for which permit is hereby applied for bears to the total area of the water shed, as of the beginning of each year;

(*b*) A sum bearing approximately the same ratio to one-half such gross operation charge as the length of the conduit, for which permit is hereby applied for, upon unreserved lands and upon patented lands, over which a right of way for ditches and canals is not reserved by the Act of August

30th, 1890 (26 Stat. 391) bears to the total length of such conduit, as of the beginning of each year;

(*c*) A sum bearing approximately the same ratio to the balance remaining after said deductions " *a* " and " *b* " as the quantity of electric energy generated from water stored artificially by the Permittee, over and above what is generated by the natural flow, bears to all electric energy generated.

The Permittee shall, except when prevented by the Act of God or the public enemy or by unavoidable accidents or contingencies, continuously operate for the generation of electric energy the works to be constructed under the permit hereby applied for, in such manner as to generate after such generation begins, not less than the following percentages of the full hydraulic capacity of the said works measured in kilowatt hours: in the first year 33⅓ per cent, in the second year 40 per cent, in the third year 60 per cent, in the fourth year 75 per cent, in the fifth year 80 per cent, and in every year thereafter 100 per cent.

The permit hereby applied for shall cease and be void upon the expiration of fifty years from the date of approval hereof, but it may then be renewed in the discretion of the duly authorized officer or agent of the United States and upon such conditions as he may in his discretion fix, Provided, That such officer or agent, in fixing such conditions, shall consider the actual value at that time for power and all other purposes of the lands and rights of way within National Forests occupied and used under the permit hereby applied for and the actual value at that time of all improvements lawfully made by the Permittee within National Forests under the permit hereby applied for, but neither the property of the Permittee, if any, outside of National Forests, nor the permit, franchises, bonds, capital stock, or other securities of the Permittee shall be considered in fixing such conditions.

There is also the usual anti-trust clause.

In the project to which this permit applies, the tax, if the drainage area and hydraulic conduit were entirely on forest reserve, and if the entire estimated power were marketed, would amount to about $350 for the first year and $5600 for the 50th year. The estimated annual operating cost of the total output of the plant *including fixed charges* is $180,000. Therefore, in such a case an hydroelectric development entirely on forest reserve would, under these terms, be subjected to a tax of from 0.2 per cent to 3.1 per cent of the total annual operating cost. The charge during the first year is not considerable. Whether the charge for the later years will prove reasonable will depend on the taxes and other burdens which may be imposed on the power company by the State.

The principal burden placed upon the power company under this permit is the 50-year limitation, with no definite assurance that the improvements made by the Company will not in effect be confiscated at the end of the period by refusal to renew.

Mr. Pinchot states " Water powers must and should be developed mainly by private capital and they must be developed under conditions which make investment in them profitable and safe." Referring further to Table I, the figures show that the proportion of first cost chargeable to land and water rights is from 6 to 14 per cent of the total cost of the project. In most of the projects which have come to the writer's attention, the conditions would not warrant a price on the land materially in excess of 10 per cent of the total cost. Therefore, in the case of a power development on Government reserve, in the neighborhood of nine-tenths of the value of the development will be outside of the rights conveyed by the Government. If the present general policy of the Forestry Service is to continue, it is proper that this large proportion of the total cost be protected either by definite provisions for renewals of the license for a similar period or periods, or a provision that the Government may at its option take over the property at an appraised valuation. Without such provisions water powers on Government reserve will not be as attractive as powers on private lands, and it would seem that the general spirit of the conservation idea should result in making the project on the Government reserve the most attractive.

D. S. Jacobus (by letter): The author should be congratulated on preparing a most useful paper, as it is one which deals ably with the subject and at the same time is written with the evident intent of bringing out the ideas of others.

The opinion is advanced that in case a steam plant is used in connection with a water-power plant, as a protection against interruptions, " the internally-fired boiler deserves careful consideration." All available types of apparatus should be considered in the design of a power plant, and the one which is best adapted for the particular conditions should be chosen; in the case at hand, however, the water-tube boiler is so particularly well adapted to the work that, were it not for the desire to bring out discussion, it would seem unnecessary to call special attention to the internally-fired boiler.

In auxiliary steam plants that are held in reserve, all the boilers are not ordinarily kept under steam. The ability to raise steam quickly, starting with cold boilers, is, therefore, an all-important item in this class of work. That there shall be but little stand-by loss in a boiler when held under pressure is also important, and, as the author has pointed out in his paper, this must be considered along with the ability of the boiler to raise steam quickly.

The water-tube boiler is universally acknowledged to be the type which is best adapted for raising steam quickly, and in well-designed boilers of this class the stand-by loss under practical conditions of service will not be greater than that which exists in internally-fired boilers, especially when the water-tube boiler settings are encased in metal to prevent loss due to air leakage. Tests with oil-fuel have shown that with large water-tube boilers the loss from this cause is much less than it is ordinarily supposed to be, as only two per cent of the oil required to run the boilers at their rated power is consumed in maintaining the full steam pressure.

With either coal or oil-fuel and a proper furnace arrangement, steam may be raised, starting with a cold water-tube boiler, up to a pressure of say 200 lb. per square inch in less than half an hour. In fact, in a test where a forced draft was available, and where a coal fire was started with wood on a bare grate, steam was raised to 200 lb. in 12.5 min. after lighting the fire, the temperature of the boiler and the contained water at the start being 72 degrees fahr. If one should attempt to do this with an internally-fired boiler he would surely come to grief, as leakage would result through excessive strains. A water-tube boiler also responds quickly in starting up from a banked fire, especially if a forced blast is available.

In cases where auxiliary steam plants are used to assist in carrying daily peak loads, it may pay to shut down the water power for a portion of the day so as to give the steam plant a more favorable load-curve. There is no better means of storing power than by collecting water behind a dam, and where this can be done it is often best to operate the water wheels at their maximum capacity during the peak loads, and to shut them down during the lighter loads. A way of obtaining continuous service, as pointed out by the author, is to combine a system of several water and steam power plants, and when this is done much can be accomplished in securing economy by making a careful study of the distribution of the load between the stations. The result of experience indicates that auxiliary steam plants in such a system must be run under a load which varies considerably throughout the day, and, furthermore, there is usually a lay-over period of four hours or more when the steam plants are shut down completely. Under these conditions the water-tube boiler is especially applicable, as the fires need not be started up after the lay-over period until a comparatively short time before the engine is started, the number of boilers in service may be reduced to that actually necessary to carry the load as an additional boiler may be quickly cut into the line in case of necessity, and the boilers will readily respond to a high overload capacity.

There is no boiler as flexible in regard to operating conditions as a water-tube boiler, and while it may be run economically at a low rate of evaporation, it may also be run with but little falling off in economy with as high a rate of evaporation as eight or even more pounds of water per hour per square foot of heating surface. In fact, the capacity of a well-designed and properly proportioned water-tube boiler depends simply on the amount of coal that can be burned beneath it, and modern practice is leaning more and more toward running such boilers at high capacities for peak loads, and also for intermittent service of the class herein discussed, because when considered as a whole the economy of the entire plant, including items of capital investment, etc., is better than that secured by running a greater number of boilers at a lower rating.

Ralph D. Mershon (by letter): I quite agree with Mr. Doherty as to the value of water-power securities and as to the probable great increase in their value with the course of time. This increase in value will come about partly through increased fuel cost; partly through the increase in available power of existing plants, due to pondage, as other powers or storage reservoirs are built on the same stream; partly through the institution of new industries which will not install heat-engine power plants and will, therefore, be able to pay a higher price for power than if they already had such power plants; partly through the greater use of off-peak power, either by rearrangement of the hours of operation of industries or by the perfecting of electrochemical processes operative intermittently; and partly through utilization of flood water power by intermittently operative electrochemical processes.

The author speaks of water power being developed under the direction of State and Federal governments and hints even at governmental financial aid to insure full, economic development of the capabilities of streams.

There are few amongst us, I think, in favor of giving to private enterprises absolute title to water power rights on the public domain. If Mr. Doherty had given us a paper devoted entirely to the consideration of the methods and means whereby such aid as that he suggests and hints at could be given without unduly favoring private enterprise, and whereby the ultimate title to water power sites on public domain could be secured to the people as a whole, he would have done a work of much greater value, in my opinion, than he has in this more general and less definite paper, valuable as it is. In fact, the adequate treatment of this one phase of water power development is perhaps more immediately important than that of all the other points he mentions; certainly than that of any one of the other points mentioned.

A carefully worked out scheme which would successfully apply to water powers the suggestion he makes, would apply with little, or obvious, change to other things as well. And one of the greatest problems before this country to-day is to devise schemes which will steer the middle course between socialism and monopoly; schemes which while preserving to the people some proper measure of the unearned increment, will yet allow sufficient profit to the investor to attract capital. I shall revert to this matter later.

Mr. Doherty speaks of the frequency with which estimates have been exceeded and the fact that the blame is usually laid upon the estimating engineer. The estimating engineer is a very convenient scapegoat. It is far from the case that the fault is always his. He estimates under reasonably favorable assumptions, or even under assumptions reasonably unfavorable, but assumes, as he has a perfect right to do, that the construction will be wisely administered. What is the result? The work is often handled either by a number of people in general and no one in particular, or by someone who has achieved fame and fortune running a bank or a pie bakery, and who is, therefore, because of such fame or fortune, assumed to be fully competent to cope with any other enterprise, however widely different from that in which he achieved success; someone who has about as much idea of the proper handling of a power enterprise as the wards of the Prodigal Son had of heaven. The estimates are exceeded and then—it is the fault of the estimating engineer!

In order that such enterprises shall be successful, some *one* must walk the floor with them. And that someone must be something more than a wet-nurse; must be a doctor, or at least know when to call the doctor in, and to call him in time.

Then there is administration by a board of engineers; from which the Lord deliver us! The petty jealousy which will sometimes animate a board of engineers and lead to unwise compromises because of pure stubbornness or vanity, is amazing. I would rather trust my financial fate, if I ever have any, to one man (and to him absolutely) who is honest, has good judgment and the engineering instinct, than the best board of the best engineering specialties every gotten together. He may make some mistakes, who does not?—but what he will save in other directions will much more than pay for any mistakes he is likely to make.

If he has the engineering instinct he will recognize the important and vital problems when they arise. If he is honest he will, if he has the least doubt of the entire adequacy of his own ability to solve them (and even, perhaps, if not in such doubt) call for the services of the best specialists in their solution. If he is wise, he will apply his wisdom in utilizing the findings of these specialists—or in discarding them altogether.

The author speaks of the fact that a good enterprise may go begging because of a conservative prospectus, where a less meritorious one is financed because of the glittering prospects outlined. This condition is not limited to the relation between the financier and the public. It obtains at times as between the financial man and the engineer. And the engineer who promises the greatest returns for the least money and will sign his name to a report setting forth such, will often get engineering work where the man with less imagination (and shall we say with higher ideas of honor?) is passed by. The latter may glean some grains of comfort of a certain sort, later, when the enterprise gets into trouble, but this is poor consolation if a meritorious proposition in which he is interested is rejected because of the distrust bred of the other failure.

This is human nature. If the shoe dealer on one side of the street states honestly just what his shoes will do, and the one on the other side lies about the shoes he sells at the same price, most of us will buy from the man we suspect to be a liar, because we know the honest man's shoes cannot possibly turn out any better than he claims, while there is a chance that the liar will make good.

An engineer's estimate and report should be made in that frame of mind which would obtain if he were going to put his own real money into the enterprise. Indeed, where it is possible, it were well for all concerned, including the engineer, if he had a relatively large " stake " in the enterprise; provided he is not to be crucified by the administration of the pie baker aforesaid.

Mr. Doherty's attitude and, generally, that of those discussing his paper, is, I think, unduly severe on the service from transmission lines. There are hydroelectric transmission plants in existence giving as reliable service as is obtained from steam plants, and there will undoubtedly be more of them as time goes on. Of course an overhead transmission line cannot be made immune to interruption, except at a prohibitive cost. And no matter what expense might be gone to, there would always be the possibility of malicious interference. Generally, whatever can happen will happen, if it has enough chances to happen; which applies to steam central stations as well as to hydroelectric transmission plants.

In the matter of rates, Mr. Doherty seems to be somewhat inconsistent, which inconsistency is partially revealed in his assent to the implied criticism of Mr. Ryerson's remarks anent the sale of off-peak power.

As I see it, there are two ruling propositions implied in Mr. Doherty's remarks on rates; which are as follows:

(1) It is fair that the supplying company should have the full advantage of non-coincidence of peaks; that it should not share this advantage with the consumer.

(2) It is fair to base the charge to the consumer on the cost to him of supplying himself from his own plant.

It seems to me that in the ultimate analysis, the whole thing hinges on (2). For instance, (1) goes to pieces immediately we apply the extreme case of non-coincidence of peaks cited by Mr. Ryerson; that is, the sale of off-peak power. In such case, Mr. Doherty is in favor of dividing some of the advantages with the consumer; and in making concessions in such case, I think it a safe wager he would be guided as to the amount of the concession by what the service would cost from the customer's own plant. I do not advance this as a destructive criticism of Mr. Doherty's well known method of charging, but simply to emphasize the fact that these seemingly fundamentally and inexorably sound schemes of charging are not necessarily so universally sound as they may appear at first sight. And indeed, when so surprising a condition arises as that cited by Mr. Doherty, where the investment and maintenance charges for meters alone exceeds that of the generating equipment to supply them, one is inclined to ask whether in such case it would not usually be better to again throw to the winds the fundamental charging scheme and supply these customers on some flat rate basis; with some cheap device for limiting their maximum demand.

The author regrets the confusion of terms, especially in the minds of the public, and speaks of the desirability of standardizing terms and endeavoring to educate the public to a clearer understanding of their significance. In this I entirely agree with him, though his paper itself is not entirely above criticism in this regard. A large part of the difficulty has arisen from the employment of the term *power* where really *energy* is meant. Usage has made this so universal that it would be hopeless to try to change it now. But strictly speaking, it is no more correct to speak of selling or transmitting power than it is to say that the distance from New York to Chicago is fifty miles per hour.

And it is not the layman only who has confused ideas on this subject. Not long ago, I saw a power contract, drawn by engineers, in which great pains had been taken as to exact expression. It reached the heights of exactness in a paragraph which read about as follows:

> Wherever, herein, the term energy is used, it is meant to signify energy measured in horse power or kilowatts.

Energy in horse power or kilowatts!!!

In his oral reply to the discussion, Mr. Doherty speaks of the practice, so called, of " watering stock." I quite agree with his remarks on the subject. We cannot expect capital to go into enterprises involving a certain amount of risk if the returns therefrom are to be no greater than could be obtained by loaning the same amount of money on security involving a risk much less than that of the enterprise. There must be a profit over and above such returns. I know of no cleaner cut or better way, *provided it is not abused*, of distributing in advance of its realization, the equity in such profit, than by the issue of profit stock. I say *provided it is not abused*, because in the past it undoubtedly has, in some cases, been very much abused by methods savoring of those of the bunco steerer or confidence man. If we could have such laws as would insure the issue at regular intervals of correct, intelligible statements of the results being achieved by corporate enterprises, so that there could be no deception as to the value of the profit stock, the public would at least have the opportunity for independently arriving at a decision as to what this stock was probably worth, and would have some chance for self-protection.

The amount of self-protection possible even under these conditions would depend upon the ability of the public to judge as to the value, or probable value, of the securities. This leads up to another subject, namely that of the ignorance on the part of the public of even the simplest questions of finance. I venture to say that not 10 per cent of the business men of this country, not 10 per cent, even, of the men who are independently conducting business on their own responsibility, could give an intelligent explanation of, for instance, the difference between first mortgage bonds and common stock.

This deficiency is not confined to the public. The engineer, who ought to know something about such matters, is often woefully ignorant. The study of this subject should be made a part of every engineering course, and I am glad to know that some engineering schools are now giving instruction in the rudiments of finance.

In fact, my ideas in connection with this matter go a good deal further. It seems to me it would be well if instruction along these lines were given in every high school, so that the average citizen might have a clearer idea of these matters. I believe that, if he had, he would be much more likely to take an interest in the various creative enterprises arising from time to time (instead of putting his money in a savings bank) thereby acquiring some portion, at least, of his share of the unearned increment; which would result in staving off and modifying, if not forever dissipating, the socialistic influences we are now beginning to feel.

As I have said before, I believe Mr. Doherty could have done us even more good than he has in his paper if, instead of it, he had presented a paper dealing with the possible methods of developing the water powers on the public domain in such a way as would, while attracting capital, secure to the public the titles to them, and at least a portion of the benefits from them. I believe he owes it to himself and this Institute to write such a paper; that there is no more patriotic or philanthropic thing that he could do at the present time.

There are a number of methods which might be devised for arriving at the end suggested. Some occurring to me are as follows:

(1) The water powers might be developed by the Federal or the State governments.

(2) They might be developed by private individuals under the supervision of the Government and with funds supplied by the Government.

(3) They might be developed by private individuals under the supervision of the Government, by the proceeds of bonds guaranteed by the Government.

(4) They might be developed by private enterprise, under the supervision of the Government, with funds raised by the private individuals and with the provision that after a certain period, the Government might take over the property created, at a price either fixed beforehand or to be determined by arbitration.

In no case, however, should they be operated by the Government, but in all cases supervised by the Government to an extent to insure proper maintenance. In the case of (1), (2), and (3), the Government might lease the plants, the lease to be made as the result of bids, contemplating either a compensation to be paid to the Government over and above the interest on the investment, or fixing the price at which power shall be sold, or both. In the case of (4), and perhaps of (3), the operation would presumably be in the first instance in the hands of those constructing the plant, to be open again for competitive bids at the end of the period of such occupancy.

I myself should be rather inclined to some such scheme as (1), (2), or (3), since it would put a premium on brains rather than on money and give an opportunity for men having no capital, but recognized standing as to efficiency and ability, to go in and on their own initiative develop the property and its market, securing a handsome return in the process.

