The Location of Opens in Toll Telephone Cables

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Synopsis: Improved methods have recently been developed for the location of opens in toll cable conductors. The discussion of these methods is prefaced by a review of older practices.

This improved open location method and equipment are sufficiently accurate that in practically all cases a fault in a 60-mile length of cable may be located within a maximum variation of plus or minus one half the length of a cable section (a section is the length of cable between splices—about 750 feet), and therefore enables one to select, prior to the opening of the cable, one or the other of the two splices between which the fault lies. This degree of accuracy is very desirable for practical reasons.

In this development, the line characteristics are considered. The accuracies of calculated locations, assuming no errors in measurements, are compared for different lengths of lines. The impedance bridge circuit is treated to bring out the method of obtaining a balance. The effects of several frequencies of testing potential are analyzed. The probable errors and inaccuracies of measurement which would interfere with the correct location of faults are classified and methods for their correction are developed. The accuracy of the method and the sensitivity of the apparatus are given.

THE location of "opens," or breaks in the continuity of telephone conductors, has always been an important problem in the testing and maintenance of the toll cables of the telephone plant. Although the number of opens encountered in the cable circuits is relatively small as compared to aerial wire lines, their location is more difficult because of certain electrical characteristics of the cable circuits. This condition, coupled with the fact that any work on a toll cable may interfere with a large number of facilities, renders the quick and accurate location of such faults imperative.

A high resistance voltmeter was used in the first feasible attempt to locate opens by means of electrical measurements. The original method of locating opens by the use of a voltmeter consisted essentially of a series of continuity tests. The faulty conductor was connected to ground or to the other wire of the pair at succeeding test stations until the fault was isolated between two adjacent test stations. The trouble was then found, either by inspection of the entire line between test stations, or by further continuity tests with a lineman, first near the middle of the section and later at points gradually approaching the location of the fault.

The inconvenience of such a procedure, however, led to an improved use of the voltmeter. The method employed afforded a rough comparison of the capacitance to ground of the portion of the faulty wire adjacent to the measuring station with that of its good mate or another conductor (of like gauge) following the same route. This was done by allowing the wire to become charged through a voltmeter and grounded battery, and noting the amount of momentary deflection on the good and bad conductors, respectively, when the polarity of the battery was reversed. The ratio of these deflections gave a general indication of the location of the fault. This method, while giving more accurate results than the continuity test, was still only an approximation and as such was materially affected by line conditions. An appreciable error was produced by leakage due to trees and other causes, and much depended on the judgment of the tester.

Later, the Wheatstone bridge [2] largely displaced the voltmeter. A standard capacitance was compared with the impedance between the open conductor and ground, by varying the ratio arms of the impedance bridge. In this comparison it was necessary to employ some form of alternating testing potential. At first, the simple expedient prevailed of reversing the bridge battery, as in the voltmeter test, the bridge being balanced until no transient unbalance current, or "kick," was indicated by the galvanometer when the battery was reversed. However, when the battery was reversed rapidly, the galvanometer displayed a tendency to stand still at all times. A considerable improvement in the method was effected by providing or the reversal of the galvanometer connections at the same time the battery was reversed. With this arrangement, the galvanometer always read in the same direction, and a balance could be more easily obtained.

Later a relay system was arranged for automatically reversing the connections to the galvanometer as well as for reversing the testing battery. This arrangement relieved the operator of the necessity of doing the reversing manually. Following this, a source of 20-cycle ringing voltage was used for the bridge and also for operating the galvanometer reversing relay. With this arrangement open locations, made on aerial wire lines and short lengths of cable, were fairly satisfactory. However, with the extensive installation of the long toll telephone cables, it was found that open locations made on this type of conductors, did not give a consistently accurate indication of the location of the fault.

As a preliminary step in the development of a suitable open location method and associated apparatus, an analysis was made of all errors which, in general, might enter into a open location. These errors can be classed in several groups for treatment or correction. One group

[2] References: Frank A. Laws, "Electrical Measurements," 1917, McGraw-Hill Book Co., Inc., N. Y.; page 381, "Bridge Measurements of Capacity and Inductance."

"Bridge Methods for Alternating-Current Measurements," D. I. Cone, *Transactions of A. I. E. E.*, July, 1920.

includes errors which are small in comparison to the accuracy of the testing equipment. Errors placed in this group obviously require no compensation. Another group of errors is produced by, or is characteristic of, certain designs of testing equipment. This class of errors has been reduced to negligible magnitude by a redesign of the testing equipment. One general group of errors results from faulty manipulation of the testing equipment or mistakes of computation. This group has been minimized by a convenient arrangement of testing equipment and by outline forms for use in computation.

Another class of errors is introduced by irregularities in the lines or cables on which open locations are made. Some of these are capable of compensation by constant correction factors included in formulae used for computation. Other errors of this class are found to be irregular functions of the length of line, and for their correction or compensation curves have been prepared for each type or condition of irregularity which can be used in the computation of the open location. To simplify the application of the corrections, the curves are so drawn that the correction is given as a simple multiplier.

