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THE CALCULATION OF COPPER CONDUCTORS FOR ALTERNATING CURRENT THREE-PHASE TRANSMISSION LINES.

By F. B. Brown, M.Sc., S. Can. Soc. C.E.

(To be read before the Electrical Section on 7th November, 1907.)

Three-phase transmission for alternating current is now conceded to be the only practical and economical means of transmitting large quantities of electrical energy over great distances.

With the increasing use of electricity for lighting, railway, and general power purposes, and the consequently larger number of generating stations required, the question of transmission line design is becoming more and more important, as the distances from source of supply to load increase, and with the consequent rise in voltage necessary to keep the line within commercial bounds.

One of the foremost problems which the engineer is called upon to solve, is the proper designing of the conducting system, including size, spacing of wires, etc., to meet the load conditions with specific losses or drop of voltage.

The present paper is intended to offer an easy method of solving such problems.

Several very able articles have appeared from time to time on the subject of "Drop in Alternating Current Lines," and the writer is indebted especially to Mr. R. D. Mershon's now classic article, originally published in the *American Electrician* for June, 1897, and rewritten for the March, 1907, number of the *Electric Journal*, and to two articles in the March, 1907, and April, 1907, numbers of the same periodical by Mr. Clarence P. Fowler, and Messrs. Chas. F. Scott and C. P. Fowler, respectively, of the latter of which two articles liberal use has been here made.

The essential part of the present paper consists of the four plates annexed and designated Diagrams 1 and 2, and Tables I and II. The diagrams were originally intended for use by the firm with which the writer is connected, where they were found so useful that it has been thought well to embody them with the tables in a short paper for the convenience of other members of the engineering profession. They have been derived, as described below, from modifications of the wiring formulæ brought out some time ago by the General Electric Company,* and these diagrams with the $\frac{\text{Reactance}}{\text{Resistance}}$ tables (Table I) and the list of drop factors following (Table II) may be used in quickly solving the conductors for almost any transmission line.

The process of development of the curves may be readily traced, but it has been thought advisable to show the steps taken in attaining the results, and in this connection it should be carefully kept in mind that in alternating current transmission at power factors of load other than unity, the loss of volts and drop of volts are by no means synonymous—the first referring to a CR loss, and the second to a CR loss multiplied by a factor; and that the % watts loss and % volts loss are not the same by any means, and neither agree with the % drop, which latter determines the regulation.

Proceeding with the derivation of the diagrams, the following equations should be noted:

On the basis of watts loss, for any conductor, the following formulæ are universal for all systems of transmission when suitable constants are used.

$$\text{Area in circular mils} = \frac{D \times W \times K^1}{P \times E^2} \quad (1)$$

$$\text{and, total wt. of copper in line} = \frac{D^2 \times W \times K^1 \times A}{P \times E^2 \times 10^6} \quad (2)$$

where D = distance one way in feet along line.
W = total watts delivered at receiver end of line.
P = per cent. of loss of power W.
E = line voltage at receiver end.
K^1 = a constant = 1080 for three-phase 100% power factor.
A = a constant = 9.06 for three-phase all power factors.

* See Foster's "Electrical Engineer's Pocket Book," pp. 124-126, and Crocker's "Electric Lighting," vol. ii., pp. 232 *et seq.*

Now if for D be substituted M = distance one way in miles instead of feet.

and for W be substituted K = kilowatts delivered instead of watts.

and for E be substituted $\varepsilon = E \div 1000$ = line voltage divided by 1000.

and for K^1 be substituted Z = a constant = 1080

the above formulæ become

$$(1)\ C.M. = \frac{(M \times 5280) \times (K \times 1000) \times Z}{P \times (\varepsilon \times 1000)^2}$$

$$= \frac{M\,K\,Z}{P\,\varepsilon^2} \times \frac{5280000}{1000000}$$

$$= \frac{M\,K}{P\,\varepsilon^2} \times 5702.4$$

and (2) total weight $= W = \dfrac{(M \times 5280)^2 \times (K \times 1000) \times Z \times A}{P \times (\varepsilon \times 1000)^2 \times 10^6}$.

$$= \left(\frac{M}{\varepsilon}\right)^2 \times \frac{K}{P} \times \left(\frac{5280}{1000}\right)^2 \times \frac{1000}{10^6} \times Z \times A$$

$$= \left(\frac{M}{\varepsilon}\right)^2 \times \frac{K}{P} \times \frac{27.8784}{1000} \times 1080 \times 9.06$$

$$= \left(\frac{M}{\varepsilon}\right)^2 \times 272.7846.$$

Allowing 2.65% for sag, etc., these formulæ become

$$(1)\ C.\ M. = \frac{M\,K}{P\,\varepsilon^2} \times 5854$$

$$(2)\ \text{Total weight} = W = \left(\frac{M}{\varepsilon}\right) \times \frac{K}{P} \times 280$$

and the weight of copper per kilowatt delivered

$$(3)\ = L = \left(\frac{M}{\varepsilon}\right)^2 \times \frac{280}{P}$$

and the weight per mile of a single wire (l) is obtained by substituting $3l \times M$ for W in formula (2), thus:

$$W = 3\ M\ l = \left(\frac{M}{\varepsilon}\right)^2 \times \frac{K}{P} \times 280$$

$$\text{or}\quad (4) = l = \frac{M}{(\varepsilon)^2} \times \frac{K}{P} \times 93,$$

and $(5) = 3\,l = L \times \dfrac{K}{M}$ by substitution in equations (3) and (4).

All the above are for three-phase 100% P. F. on basis of watts lost. These formulæ are therefore applicable to practical cases, when miles, kilowatts, and kilo volts are used.

The various symbols used have the following meanings:

l = Weight per mile of one of the three conductors used, or = weight per mile per phase.
M = Length of line (one way) in miles.
K = Kilowatts delivered at receiver end of line.
P = Per cent. loss of power K in line.
ε = Delta line voltage at receiver end ÷ 1000 = kilo volts.
Z = A constant = 1080 for three-phase 100% p. f.
A = A constant = 9.06 for three-phase all power factors.
W = Total weight of copper in all conductors.
L = Pounds of copper per kilowatt delivered = $W \div K$.
$C.M.$ = Circular mils area of copper in each phase.