The above suggestions are made merely as tentative suggestions and not even as carefully considered ones. In fact, one of the controlling motives in making them is that they may stimulate the fertile brain of my friend Mr. Doherty, and by arousing his antagonism or otherwise, induce him to write for the High-Tension Transmission Committee the paper I have suggested, and thus lead to more carefully worked out suggestions for arriving at the desired end.

D. B. Rushmore (by letter): The paper presented this evening deals, in an interesting manner, with some of the engineering and commercial features of our power developments, the greater emphasis being laid on the commerical point of view. Some of the statements which have been made this evening concerning the unreliability of electric power transmission in connection with our power developments need modification. While experience has proven that all water powers are not reliable and the disturbances may take place on transmission lines, the troubles which are had are as a rule more or less peculiar to each particular plant. It is doubtful if long-distance power transmission, with the great exposure which comes from the long line traversing unsettled country, can ever be made as reliable as power from a steam station, where the conductors are laid underground, but in certain instances it has been made to very closely approximate this. Of late years the type of construction in both the hydraulic and electrical features has been very much improved over that used in the first hydroelectric developments. The long exposed wooden flume and the wooden pole line have both been replaced by more substantial construction, and in general the factor of insulation has been very much increased.

With regard to the limitations of water power developments, until voltages above 150,000 are reached the financial problem is much more difficult than the engineering one, for with the best of modern engineering transmission lines can be made practically free from troubles.

Supervision of public utilities seems sure to come, and as both engineers and citizens we shall welcome this, but we want it to come in the right way, and in the development and use of our natural resources we have every right to expect the assistance of the Government.

Due to the very large number of features brought up in Mr. Doherty's paper, it is somewhat difficult to discuss as a whole, as it touches on practically all of the important points of hydroelectric developments. Such enterprises are in their very nature almost entirely special, and it is difficult to find any two which have even approximately the same conditions. Where the capacity of the plant is below the minimum stream flow, with or without storage, a steam auxiliary should always be considered, and only the type of hydroelectric plant such as we have at Niagara Falls should be considered as an independent development.

With regard to electrical securities, we have been passing through a period of evolution, and with the formation of larger companies, either as independent growths or as a consolidation of a number of smaller ones, an increased stability is being given to this form of investment. When properly installed and managed there is no form of security which should be more attractive to the general public.

John Martin (by letter): In regard to the relation of water power development to the conservation of our natural resources, I will say that in September this year I read a paper before the Pacific Coast Gas Association, on the subject of the public benefits derived from the development of water power in California. I was particular to mention California, because all of my experience has been in that State, and primarily because our conditions are so different from anything else which exists in the United States. We have wet and dry seasons—sometimes eight months without a drop of rain—and when you consider an engineer must, in order to be wise in his installation, install a capacity not in excess of the minimum flow of the stream, unless he is fortunate enough to find economical water storage, you can understand what difficulties we have to encounter. In all the installations made by our companies we have yet to find the year when we have been short of water for the installations we have made.

The Government in its wisdom, or lack of wisdom, is at this time attempting to make charges for the utilization for power purposes of water on Government lands. Let me tell you that the ownership of the water which the Government wants to charge for in California, is only that of a riparian owner, the same as that of any man who owns land, particularly so where the water for which it wishes to charge is not the water contained in navigable streams, but water which can be stored in reservoirs on land owned by the Government, and these streams pass over the lands in limited quantity, not available for navigation. When that land is disposed of by the Government, its right of control ceases, but it proposes to charge for the use of the water, and thereby conserve (?) the natural resources for the benefit of the people. If it would give the use of that water power free, and would fix a maximum charge for that power, that a company could demand of the people it serves from such development, it would then be conserving some of the rights of the people.

A man securing a water right and wanting to develop a power plant, is like a man who wants a horse and buggy, and first buys the whip. Filing notice of location on a stream gives initial ownership of a water right.

None of the work I have been connected with, aggregating a great many thousands of horse-power developed, is in any way involved with the Government, so I am not speaking from any pique or personal interest.

The greatest difficulty we have encountered in trying to finance our enterprises has been due to the lack of wise installations elsewhere, as a result of greedy capitalists guided by incompetent or dishonest reports from engineers, (who either do not know or would not tell the truth,) and as the result there have been very many financial failures. There is no reason why the man who puts his money into a water plant should not know what the plant is going to cost just as much as the man who has a house to build. We insist on knowing in advance, and having our investments carried out according to some definite scale. We have employed expert independent engineers in the past, but have given them up. Our experiences were with a number of comparatively smaller plants, and not with one large plant.

I take up the part of the paper with regard to compensation for interruption of service. I maintain that no hydroelectric transmission plant can afford to asume an uncertain element of risk of this kind. On the basis of the calculations stated here, in which the first interruption means a penalty of ten days of service, plus one day for each additional minute of interruption. If you have the pole line go out at twelve o'clock at night, and it is not repaired until morning, you would have to run the steam plant for the rest of the year for that interruption, which may not have caused the railway company any inconvenience whatever. The best plan for those who contemplate serving large cities is to depend primarily on the steam plants, as we do, and consider hydroelectric transmission as of fuel value only, or as incidental power.

The question of depreciation is largely a question as to how well you maintain your plant. If you do not take care of the plant properly, the depreciation cost runs very high. This is an individual matter, and, as Mr. Doherty fairly states, every item of construction is a proper charge for amortization or depreciation.

As to the methods of insuring against interruptions, or lessening the harmful effects of interruptions—it may be interesting to you to have me read to you the story of how we handle our power system, over sixteen hundred miles of high voltage lines, by means of a power dispatcher. It will give you some idea as to how we have had to work that matter out, from an operating condition, in a large system covering many miles, with some seventeen or eighteen units.

Mr. Martin then read an article by P. M. Downing, engineer of operation and maintenance of the Pacific Gas and Electric Company on "The Load Dispatching System" of that company, from which the following is an extract:

On the load dispatcher rests the responsibility of keeping the voltage normal and seeing that the fluctuations of load are properly taken care of among the different power houses. To do this requires not only a thorough knowledge of the power house conditions, but a knowledge of the character of the load on the system throughout the day, as this has a decided effect on the regulation of the lines.

A superintendent cannot take out of service a power house, transmission lines, or any other part of the system which would affect the operation of the whole, without first receiving authority to do so from the load dispatcher's office. However, the division of load and regulation of voltage is by no means the most important part of the load dispatcher's duties; that of reestablishing service after an interruption, without unnecessary delay, is a far more difficult problem, and very often calls for quicker and more decisive action. Operating as we do with everything running in together on a common network consisting of approximately sixteen hundred miles of sixty kilovolt lines, trouble on any line will affect the entire system. Then it is that the load dispatcher is busiest. The trouble must be located and the particular section of line on which the trouble occurs must be cut out. The different generating stations may be thrown out of synchronism, or the trouble may even be so severe that the different machines in the power house may be thrown out of synchronism. If the trouble is far enough removed from the station, the generators will not be thrown out, and the interruption is therefore only momentary; nor is trouble on one part of the system always noticed over the entire system. This is taken care of by the system of switching in use, whereby immediately when trouble occurs the different power houses are separated, leaving one or more running together with such lines and load as they can conveniently carry.

An experienced operator can, from the sound of a transformer motor, or regulator, at once tells when trouble occurs. If the station be a switching point, he should be able to handle the switching quickly enough for the trouble to show only as a slight momentary drop in voltage on the unaffected section of line. This condition is possible by reason of the inductance and capacity of the line and would not obtain on shorter lines of higher conductivity.

Immediately after the operation of any high tension switch, either on a direct order from the load dispatcher's office, or during trouble when the regular routine tests are being made, such action is immediately reported to the dispatcher. In this office is located a board showing diagramatically every generating station, transmission line, sub or switching station, also every switch in any of these different stations or on the lines. Stations and lines are represented by being painted on the board, but the switches are represented by dummies which can be adjusted to show the switch open or closed. The particular kind of switch, *i.e.*, whether oil or air, is shown by the shape of the dummy; the oil switches being circular and the air rectangular.

The advantages of a board of this kind will be appreciated when one considers that there are in service on the entire system, approximately one hundred and twenty-five oil and three hundred and fifty air switches, the position of every one of which must be known by the load dispatcher.

Irving E. Brooke (by letter): As a greater number of the possible hydroelectric developments of the United States are taken up, the value of the remaining, as well as the present, developments are increased rather than diminished. The more hydroelectric developments there are constructed, within certain limits, the more readily will their value be recognized, first, by serving as additional means of investment, and, second, by reducing the possible number of developments that can be made. It was only a few years ago that the money interests looked upon water power developments as of very doubtful value, but as numerous examples have proved successful the value of water power securities has been more widely recognized. One point that may be emphasized is that pointed out by the author, that the value of water power development is more likely to increase than is the value of a great many other enterprises, as the cost of coal increases; and until some more economical way of developing energy is found, the value of water power will surely tend to increase. The proper development of water power should be highly encouraged, but enterprises which are unintelligently handled or engineered should be held in check by the state or federal government, the idea being to conserve the water powers until they can be developed in the best possible manner so as to benefit the greatest number.

The possibility of combining water power with irrigation work is one that should be given a great deal of attention at the present time. During the very rapid growth of irrigation enterprises in the West within the past few years it is probable that the chance for power development has been underestimated or even entirely overlooked. Many of these irrigation projects are handled by men familiar only with irrigation developments, who may plan a good irrigation system, but in such a manner as to practically prohibit any future water power development, which development, as well as the irrigation project, might have been designed by one familiar in detail with the requirements of both projects. It is not unusual to see a possible power development greatly handicapped by an irrigation project, or to see an irrigation project almost entirely eliminated by a power development. The possibility of supplying power for pumping water for irrigation purposes is something that required consideration in planning a hydroelectric development in the West. The pumping of water for irrigation can be made to provide a very suitable non-peak load and greatly to improve the load factor of the station.

In considering the development where a combination of irrigation and water power is contemplated the writer has found it convenient to divide the combined developments into two classes, the first being designated as a "direct double-duty development;" the second, "indirect double-duty development." The first term may be applied to a combination irrigation and power development where the water is used first by the hydroelectric plant and then by a gravity system for irrigation; the second, or indirect double-duty development being where the water is used in a hydroelectric development and the power so generated used to pump water for irrigation service. The handicap placed on the direct double-duty development is that the commercial hydroelectric plant requires water at a fairly constant rate for 365 days in the year, while the irrigation requires all of the water necessary during a period of from 100 to 130 days, depending upon the location and length of the irrigation system. Unless the power plant is placed above the storage reservoir, or in case it is placed below where there is a sufficient quantity of water, provision must be made in the former case for letting water pass the hydroelectric plant during the irrigation season, and in either case one project or the other must suffer during some part of the year unless ample storage capacity is provided.

The writer has in mind what might be termed an ideal direct double-duty development; a project where the pipe line leads from the stream to the power house where use is made of the water in the power plant, the water being returned to a natural lake as a storage reservoir below the power house to be used as required for irrigation. However, the natural sites for this ideal development are very few, and in most cases some other provision must be made for taking care of the irrigated lands during the irrigation season.

The author states that a transmission line is the weak point of a hydroelectric development. The reliability of transmission lines is constantly increasing, and as more hydroelectric plants are developed the possibility of any large area or large amount of business depending on any one transmission line is not nearly as great. There is no reason why a transmission line if properly designed and constructed should be considered as great an element of risk as is generally supposed. Proper method of protection from lightning or static disturbances by ground wires, properly designed and tested insulators with protecting rings where severe lightning conditions are encountered, together with anchored or guyed poles at regular intervals along the line, should make a transmission line that will be reliable. The many transmission line failures are in a large measure due to the small consideration that is given this part of the work by the men who are financially responsible for some of our developments.

The writer is familiar with one particular case where the owners were perfectly willing to spend almost any amount of money on the station to secure the most modern and reliable equipment, but were willing to entrust the location and building of the transmission line to one with little or no experience in this work, saying " There is nothing to a transmission line but to set the poles and string the wire ".

The fact that complete and thorough investigation of any project is expensive, and that most promoters do not wish to advance a sufficient amount of money for this purpose, usually results in the project being attempted with an incomplete investigation which may mean a poor development or even absolute failure in the end. That all bankers do not follow the rules given by the author is evidenced by the way in which bonds for reliable water power projects are sold.

Where the development company controls and operates the distributing systems, it is evident that no system of penalties need be adopted; in this case the failure to supply continuous and satisfactory service gains its own reward.

In designing a steam plant as an auxiliary to a water power plant, to operate from 40 to 60 days during the year, the first investment in steam plant should be kept as low as possible consistent with obtaining a reliable and serviceable plant. In an installation of this character there are two so-called losses; one is the interest on the investment, and the other is the value of power lost. When these two losses are equal their sum will be a minimum. This means that the interest for one year on the plant investment must equal the value of power lost in the plant from 40 to 60 days. When this condition obtains we have the most economical installation.

In consideration of the above it is usually well to put in a simple steam plant; in some cases even simple engines and tubular boilers may be justified.

The engineer who investigates any proposed project can only estimate what the earning power of such a development will be, based on competent and well-directed management. This is a matter which is often the source of much trouble to the investigating engineer and in many cases is the cause of the development not coming up to the expectation of the owners.

W. G. Chace (by letter): A steam plant which is not run all the time cannot be considered, in any sense, of value in the effort to avoid interruptions of momentary nature or of brief duration. For this purpose nothing but a storage battery can be considered of value, and on account of its large expense it can be maintained with a view of furnishing, during moments of interruptions of service from the hydraulic plant, only those customers to whom such momentary shutdown is serious. The desire to so utilize a battery will naturally affect (1) the choice between alternating current and direct current service as applied to this class of customers, and (2) the number of distribution circuits upon which such a battery can be permitted to float.

The continuous use of steam plant in connection with a service supplied from hydroelectric source and where the supply of water is sufficient for all hours of the day and all seasons of the year, is, generally speaking, inexcusable; and its chief reason for existence is the fact that it may have been in the service prior to the construction of the hydraulic plant. When the hydraulic plant shall have been loaded so as to be taxed to its limit for the winter peak, there remains to the management in many instances the choice between putting in new steam plant, and building a second hydraulic plant, and this choice will not be governed by the variation of cost of the kilowatt-hour at different hours of a given day, as referred to in the discussion by Mr. Stott, but will be governed by the relative magnitude of all charges for the year of operation; because, although usually the income is based on the rate charged by the company per kilowatt-hour and although frequently the cost per kilowatt-hour throughout a considerable portion of the day may be found lower with the steam plant than with the hydraulic plant, still it is not the relative cost of such a unit of energy, but the relative cost of the year's operation, which should serve as the basis of choice in this contingency.

A recent experience of a large company, whose hydraulic plant was shut down completely for two days and partially thereafter limited in output for six weeks, developed the fact that the steam station owned by the company, and of capacity nominally 40 per cent that of the hydraulic plant, and which had served the company up to a period of three years prior to the accident, could not be depended upon for anything like its nominal output in the emergency; and the effort to operate it developed such a series of difficulties due to the long period of idleness and to the consequent lack of attention (and perhaps reasonable lack of attention), that but a very limited portion of the load could be carried by it. With expensive fuel and labor and with a proven hydraulic plant, the owners had not considered themselves warranted in expending large sums upon the maintenance and necessary regular operation of the steam plant, required to keep it in condition. That this is a common feeling in the presence of a dependable hydroelectric development and high tension transmission, is supported by the statements of Mr. Barton concerning the Buffalo steam plants on the advent of Niagara power.

The best insurance available in a given area is that contingent upon the existence of two hydroelectric plants of similar frequency and capacity, whether they be operated by the same owner or in competition. With such plants there is much less need of expensive stand-by equipment than there is in isolated steam plants, each of which would necessarily carry a considerable proportion of spare capacity; and, moreover, so long as the water power is not completely developed, the costs of hydroelectric stand-by in the shape of spare units is less than that of steam stand-by in a separate station fully equipped with labor and carrying a considerable investment in fuel.

Depreciation. There can be no question but that the proper annual charges for depreciation in a well maintained hydroelectric plant are relatively small figures. It may be interesting to set forth here some facts concerning a large hydroelectric plant with whose construction the writer has had connection. Table I sets forth the distribution of the gross cost of this development, the figures being given in percentages. The equipment now being installed has a rated generator output of 15,000 kw. and the excavations and permanent structures are designed, and are being built for an ultimate rated equipment of 45,000 kw. From this table it will be noted, incidentally, how moderate is the cost per unit of the capacity to be added after the completion of the original construction, a triplication of capacity being obtained with an addition of only 80 per cent to the original investment, all calculations on this subject being based upon the construction and equipment contracts let during the period of 1909–1910.

TABLE I

	15,000 kw.		30,000 kw.		45,000 kw.
	Per cent initial cost	Per cent ultimate cost	Per cent total cost	Per cent ultimate cost	Per cent ultimate cost
A. Real estate, preliminary expenses, excavations, cofferdams and engineering..............	22.5	12.63	19.1	14.50	16.35
B. 25 miles of standard-gauge railway with two river crossings.........	14.6	8.05	11.5	8.70	9.78
C. Permanent structures consisting of dams, weirs and buildings....	24.9	13.76	21.7	16.47	22.27
D. Equipment of power house and terminal station, including transforming and control apparatus for 66,000 volts..................	22.7	12.50	29.1	22.08	35.30
E. Transmission and telephone line structures..	15.3	8.41	18.6	14.13	16.30
	100.00	55.35	100.0	75.88	100.00

The proper charge for depreciation is a relative one and depends upon the class of construction, on the nature of the design, on the character of the attendance, on the amounts of money expended for maintenance and on conditions of climate and surroundings. Then again, a property cannot depreciate to a value less than that which it possesses as scrap, and although this item is generally omitted from such discussion, it is worthy of consideration. Mr. W. R. Cooper, in discussing a paper read by Mr. Robert Hammond before the Institution of Electrical Engineers, April 25, 1907, gives a table of the probable life of the various elements of the power plant and of the probable scrap value at the end of the period. On some of the elements of a hydroelectric plant the market price at the date of purchase enters largely into the scrap value which may be assumed, and this applies most particularly to the copper, purchase of which in the shape of conductors during recent years has varied in Canada from fifteen cents to twenty-eight cents per pound, so that a scrap value of ten cents per pound, which is not unreasonable at any time and which is unreasonably low under certain market conditions, will vary from 66 per cent to 53 per cent of the original costs, and the possible proportion of depreciation during the life of the transmission line may range from 34 to 47 per cent under the above mentioned conditions of market, and may even be zero or a negative quantity if purchase be made at the lowest price mentioned and the property be scrapped under conditions of a much higher price of copper.