The preparation of other types of corrections will be developed later in connection with the analysis and treatment of certain specific errors.

In the development of a more sensitive and reliable method of locating opens in telephone lines and cables, it was necessary to make an exact study of the electrical constants of the several types of conductors on which open locations are required. This involved the capacitance and leakance of the conductor to ground, or to neighboring conductors, as well as the series resistance and inductance. The general formula for the impedance of a line open at the distant end is

$$Z_l = Z_0 \coth \theta, \tag{1}$$

where Z_0 is the characteristic impedance of the line and $\theta = Pl$, where P is the propagation constant and l is the length. More fully

$$P = \sqrt{(R + j\omega L)(G + j\omega C)},$$

where R is the series resistance, L the inductance, G the leakance, and C the capacitance, all expressed in terms of the same unit length, and $\omega = 2\pi f$.

In formula (1)

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}},$$

the terms having the same significance as above.

In cable circuits, G is usually zero, and for non-loaded lines, L is also practically zero. For loaded lines, the inductance is effectually that of the loading coils, and for the frequencies usually employed in open location tests it can be considered as being uniformly distributed. For non-loaded lines, the equation of line impedance is reduced to one of series resistance and capacitance to ground. These constants can be determined by the measurement of short lengths of cable. In making capacitance measurements, the remaining three wires of the quad should be grounded to eliminate their capacitances to ground. When the other three wires of the quad are left free, the capacitance to ground of the faulty wire increases as the length of good wire beyond the break increases. This effect is shown in Fig. 1.

The values of R and C obtained by measuring short lengths of cable are used to calculate P and Z_0. Where the lines are loaded, the nominal inductance and resistance of the loading coils are used and the characteristic constants R and C are, if possible, determined from non-loaded conductors. These constants for one particular cable are listed as follows:

TABLE 1

Constant per Mile	Grade of Loading			
	Non-Loaded	H-44-25	H-174-106	H-245-155
	19-Gauge Inner Layer Conductors			
R	42.90	44.65	47.78	50.34
L	.000+	.015	.062	.089
C	.100	.100	.100	.100
	19-Gauge Outer Layer Conductors			
R	44.00	45.75	48.88	51.44
L	.000+	.015	.062	.089
C	.110	.110	.110	.110
	16-Gauge Conductors			
R	21.00	22.75	25.88	28.44
L	.000+	.015	.062	.089
C	.100	.100	.100	.100

These constants represent values per single-wire mile, R being in ohms, L in henries and C in microfarads.

In making an open location, two impedance measurements are made. One measurement is made on the faulty wire. The other measurement is made on a good wire which follows the same route as the faulty wire. The input impedance of the open conductor divided by the input impedance of the good wire gives an indication of the location of the fault. For short cables, the impedance measured to ground may be regarded as identical with the capacitance component of the impedance, because the resistance component of the impedance is negligibly small. However, as the length of cable increases, the input impedance can no longer be regarded as equivalent to the capacitance component of the impedance between the conductor

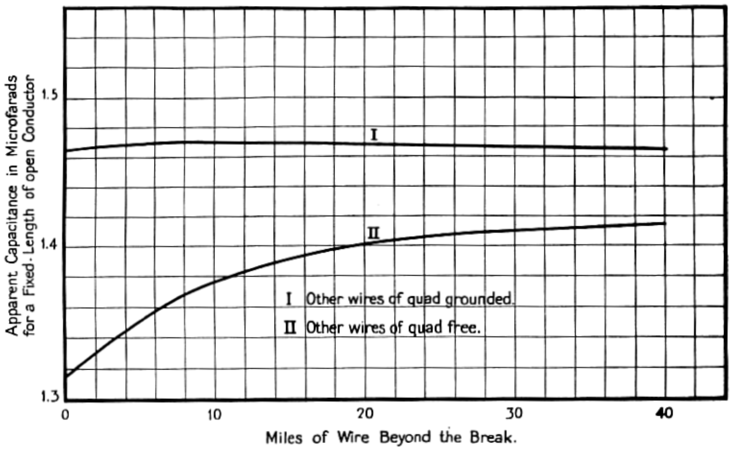


Fig. 1

and ground, because the input impedance is not proportional to the capacitance but varies as the hyperbolic cotangent (Formula 1). The significance and magnitudes of errors inherent in this relation are analyzed and discussed below.

In a homogeneous line, then, if Z_1 and Z_2 represent the input impedances of the bad and good wires respectively, the percentage distance to the fault is most accurately determined by separating the impedances into their real and imaginary parts.

Thus

$$Z_1 = a_1 - jb_1$$

and

$$Z_2 = a_2 - jb_2.$$

If the corresponding lengths are respectively l_1 and l_2, the true distance ratio is l_1/l_2. Assuming that b_2/b_1 is the ratio given by measurement (the shorter line having the higher capacitive reactance),

$$\frac{l_1}{l_2} - \frac{b_2}{b_1} = c,$$

where c is a correction which must be added to or subtracted from the ratio of capacitive reactances to secure the ratio of total capacitance, i.e., the distance ratio.