On the basis of watts loss being fixed, the constant Z being equal to 1080 for unity power factor, its value for lower power factors will increase inversely as the square of the power factor $\left(\text{since the copper for watts loss fixed increases as } \frac{1}{(\text{power factor})^2}\right)$ therefore the values for the five equations for various power factors are as shown below:

No.	Equation	For power factors of 100%	90%	80%	70%
1.	$C.M. = \frac{M\,K}{P\,\varepsilon^2} \times$	5854	7200	9140	11950
2.	$W = \left(\frac{M}{\varepsilon}\right)^2 \times \frac{K}{P} \times$	280	344	437	571
3.	$L = \left(\frac{M}{\varepsilon}\right)^2 \times \frac{1}{P} \times$	280	344	437	571
4.	$l = \frac{M}{\varepsilon^2} \times \frac{K}{P} \times$	93	114	145	190
5.	$3l = L \times \frac{K}{M}$	—	—	—	—

On the basis of volts loss being fixed, the value of Z will increase inversely as the power factor (since the copper for volts loss fixed increases as $\frac{1}{\text{power factor}}$). Therefore the values of the five equations for the same power factors as the above are as follows:

No.	Equation.	For power factors of			
		100%	90%	80%	70%
1.	$C.M. = \frac{MK}{Pr^2} \times$	5854	6498	7317	8371
2.	$W = \left(\frac{M}{r}\right)^2 \times \frac{K}{P} \times$	280	311	350	400
3.	$L = \left(\frac{M}{r}\right)^2 \times \frac{1}{P} \times$	280	311	350	400
4.	$l = \frac{M}{r^2} \times \frac{K}{P} \times$	93	103	116	133
5.	$3l = L \times \frac{K}{M}$	—	—	—	—

It will be noted that the increase in copper over that required for a line having a fixed per cent. loss in volts, to give the same percentage watts loss, increases inversely as the power factor.

Diagram 1 (which shows pounds of copper per K. W. delivered, etc.) is calculated from formula 3, by successively assuming values of P from 1 to 28, and on each of the vertical lines corresponding to these, finding a certain number of points equal to the values of L for various assumed values of $\left(\frac{M}{r}\right)^2$ corresponding to the "volts per mile" of the line. This is worked out in detail for various percentages of watts loss for unity power factor, and then the values for other power factors, as well as for the volts loss corresponding to the watts loss for 90%, 80%, and 70% power factors, were inserted after multiplying the first results by the proper factors as shown above. The diagram can easily be extended to apply to lower power factors than 70%, but for ordinary use should be found sufficient.

Diagram 2, translating pounds of copper per K. W., into commercial sizes of wire, was plotted from equation 5 as follows: Various total weights of wire per mile for three conductors were chosen, corresponding to commercial sizes B. and S. gauge ($=3l$), and then, by dividing each value of $3l$ by various quantities from 5 to 200 corresponding to the pounds of copper required per kilowatt delivered ($=L$), a series of points corresponding to $\frac{K}{M}$ were plotted, and by joining these the curves shown were traced.

Of course, more curves on both diagrams could have been plotted, but for all practical purposes they are close enough, as amounts falling between the curves can be readily estimated at sight.

Due to the excessive induction factors of wires larger than No. 0000 B. & S. gauge, the weights on the curves are given as corresponding to multiples of standard sizes for all wires larger than No. 0000, and for the same reason it is better to subdivide lines requiring larger copper than No. 0000 into two or three separate circuits, each carrying one-half or one-third of the whole load, as the case may require, and calculating reactance, etc., on the basis of the subdivided lines.

Now, considering the use of the diagrams, let the following conditions be assumed:

Given the receiver voltage of a three-phase line, its length in miles, the power factor of the load, the power to be delivered and the frequency decided upon, find the size of wire required for any given per cent. loss in watts or volts (CR) (since Diagram 1 can be used for either by transferring to the corresponding figures at top or bottom of the page) and the total drop in the line, and consequently its regulation.

From the point on the top horizontal scale corresponding to the allowed line loss in per cent., drop a perpendicular until it strikes the curve corresponding to the delivered volts per mile of the line; from this point draw a line horizontally and to the right until the figures are reached giving pounds of copper per K. W. delivered, corresponding with the power factor of the load. (Or, if ohmic volts loss be given, start from the bottom horizontal scale, erect a perpendicular from the per cent. loss given to the volts per mile curve, and trace horizontally and to the left until the figures are reached corresponding to the lbs. per K. W. for the proper power factor assumed for the load.)

An approximation to the most economical weight of copper per kilowatt can be readily obtained in two or three trials, and in a very few seconds, by observing whether the intersection of ordinate and curve falls near the knee of the curve, for if the curve gets very steep, it is obviously unwise to try and save one or two per cent. of power at the expense of several pounds of copper per K. W. delivered, and if the point of intersection on the curve shows at a very flat part, this means that the loss allowed can safely be reduced several per cent. without materially affecting the copper.*

Now, in Diagram 2, find the intersection of the horizontal line corresponding to the pounds of copper per K. W. delivered as found in Diagram 1, with the vertical line corresponding to the kilowatts

* For further information on the subject of economy in conductors, see Perrine's "Elec. Conductors," chap. viii, where a very full discussion of Kelvin's Law may be read.

per mile of the line (total K. W. delivered divided by miles of distance), and from the closest curve outside this intersection is obtained the nearest commercial size of wire to use to obtain the required results with the given conditions. Knowing the mechanical properties of the conductor thus found, experience will tell the best spacing to be used, allowing for swing, sag, length of spans, etc. Having assumed the spacing, and knowing the frequency, the ratio of reactance to resistance in the line itself may be obtained directly from Table I, for any usual size of wire, and from Table II the drop factor for the given power factor of load may be obtained, and hence the line drop, which added to the receiver voltage, gives the impressed e. m. f. at the generator end, and consequently the regulation is known.

It is obvious that these diagrams may be used in reverse order to determine also what percentage of watts or volts loss would occur in a line with a given size of wire carrying a given quantity of power at a given voltage, for, by finding *L* on Diagram 2 corresponding to the given size of wire and kilowatts per mile, and transferring it to Diagram 1 under the proper power factor column at right or left for watts or volts respectively, and tracing a horizontal line to the proper volts per mile curve, the per cent. loss opposite the perpendicular from this point can be obtained in a few seconds.

The main difference between Messrs. Scott & Fowler's article above mentioned, and the present one, is that the former assume a size of wire, and work with it to find the total drop, impressed e. m. f., etc., of the system, necessitating several more or less cumbersome trials before the best line is derived, while the diagrams following show how to quickly find the best size of wire for any given line of certain length, receiver voltage, kilowatts delivered, frequency and power factor of load.