It is interesting to note that our friends the salesmen for the aluminum companies claim that their principals can get more for aluminum in almost any other form than in that of electric conductors, although doubting Thomases may point out that these same gentlemen are particularly anxious to sell aluminum for electric purposes.

The same argument regarding scrap value applies to all machinery as well as to the conductors. It may be generally remarked that it is not reasonable, in view of the broad assumptions as to the life of the various portions of the equipment, to carry the calculations for depreciation to many significant figures. If this item were called by the name of " Renewal Fund " it might appear a much more necessary element than the accountants of some of the operating companies now seem to consider it.

Table II sets forth a calculation of the charges for depreciation which would be reasonable for the plant referred to in Table I. Ability on the part of the owner to borrow money at very low rates permitted extremely substantial constructions at the present date, so that the depreciation and maintenance charges thereon can be safely estimated very low.

TABLE II

SCHEDULE OF DEPRECIATION CHARGES ON PLANT REFERRED TO IN TABLE I

A	*B*	*C*	*D*	*E*	Interest 4½ per cent ultimate period 50 yrs.
22	15	25	23	15	Per cent of total cost.
50	30	50	25	30	Life—years.
100	2	0	10	20	Final scrap value—per cent original cost.
0	98	100	90	80	Value disappearing—per cent original cost.
0	1.64	0.56	2.26	1.64	Rate depreciation—per cent.
0	0.24	0.14	0.47	0.20	Annual depreciation—per cent original cost.

Total annual depreciation 1.05 per cent of gross original cost.
Of this depreciation the groups contribute respectively the following percentages:

A	*B*	*C*	*D*	*E*
0	22.8	13.3	44.8	19.1

This table is self explanatory.

It is interesting to note that the annual charge, namely, 1.05 per cent of the gross original cost, is practically identical with that given in Table II in the discussion by Dr. Hutchinson. It is also interesting to note that item *B*, the construction railroad, which it was necessary to build for this plant, demands 22.8 per cent of the entire annual charge for depreciation.

The item called "Obsolescence" should not, in general, be calculated upon elements of the installation other than equipment, and it is a mistake to make such a charge on the basis of the cost of the entire plant. With 4½ per cent money, Dr. Hutchinson's allowance for this item in connection with a steam plant, 6 per cent, corresponds to a life of thirteen years only, and would seem unreasonably large even as applied to the equipment alone, though it might have been reasonable fifteen years ago. His corresponding charge for the hydraulic plant corresponds to a life of thirty-two years and can surely not be accepted, even as applied to the equipment alone when we consider that in very many installations now being constructed the individual unit is designed of the largest size which is consistent when matters of speed, cost, ultimate capacity of water power, water velocities and dimensions of market are kept in mind, and when the present very high efficiency obtained on both the electric and the hydraulic ends of the machinery is considered. In fact, it is hardly comprehensible that any charge for obsolescence should be allowed or required in a conservative engineering estimate of the cost of the energy to be delivered from a hydroelectric plant.

In this connection the word "obsolescence" has not the same meaning as it had twenty years ago when the gas engine, the alternating current machine, the steam turbine, and even the modern steam reciprocating engine, to say nothing of the steam boilers now available, were yet things of the future; and it has even less meaning than it had fifty years ago when the practical applications of the various elementary principles of nature, such as heat, magnetism and electricity were in their infancy; in other words, we have now at our command mechanical applications of most of the known principles of energy and the prospects of future radical advances are, to that extent, limited.

Moreover, the idea of obsolescence as advanced in the discussion by Dr. Hutchinson, where he refers particularly to the New York Edison Waterside Station No. 1, relates particularly to land values, and it cannot be that there is much prospect of the early shutting down of this station by reason of obsolescence of the equipment as such.

In General. The writer is of the opinion that electrical engineers, a majority of whose experience is gained in connection with steam electric stations, often have erroneous ideas of the overload capacity which can be reasonably counted upon in hydroelectric plants carefully designed. Modern reaction turbine practice has established comparatively high efficiency above one-half load, and in sofar as water economies are concerned the point of maximum efficiency being about three-quarter gate opening, it is reasonable to choose turbines whose ultimate capacity is from 25 per cent to 40 per cent beyond the rated capacity of the direct connected electric generators. Then, too, no plant should be designed for operation with fewer than four generating units so that a very reasonable degree of insurance against shutdown and, ipso facto, overload capacity, would exist at all hours of the day.

The plant to which the Tables I and II apply consists of units made up of generators of 3,000 kw. rated capacity, direct connected to twin turbines, on horizontal shaft, of 5,200-h.p. ultimate capacity.

With steam stations of less than 5,000-h.p. capacity and with coal costing from $4.00 to $7.00 per ton, as is quite common in many of our centers of distribution, steam-electric power cannot be generated as cheaply as is claimed by Dr. Hutchinson.

In the matter of maintenance—Mr. Barton's statements are most interesting as applied to stations of the Niagara type. As to the costs of maintenance of the electrical equipment, these can be considered fairly representative; but as to the 2 per cent cost of maintenance of the hydraulic equipment it must be borne in mind that all of these generating units are of the vertical type with shafts approximately 120 feet long, with elaborate and complicated thrust bearing mechanism, including auxiliaries, and are in all much more bulky than the hydraulic equipment of horizontal shaft outfits as ordinarily designed, even for heads as great as those existing at Niagara Falls; so that if 2 per cent is a proven figure for this type of equipment, it would be fairly safe to estimate that for a horizontal equipment up to, say, 50 ft. of operating head such maintenance should not exceed 1 per cent per annum and but slightly greater than 1 per cent for plants with heads higher than 50 ft.

As to Mr. Doherty's conclusions, the writer is of the opinion that items 3, 4, 5 and 7 are subjects to which the Institute might well turn its attention for a few months. It is unfortunate that work along the lines of item 3 should have been so much neglected. Consulting engineers find it extremely difficult to obtain enough or reliable data concerning the streams whose water falls they are called upon to consider. The work done recently in Wisconsin is typical of what should be carried out under Government care throughout the whole of America, and especially it is desirable that these studies be undertaken in connection with the efforts of both Canada and United States to conserve their forests and other resources. In Ontario, the first Hydroelectric Power Commission issued, in 1906, a file of five papers covering the streams south of the " height of land," that is, within the now populated area, and though upon this work not enough of moneys have been expended, nor, unfortunately, has a systematic series of river studies been inaugurated, still it is an indication of what can be done at moderate expense, and it is typical of the kind of information which should be accessible concerning all water powers whose location makes them of early value.

A paper presented at a meeting of the Toronto Section of the American Institute of Electrical Engineers, Toronto, Ont. December 18, 1908.

NOTES ON THE COST OF POWER.*

BY H. G. STOTT.

In engineering estimates there is probably no item which contains so many variables as that representing the cost of power. Consequently we frequently find a wide divergence of opinion as to the results which may be expected under different conditions. In all types of plants the influence of investment upon the cost of power is one which is apt to be slighted in the estimates, and if not slighted it seems to be subject to more errors than any other factor which enters into this cost. This is particularly the case with hydraulic plants, as of necessity water storage, flumes, racks, tail-race, etc., enter into the estimate, with the result that the actual cost has sometimes been found to be 100 per cent greater than the estimated cost.

In the same way indeterminate items of cost, such as foundations, cost of labor, etc. enter into practically all the calculations, so that when we take into consideration the influence of location upon the cost of coal, labor and water, as well as upon the investment, it is readily seen that the actual cost of power is of necessity so variable as to make impossible anything like a standard cost per kilowatt-hour.

With the above limitations in mind, the following notes on the cost of power have been compiled with the idea that they might form a guide to show at least the fundamental relations between the various items going to make up the cost of power, and at the same time show what is actually being done to-day in large plants having a maximum load of over 30,000 kw.

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* The author wishes to acknowledge the work of Messrs. G. I. Rhodes and R. J. S. Pigott in calculating and plotting curves, and the kindness of the New York Edison Co. and Interborough Rapid Transit Co. in furnishing load-curves.

The following table has been taken from a paper* contributed by the author two years ago and has been expanded and revised so as to bring it up to the results now obtained in actual practice. The principal changes made have been due to the better economy obtained in the steam turbine, and in the reduction of the total fixed charges from 12 per cent to 11 per cent; fixed charges composed of 5 per cent interest, 1 per cent taxes and general administrative expenses, and 5 per cent for amortization or obsolescence in the steam and hydraulic plants.

RELATIVE COSTS PER KILOWATT-HOUR. DISTRIBUTION OF MAINTENANCE AND OPERATION

	Recip-rocating steam plant	Steam tur-bine plant	Recip-rocating engines and low-pressure steam turbines	Gas-engine plant	Gas engines and steam tur-bines	Hy-drau-lic
MAINTENANCE						
1. Engine room, mechanical.......	2.59	0.51	1.55	5.18	2.84	0.51
2. Boiler or producer room........	4.65	4.33	3.55	1.16	1.97	....
3. Coal and ash-handling apparatus	0.58	0.54	0.44	0.29	0.29	....
4. Electrical apparatus...........	1.13	1.13	1.13	1.13	1.13	1.13
OPERATION						
5. Coal........................	61.70	55.53	52.44	26.52	25.97	....
6. Water.......................	7.20	0.65	0.61	3.60	2.16	....
7. Engine room, labor............	6.75	1.36	4.06	6.76	4.06	1.36
8. Boiler or producer room labor..	7.20	6.74	5.50	1.81	3.05	....
9. Coal and ash-handling labor....	2.28	2.13	1.75	1.14	1.14	....
10. Ash removal.................	1.07	0.95	0.81	0.54	0.54	....
11. Electrical labor..............	2.54	2.54	2.54	2.54	2.54	2.54
12. Engine room lubrication........	1.78	0.35	1.02	1.80	1.07	0.20
13. Engine room waste, etc........	0.30	0.30	0.30	0.30	0.30	0.20
14. Boiler room lubrication, etc....	0.17	0.17	0.17	0.17	0.17	....
Relative operating cost per cent....	100.00	77.23	75.87	52.94	47.23	5.94
Relative investment per cent.......	100.00	75.00	80.00	110.00	96.20	100.00
Probable average cost per kilowatt.	125.00	93.75	100.00	137.50	120.00	125.00
Probable fixed charges............	11%	11%	11%	12%	11.5%	11%

For steam-turbine plants larger than 60,000 kw. the cost per kilowatt may be reduced to $75.00.

In the other items will be found changes due to the reduced cost of steam turbines, and also due to the possibility of saving the water of condensation by separating out the oil between the reciprocating engine and the steam turbine. Under the

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* Power Plant Economics, by Henry G. Stott. Transactions A.I.E.E., 1906. Vol. xxv. pp. 1-27.

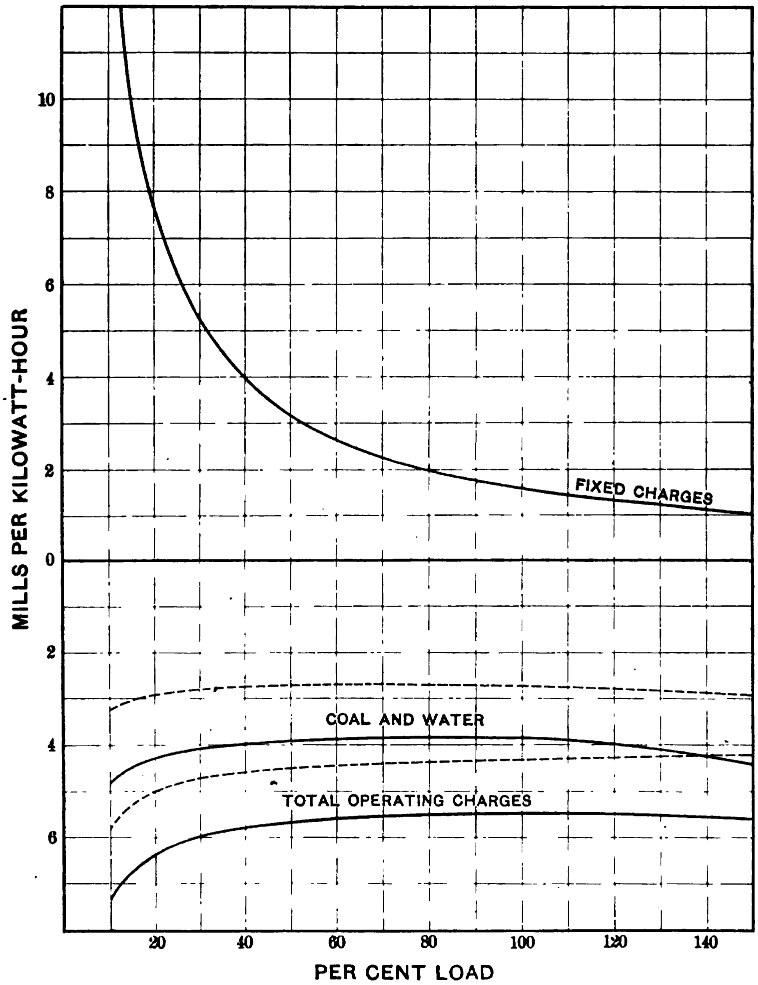

FIG. 1.—Cost of power. Reciprocating steam-plant.
Plant cost = $125 per kilowatt.
Interest, taxes, depreciation, etc. = 11%.
Solid lines = coal @ $3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

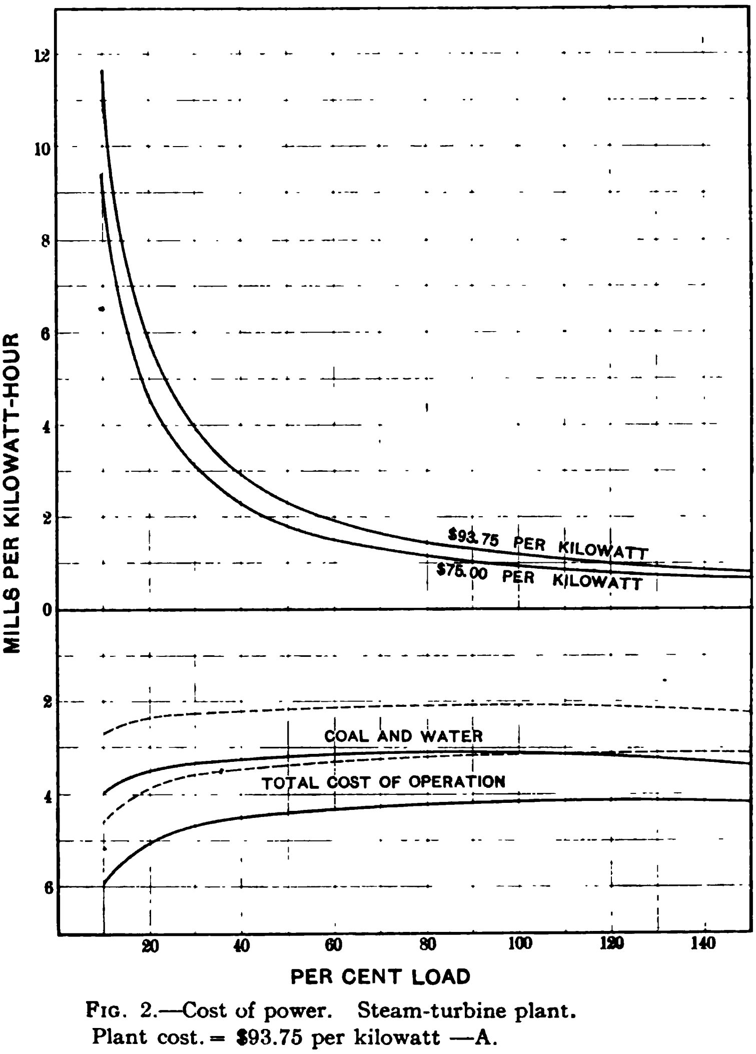

FIG. 2.—Cost of power. Steam-turbine plant.
Plant cost. = $93.75 per kilowatt —A.
Plant cost = $75.00 per kilowatt—B.
Interest, taxes, depreciation, etc. = 11%.
Solid lines = coal @ $3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

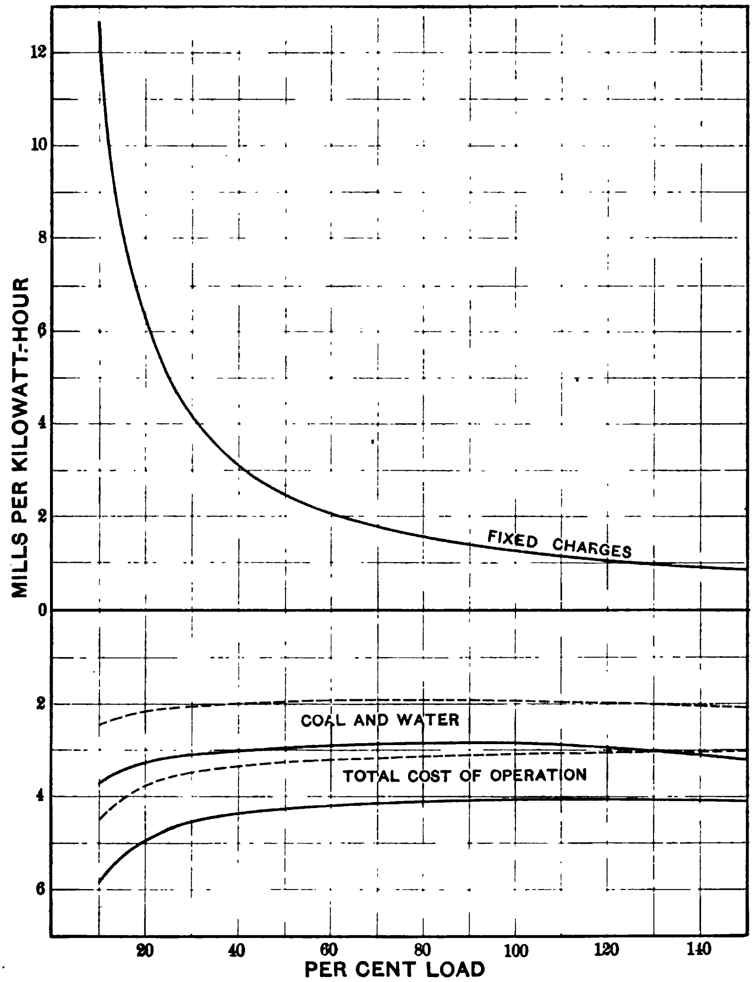

FIG. 3.—Cost of power. Reciprocating engine and low-pressure turbine plant.