It is necessary, then, to calculate the ratio b_2/b_1 and the correction c for the different lengths of good and bad wires l_2 and l_1 in order to determine the amount of error arising from the assumption that $b_2/b_1 = l_1/l_2$. The values of capacitive reactance are determined from the fact that

$$b = Z \sin \phi,$$

where Z is the impedance and ϕ its angle as determined from formula (1).

The variation in b with variation in length of line is shown diagrammatically in Fig. 2. The total length of line is represented by Ol_2. The reciprocal of b is plotted on the vertical axis for different lengths of line. For an open at l_1 the location indicated by the ratio b_2/b_1 is at n whereas the true location is at m. The correction $mn = c$ must be subtracted from the apparent location to give the true location of the open. In the lower curve, this error is plotted against the total length of line l.

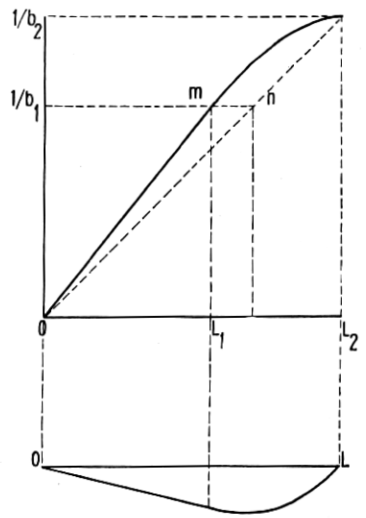


Fig. 2—Diagram showing the construction of a correction curve. Abscissas represent true linear distance; ordinates of upper curve represent measured capacitance; ordinates of lower curve represent errors of computed location.

It remains, then, to calculate b for a large number of lengths from zero to the maximum length of cable to be encountered. These values of b are used to calculate b_2/b_1 for different total lengths of line l and different fault locations l_1: that is, b is calculated for different lengths up to one hundred miles; then a set of ratios of b_2/b_1 and l_1/l_2 can be determined using the b of one hundred miles as b_2 and b for all the shorter lengths as b_1. Similarly, a set of ratios can be calculated for 95, 90, 85, 80, 75, etc., miles as total lengths. Since the interpolation of hyperbolic functions is at best a tedious calculation, even values of hyperbolics can be used in formula (1) and the corresponding odd lengths in miles calculated.

The ratio b_2/b_1 is then subtracted from the ratio l_1/l_2, in each instance this procedure resulting in a family of correction curves expressed in percentage such as that shown in Fig. 3. In this figure the correction is plotted against apparent rather than actual percentage distance in order to facilitate the use of the curves in locating actual cases of trouble. Where the length of line being measured does not correspond to one of the curve indices, the curves can be interpolated and the desired curve drawn in.

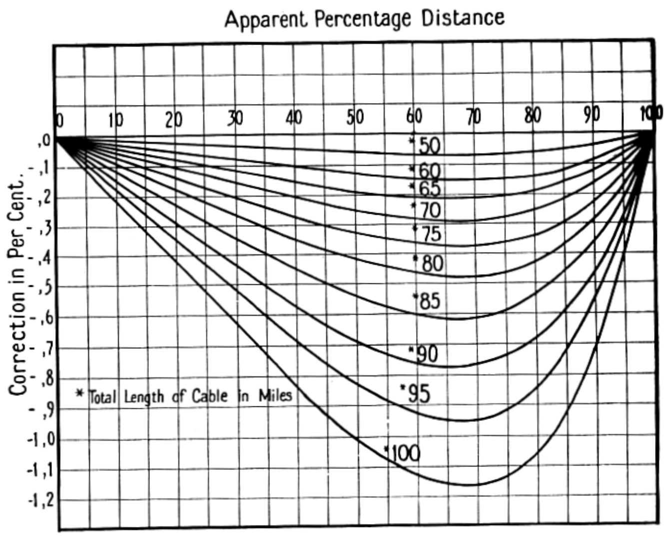


Fig. 3—Corrections to be used in finding true position of a fault from the apparent position. Apparent distance to the fault is indicated as a percentage of the total length of the cable.

The treatment becomes more involved for cables which are not homogeneous. The quads in the outer layers of any unspliced length of cable tend to differ in resistance from pairs in the inner layers, both because of greater length of turn in the outer layers and because of a possible difference in temperature between inner and outer layers. For homogeneous cables treated above these variations in resistance as well as attendant differences in capacitance to ground are equalized by mixing the quads among the various layers at each splice. In general, cables are spliced in this way, although there are several long distance cables now in service which are not homogeneous in this respect. Such cables are spliced in a special arrangement which is essentially a "transposition" system of splicing.

The "transposed" cable may readily be visualized by a consideration of the system of splicing which is employed. Instead of the 19-gauge quads being mixed promiscuously among all the layers, they are divided into an outer layer group and an inner layer group. The quads of each group are mixed among themselves (but not with quads of the other group), at every splice but one. This particular splice, near the middle of the cable, is known as the "transposition point." At this splice the two groups are "transposed," that is, outer layer quads are spliced to inner layer quads and inner layer quads are spliced to outer layer quads. In this way the differences in resistance and capacitance to ground of outer and inner layer quads are averaged at the "transposition point" for each group. The average resistance or capacitance to ground of a conductor of the outer layer group will therefore differ appreciably from the average resistance or capacitance to ground of a conductor of the inner layer group. The constants given in Table 1 are for a cable of this type.