In most ordinary lines the static capacity of the line itself is negligible as compared with its resistance and reactance, and in any case its effect is to neutralize reactance, and so reduce the total drop in the line, so that no account has been here taken of that factor, but it is well to say that lines calculated by these diagrams will be amply large for all ordinary cases. However, on certain long lines carrying heavy loads, with consequently large conductors, the question of capacity is sometimes very important, involving the supplying of charging current to a considerable amount, and in one or two cases which have come under the writer's observation, the capacity effect was enough to require charging current, simply to keep the line alive, to the extent of a large generator's full load output.

Very full information as to capacity effect in lines may be found in Professor F. A. C. Perrine's interesting book referred to in a previous footnote,* and for all long lines transmitting large power at high voltages, it would be well to work out each case individually with regard to capacity effect.

For the benefit of the members of this Society who may not be familiar with the article from which Tables I and II are taken, and which was referred to above, the following quotation from it will be of service:

"In a direct-current circuit the drop in voltage depends upon the current and the ohmic resistance. In an alternating current circuit the total drop depends not only upon the current and the ohmic resistance, but also upon the reactance of the circuit and the power factor of the load. The method of finding the drop under given conditions is set forth in an article by Mr. Mershon which appeared in the March issue of the *Journal*. A modification of that method is here described in which the drop or 'resistance volts' which would result were a direct current to flow through the circuit is first determined, and then a 'drop factor' is found by which the drop with direct current must be multiplied in order to obtain the drop produced by alternating current. The drop factor depends upon three things—(1) the ratio between the reactance volts and the resistance volts, (2) the power factor of the load, and (3) the percentage value of the resistance volts.

"The first of these quantities depends upon the size of wire, the distance between wires, and the frequency. Table I gives the ratio of reactance volts to resistance volts for conditions which are most likely to occur. This table is readily deduced from the table in the article by Mr. Mershon.

"The effect of the second element, the power factor of the load, is given in Table II, in which the drop factors for various ratios of resistance volts to reactance volts and various power factors are given. These have been determined from Mr. Mershon's chart using a resistance e.m.f., equal to ten per cent. of the delivered e. m. f.

"The third element, the percentage value of the resistance e. m. f., has a relatively small effect on the value of the drop factor, so that the values given, which are determined for a resistance e. m. f., of ten per cent., may be accepted as practically correct for all resistance values not exceeding fifteen or twenty per cent. The greatest discrepancy occurs when the ratio is high and power factor is 100 per cent.

* "Conductors for Electrical Distribution," by F. A. C. Perrine, published by D. Van Nostrand & Co. in 1903.

"In Table I the ratio of the reactance to the resistance is given for wire sizes ranging from No. 6 B. & S. gauge to 300,000 circ. mils, for 60 cycles, and for separations between conductors ranging from six to sixty inches. In the same table will be found ratios of reactance to resistance for sizes of wire ranging from No. 6 B. & S., to 400,000 circ. mils for 40 cycles, and from No. 6 B. & S., to 500,000 circ. mils for 25 cycles, both of these covering the same range of wire separations as in the case of 60 cycles. Table I also contains ohmic resistance per thousand feet of line and per mile of line for the various sizes of wire tabulated.

"Table II contains various ratios of reactance to resistance which cover approximately the same range as those which appear in Table I. Opposite the ratios in this table are given the drop factors corresponding to power factors from 100 per cent. down to 20 per cent. The drop factors are determined for a value of the resistance volts equal to ten per cent. of the delivered e. m. f."

(Then follow several examples worked out in the text of the article for different conditions, showing the use of the tables.)

The writer's best thanks are due to Mr. R. A. Ross for help and suggestions in connection with the preparation of the present paper.

The following examples will serve to show some of the uses of the tables:

Examples.

Example I.—Given E. M. F. at receiver.. .. .. = 8800
K. W. delivered.. .. .. = 750
length of line in miles.. .. .. .. = 12½
watts loss % allowed.. .. .. .. = 14%
frequency.. .. .. = 40 cycles
power factor of load.. .. .. = 85%

Find total drop in the line and the e. m. f. at the generator end.

Calculated volts per mile.. .. .. = 703
K. W. per mile.. .. .. = 60

From Diagram 1, copper per K.W. deliv. = approximately 54 lbs.

From Diagram 2, size of wire = No. 2 B. & S.

From Table I, ratio $\frac{\text{reactance}}{\text{resistance}}$ of No. 2 wire spaced 18" (say) = 0.50.

From Table II, drop factor at 85% P. F. = 1.13.

From tables on Diagram 1, volts loss equivalent to 14% watts loss at 85% P. F. = 11.9.

Therefore total drop in line = 11.9 x 1.13 = 12.44% or = 1182 volts.

∴ Generator end e. m. f. = 9982 volts.

Example II.—Given E. M. F. delivered . . . . = 30000 volts
length of line . . . . = 27 miles
frequency . . . . = 60 cycles
power delivered . . . . = 4300 K. W.
P. F. of load . . . . = 70%

Design the line.

Calculated volts per mile . . . . = 1111
K. W. per mile . . . . = 159

From diagram 1 on 1100 V. per mile curve the economical losses must be somewhere between 5% and 13%, and a good average value will be say 10%.

Let us then assume 10% volts loss, therefore copper required = 33 lbs. per K. W. for 70% P. F.

From Diagram 2, using 33 lbs. per K. W., and $\frac{K}{M} = 159$ is found a size between No. 0 and No. 00 wire, but since point falls almost on the curve for No. 0, let that be taken.

From Table I, opposite No. 0 wire at 60 cycles, spaced 24″ (assumed), the ratio of reactance to resistance = 1.22.

From Table II, with ratio = 1.22, drop factor for 70% P. F. = 1.56.

Hence total drop = 10 x 1.56 = 15.6%.
= 4680 volts.

∴ E. M. F. at generator end = 34680.

Note.—The % watts loss for 70% P. F. corresponding to 10% volts loss = 14.3 from table at bottom of page. Taking 14.3% watts loss, erecting perpendicular to curve for 1100 volts per mile and following horizontally to the right to 70% P. F. we get 33 lbs. per K. W., which is the same weight found for 10% volts loss.

The power loss then amounts to 14.3% x 4300 = 615 K. W.

Total power required at generator end of line = 4915 K. W.

If we had chosen No. 00 wire instead of No. 0, this would have allowed us 40 lbs. per K. W. at 159 K. W. per mile from Diagram 2; and transferring 40 lbs. per K. W. at 70% P. F., to Diagram 1, on volts loss side, our ohmic drop would be reduced to 8%, as may be seen by tracing a horizontal from 40 lbs. at 70% P. F., to 1100

V. per mile curve and dropping a perpendicular to lower horizontal scale.

No. 00 wire at 60 cycles spaced 24" gives ratio of 1.50 and drop factor for 70% P. F. from Table II = 1.77. Total drop = 8 x 1.77 = 14.16% or = 4248 volts.