Plant cost = $100 per kilowatt.

Interest, taxes, depreciation, etc. = 11%.

Solid lines = coal @ $3.00—14,500 B.t.u. per lb.

Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

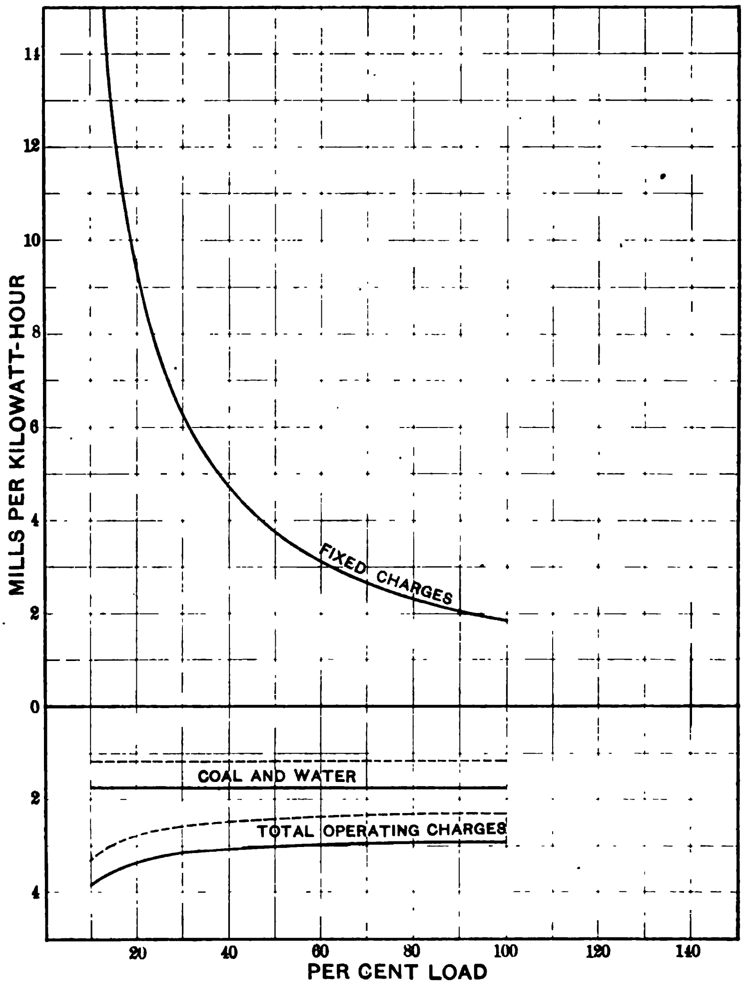

FIG. 4.—Cost of power. Gas-engine plant.
Plant cost = $137.50 per kilowatt.
Interest, taxes, depreciation, etc. = 12%.
Solid lines = coal @ $3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

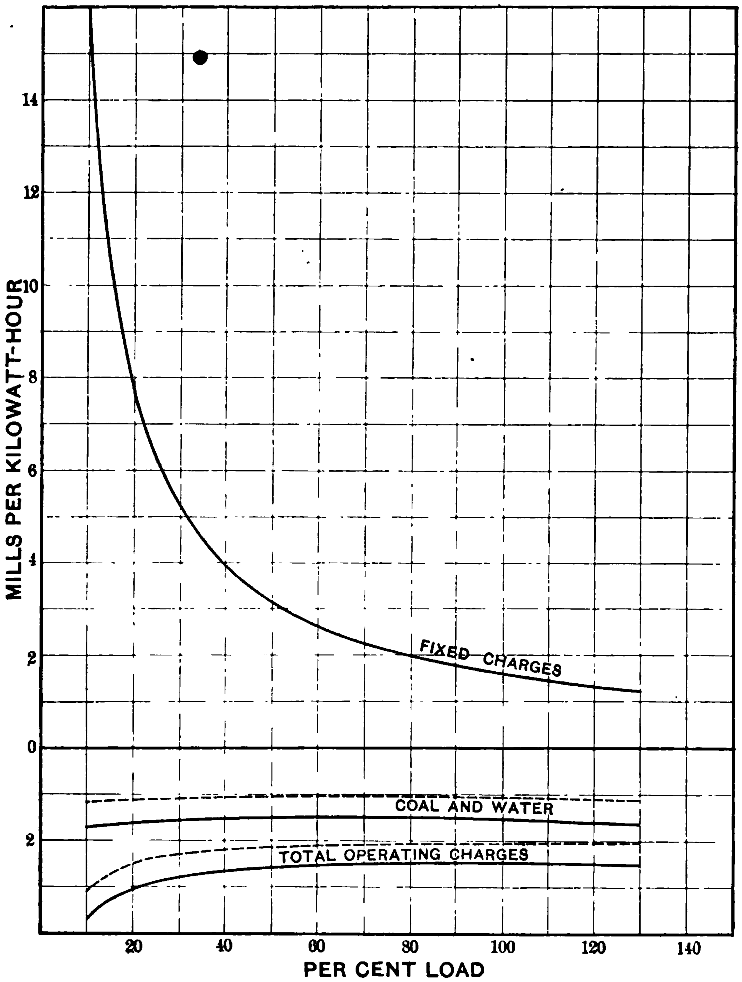

FIG. 5.—Cost of power. Gas-engine and steam-turbine plant.
Plant cost = $120 per kilowatt.
Interest, taxes, depreciation, etc. = 11.5%.
Solid lines = coal @$3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

heading of *Coal*, in the reciprocating engine and steam turbine plant, it will be found that this amount has been increased so as to cover the difference between the theoretical amount which had to be assumed in 1906, and the actual amount guaranteed by the manufacturer in 1909.

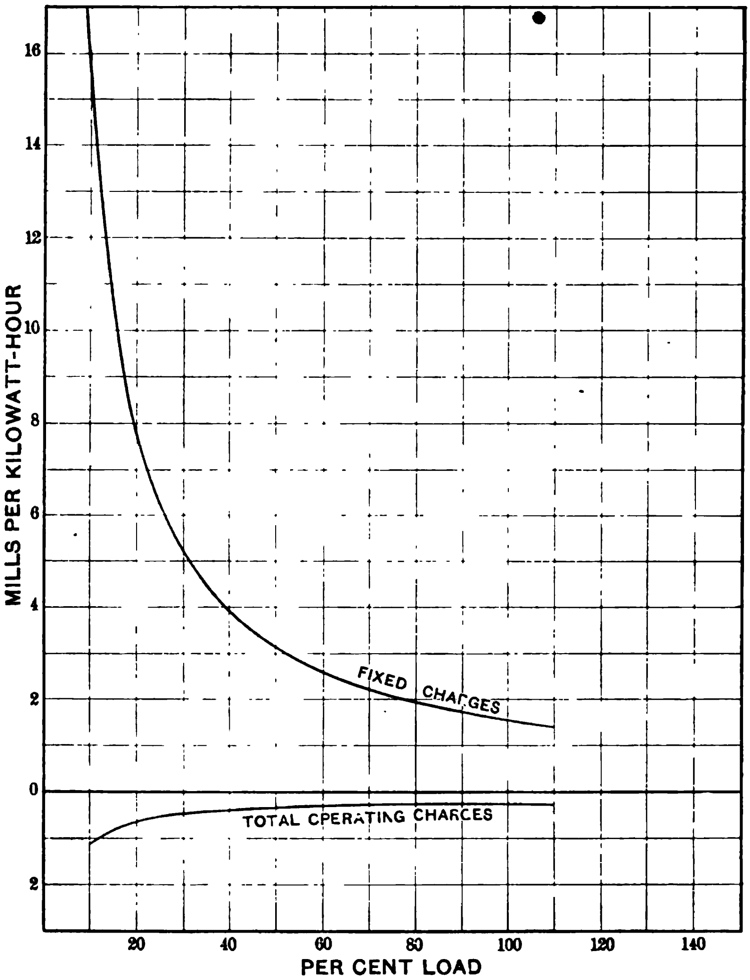

Fig. 6.—Cost of power. Hydraulic plant.
Plant cost = $125 per kilowatt.
Interest, taxes, depreciation, etc. = 11%.

In the accompanying curves, the cost of delivered coal has been assumed at $3.00 per ton for a high-grade coal having 14,500 B.t.u. per lb. and also at $1.50 per ton for a low-grade coal having 11,000 B.t.u. per lb. so as to illustrate the effect upon the cost of power.

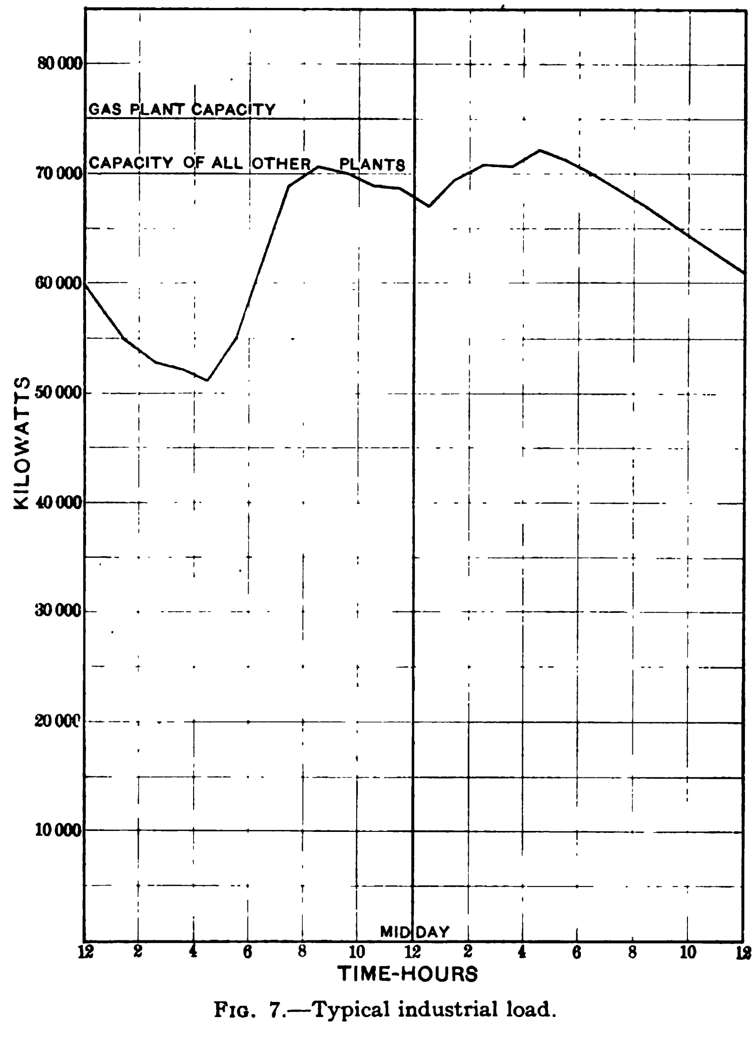

FIG. 7.—Typical industrial load.

Figs. 1 to 6 inclusive show, with various types of plants, the fixed charges upon the upper curve and the operating charges below the axis, so that the sum of the ordinates gives the total cost per kilowatt-hour for any load-factor on the plant. It will be

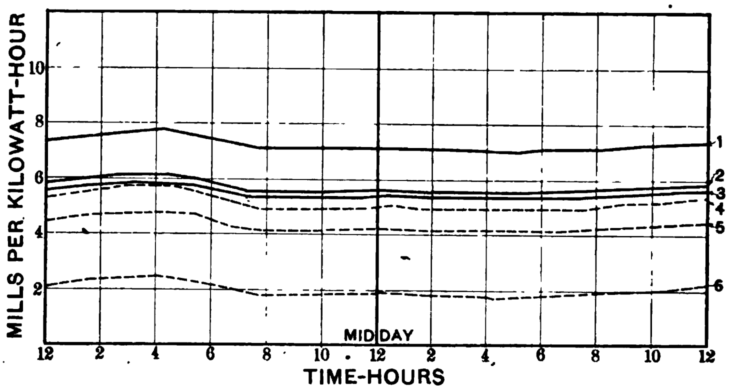

FIG. 8.—Typical industrial load. Cost of power throughout the day.

1. = Reciprocating steam-plant.
2. = Steam-turbine plant.
3. = Reciprocating-engine and low-pressure turbine plant.
4. = Gas-engine plant.
5. = Gas-engine and steam-turbine plant.
6. = Hydraulic plant.

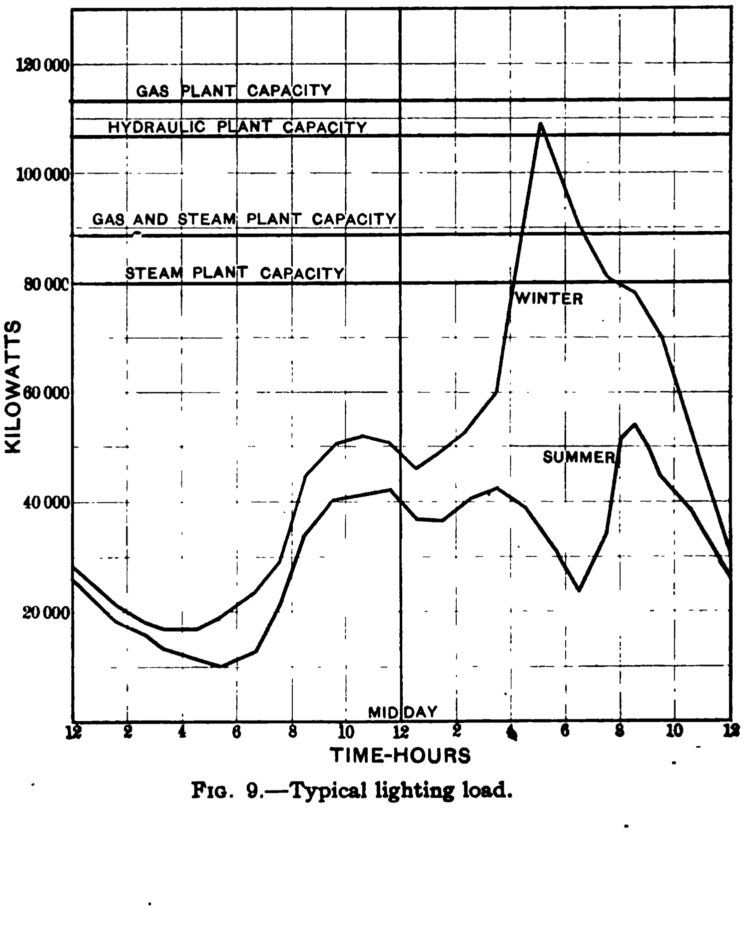

FIG. 9.—Typical lighting load.

noted that all the steam plants are assumed to have 50 per cent overload capacity, sufficient to carry them over a peak-load of two hours, whilst the gas plant has no overload capacity. The combined gas-engine and steam-turbine plant has 25 per cent and the hydraulic plant 10 per cent overload capacity.

Figs. 7 to 14 inclusive show typical industrial, lighting, (summer and winter) and railroad (summer and winter) load-curves. On these curves will be found straight lines drawn through points corresponding to the necessary installed capacity of the various types of plants, and a second series of cost curves bringing out in a very suggestive manner the cost of furnishing power at every hour of the day. As an illustration, refer to Fig. 11, which shows the cost of power on a summer lighting load.

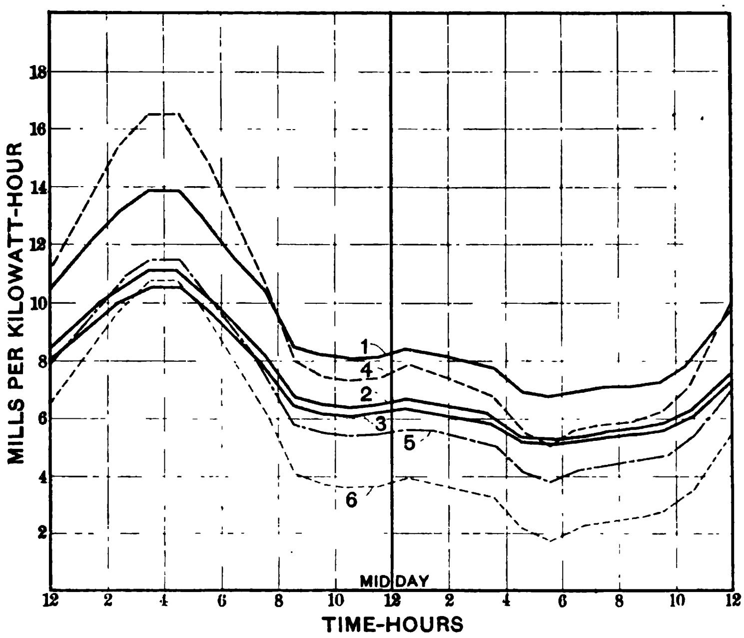

FIG. 10.—Typical winter lighting load. Cost of power throughout the day. Curves, 1 2, 3, 4, 5, and 6 same as in Fig. 8.

During the greater part of the day, No. 4, or the gas-engine plant, is the most expensive, owing to the necessarily high fixed charges. For the same reason, the reciprocating steam-engine plant is also high.