As in the case of the non-transposed cable, it is necessary to calculate values of b for different lengths of line. Up to the transposition point the procedure is the same as above, viz.,

$$Z_{l1} = Z_{O1} \coth P_1 l_1,$$

where the subscript denotes the first section adjacent to the measuring station. As soon as the point of open falls on the distant side of the transposition point, where the conductor changes layers, the calculation of Z_l is a composite one. That is

$$Z_{l12} = Z_{O1} \tanh\,(P_1 l_1 + \delta), \tag{2}$$

where Z_{l12} is the combined input impedance, Z_{O1} is the characteristic impedance of the adjacent section, P_1 and l_1 its propagation constant and length respectively, and

$$\delta = \tanh^{-1} \frac{Z_{l2}}{Z_{O1}},$$

where Z_{l2} is the input impedance of the distant section calculated from the formula

$$Z_{l2} = Z_{O2} \coth P_2 l_2.$$

However, the calculation of formula (2) involves practical difficulties, and it is best reduced as follows:

Denoting $P_1 l_1$ as θ_1 and $P_2 l_2$ as θ_2,

$$Z_{l12} = Z_{O1} \tanh\left(\theta_1 + \tanh^{-1}\frac{Z_{l2}}{Z_{O1}}\right),$$

and expanding,

$$Z_{l12} = Z_{O1}\left\{\frac{\tanh\theta_1 + \dfrac{Z_{l2}}{Z_{O1}}}{1 + \tanh\theta_1\left(\dfrac{Z_{l2}}{Z_{O1}}\right)}\right\}.$$

But

$$Z_{l2} = \frac{Z_{O2}}{\tanh \theta_2},$$

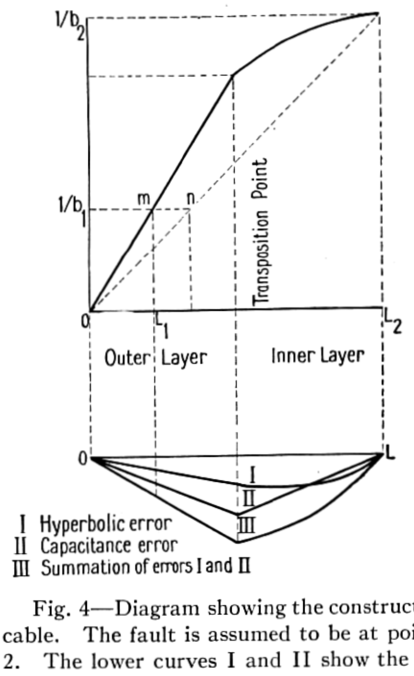
whence, substituting,

$$Z_{l12} = Z_{O1}\left\{\frac{\tanh\theta_1 + \dfrac{Z_{O2}}{Z_{O1}}\cdot\dfrac{1}{\tanh\theta_2}}{1 + (\tanh\theta_1)\left(\dfrac{Z_{O2}}{Z_{O1}}\right)\left(\dfrac{1}{\tanh\theta_2}\right)}\right\}$$

$$= Z_{O1}\left\{\frac{\tanh\theta_1\tanh\theta_2 + \dfrac{Z_{O2}}{Z_{O1}}}{\tanh\theta_2 + \tanh\theta_1\dfrac{Z_{O2}}{Z_{O1}}}\right\}$$

$$= Z/\phi.$$

Here, as in the case of the non-transposed cable, even values of hyperbolic functions are chosen and the corresponding odd values of length are calculated. Thus, the impedances of different arrange-



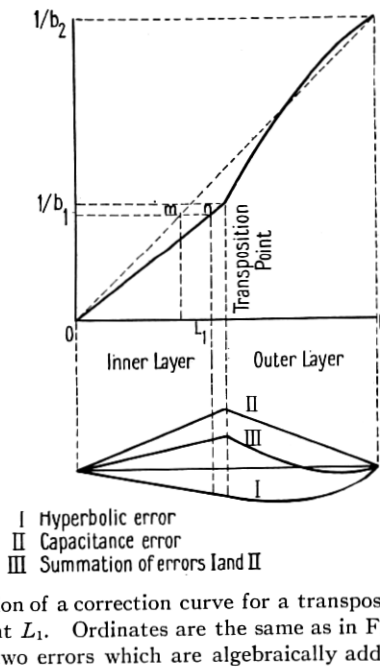


Fig. 4—Diagram showing the construction of a correction curve for a transposed cable. The fault is assumed to be at point L_1. Ordinates are the same as in Fig. 2. The lower curves I and II show the two errors which are algebraically added to give the total error.