Generator end e. m. f. = 34248.

Power loss using No. 00 wire (8% volts loss) = 11.4% for 70% P. F. and total lost power = 11.4% x 4300 = 490 K. W. or = 4790 K. W. required at generator end of line.

Knowing the operating conditions of the line, it can thence easily be seen whether it will be more economical to use No. 0 or No. 00 wire, allowing for average and max. power required, cost of copper and cost of power generated.

Example III.—Given E. M. F. at receiver.. .. = 4500 volts
length of line.. .. .. .. = 5 miles
K. W. to be transmitted.. = 1750 K. W.
P. F. of load.. .. .. = 80%
frequency.. .. .. = 25 cycles
loss allowed.. .. .. = 11.5% watts loss

Find size of wire and total drop.

Calculated volts per mile.. .. .. = 900
K. W. per mile... ... = 350

From Diagram 1, copper required = 46 lbs. per K. W.
From Diagram 2, size = 2 x No. 000 per conductor.
= 334000 c. m.

Two courses are open, either to use one circuit of three conductors, each 334000 c.m. in area, or to split the line into two circuits, each consisting of three conductors equal to No. 000 in area.

Consider both of these cases with regard to total drop.

From Diagram 1, the volts loss equivalent to 11.5% watts loss for 80% P. F. = 9.2%.

Case 1.—One circuit. From Table I, ratio of reactance to resistance for 334000 c. m. wire spaced 36" (assumed) = 1.56 approximately, and from Table II the drop factor at 80% P. F. = 1.74.

Hence total drop = 9.2 x 1.74 = 16% = 720 volts.

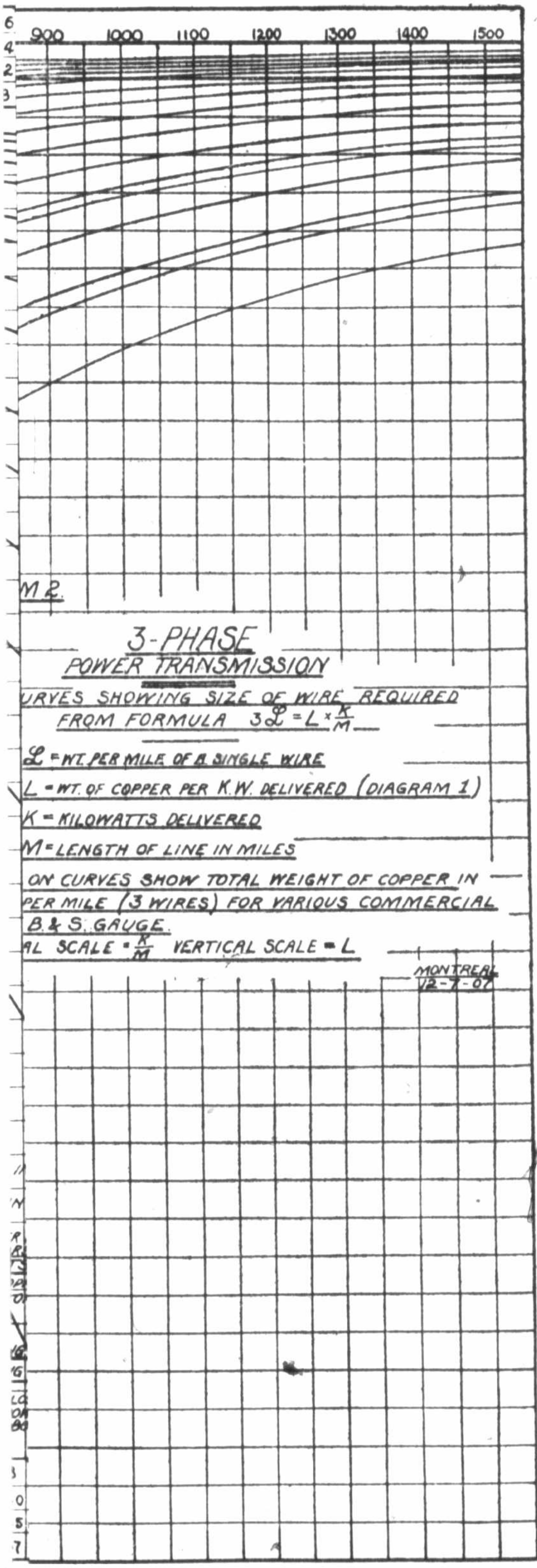
Case 2.—Two circuits. With single 000 wires we can safely reduce the spacing to 24 inches, hence from Table I, ratio = .78 and drop factor from Table II for 80% P. F. = 1.26.

Hence total drop = 1.26 x 9.2% = 11.6% = 520 volts.

From this it is easily seen that the regulation of the line is much bettered by splitting the circuit into two.