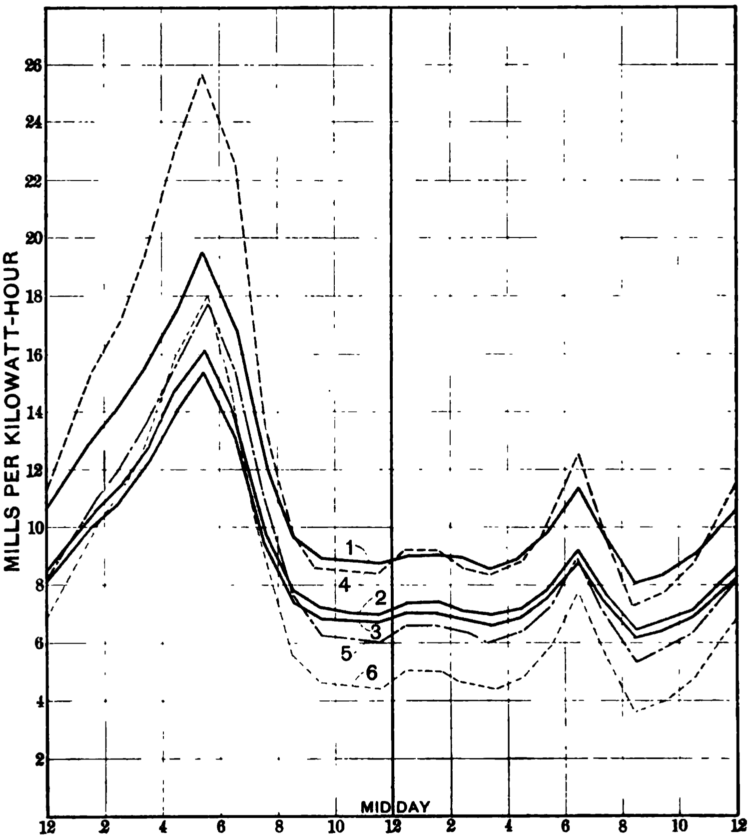

FIG. 11.—Typical summer lighting load. Cost of power throughout the day. Curves 1, 2, 3, 4, 5, and 6 same as Fig. 8.

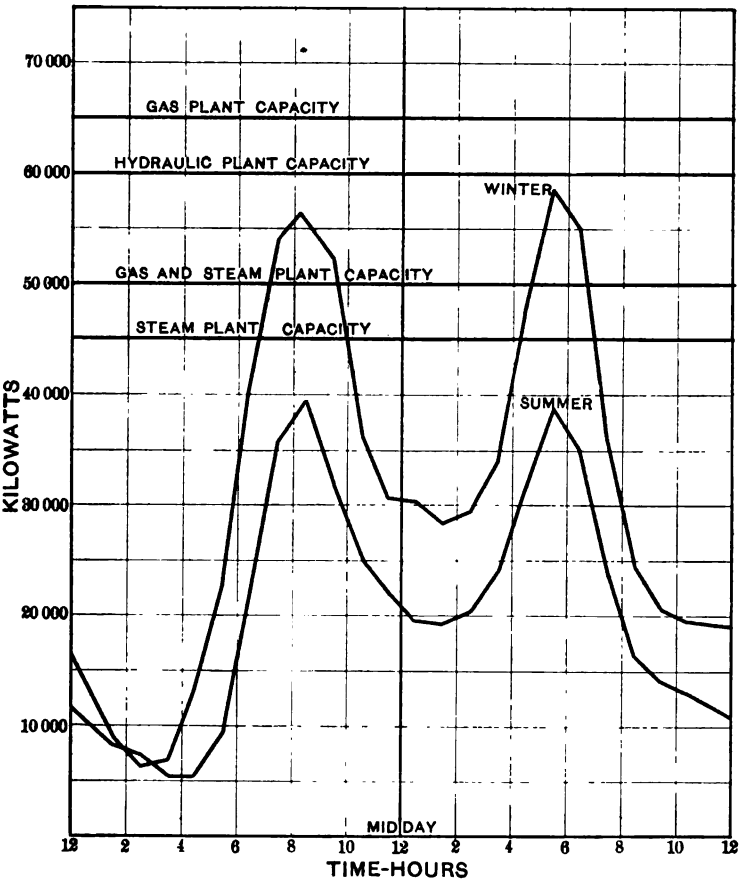

Fig. 12.—Typical railway load.

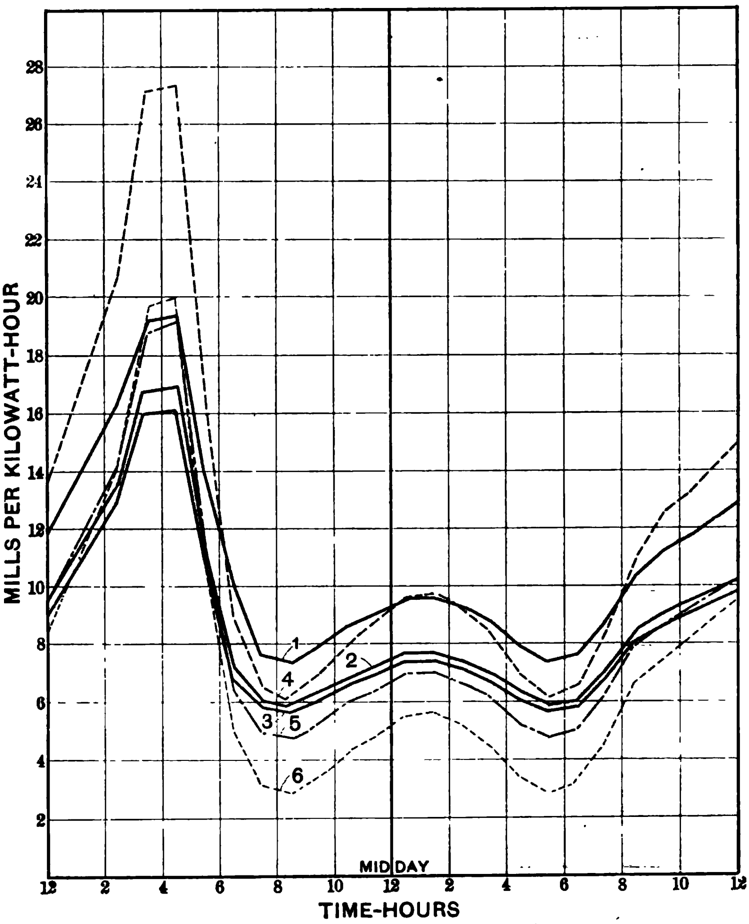

FIG. 13.—Typical summer railway load. Cost of power throughout the day. Curves 1, 2, 3, 4, 5 and 6 same as in Fig. 8.

During the light morning load the hydraulic plant is also handicapped by the fixed charges, but the low operating costs render it the most efficient upon the whole.

Fig. 5, representing the plant in which one-half the installed capacity consists of gas engines and the other half of steam turbines, makes so excellent a showing on all the load-diagrams that we may expect to hear more of this type of plant in the future.

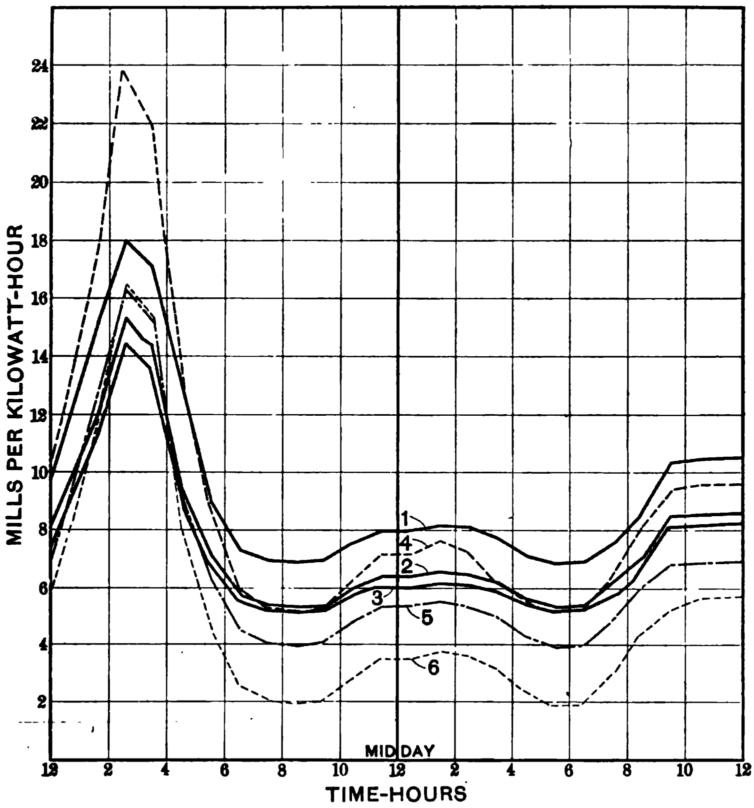

Fig. 14.—Typical winter railway load. Cost of power throughout the day. Curves 1, 2, 3, 4, 5, and 6 same as in Fig. 8.

In all these comparisons it must be remembered that the costs are worked out to the generating plant *bus-bars only*. In practically all cases, therefore, the costs discriminate in favor of

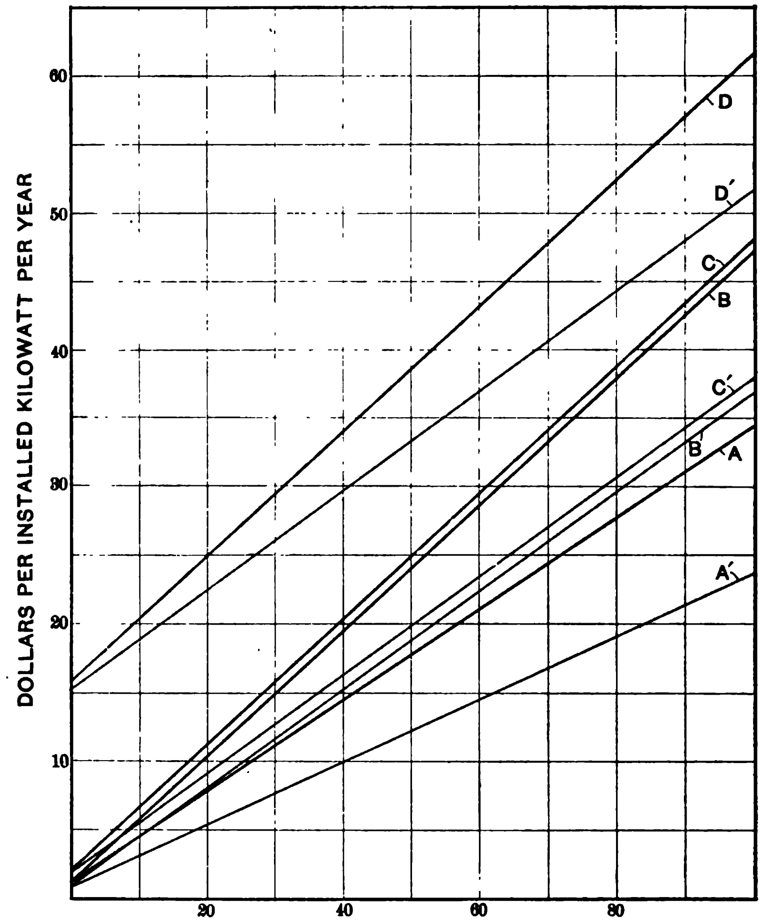

FIG. 15.—Cost of power per kilowatt per year. Reciprocating steam-plant.

Plant cost $125 per kilowatt.
Fixed charges = 11%.
A, B, C, D = coal @ $3.00—14,500 B.t.u. per lb.
A', B', C', D' = coal @ $1.50—11,000 B.t.u. per lb.
A = Coal and water.
B = A + Mechanical maintenance and operation.
C = B + Electrical maintenance and operation.
D = C + Fixed charges.

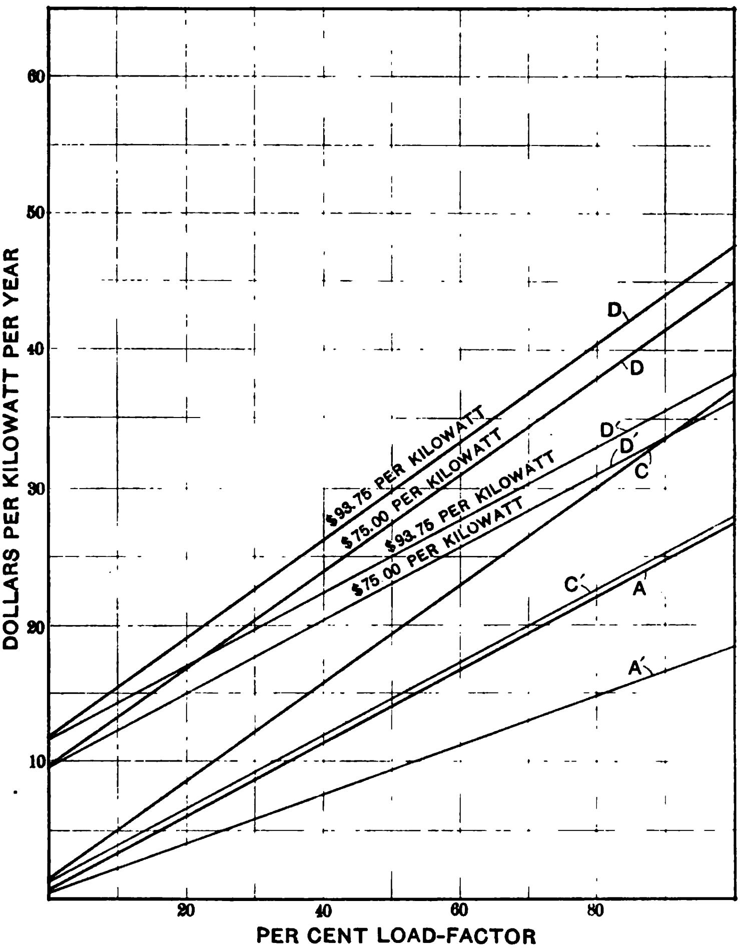

FIG. 16.—Cost of power per kilowatt per year. Steam-turbine plant. Plant cost $93.75 and $75 per kilowatt.
Fixed charges, 11%.
A, B, C, and D same as in Fig. 15 = coal @ $3.00—14,000 B.t.u. per lb.
A', B', C' and D' " " " " " = coal @ $1.50—11,000 B.t.u. per lb.

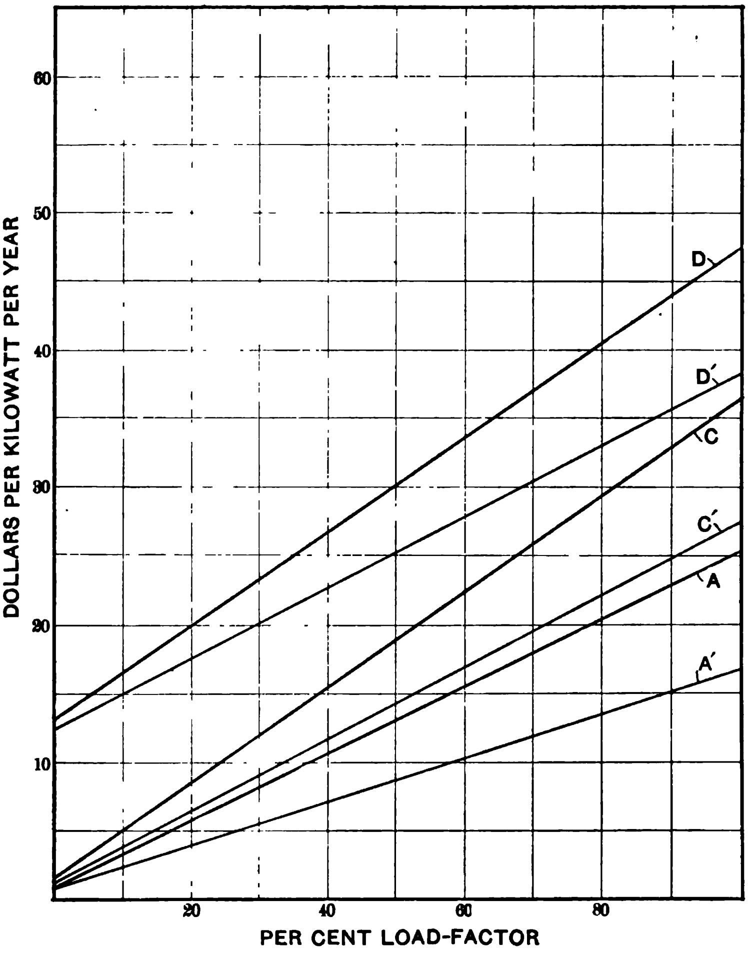

FIG. 17.—Cost of power per kilowatt per year. Reciprocating-engine and low-pressure turbine plant.

Plant cost $100 per kilowatt.

Fixed charges 11%.

A, B, C, D }
A′, B′, C′, D′ } same as Fig. 15.