Fig. 5—This diagram is similar to Fig. 4 except that the fault at L_1 is in that group of conductors which enters the measuring office in the inner layer of the transposed cable.

ments of conductor for a given transposed cable can be found and the calculated values of b_2 and b_1 may be used to plot a correction curve.

If, for a given transposed cable, a correction curve is calculated as outlined above, it will be found to have the general characteristics shown diagrammatically in Figs. 4 and 5. Fig. 4 is for the case where the faulty conductor enters the measuring station in the outer layer and Fig. 5 for the case where the faulty conductor enters the measuring station in the inner layer. In the lower half of each figure the total errors are separated into their component parts. In either Fig. 4 or Fig. 5 the total error curve can be assumed to be made up of two factors, a hyperbolic error similar to that shown in Fig. 2, and a straight line error due to the fact that the two halves of the cable do not have the same unit capacitance. The latter error would be present in such a cable even though its length were insufficient to cause a hyperbolic error. Such a division can be made because the constants of the inner and outer layers do not differ enough to affect the hyperbolic error appreciably. It is not possible to plot a general family of curves of the type shown in Fig. 3 due chiefly to the fact that the location of the transposition point and the difference in total length of different cables constitute a double variable. The need for a correction involving the double variable has been met by the development of open location equipment and methods which reduce this error to a negligible magnitude for the lengths and types of lines encountered in practice. The rigid treatment is, however, that outlined in formula (2).

The amount of the hyperbolic error can be calculated closely enough using the average constants of the inner and outer layers. The size of the straight line error due to the different capacitances of the inner and outer layers is found as follows:

Let C_1 and C_2 represent the adjacent and far end capacitances per unit length and D_1 and D_2 the respective lengths of these sections. The total conductor capacitance is then $D_1C_1 + D_2C_2$. If D is the location of the fault and D is less than D_1, that is, the fault is in the half of the cable adjacent to the measuring station, the bad wire capacitance is DC_1. The apparent location is

$$\frac{DC_1}{D_1C_1 + D_2C_2}$$

and the correction is

$$\frac{D}{D_1 + D_2} - \frac{DC_1}{D_1C_1 + D_2C_2}.$$

Similarly when the trouble occurs beyond the transposition point, and D is greater than D_1, the capacitance of the bad wire is

$$\frac{D_1C_1 + (D - D_1)C_2}{D_1C_1 + D_2C_2}$$

or

$$\frac{D_1(C_1 - C_2) + DC_2}{D_1C_1 + D_2C_2}$$

and the correction is

$$\frac{D}{D_1 + D_2} - \frac{D_1(C_1 - C_2) + DC_2}{D_1C_1 + D_2C_2}.$$

The relative sizes of the capacitance and hyperbolic errors are shown in Fig. 6 where these two components and their sum are plotted as corrections against the apparent percentage distance to the fault.

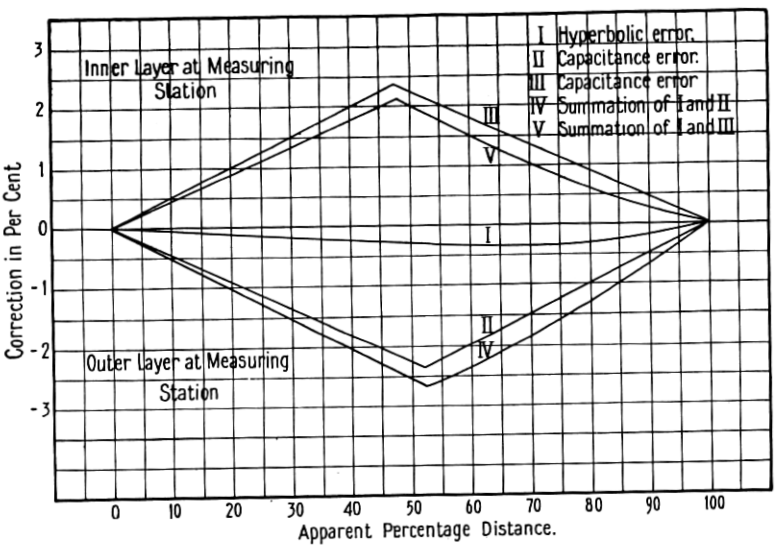


Fig. 6—Diagram for a transposed cable, showing the hyperbolic error as compared to the capacitance error,—measuring frequency four cycles.

In the development of a suitable open location method, it was necessary to select a definite frequency of testing potential for use with an impedance bridge. It was desirable that the selected frequency of testing potential should permit of a design of testing equipment which would have convenient operating characteristics. It was also desirable that the frequency of testing potential be selected to minimize errors which varied with frequency. The calculation of hyperbolic errors for different frequencies of testing potential showed that this error decreased with frequency, the optimum value of frequency being zero. This relation is shown in Fig. 7, where the maximum errors at different frequencies for a 60-mile length of 19-gauge, non-loaded cable are plotted. However, with zero frequency, the sensitivity to unbalance for an impedance bridge network is also zero, increasing as the frequency increases.