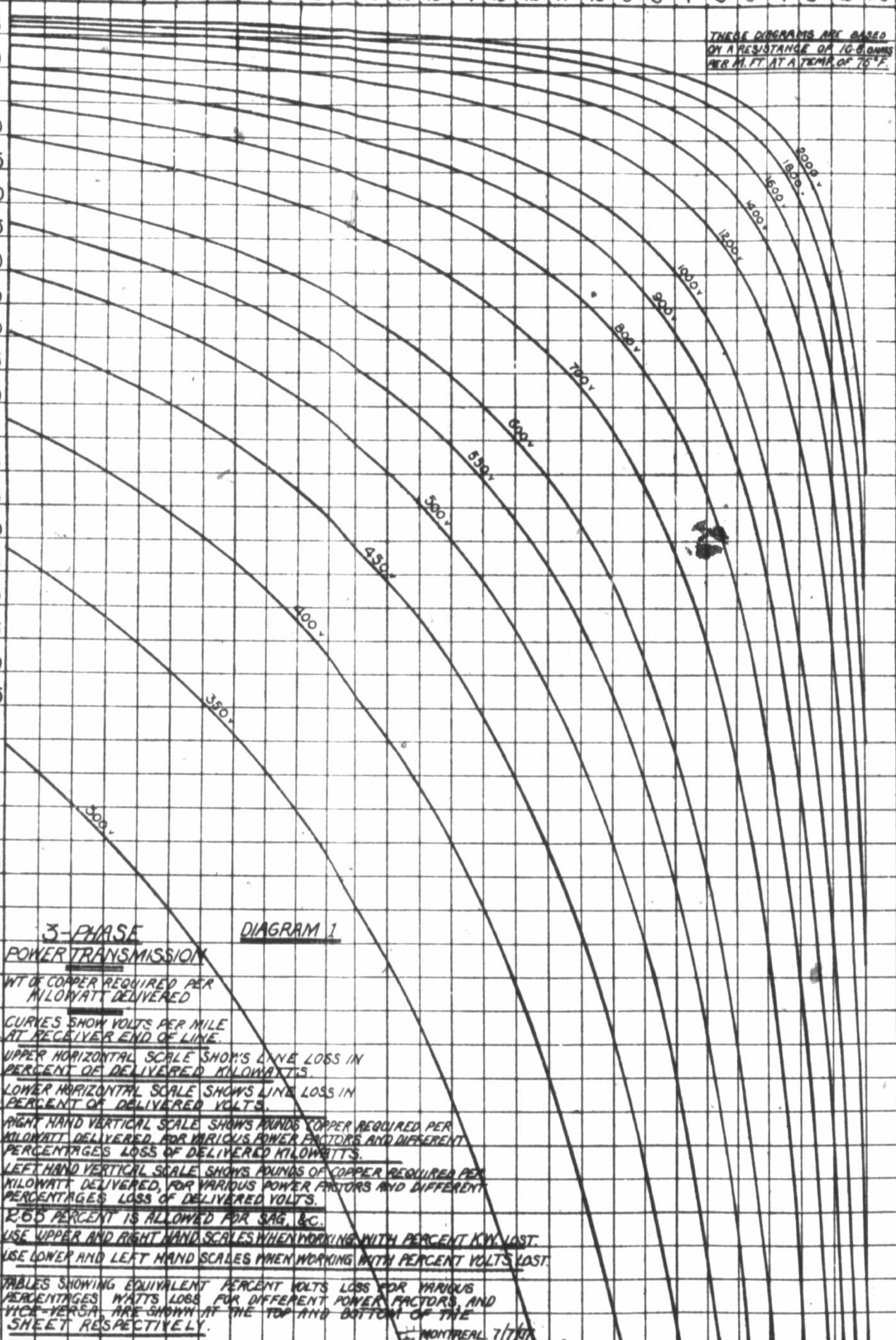
EXAMPLES OF CALCULATION OF THREE-PHASE A.C. CIRCUITS

Items.	Example No. 1	2	3	4	5	6	7	8	9
Given—E.M.F. delivered	660	5000	440	10000	8000	2125	70000	21600	45000
K.W. delivered (real power)	190	600	18	2500	350	75	16000	1200	20000
Power factor (%)	90	70	75	80	85	90	70	80	95
Frequency	60	60	60	40	40	40	25	25	25
Length of line one way, miles	..	7¼	..	22½	8	..	80	18	60
Length of line one way, feet	6600	..	2900	..	..	8000	..	..	..
Calculated—Volts per mile	528	690	800	445	1000	1400	875	1200	750
K.W. per mile	237	82.8	32.8	111	43.75	113.8	200	66.7	333.3
Ohmic loss in line allowed (%), volts	13.5	8	7.5	20	6.8	6	10	7.2	11.4
Ohmic loss in line allowed (%), or watts	15	11.4	10	25	8	8.00	14.3	9	12
From diagram 1. Lbs. copper per K.W. delivered	82.1	105	76	88	47	26.5	51.5	33.7	44.5
From diagram 2. Size of wire to be used	2xNo. 0000	No. 0000	No. 3	No. 0000	No. 3	No. 2	No. 0000	No. 3	2xNo. 000
Spacing assumed for this size of wire	18 in.	24 in.	12 in.	24 in.	12 in.	12 in.	36 in.	18 in.	24 in.
From Table I.—Ratio $\frac{\text{reactance}}{\text{resistance}}$	2.15	2.30	0.57	1.53	0.38	0.47	1.04	0.26	0.78
From Table II.—Drop factor	1.95	2.37	1.13	1.72	1.07	1.13	1.44	1.03	1.20
Total drop in % of delivered e.m.f.	26.3	18.96	8.48	34.4	7.28	6.78	14.4	7.42	13.68
E.M.F. impressed at genr. end of line	833	5948	477	13440	8582	2269	80080	23202	51156


900
1000
1100
1200
1300
1400
1500
M 2.
3-PHASE
POWER TRANSMISSION
URVES SHOWING SIZE OF WIRE REQUIRED
FROM FORMULA 3𝓛 = L × K/M
𝓛 = WT. PER MILE OF A SINGLE WIRE
L = WT. OF COPPER PER K.W. DELIVERED (DIAGRAM 1)
K = KILOWATTS DELIVERED
M = LENGTH OF LINE IN MILES
ON CURVES SHOW TOTAL WEIGHT OF COPPER IN
PER MILE (3 WIRES) FOR VARIOUS COMMERCIAL
B.& S. GAUGE.
AL SCALE = K/M VERTICAL SCALE = L
MONTREAL
12-7-07

EQUIVALENT % VOLTS LOSS																													
70%	19.6	18.9	18.2	17.5	16.8	16.1	15.4	14.7	14.0	13.3	12.6	11.9	11.2	10.5	9.8	9.1	8.4	7.7	7.0	6.3	5.6	4.9	4.2	3.5	2.8	2.1	1.4	.7
80%	22.4	21.6	20.8	20.0	19.2	18.4	17.6	16.8	16.0	15.2	14.4	13.6	12.8	12.0	11.2	10.4	9.6	8.8	8.0	7.2	6.4	5.6	4.8	4.0	3.2	2.4	1.6	.8
90%	25.2	24.3	23.4	22.5	21.6	20.7	19.8	18.9	18.0	17.1	16.2	15.3	14.4	13.5	12.6	11.7	10.8	9.9	9.0	8.1	7.2	6.3	5.4	4.5	3.6	2.7	1.8	.9
LINE LOSS IN % OF K.W. DELIVERED	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1.0