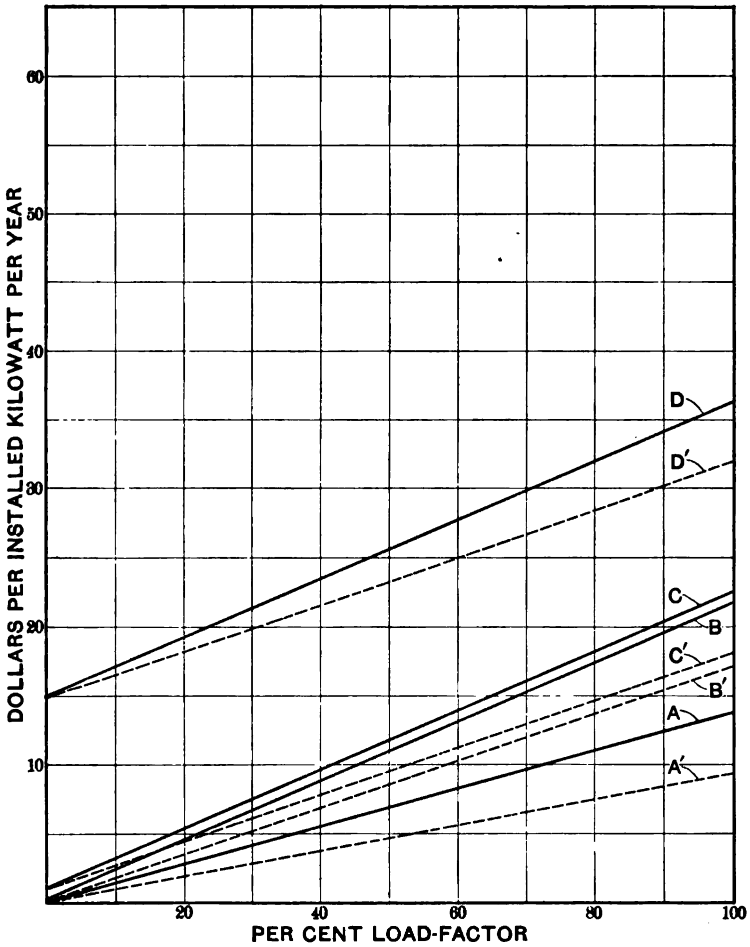

FIG. 18.—Cost of power per kilowatt per year. Gas-engine plant.
Plant cost = $137.50 per kilowatt.
Fixed charges 12%.
Solid lines }
Dotted lines } same as Fig. 15.
A, B, C, D }

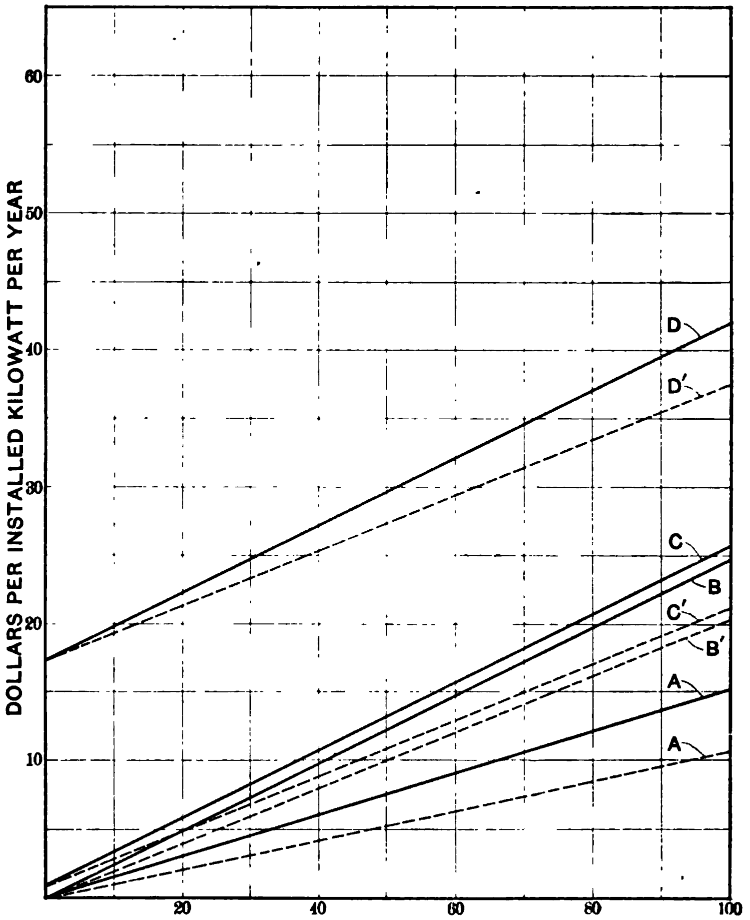

FIG 19.—Cost of power per kilowatt per year. Gas-engine and steam-turbine plant.

Plant cost = $120 per kilowatt.
Fixed charges 11.5% per annum.
Solid lines
Dotted lines } same as in Fig. 15.
A, B, C D

the hydraulic plant, which almost invariably has to assume as a part of its expenses, the fixed charges and operating expenses of the transmission lines. Obviously, it was inadvisable to bring such an unknown quantity into this comparison; but the fixed charges and operating expenses of a long-distance transmission line connecting to an hydraulic plant may be sufficient

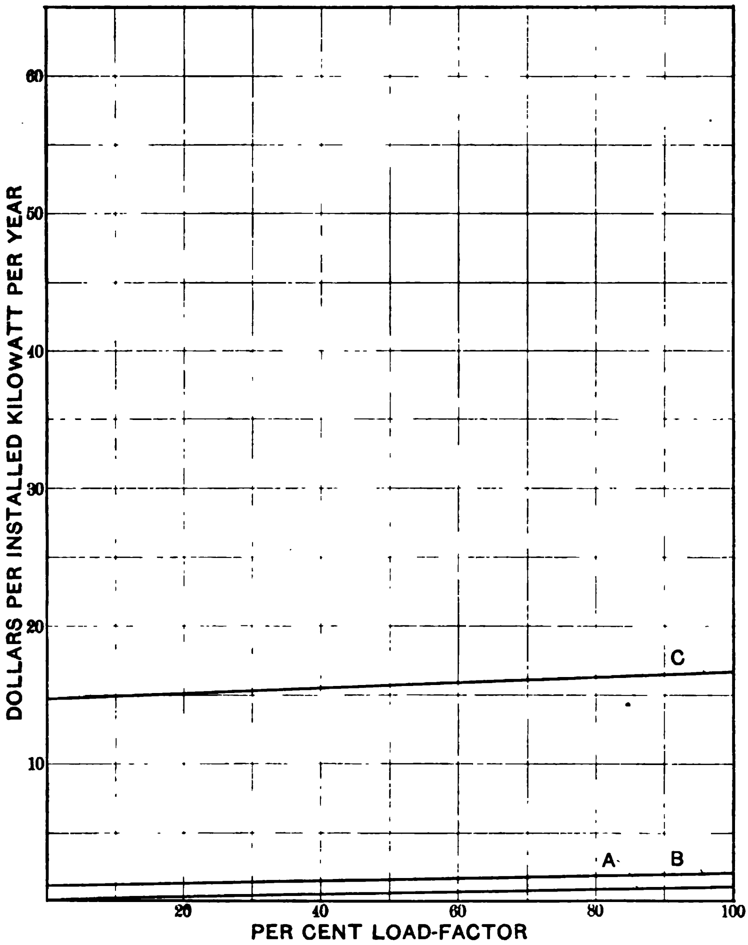

FIG. 20.—Cost of power per kilowatt per year. Hydraulic plant.
Plant cost = $125 per kilowatt.
Fixed charges 11% per anum.
A = Mechanical maintenance and operation.
B = A + Electrical " " "
C = B + Fixed charges.

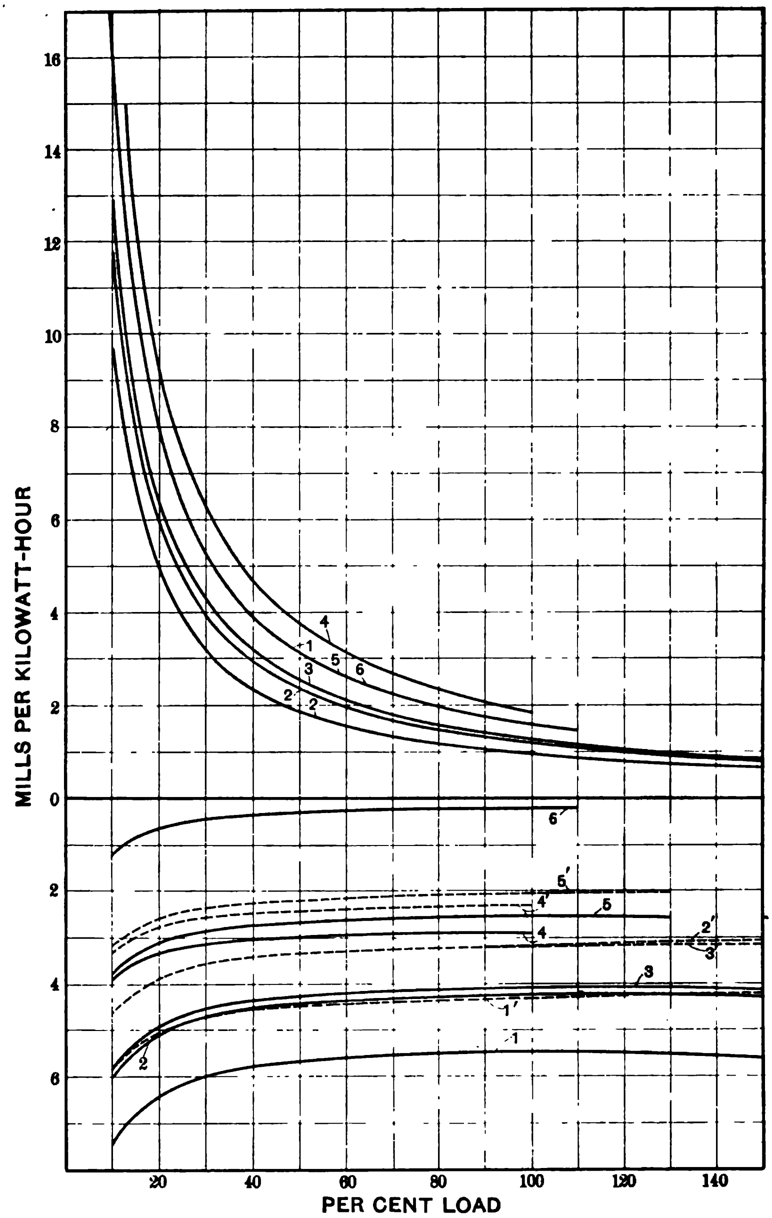

FIG. 21.—Summary of Figs. 1 to 4 inclusive.
Curves 1 2, 3, 4, 5, and 6 same as Fig. 8.

in many cases to decide the question of local steam or gas plant versus long-distance transmission from an hydraulic plant.

Figs. 15 to 20 inclusive are calculated from Figs. 1 to 6, and show the power-plant costs per kilowatt per annum for various load-factors for each of the six types of plants. Attention is called to the fact that the result shown in Fig. 20 is for power at the bus-bars only, and that this must of necessity be increased

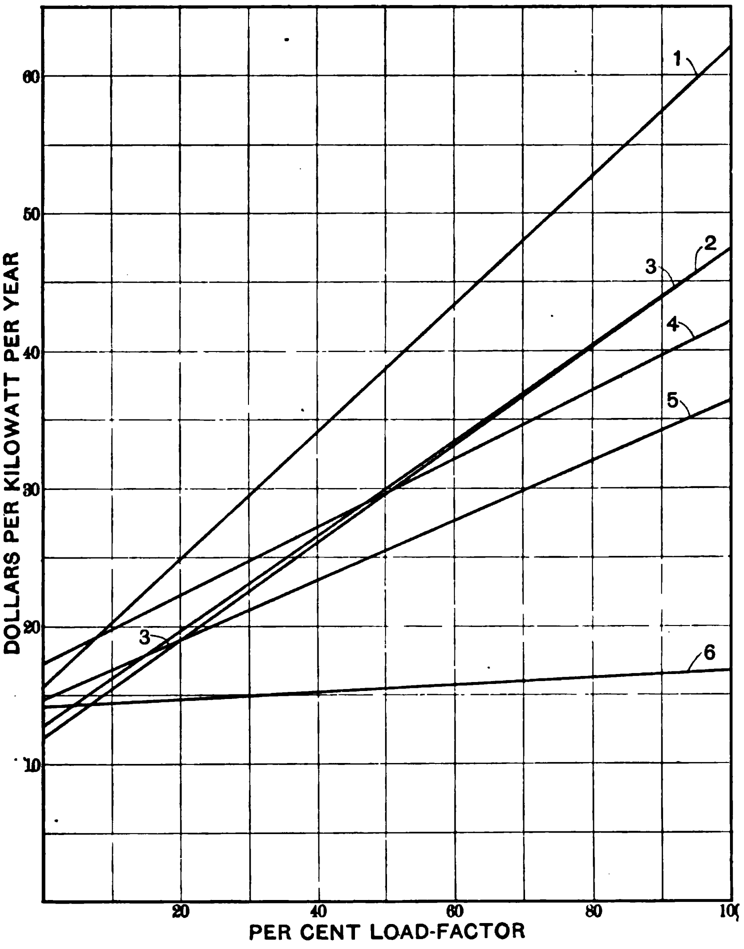

FIG. 22.—Summary of Figs. 15 to 20 inclusive.
Curves 1, 2, 3, 4, 5, and 6 same as Fig. 8.
Coal @ $3.00—14,500 B.t.u. per lb.

by the fixed charges and maintenance costs of the transmission lines and transformers.

In conclusion, the author trusts that the data presented in the shape of 20 curves will be found useful in the preliminary work leading up to the design of a power plant to meet given conditions of load-factor and locality.

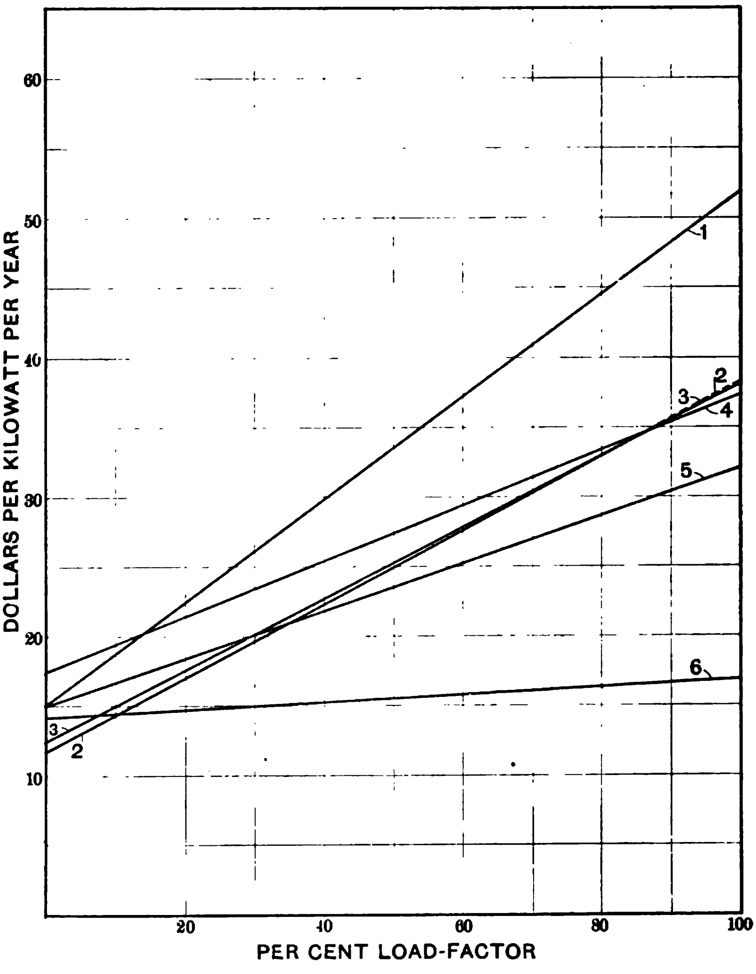

FIG. 23.—Summary of Figs. 15 to 20 inclusive.
Curves 1, 2, 3, 4, 5, and 6 same as Fig. 8.
Coal @ $1.50—11,000 B.t.u. per lb.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1909.

The Board of Directors presents herewith for the information of the membership its annual report, including brief references to the work of the various standing and special committees; also the usual statements showing the financial standing of the organization.

The Annual Convention was held at Atlantic City, June 29–July 2, 1908. The total registered attendance was 469. Thirty-five professional papers, including the President's annual address, were presented and discussed.

The Board of Directors has held 10 regular monthly meetings during the year.

On recommendation of the Finance Committee the Board directed the investment of certain Institute funds, during the year, as follows:

On June 1, 1908, of the cash surplus on deposit, drawing interest at the rate of 3%, there was invested in New York City 4½% bonds of 1957, par value $1,000 each, $10,950. On September 17, 1908, there was effected an exchange of eight $1,000 U. S. Government 3% bonds, value $8,107.50, for eight $1,000 New York City 4½% of 1917, purchase price $8,502.25. The difference in the respective values of the bonds, $394.75, was paid from the cash-surplus on deposit. On October 13, 1908, there was drawn from the International Electrical Congress Fund, the total amount of which was $2,333.07, drawing interest at the rate of 3%, the amount of $2,268, which amount was invested in two $1,000 New York City 4½% bonds of 1957, leaving a balance on deposit, in the International Electrical Congress Fund, of $65.07.

During the year the Institute By-laws were revised by a special committee of the Board of Directors, and were adopted by the Board on November 13, 1908, as revised by the committee, going into effect immediately.

Building Fund Committee.—The amount collected from subscribers during the year was $7,719.40. The interest on the bank balances amounted to $383.36. In addition to these amounts, $9,221.95 was refunded to the Building Fund for payments of interest on the mortgage during the period of occupancy of the building 25-33 West Thirty-ninth Street. These items make a total to the credit of the Building Fund during the year, of $17,324.71. (See financial statements at end of this report.)

Board of Examiners.—The Board held nine meetings during the year, and considered applications for election as Associates, enrolment as Students, and transfer to the grade of Member which were reported to the Board of Directors, as follows:

Recommended for election as Associates	916
Recommended for enrolment as Students	687
Recommended for transfer to the grade of Member	45
Not recommended for election as Associates	2
Not recommended for transfer to the grade of Member	20
Total number of cases considered	1,670

In accordance with the Constitution, Local Representatives of the Board of Examiners were appointed last fall, in various cities of the United States, Canada, and Mexico, to assist the Board in procuring information regarding applicants in their respective territories.

Sections Committee.—The reports of the secretaries of the Sections and Branches show a marked increase in the activity of the local organizations during the year. There are now 23 active Sections. A year ago there were 22 Sections, two of which, however, were inactive. Three new Sections were organized during the year, as follows:

Fort Wayne, Ind., authorized August 14, 1908.
Los Angeles, Cal., authorized May 19, 1908.
Madison, Wis., authorized January 8, 1909.

The Madison Section was formerly the University of Wisconsin Branch, and its change to a Section indicates increased interest in the local organization. In addition to the Section authorized, several meetings of local members have been held at Portland, Oregon and a petition from the Portland members for authority to organize a section has been received and will probably be acted upon at the May meeting of the Board of Directors.