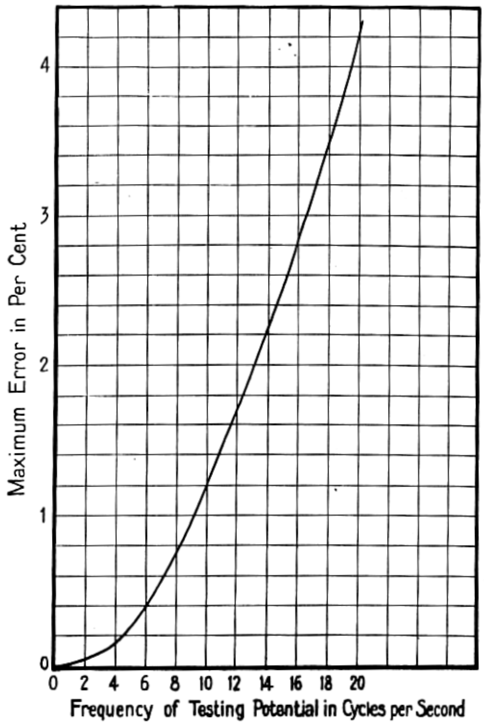


Fig. 7—The maximum hyperbolic error for various frequencies of testing potential.

The problem, then, was one of selecting a frequency which would be low enough to make the hyperbolic errors negligible for all cases of lines as regards length, gauge, and loading, and at the same time provide a sensitivity which would be sufficient to permit an accurate balance of a bridge. From this standpoint it may be observed that for a decreasing frequency of testing potential the maximum rate of decrease of hyperbolic error appears at about four cycles as shown by Fig. 7. A computation of the hyperbolic error for measurements made at four cycles on sixty miles of cable gives results as follows:

Type of Cable Circuit	*Average Percentage Error*
Extra Light or Non-Loaded 19-Gauge Cable	0.083%
Medium Heavy or Heavy Loaded 19-Gauge Cable	0.033
Extra Light or Non-Loaded 16-Gauge Cable	0.022
Medium Heavy or Heavy Loaded 16-Gauge Cable	0.090

Since these errors, at a frequency of four cycles, are for the maximum length of line which may be encountered in practice, it was considered that they might be neglected in comparison with the importance of securing a frequency of testing potential which would be high enough to give an impedance bridge a suitable sensitivity to unbalance. Hence, a computation of the sensitivity appeared to be the next step in the selection of a suitable frequency of testing potential.

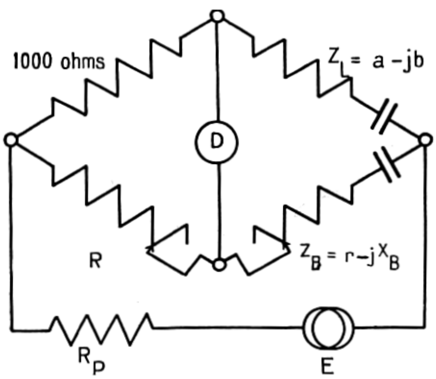


FIG. 8.

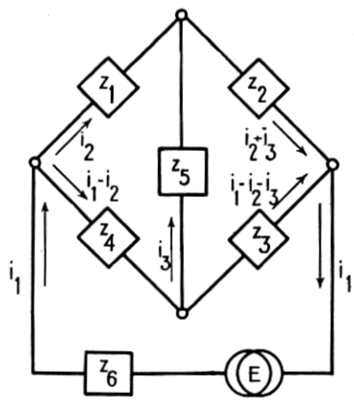


FIG. 9.

Fig. 8—Bridge used in the location of opens. E represents the low-frequency source, and R_p a protective resistance. The rheostat R and the 1000-ohm resistance may be regarded as the ratio arms of the bridge. The impedance of the line is represented by Z_L, a resistance and capacitance in series. The rheostat r is used in balancing the resistance component of the line impedance, so that the impedance angle of Z_B will equal the impedance angle of Z_L.

A very sensitive electrodynamometer, or a galvanometer equipped with an electromagnetic field, was used as a detector in the impedance bridge network shown in Fig. 8. The sensitivities for several frequencies of testing potential were computed for this modified form of the De Sauty bridge. The condition for balance in this impedance bridge network is

$$RZ_l = 1000Z_B$$

or

$$R(a - jb) = 1000(r - jX_B).$$

Collecting reals and imaginaries,

$$Ra = 1000r$$

and

$$Rb = 1000X_B.$$

If measurements R_1, r_1 and R_2, r_2 are made on the bad and good wires respectively,

$$R_1a_1 = 1000r_1$$

and

$$R_2a_2 = 1000r_2;$$

also

$$R_1b_1 = 1000X_B$$

and

$$R_2b_2 = 1000X_B,$$

$$R_1b_1 = R_2b_2,$$

or

$$\frac{R_1}{R_2} = \frac{b_2}{b_1}.$$

Yet the design of a suitable bridge is not concerned alone with balanced condition, but rather with the sensitivity and ease of balance with slight unbalances present. An indication of the probable sensitivity is afforded by a solution of this bridge network to determine the phase and magnitude of the galvanometer unbalance current with respect to the impressed voltage. These have been obtained from the equation

$$i_3 = \frac{E(z_2z_4 - z_1z_3)}{\begin{vmatrix} -z_5 & (z_1 + z_4) & -z_4 \\ (z_2 + z_3 + z_5) & (z_2 + z_3) & -z_3 \\ -z_3 & -(z_3 + z_4) & (z_3 + z_4 + z_6) \end{vmatrix}} \qquad (3)$$

in which the denominator is a determinate, and the symbols are those used in Fig. 9.