WATTS



L = POUNDS OF COPPER PER K.W. DELIVERED

70%	80%	90%	100%	100%	90%	80%	70%
7.15	6.25	5.55	5	5	6.15	7.8	10.2
14.3	12.5	11.1	10	10	12.3	15.6	20.4
21.4	18.75	16.6	15	15	18.5	23.4	30.6
28.6	25	22.2	20	20	24.6	31.2	40.8
35.7	31.2	27.8	25	25	30.8	39.0	51.0
42.8	37.5	33.3	30	30	36.9	46.8	61.2
50.0	43.8	38.8	35	35	43.0	54.6	71.3
57.1	50.0	44.4	40	40	49.2	62.4	81.5
64.3	56.2	50.0	45	45	55.3	70.2	91.7
71.5	62.5	55.5	50	50	61.5	78.0	102
78.6	68.8	61.0	55	55	67.6	85.8	112
85.7	75.0	66.5	60	60	73.8	93.5	122
92.9	81.2	72.1	65	65	79.9	101	133
100	87.5	77.7	70	70	86.1	109	143
107	93.8	83.2	75	75	92.2	117	153
114	100	88.8	80	80	98.4	125	163
121	106	94.3	85	85	105	133	173
129	112	99.9	90	90	111	140	184
136	119	105.5	95	95	117	148	194
143	125	111	100	100	123	156	204
150	131	117	105	105	129	164	214
157	137.5	122	110	110	135	172	224
164	144	128	115	115	142	179	235
171	150	133	120	120	148	187	245
179	156	139	125	125	154	195	255
186	162.5	144.5	130	130	160	203	265
193	169	150	135	135	166	211	275
200	175	155.5	140	140	172	218	286
207	181	161	145	145	178	226	296
214	187.5	166.5	150	150	185	234	306
222	194	172	155	155	191	242	316
229	200	177.5	160	160	197	250	326
236	206	183	165	165	203	258	336
243	213	189	170	170	209	265	347
250	219	194	175	175	215	273	357
257	225	200	180	180	221	281	367
264	231	205	185	185	227	289	377
272	237	211	190	190	234	296	388
279	244	217	195	195	240	304	398
286	250	222	200	200	246	312	408

VOLTS																												
LINE LOSS IN % OF VOLTS DELIVERED (100%)	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
90%	31.1	30.0	28.8	27.7	26.6	25.5	24.4	23.3	22.2	21.1	20.0	18.9	17.8	16.7	15.6	14.4	13.3	12.2	11.1	9.99	8.88	7.77	6.66	5.55	4.44	3.33	2.22	1.11
80%	35.0	33.75	32.5	31.25	30.0	28.75	27.5	26.25	25.0	23.75	22.5	21.25	20.0	18.75	17.5	16.25	15.0	13.75	12.50	11.25	10.0	8.75	7.50	6.25	5.00	3.75	2.50	1.25
70%	40.0	38.6	37.2	35.7	34.3	32.9	31.4	30.0	28.6	27.2	25.7	24.3	22.9	21.5	20.0	18.6	17.2	15.7	14.3	12.9	11.4	10.0	8.58	7.15	5.72	4.29	2.86	1.43

EQUIVALENT % WATTS LOSS

70% 80% 90% 100%	← WATTS ↓ 90%	80%	70%
5	6.15	7.8	10.2
10	12.3	15.6	20.4
15	18.5	23.4	30.6
20	24.6	31.2	40.8
25	30.8	39.0	51.0
30	36.9	46.8	61.2
35	43.0	54.6	71.3
40	49.2	62.4	81.5
45	55.3	70.2	91.7
50	61.5	78.0	102
55	67.6	85.8	112
60	73.8	93.5	122
65	79.9	101	133
70	86.1	109	143
75	92.2	117	153
80	98.4	125	163
85	105	133	173
90	111	140	184
95	117	148	194
100	123	156	204
105	129	164	214
110	135	172	224
115	142	179	235
120	148	187	245
125	154	195	255
130	160	203	265
135	166	211	275
140	172	218	286
145	178	226	296
150	185	234	306
155	191	242	316
160	197	250	326
165	203	258	336
170	209	265	347
175	215	273	357
180	221	281	367
185	227	289	377
190	234	296	388
195	240	304	398
200	246	312	408