There are 27 Branches, two of which were organized during the year, as follows: Case School, Cleveland, O., authorized January 8, 1909, and New Hampshire College, Durham, N. H., authorized February 19, 1909.

The increased activity of the Sections and Branches is indicated by the following brief summary made up from the reports received at the Secretary's office.

Sections.

	May 1, 1907 to April 30, 1908	May 1, 1908 to March 31, 1909	Increase over last year
Section meetings held	141	169	28
Original papers presented	120	167	47
Institute papers "	38	24	
Attendance	7,476	16,427	8,951

Branches.

	May 1, 1907 to April 30, 1908	May 1, 1908 to March 31, 1909	Increase over last year
Branch meetings held	143	198	55
Original papers presented	84	158	74
Institute papers "	66	52	
Attendance	4,128	8,443	4,315

It will be noted from the above summary that the figures for 1908–1909 cover a period of only 11 months. This large increase is due in some measure to the coöperation of the local secretaries with the Institute office in sending in reports regularly, but more particularly to greater local interest and activity.

Standards Committee.—A meeting of this committee was held at Institute headquarters on December 10, 1908. It was decided to attempt no revision of the Standardization Rules during the present year. At the request of the U. S. National Committee of the International Electrotechnical Commission, certain questions on international nomenclature were considered.

International Electrotechnical Commission.—The U. S. National Committee of the International Electrotechnical Commission held a meeting on June 30, 1908, at Atlantic City on the occasion of the A.I.E.E. Convention.

A communication dated July 15, 1908, was received from the French committee, at the instance of the Bureau of Standards, proposing an international candle. The endorsement of this proposal was obtained from the members of the present U. S. committee and reported to the General Secretary in London, on September 25, 1908. The council meeting of the commission was held in London, on October 19, 1908. At this meeting Professor Elihu Thomson was unanimously elected President of the commission, to succeed the late Lord Kelvin. Certain modifications were adopted in the rules of the commission. It was voted that the commission should undertake to prepare a glossary of important international terms. The proposal of the French committee in regard to an international candle was laid over for consideration by the national committees. It was agreed that in future all measurements used by the commission should be expressed in terms of the metric system, with equivalents in parentheses when desired. A proposal has been received from the British committee to adopt an international candle = 10/9 of a hefner = 0.104 carcel = 1 bougie decimale = 1 pentane candle. This would place the American, British and French candles on a parity, to be maintained by the national standardizing laboratories of those countries. It involves a reduction of 1.6% of the unit of candle-power heretofore maintained by the Bureau of Standards. The proposal has been endorsed by the Bureau of Standards and all of the members of the U. S. committee. The 1.6% change in candle-power has been approved by the American Institute of Electrical Engineers, the American Gas Institute, and the Illuminating Engineering Society. National committees of the commission now exist, in addition to the United States; in Canada, Mexico, Great Britain, Germany, France, Hungary, Belgium, Italy, Spain, Sweden, Denmark and Brazil.

Library Committee.—We submit herewith our report for the year ending April 30, 1909, covering the growth and operation of the library and a statement of the present condition of the various library funds, and of the expenditures for the year.

The gifts to the library during the year reach a total of 273 volumes and pamphlets, while the additions by purchase were 335 volumes and by exchange 201 volumes, making a total of 809 accessions. At the time of the last annual report the library has just received some large additions that had not yet been entered on the library records. From these additions 492 volumes and pamphlets have been acquired making the total increase over the report of one year ago 1301 volumes and pamphlets. The total valuation now placed on the library and the increase for the year is shown in the table of library statistics.

The complete list of donors with the number of volumes presented by each is as follows:

DONORS

ADAMS, E. D	6
ALLGEMEINS ELEKTRICITATS GESELLSCHAFT	1
AMERICAN BELL TELEPHONE COMPANY	2
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS	2
AMERICAN STREET RAILWAY ASSOCIATION	8
BOSTON TRANSIT COMMMISSION	4
BUREAU OF RAILWAY NEWS	1
CALDWELL, EDWARD	68
CARBO, L. A	2
CARNEGIE TECHNICAL SCHOOL	1
CENTRAL ELECTRIC COMPANY	1
CHICAGO DEPARTMENT OF PUBLIC WORKS	1
CLARK, MYRON C., PUBLISHING COMPANY	1
CLAYTON, W. B. & CRAIG, J. U	1
CONNECTICUT BOARD OF ELECTRICAL COMMISSIONERS	1
DIXON CRUCIBLE COMPANY	1
ELECTRIC JOURNAL	1
ENGINEERS SOCIETY, UNIVERSITY OF MINNESOTA	1
FOSTER, H. A	2
FRENCH, MRS. E. D	1
GAS ENGINE	2
GENERAL ELECTRIC COMPANY	1
HERING, CARL	1
INTERNATIONAL ASSOCIATION OF MUNICIPAL ELECTRICIANS	1
IOWA ENGINEERING SOCIETY	3
IRON AGE	1
KANSAS GAS ASSOCIATION	1
McGRAW PUBLISHING COMPANY	55
MACMILLAN COMPANY	2
MAILLOUX, C. O	25
MARTIN, T. C	7
MASSACHUSETTS GAS COMMISSION	1
MASSACHUSETTS GAS & ELECTRIC LIGHT ASSOCIATION	1
MICHIGAN ELECTRICAL ASSOCIATION	5
MUNICIPAL OWNERSHIP PUBLISHING COMPANY	1
NEW JERSEY COMMISSIONER OF PUBLIC ROADS	1
NEW YORK COMMISSIONER OF ACCOUNTS	1
NEW YORK STATE COMMISSION OF GAS & ELECTRICITY	1
NEW YORK STATE LIBRARY	1
NEW YORK STATE PUBLIC SERVICE COMMISSION, FIRST DISTRICT	1
NEW YORK STATE PUBLIC SERVICE COMMISSION, SECOND DISTRICT	4
NEW YORK STREET RAILROAD ASSOCIATION	1
NEW YORK STATE WATER SUPPLY COMMISSION	1

NEW YORK UNIVERSITY (SENATE)	1
OHIO ELECTRIC LIGHT ASSOCIATION	1
PENNSYLVANIA STATE BOARD OF AGRICULTURE	1
PERTIG, W	1
POOLE, C. E	1
ROEBLING'S SONS COMPANY	1
ROEDDER, O. C	1
ROSENTHAL, L. U	1
SNOW, W. B	5
SPRINGER, J	1
STONE & WEBSTER	6
THOMPSON, S. P	2
TORONTO, (CITY ENGINEER)	1
UNDERWRITERS LABORATORY	1
UNIVERSITY OF WASHINGTON	1
VAIL, T. N	1
VAN NOSTRAND COMPANY	10
WEAVER, W. D	1
WESTERN SOCIETY OF ENGINEERS	1
WILEY, JOHN & SONS	1
DONORS UNKNOWN	9
Other Accessions:	
Purchases	335
Exchanges	201
Back Accessions	492
Total Accessions	1301

During the year a reorganization of the library staff and the general administration of the library has been effected. At a meeting of the Trustees of the United Engineering Society held on June 4, 1908, the following plan for the administration of the library was recommended to the governing bodies of the three founder societies:

> First: That the administration of the library be placed in the hands of a chief librarian, all employes in the library to be subject to the direction of said chief librarian. It was agreed that Miss L. E. Howard should be appointed chief librarian, her present yearly compensation to be increased $200 in this connection.
>
> Second: That each new employe in the library shall be approved both by the authorized representative of the founder societies interested, and by the chief librarian.
>
> Third: In the event of any employe not being satisfactory to said representative of the founder society interested, or to the chief librarian, the fact shall be reported by the chief librarian to the House Committee, which shall have the power to act.
>
> Fourth: That in the absence of the chief librarian the House Committee shall have the right to specify an employe of the library to act as chief librarian during such period of absence.
>
> Fifth: That the United Engineering Society be requested to pay the salaries of all the library employes, and the amount to be repaid by the founder societies respectively shall be distributed in such proportion as may be jointly agreed upon.

At the meeting of the Institute Directors held on Friday June 12, 1908, the above recommendations were approved, to take effect July 1, 1908. These recommendations were also approved by the American Society of Mechanical Engineers and the American Institute of Mining Engineers, and since July 1, 1908, the library staff has been in charge of Miss Howard. Previously to that date each library had its own librarian with an assistant working independently of the others. The new arrangement has proved to be entirely satisfactory and a decided improvement over the previous method of operation.

The following tabulations give the state of the five funds from which the Library Committee is entitled to draw·

DONATIONS (GENERAL LIBRARY FUND)

Dr.		Cr.	
Balance May 1, 1908	$244.15		
Interest May 1, 1909	7.36	Unexpended	$251.51
	$251.51		$251.51

CARNEGIE FUND

Balance May 1, 1908	3,168.19		
Interest	88.72	Wheeler Bibliography	3,256.91
	$3,256.91		$3,256.91

MAILLOUX ENDOWMENT FUND ($1,000)

(Proceeds for the maintenance of certain sets of periodical publications)

Balance May 1, 1908	$ 17.35	Subscriptions	$ 17.00
Interest May 1, 1909	30.00	Unexpended	30.35
	$ 47.35		$ 47.35

INTERNATIONAL ELECTRICAL CONGRESS OF ST. LOUIS, 1904 FUND

Principal, May 1, 1908	$2,146.12		
Additions to Fund	121.88		
Invested in New York City 4½% Bonds	$2,268.00		
Interest May 1, 1909		Unexpended	$124.72

WEAVER FUND

Balance May 1, 1908	$ 75.00	Expended	$ 9.56
		Unexpended	65.44
	$ 75.00		$ 75.00

INSTITUTE APPROPRIATION ACCOUNT

Dr.		Cr	
Appropriation for maintenance for year ending October 1, 1909	$3,000.00	Librrian and assistants	$1,250.68
		Cataloging	199.17
		Desk attendant	68.01
		Insurance	88.79
		Binding	247.75
		Supplies	51.69
		Subscription	89.25
		Books	397.12
		Typewriter	15.70
		Printing	17.66
		Book plates	24.50
		Miscellaneous	10.27
		Unexpended	539.41
	$3,000.00		$3 000 00

The general statistics of the Library and its valuation are shown in the following tabulation:

STATISTICS OF LIBRARY, MAY 1, 1909

Source	Titles	Volumes	Pamphlets	Valuations
Report of May 1, 1908	7,976	11,828	565	$23,406.55
PURCHASES:				
Mailloux Fund	4	8		17.00
Weaver Fund	8	10		9.65
Institute Appropriation	120	174		397.12
Periodicals	170	218		436.00
Gifts and Exchanges		1,277		300.00
Totals	8,278	13,515	565	$24,566.23
Duplicates	501	714		900.00

In the following table are given the figures for the total valuation of the library property:

Books	$24,566.23
Stacks	1,761.05
Furniture, Catalogue Cases, etc	208.28
	$26,535.56

LIBRARY ATTENDANCE

	Day	Evening
May, 1908	400	196
June "	419	136
July "	441	Closed
August "	362	Closed
September "	393	125
October "	381	180
November "	425	200
December "	520	441
January 1909	485	250
February "	533	254
March "	535	280
April "	529	219
Totals	5,423	2,281
Total day and evening		7,704

IMPORTANT GIFTS AND ACCESSIONS

Mr. Edward D. Adams has continued his special interest in the library and has donated as heretofore the yearly *Proceedings* and *Transactions* of the Royal Society of London, and the additional volumes of the International Catalogue of Scientific Literature. He has also borne the expense of binding the volumes of the catalogue heretofore added to the library. The fund of $1000, known as the " C. O. Mailloux Fund," has again been drawn upon for the subscription price of the four important periodical sets originally presented by Mr. Mailloux to the library. The proceeds of the International Congress Fund, which is now invested so as to yield an annual income of nearly $100, has been drawn upon for the very recent purchase of several reports of international congresses and international electrical exhibitions. The Public Service Commission of the Second District, State of New York has presented a set of its publications. Some incomplete sets have been entirely or nearly completed, and a complete set of " Terrestrial Magnetism " has been added. The principal purchases have been publications of recent years.

GENERAL INVENTORY AND INSPECTION

This work which was in progress at the time of the last annual report has been continued and completed. The errors and deficiencies discovered have been corrected by the present librarian and the entire collection thus put into excellent shape for the preparation of the union card catalogue.

THE UNION CARD CATALOGUE

Early in the year it was decided to prepare a union card catalogue of all the books belonging to the three founder societies. For this purpose an expert cataloger was employed and the work has progressed so rapidly that the catalogue is already completed. A new card cabinet of 180 drawers with a capacity for nearly 200,000 cards has been installed in the general library and the union catalogue is now in public use.

TRADE CATALOGUES

A new feature of the library is the file of trade and manufacturers' catalogues. These are arranged in the drawers of a vertical file and are indexed both by names and subjects. As new editions of catalogues are received the old ones are displaced.

THE ENGINEERING INDEX

An effort has been made to have available for the use of searchers every general index to engineering literature, and the library now has a fine collection of such reference books. These include Kerl's *Repertorium*, The Royal Society's *Catalogue of Scientific Papers* and its successor, the *International Catalogue of Scientific Literature*, both of which were the gift of Mr. Edward D. Adams; a complete set of the *Engineering Index*, a complete set of *Science Abstracts*; and many other valuable helps. Reference to the *Engineering Index* is facilitated by clipping each monthly issue as it appears and arranging the titles on cards which are then arranged in a subject classification for the use of the public. This index is thus kept up to date as closely as possible The publishers of the *Electrical World* have just contributed a complete set of its semi-annual indexes, specially bound with thumb index tabs, making a very handy and serviceable volume.

TELEPHONE RECORDS

The very vaulable set of telephone records presented to the library by the American Bell Telephone Company, and comprising about 100 volumes, is now being catalogued in detail. Each volume contains many pamphlets and other material, either printed or in manuscript form, and it is hoped that the catalogue when completed may be printed by the Institute so that the contents of this vaulable set may be made available for more general consultation.

HARMONIOUS OPERATION

We take pleasure in reporting that the authorities in charge of the libraries of the American Institute of Mining Engineers and the American Society of Mechanical Engineers have coöperated with us to bring about an efficient service under conditions that are not always the most favorable. The three libraries here housed together still remain under separate and independent ownership, but each has shown its desire to make the various collections as useful as possible to the members of all societies alike as well as to the general public. A further movement in this direction is now under way, and a recommendation that each society print and circulate to all members alike the accessions of all three libraries is now being considered by each society.

HISTORICAL MUSEUM

While we have not actively pushed the affairs of the Historical Museum which was established about three years ago the matter has had our attention from time to time. At present there seems especially to be no satisfactory space at our disposal for the proper carrying out of the original plan. The space originally set aside on the twelfth floor has been required for library purposes during the past year and with the increase in the library this condition will no doubt continue. The project however is one that is important and deserves some more adequate provision for the preservation and display of historical apparatus.

Respectfully submitted,

The Library Committee,
EDWARD CALDWELL,
Chairman.
W G. CARLTON.
H. E. CLIFFORD.
MAX LOEWENTHAL.
PHILIP TORCHIO.

Committee on Intermediate Grade of Membership.—The committee has considered along broad lines the question of the need and practicability of adding one or more grades of membership to those now existing It has examined the classification of other organizations having various grades of membership. The subject has proved an extremely difficult one, involving, as it does, general policy, as well as a large amount of detail. The committee is now formulating its views in regard to the various points involved, and will probably suggest that its report be printed in the PROCEEDINGS, and the views of the membership in regard to the subject be invited.

Committee on Bibliography.—This committee has completed its work upon the catalogue of the Wheeler Gift of Books, Pamphlets and Periodicals. The catalogue has been published in two volumes and is now being distributed.

Meetings and Papers Committee.—During the past year this committee arranged for eight regular and two special meetings. Nine papers were presented at the eight regular meetings. One of the special meetings was devoted to the subject of conservation of natural resources, and the other to industrial education. The efforts of the committee, throughout the year, have been directed towards securing a single paper of unusual merit for each regular meeting. The subjects were selected so as to cover as fully as possible the broad field of electrical engineering, in order to appeal to the diversified membership. The several sub-committees of the Meetings and Papers Committee have been utilized during the year to supply papers and discussions on their special subjects, with gratifying results.

Educational Committee.—The committee held two meetings during the winter, in New York City, at which the scope of the work was discussed and plans were made for two special meetings of the Institute. At the outset it was decided that as technical education had been treated exclusively during the preceding year, industrial training should be adopted, as the topic for the current year. As a part of this plan a special meeting of the Institute was held in New York, under the auspices of the committee, on April 16, 1909. As a further part of the plan, a special session of the 1909 Convention will be occupied with papers and discussions on the general subject of industrial education. In addition to the preparations for the meetings mentioned, the committee has carefully considered a plan for holding examinations throughout the country, under the auspices of the Institute. The committee has also considered a plan for assisting in research work throughout the country, by compiling lists of suitable subjects for investigation.

High-Tension Transmission Committee.—The Institute has held one meeting under the auspices of this committee, on April 9, 1909. Two papers were presented and discussed at this meeting, and there were conducted on the stage of the auditorium some tests of terminals at voltages up to 250,000. It is contemplated that at least one session at the annual convention will be under the auspices of this committee.

Committee on Industrial Power.—A number of meetings of this committee have been held during the year. Nearly all of the Sections have held meetings devoted to the subject of industrial power, as a result of the efforts of the committee. It was hoped that the papers presented at these meetings could be collected and published in book form, but it was found impossible. It may be possible, however, to do this next year. The regular March meeting of the Institute was devoted to the subject of industrial power. It is planned to devote one of the sessions of the annual convention to this subject.

Editing Committee.—Since September, 1908, there have been edited and published eight numbers of the PROCEEDINGS. The total number of pages of these PROCEEDINGS is 1701; of this total, 304 pages have appeared in Section I; 767 pages in Section II. Of the 767 pages in Section II, 354 pages were devoted to technical papers and 413 pages to discussions.