Since the condition for balance is

$$z_1z_3 = z_2z_4$$

we have, using the notation of Fig. 8,

$$1000(r - jX_B) = R(a - jb)$$

and, equating reals and imaginaries,

$$1000r = aR, \qquad (4)$$

$$1000X_B = bR. \qquad (5)$$

This impedance bridge can be balanced in two ways: by varying r and X_B, keeping R constant, or by varying R and r, keeping X_B constant (Fig. 8). The effect is essentially the same in either case. When R is varied instead of X_B, the only difference is that the balance of the bridge is disturbed for both the real and imaginary components. This fact necessitates a correction of r each time R is changed in securing a balance of b against X_B. If X_B is varied, the balances of r against a, and X_B against b, are independent functions. In practice, it is easier to vary R and keep X_B constant, but for the purpose of theoretical discussion it lends clarity to consider X_B to be variable from the condition of balance.

From the equation (1) above the impedances of different lengths of line may be computed. For the purpose of designing a suitable impedance bridge arrangement, it is sufficient to consider the 19-gauge, non-loaded cable only, as the effect of loading on the general line characteristic is small at the frequencies employed. A number of impedance values representing different lengths of 19-gauge, non-loaded

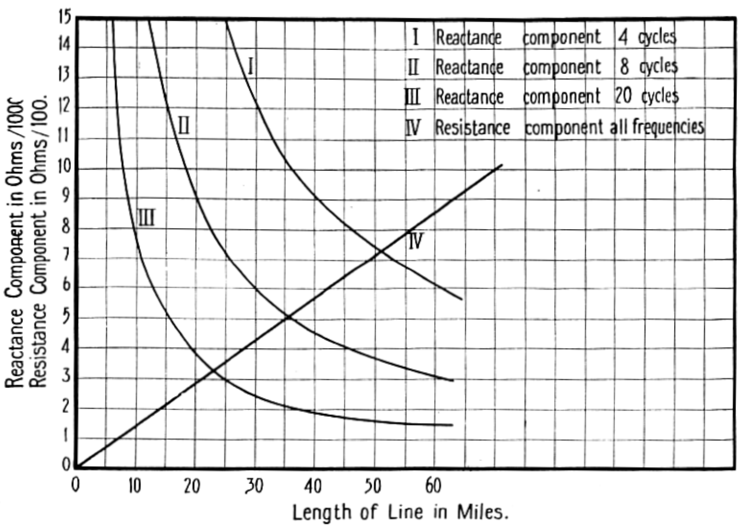


Fig. 10—Characteristics of the resistance component and capacitance component of the impedance of lengths 19-gauge, non-loaded cable.

cable up to sixty miles, at three frequencies, viz., twenty, eight and four cycles, were selected and the condition of balance of the impedance bridge calculated for each case from equations (4) and (5). Curves of these impedances are shown in Fig. 10, where the reactances and resistances at the three chosen frequencies are plotted.

Since the sensitivity of the bridge network should be a maximum when the unbalance is small, i.e., when a balance is about to be secured, this condition is the one with which the sensitivity calculation is concerned. The capacitance X_B of the bridge network was assumed to vary 10% from the condition of balance and the galvanometer

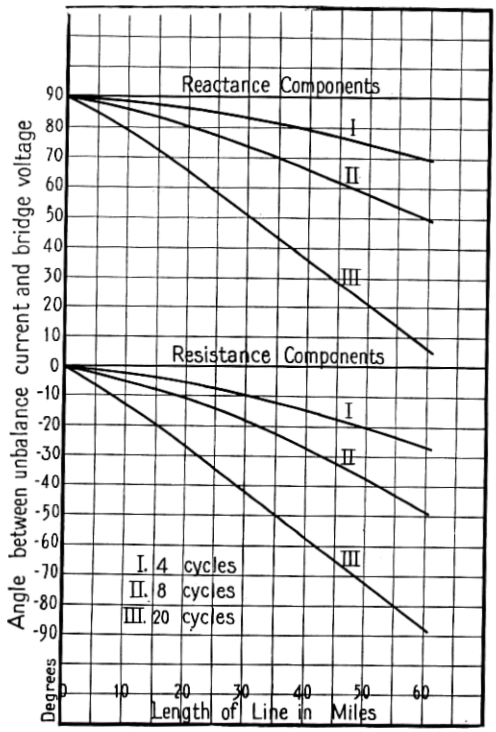


Fig. 11—The variation of the angle between the bridge voltage and the unbalance current for the reactance component and resistance component of non-loaded 19-gauge cable in lengths varying from zero to sixty miles. The curves represent characteristics for frequencies of four, eight and twenty cycles.