LINE LOSS IN % OF VOLTS DELIVERED

EQUIVALENT % WATTS LOSS

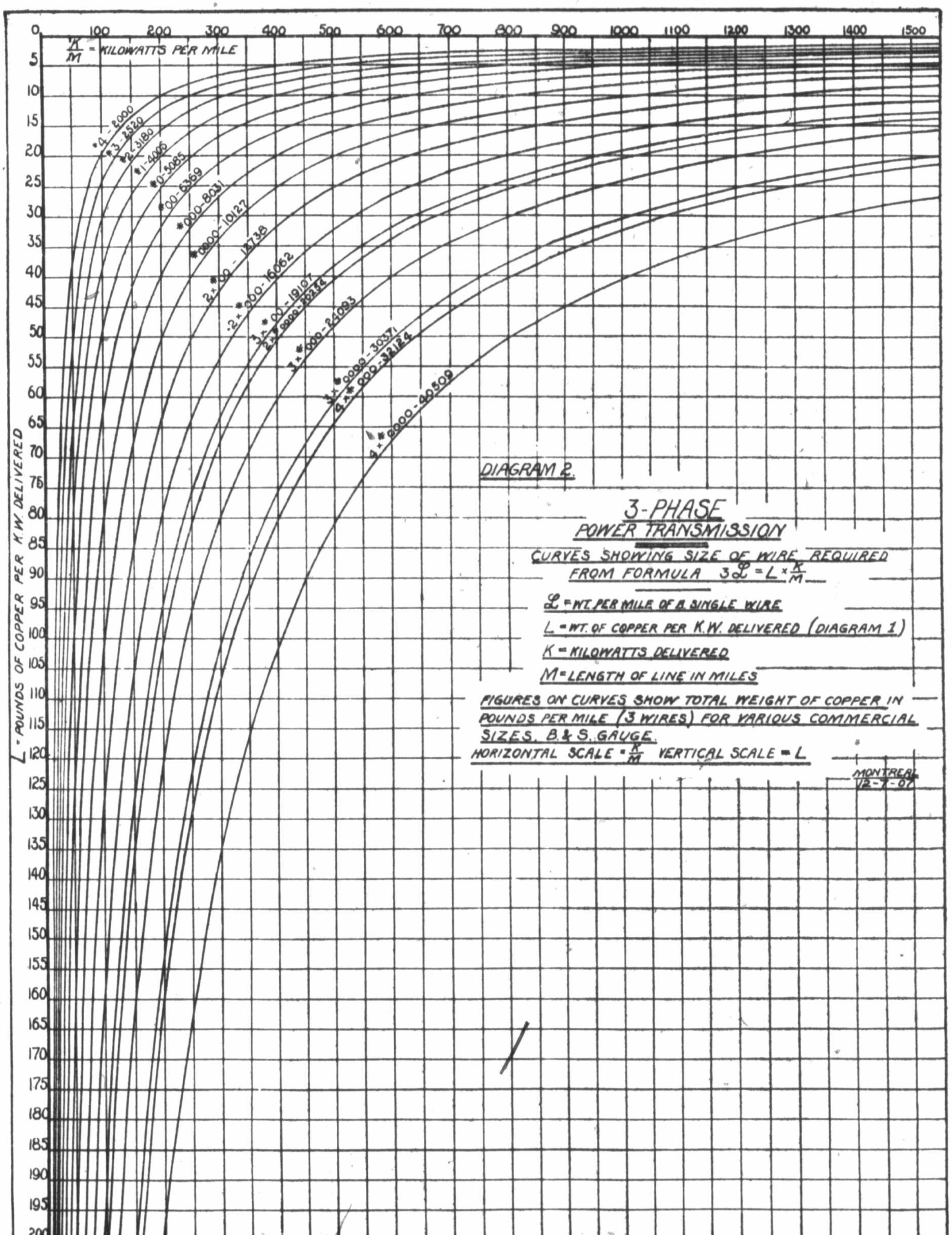


TABLE II.—DROP-FACTORS WHEN RESISTANCE VOLTS ARE TEN PER CENT. OF THE DELIVERED VOLTS.

Ratio of Reactance to Resistance.	Drop-factors for Power factors of								
	100%	95%	90%	85%	80%	70%	60%	40%	20%
0.1	1.00	1.00	1.00	0.94	0.88	0.80	0.70	0.60	0.30
0.2	1.00	1.01	1.01	0.98	0.92	0.86	0.82	0.67	0.40
0.3	1.00	1.05	1.05	1.02	0.99	0.93	0.89	0.74	0.50
0.4	1.00	1.08	1.10	1.08	1.04	1.00	0.93	0.82	0.60
0.5	1.00	1.11	1.14	1.13	1.10	1.07	1.01	0.92	0.70
0.6	1.01	1.15	1.18	1.19	1.15	1.14	1.09	1.01	0.80
0.7	1.02	1.18	1.23	1.24	1.21	1.20	1.17	1.11	0.91
0.8	1.02	1.21	1.28	1.29	1.28	1.27	1.24	1.20	1.01
0.9	1.03	1.25	1.33	1.34	1.34	1.35	1.32	1.29	1.11
1.0	1.04	1.28	1.37	1.39	1.40	1.41	1.39	1.38	1.20
1.1	1.05	1.32	1.41	1.44	1.45	1.48	1.47	1.46	1.30
1.2	1.06	1.35	1.46	1.50	1.51	1.55	1.54	1.55	1.40
1.3	1.07	1.39	1.51	1.55	1.57	1.62	1.63	1.64	1.49
1.4	1.08	1.43	1.55	1.61	1.64	1.70	1.71	1.72	1.59
1.5	1.10	1.47	1.60	1.67	1.70	1.77	1.80	1.81	1.70
1.6	1.10	1.51	1.65	1.74	1.77	1.85	1.87	1.90	1.80
1.7	1.13	1.55	1.70	1.79	1.84	1.92	1.95	1.99	1.90
1.8	1.15	1.59	1.76	1.85	1.91	1.99	2.04	2.08	1.99
1.9	1.17	1.63	1.82	1.91	1.98	2.06	2.11	2.16	2.08
2.0	1.18	1.68	1.87	1.96	2.04	2.14	2.19	2.25	2.18
2.1	1.20	1.72	1.92	2.03	2.10	2.21	2.28	2.35	2.28
2.2	1.22	1.77	1.98	2.09	2.17	2.29	2.37	2.45	2.38
2.3	1.23	1.82	2.03	2.15	2.23	2.37	2.45	2.53	2.48
2.4	1.25	1.87	2.09	2.22	2.30	2.44	2.53	2.62	2.58
2.5	1.27	1.91	2.14	2.28	2.37	2.52	2.60	2.71	2.67
2.6	1.30	1.95	2.20	2.34	2.44	2.60	2.67	2.80	2.76
2.7	1.32	1.99	2.26	2.41	2.51	2.68	2.74	2.98	2.86
2.8	1.35	2.05	2.32	2.47	2.57	2.76	2.82	3.07	2.95
2.9	1.37	2.10	2.39	2.54	2.64	2.83	2.91	3.15	3.05
3.0	1.40	2.15	2.45	2.60	2.72	2.90	3.00	3.23	3.15
3.1	1.42	2.20	2.51	2.66	2.80	2.97	3.10	3.31	3.25
3.2	1.45	2.26	2.57	2.73	2.87	3.05	3.20	3.39	3.35
3.3	1.48	2.31	2.63	2.80	2.93	3.12	3.30	3.47	3.45
3.4	1.51	2.36	2.69	2.87	3.00	3.20	3.39	3.56	3.54
3.5	1.53	2.42	2.74	2.94	3.08	3.27	3.48	3.65	3.63
3.6	1.57	2.47	2.80	3.00	3.15	3.35	3.56	3.75	3.72
3.7	1.60	2.52	2.86	3.07	3.23	3.43	3.65	3.85	3.80

TABLE I.—OHMIC RESISTANCE AND APPROXIMATE RATIOS OF REACTANCE TO RESISTANCE.