Vol. XXVII, of the TRANSACTIONS, consisting of the papers, and discussions during the calendar year 1908, the report of the Board of Directors for the fiscal year ending April 30, 1908, and the By-Laws, contains 1716 pages. Vol. XXVII will be issued in two parts. Part I, consisting of 858 pages, will contain the papers and discussions presented between January 1, 1908, and the end of the morning session on June 30, 1908, at the Annual Convention at Atlantic City, the report of the Board of Directors, and the By-Laws. Part II, also consisting of 858 pages, will contain the papers and discussions presented between the evening session on June 30, 1908, at the Atlantic City Convention, and December 31, 1908. The volume will probably be ready for distribution about August 1, 1909.

The chairman of the Editing Committee has given personal attention to all the MSS., of the papers and discussions at the Institute Sections and Branches that have been forwarded to the Secretary's office during the present administration. Thirty-six MSS., of this nature have been received and passed upon. These MSS., consisted of approximately 700 pages of typewritten matter.

Law Committee.—The Law Committee considered and reported upon various questions submitted to it by the Board of Directors during the past year, the most important matter being the advisability of drafting by-laws to govern the actions of the Meetings and Papers, and Editing committees. After careful consideration of the subject it was the unanimous opinion of the committee that the conditions governing the acceptance of papers and discussions were so varied as to make it impossible to draft any rigid rules for the guidance of those committees, and that the present right of appeal to the Board of Directors, which any member now has, was a sufficient safeguard of the rights of all members.

Code Committee.—The Code Committee has held a number of meetings during the year. The most important matter that has been considered was in connection with Rule 13-A of the Board of Fire Underwriters. This rule deals with the grounding of secondary circuits. The committee agreed that the rule should be made mandatory up to and including 150 volts between any wire and ground, and optional up to and including 250 volts between any wire and ground. This resolution was handed to the president of the National Conference on Electrical Rules. Final action on the resolution was deferred, pending an arrangement for a meeting of the Code Committee with a committee of the National Board of Fire Underwriters.

Committee on Conservation of Natural Resources.—During the past year the Committee on Natural Resources has carried on correspondence and held informal conferences with representatives of the U. S. Government and with other societies, looking to the furtherance of the legitimate object of the conservation movement. The committee also originated the movement which resulted in a very successful joint meeting held March 24, 1909, under the auspices of the four national engineering societies. The committee feels that two extremely valuable objects were gained in this joint meeting: 1. The presentation of the engineers' views on the conservation movement. 2. Bringing the four societies to act jointly on this subject, which establishes a precedent for similar action on other important subjects of common interest to all, and has a tendency to promote cordial relations between the societies.

Edison Medal Committee.—Before the new deed, entitled " Amended and Substitute Deed of Gift Creating the Edison Medal ", was executed, on March 26, 1908, five graduate students from institutions of learning, duly qualified to compete for the Edison Medal under the old deed, had submitted theses in competition for the medal for 1907. These students, at the request of the Institute, withdrew from competition for the medal, and resubmitted their theses in a special competition for a Diploma of Merit, plus a cash award of $150.00. A sub-committee of the Edison Medal Committee reported to the chairman on May 8, 1909, its recommendation in respect to the award on the student theses, which will be acted upon at a meeting of the Edison Medal Committee on May 18.

Revision of the by-laws of the Edison Medal Committee was begun in October, 1908, and a final draft as approved by the committee was presented to the Board of Directors on December 11, 1908.

John Fritz Medal.—The John Fritz Medal Board of Award upon which the Institute is represented arranged for a meeting which was held on April 13 at which the medal for 1909 was presented to Mr. Charles T. Porter, for meritorious service in the advancement of steam engineering. Four addresses were made at this meeting by representatives of the four national engineering societies.

Increase of Membership Committee.—This committee has held several meetings during the year, and has sent out numerous letters and circulars. A special effort was made to interest engineers in the U. S. Army and Navy. During the year ending May 1, 1909, 1079 applications for membership were received—almost as many as were received during each of the two preceding years.

Membership. The present total membership and the increase during the past year are indicated below:

	Hon. Mem.	Mem.	Assoc.	Total
Membership, April 30, 1908	1	573	5,100	5,674
Additions:				
New Associates			1,005	
Transferred		53		
Deductions:				
Died		4	13	
Resigned		4	66	
Dropped		11	181	
Transferred			53	
Membership April 30, 1909	1	607	5,792	6,400

Net increase during the year in membership........................726

Resignations.—The following Members and Associates have resigned during the year in good standing.

Members.—F. W. Brady, J. W. Swinburne, C. H. Wilmerding, C. H. Wordingham.

Associates.—J. C. T. Baldwin, R. J. Barker, B. H. Bendheim, E. R. Berry, R. H. Black, A. E. Blondel, C. A. Bramhall, A. U. Brandt, J. Brayshaw, W. S. Brewster, A. J. Brown, W. D. Brown, Leonard Carpenter, M. E. Chester, A. S. Clift, B. W. Cooper, W. R. Cooper, W. W. Dean, B. M. Drake, Edward Durant, C. D. Ehret, Albert Esling, E. E. Ferrin, W. S. Ford, M. J. Francisco, J. B. Edwards, E. E. Gage, H. L. Gilbert, Leon Goldsmith, W. M. Haddock, C. G. Halleck, W. L. Hildburg, Christopher Hoff, Jr., B. K. Hough, James C. Howe, W. McA. Johnson, Henry Kaetker, P. H. Knight, F. N. Koziell, P. J. Kreusi, F. F. Lee, Norman Leeds, C. H. Machen, Benjamin Magnus, B. F. Mechling, Jr., L. G. E. Morse, M. M. Neurath, M. L. Norris, R. B. Parrott, Carroll Potter, J. D. Ross, E. H. Rupe, R. A. Scott, T. G. Seidell, A. B. Skelding, W. W. Sloane, W. Stuart Smith, A. B. Stetson, F. K. P. Stilwell, Julius Strauss, S. Tada, J. C. Van Buren, W. M. Venable, S. T. Wellman, Charles West, J. M. Zapata.

Total resignations, 70.

Deaths.—The following deaths have occurred during the year:

Members.—W. A. Anthony, E. V. Baillard, C. E. Gifford, F. A. C. Perrine.

Associates.—H. C. Buck, A. M. Bullard, W. H. Cordell, Theodore Dimon, E. G. Eberhardt, A. B. Elliott, Otto Holz, J. M. Mahoney, W. S. Scarlett, E. F. Schaefer, Paul von Lehoczky, F. G. Warman, E. L. Zalinski.

Total deaths, 17.

Delinquent.—Dropped as delinquent during the year, 192.

The average receipts and disbursements *per capita* for the past seven years, are shown in the following table:

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past seven years.

Year	1903	1904	1905	1906	1907	1908	1909
Membership, April 30th, each year	2230	3027	3460	3870	4521	5674	6400
RECEIPTS PER MEMBER:							
Entrance Fees	$1.59	$1.65	$0.83	$0.75	$0.90	$1.21	$0.79
Dues	9.01	9.33	9.30	9.47	8.95	9.36	10.19
Transactions, Sales, Advertising	1.79	2.11	1.70	2.15	1.81	1.83	1.68
Badges	.35	.39	.28	.27	.30	.43	.32
Interest	.21	.18	.21	.13	.25	.18	.23
	$12.95	$13.66	$12.32	$12.77	$12.21	$13.01	$13.21
DISBURSEMENTS PER MEMBER:							
Transactions	$4.67	$3.43	$3.77	$3.33	$2.83	$3.51	$3.65
Salaries	2.49	2.50	2.20	2.64	2.53	2.55	1.93
Meeting Expenses, incl. Sections	.87	1.16	.82	.68	.68	.91	.84
Housing	.65	.79	.75	.68	1.33	1.15	.96
Library, incl. Salaries	1.38	1.39	.81	.69	1.37	.51	.39
Postage	.69	.66	.66	.58	.59	.65	.74
Stationery and Miscel. Printing	.96	1.01	.70	.78	.85	.80	.82
General Expenses	.52	.45	.54	.29	.43	.62	.29
Badges	.27	.35	.25	.22	.29	.40	.28
Express	.15	.28	.22	.23	.28	.14	.23
Advertising				.36	.30	.35	.27
Office Fittings					.14	.14	.09
Total	$12.65	$12.02	$10.72	$10.48	$11.62	$11.73	$10.49
Credit Balance per Member	$0.30	$1.64	$1.60	$2.29	.59	1.28	2.72

LAND, BUILDING AND ENDOWMENT FUND.

RECEIPTS.		DISBURSEMENTS.	
Before appointment of committee	$ 6,100.00	Paid United Engineering Society, acct. of contract	$ 8,000.00
Collected by Committee	143,328.90	Paid United Engineering Society, acct. of mortgage	99,000.00
Interest on balances	5,381.76	Paid United Engineering Society, acct. of interest	19,529.45
Reimbursement by Institute	9,221.95	Expenses of Committee	10,440.73
		Balance in bank, May 1, 1909	27,062.43
Total	$164,032.61	Total	$164,032.61

New York May 18, 1909.

MR. LOUIS A. FERGUSON,
President American Institute of Electrical Engineers,
No. 33 West Thirty-ninth Street, New York.

Dear Sir: During the past year your Finance Committee has performed its prescribed duties as provided for in the Constitution and By-laws. We respectfully submit herewith the report of the chartered accountants, Messrs. Peirce, Struss & Company, who have audited the books of the Institute for the year.

Your committee, in company with the Secretary and a representative of the chartered accountants, has examined the securities held by the Institute, and finds them to be as stated in the balance sheet.

In preparing the annual statement this year, the chartered accountants have followed previous practice in omitting from the assets and from the liabilities, any accruals of interest, but we recommend that the Board of Directors instruct that in future statements these accruals be entered on both sides of the balance sheet.

Similarly, the item of Office Furniture and Fixtures is this year set up at its present appraised value, such value being determined by a recent re-appraisal. We recommend that the Board of Directors direct the furniture account to be set up at its full cost value, to which shall be added each year the cost of additional furniture which may be purchased from time to time; that as against this amount a reserve liability fund be created, to which shall be added annually a sum equivalent to a suitable per cent of the total furniture account, such reserve fund to be held against possible replacement of furniture and fittings.

You will note the sum of $9,921.95 entered as a reimbursement of the Land, Building and Endowment Fund, which amount is deducted from the year's surplus. In explanation of this item it seems proper to state that by authorization of the Board of Directors, all payments of interest on the unpaid balance of the cost of land since the Institute has occupied its present quarters, have been adjudged a current expense payable from the Institute current income, and inasmuch as certain sums for this purpose had previously been paid out of the Land, Building and Endowment Fund, an equivalent amount with all interest received on same has been restored to that fund, which accounts for the item referred to.

Respectfully submitted,

CALVERT TOWNLEY,
Chairman Finance Committee.

New York, May 11, 1909.

MR. CALVERT TOWNLEY,
Chairman Committee on Finance.

Dear Sir: In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers, for the year ended April 30th, 1909.

The results of this examination are presented in four exhibits, attached hereto, as follows:—

Exhibit A. Balance Sheet, April 30th, 1909.

Exhibit B. Receipts and Disbursements for general purposes for year ended April 30, 1909.

Exhibit C. Receipts and Donations for designated purposes, also expenditures for year ended April 30, 1909.

Exhibit D. Condensed Cash Statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,
(Signed) PEIRCE, STRUSS & Co.
Certified Public Accoutants.

New York, May 11, 1909.

MR. CALVERT TOWNLEY,
Chairman Committee on Finance.

Dear Sir: Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1909, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30, 1909, and that the accompanying statements of Cash Receipts and Disbursements are correct.

(Signed) PEIRCE, STRUSS & Co.
Certified Public Accountants.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

BALANCE SHEET, APRIL 30, 1909.

EXHIBIT A.

ASSETS.

CASH:		
Land, Building and Endowment fund.	$27,062.43	
General Library fund	251.51	
Compounded Membership fund......	5,355.57	
*Mailloux fund.....	1,000.00	
		33,669.51
†General cash in bank............	9,198.65	
Secretary's petty cash on hand.....	500.00	
		9,698.65
International Electrical Congress of St. Louis, 1904, Library fund Bonds	2,268.00	
		2,268.00
New York City 4½% Gold Bonds......	30,000.00	
Premium on Bonds.	1,952.50	
		31,952.50
Westinghouse Elec. & Mfg. Co's stock.		50.00
Equity in Societies Building (25 to 33 West 39th Street)	353,346.61	
One-third cost of land (25 to 33 West 39th Street)	180,000.00	
		533,346.61
Library volumes and fixtures..........	26,644.67	
Transactions........	5,480.25	
Office furniture and fixtures..........	5,139.75	
Works of art, paintings, etc.........	2,300.00	
Badges............	495.30	
		40,059.97
ACCOUNTS RECEIVABLE:		
Members for past dues suspense acct.	11,283.75	
Members for entrance fees.......	265.00	
Miscellaneous.......	478.51	
For advertising.....	1,762.00	
		13,789.26
Total Assets................		$664,834.50

LIABILITIES AND SURPLUS.

FUNDS		
Land, Building and Endowment Fund	$27,062.43	
General Library Fund............	251.51	
Compounded Membership Fund.....	5,355.57	
Mailloux Fund......	1,000.35	
International Electrical Congress of St. Louis, 1904, Library Fund:		
Principal.........	2,268.00	
Unexpended Income..........	124.72	
Accounts Payable subject to approval by Finance Committee......	4,035.38	
		40,097.96
United Engineering Society (for cost of land)..........		81,000.00
Total liabilities.		$121,097.96
SURPLUS:		
In cash............	9,573.58	
New York City bonds............	31,952.50	
In property and accounts receivable.	502,210.46	
		543,736.54
Total liabilities and surplus......................		$664,834.50

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* The Farmers' Loan and Trust Co. deposit account includes 35c. of the Mailloux Fund.

† $65.44 of the Weaver donation. $124.72 of Int. Elec. Congress of St. Louis Library Fund.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1909.

EXHIBIT B.

RECEIPTS.		
Entrance Fees	$5,025.00	
Current Dues	54,759.50	
Past Dues	5,726.00	
Advance Dues	290,50	
Students' Dues	3,957.00	
Transfer Fees	480.00	
Badges	2,084.50	
		$72,322.50
Sales, Transactions, etc.	1,787.26	
Subscriptions, Proceedings	1,439.76	
Advertising	7,228.89	
Binding	137,25	
Exchange	28.21	
Library Sales	114.29	
INTEREST:		
Bonds	977.07	
Bank Balances	512.22	
		$12,224.95
Total		$84,547.45

DISBURSEMENTS.		
Stationery and Printing	4,766.10	
Postage	4,706.43	
General Expenses	1,887.79	
Meeting Expenses	1,960.60	
Section Meetings	3,389.54	
Badges	1,824.05	
Salaries	9,964.00	
Bibliography	485.05	
Office Furniture	546.90	
		$29,530.46
PROCEEDINGS—TRANSACTIONS:		
Printing	16,009.84	
Salary	2,400.00	
Engraving	1,261.10	
Volumes	3,294.57	
Electrotyping	1,023.49	
Binding	1,787.07	
Express	1,475.25	
Advertising Commissions	1,714.27	
		$28,965.59
LIBRARY:		
Librarian & Asst's.	$1,250.68	
Cataloguing	199.17	
Desk Attendant	68.01	
Insurance	88.79	
Binding	247.75	
Supplies	51.69	
Subscription	89.25	
Books	397.12	
Typewriter	15.70	
Printing	17.66	
Book plates	24.50	
Miscellaneous	10.27	
		$2,460.59
United Engineering Society Assessments (Rent)		$6,166.68
Total		$67,123.32
Excess receipts over disbursements		17,424.13
		$84,547.45
To Surplus—as above		17,424.13
Reimbursement of Land Building and Endowment Fund		9,221.95
Net to surplus		$8,202.18

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES, ALSO EXPENDITURES FOR YEAR ENDED APRIL 30, 1909.

EXHIBIT C.

RECEIPTS.	
Land, Building and Endowment fund, Donations, Interest, etc.	$17,324.71
Carnegie (Library) Fund, Interest	88.72
General Library Fund, Interest	7.36
Compounded Membership Fund, Interest	195.57
International Electrical Congress of St. Louis, 1904, Library Fund, on account of Principal	31.10
International Electrical Congress of St. Louis, 1904, Library Fund, on account of interest	108.28
	$17.755.74
Mailloux Fund Interest ($30.00) received after April 30th 1909	
EXPENDITURES.	
Land, Building and Endowment Fund, on account of Interest and Expense	$3,610.59
Carnegie (Library) Fund	3,256.91
Compounded Membership Fund	440.00
Mailloux Fund	17.00
Weaver Donation	9.56
International Electrical Congress of St. Louis, 1904, Library Fund for Bonds	2,268.00
Total Expenditures	9,602.06
Excess of Receipts over Expenditure	8,153.68
	$17,755.74

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

CONDENSED CASH STATEMENT.

EXHIBIT D.

Cash on deposit April 30th 1908	$37,857.05	
Secretary's petty cash, April 30th, 1908	500.00	
	$38,357.05	
Receipts for general purposes, Exhibit " B "	84,547.45	
Receipts for designated purposes, Exhibit " C "	17,755.74	
		$140,660.24
Disbursements for general purposes, Exhibit " B "	67,123.32	
Expenditures for designated purposes, Exhibit " C "	9,602.06	
Expended for New York City 4½% Bonds	11,344.75	
Reimbursement of Land Building and Endowment Fund	9,221.95	
		97,292.08
Balance on hand, April 30th, 1909		43,368.16
On deposit for designated purposes, Exhibit " A "	33,669.51	
On deposit for general purposes, Exhibit " A "	9,198.65	
Secretary's petty cash, Exhibit " A "	500.00	
		$43,368.16

PROPERTY ACQUIRED DURING THE YEAR.

Office Furniture and Fixtures	$546.90
Library Books and Binding	644.87

Respectfully submitted for the Board of Directors.

RALPH W. POPE, *Secretary.*

New York, May 18, 1909.

TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

JUNE 30 TO DECEMBER 31, 1909

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