SIZE OF WIRE	Resistance.		Ratio of Reactance to Resistance for the distance between wires of						
	per mile of line.	per 1000 ft. of line.	6 in.	9 in.	12 in.	18 in.	24 in.	36 in.	60 in.
60 CYCLES.									
300 000 C.M	0.365	0.069	2.10	2.40	2.60	2.90	3.05	3.30	3.65
No. 0000	0.518	0.098	1.65	1.82	2.00	2.15	2.30	2.50	2.70
000	0.653	0.124	1.35	1.50	1.60	1.75	1.86	2.00	2.20
00	0.824	0.156	1.10	1.22	1.32	1.44	1.50	1.65	1.80
0	1.04	0.197	0.91	1.00	1.06	1.15	1.22	1.34	1.45
1	1.31	0.248	0.74	0.81	0.86	0.94	0.98	1.08	1.15
2	1.65	0.313	0.60	0.65	0.70	0.75	0.80	0.86	0.94
3	2.08	0.394	0.50	0.53	0.57	0.62	0.65	0.70	0.75
4	2.63	0.497	0.41	0.43	0.46	0.50	0.53	0.57	0.62
5	3.31	0.627	0.31	0.35	0.38	0.41	0.43	0.46	0.50
6	4.18	0.791	0.26	0.29	0.31	0.33	0.35	0.37	0.40
40 CYCLES.									
400 000 C.M.	0.275	0.052	1.80	2.00	2.15	2.48	2.65	2.90	3.20
300 000 "	0.365	0.069	1.42	1.60	1.74	1.91	2.03	2.20	2.44
No. 0000	0.518	0.098	1.10	1.22	1.32	1.45	1.53	1.66	1.82
000	0.653	0.124	0.91	1.00	1.07	1.17	1.25	1.34	1.47
00	0.824	0.156	0.74	0.82	0.88	0.95	1.01	1.09	1.20
0	1.04	0.197	0.61	0.67	0.71	0.77	0.82	0.90	0.96
1	1.31	0.248	0.50	0.54	0.58	0.63	0.66	0.72	0.78
2	1.65	0.313	0.40	0.43	0.47	0.50	0.53	0.57	0.63
3	2.08	0.394	0.34	0.36	0.38	0.42	0.43	0.46	0.50
4	2.63	0.497	0.27	0.29	0.31	0.33	0.35	0.38	0.41
5	3.31	0.627	0.21	0.23	0.25	0.27	0.29	0.31	0.33
6	4.18	0.791	0.18	0.19	0.21	0.22	0.24	0.26	0.27
25 CYCLES.									
500 000 C.M.	0.211	0.040	1.40	1.60	1.75	1.95	2.05	2.30	2.50
400 000 "	0.275	0.052	1.15	1.25	1.35	1.55	1.65	1.80	1.98
300 000 "	0.365	0.069	0.89	1.00	1.08	1.20	1.27	1.38	1.52
No. 0000	0.518	0.098	0.69	0.76	0.84	0.90	0.96	1.04	1.12
000	0.653	0.124	0.56	0.63	0.67	0.73	0.78	0.84	0.92
00	0.824	0.156	0.46	0.51	0.55	0.60	0.63	0.68	0.75
0	1.04	0.197	0.38	0.42	0.44	0.48	0.51	0.56	0.60
1	1.31	0.248	0.31	0.34	0.36	0.39	0.41	0.45	0.48
2	1.65	0.313	0.25	0.27	0.29	0.31	0.33	0.36	0.39
3	2.08	0.394	0.21	0.22	0.24	0.26	0.27	0.29	0.31
4	2.63	0.497	0.17	0.18	0.19	0.21	0.22	0.24	0.26
5	3.31	0.627	0.13	0.15	0.16	0.17	0.18	0.19	0.21
6	4.18	0.791	0.11	0.12	0.13	0.14	0.15	0.16	0.17

NOTE.—The resistance in the table is given per mile and per 1000 feet of line; the length of wire is two miles and 2000 ft. respectively.

TABLE II.—DROP-FACTORS WHEN RESISTANCE VOLTS ARE TEN PER CENT. OF THE DELIVERED VOLTS.

Ratio of Reactance to Resistance.	Drop-factors for Power-factors of								
	100%	95%	90%	85%	80%	70%	60%	40%	20%
0.1	1.00	1.00	1.00	0.94	0.88	0.80	0.70	0.60	0.30
0.2	1.00	1.01	1.01	0.98	0.92	0.86	0.82	0.67	0.40
0.3	1.00	1.05	1.05	1.02	0.99	0.93	0.89	0.74	0.50
0.4	1.00	1.08	1.10	1.08	1.04	1.00	0.93	0.82	0.60
0.5	1.00	1.11	1.14	1.13	1.10	1.07	1.01	0.92	0.70
0.6	1.01	1.15	1.18	1.19	1.15	1.14	1.09	1.01	0.80
0.7	1.02	1.18	1.23	1.24	1.21	1.20	1.17	1.11	0.91
0.8	1.02	1.21	1.28	1.29	1.28	1.27	1.24	1.20	1.01
0.9	1.03	1.25	1.33	1.34	1.34	1.35	1.32	1.29	1.11
1.0	1.04	1.28	1.37	1.39	1.40	1.41	1.39	1.38	1.20
1.1	1.05	1.32	1.41	1.44	1.45	1.48	1.47	1.46	1.30
1.2	1.06	1.35	1.46	1.50	1.51	1.55	1.54	1.55	1.40
1.3	1.07	1.39	1.51	1.55	1.57	1.62	1.63	1.64	1.49
1.4	1.08	1.43	1.55	1.61	1.64	1.70	1.71	1.72	1.59
1.5	1.10	1.47	1.60	1.67	1.70	1.77	1.80	1.81	1.70
1.6	1.10	1.51	1.65	1.74	1.77	1.85	1.87	1.90	1.80
1.7	1.13	1.55	1.70	1.79	1.84	1.92	1.95	1.99	1.90
1.8	1.15	1.59	1.76	1.85	1.91	1.99	2.04	2.08	1.99
1.9	1.17	1.63	1.82	1.91	1.98	2.06	2.11	2.16	2.08
2.0	1.18	1.68	1.87	1.96	2.04	2.14	2.19	2.25	2.18
2.1	1.20	1.72	1.92	2.03	2.10	2.21	2.28	2.35	2.28
2.2	1.22	1.77	1.98	2.09	2.17	2.29	2.37	2.45	2.38
2.3	1.23	1.82	2.03	2.15	2.23	2.37	2.45	2.53	2.48
2.4	1.25	1.87	2.09	2.22	2.30	2.44	2.53	2.62	2.58
2.5	1.27	1.91	2.14	2.28	2.37	2.52	2.60	2.71	2.67
2.6	1.30	1.95	2.20	2.34	2.44	2.60	2.67	2.80	2.76
2.7	1.32	1.99	2.26	2.41	2.51	2.68	2.74	2.98	2.86
2.8	1.35	2.05	2.32	2.47	2.57	2.76	2.82	3.07	2.95
2.9	1.37	2.10	2.39	2.54	2.64	2.83	2.91	3.15	3.05
3.0	1.40	2.15	2.45	2.60	2.72	2.90	3.00	3.23	3.15
3.1	1.42	2.20	2.51	2.66	2.80	2.97	3.10	3.31	3.25
3.2	1.45	2.26	2.57	2.73	2.87	3.05	3.20	3.39	3.35
3.3	1.48	2.31	2.63	2.80	2.93	3.12	3.30	3.47	3.45
3.4	1.51	2.36	2.69	2.87	3.00	3.20	3.39	3.56	3.54
3.5	1.53	2.42	2.74	2.94	3.08	3.27	3.48	3.65	3.63
3.6	1.57	2.47	2.80	3.00	3.15	3.35	3.56	3.75	3.72
3.7	1.60	2.52	2.86	3.07	3.23	3.43	3.65	3.85	3.80