unbalance current, i_3, was then calculated from equation (3) for each length of line at each frequency. Both the magnitude and phase angle were found. Similarly the resistance r was assumed to vary 10% from the condition of balance, X_B remaining balanced, and another set of galvanometer unbalance currents was determined. Such calculations are particularly tedious, involving successive additions and subtractions, multiplications and divisions of complex quantities. The results of these calculations are shown in Figs. 11, 12 and 13. Fig. 11 represents the variation in phase angle of i_3 with respect to the bridge potential, Fig. 12 the magnitude of i_3, and Fig. 13 the relative sensitivities obtained with different frequencies and different lengths of line. These sensitivities are proportional to i_3 (Fig. 12) and to the cosine of the angle between i_3 and the field current

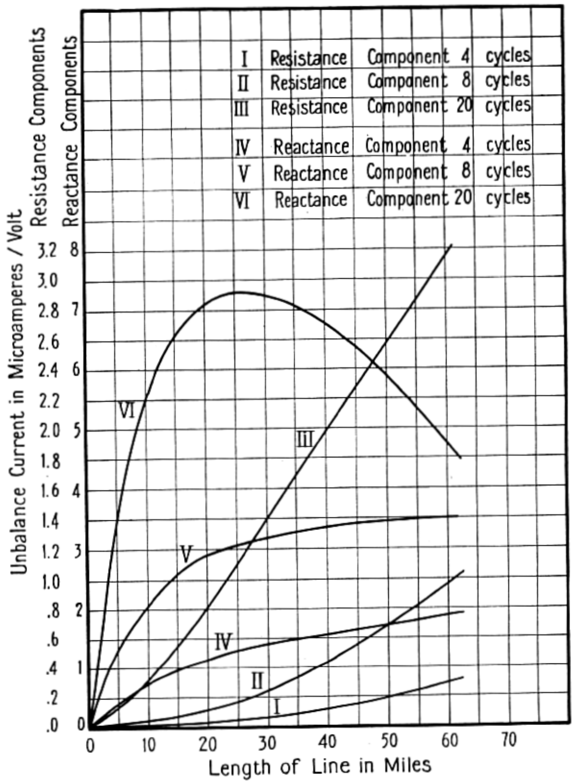


Fig. 12—Magnitude of the unbalance current for measurements, on the impedance of non-loaded 19-gauge cable, at frequencies of four, eight, and twenty cycles.

of the alternating-current galvanometer. In the calculation of the curves of Fig. 13 the field current of the galvanometer was assumed to be in phase with the bridge potential for the case of an unbalance in r, and leading the bridge potential by ninety degrees for the case of an unbalance in X_B.

Referring to Fig. 11, it is seen that for short lengths of line the unbalance current caused by unbalancing r is almost in phase with the voltage, while the unbalance current due to unbalancing X_B leads the voltage by approximately ninety degrees. As the length of line increases, the phase angles tend to lag from these positions, due to the effect of the convergent variation of the resistive and reactive components of the line impedance, that is, the resistance increases and the reactance decreases with increase in length of line. This lag is greater for the higher frequencies. The total variation for sixty miles of cable measured at twenty cycles is practically ninety degrees which means that for a given field current the sensitivity using twenty cycles must approach zero with some length of line between zero and sixty miles. This condition is illustrated in Fig. 13, where the sen-

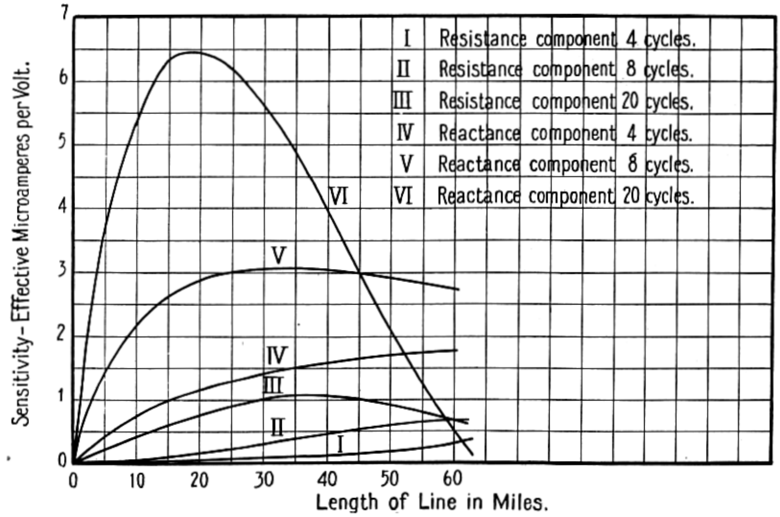


Fig. 13—Sensitivity to unbalance for the bridge network for impedance measurements on lengths of non-loaded 19-gauge cable. These curves represent sensitivities for frequencies of testing potential of four, eight and twenty cycles.

sitivity for twenty cycles is a maximum at twenty to thirty miles, but falls rapidly toward zero at the longer lengths of line. With the lower frequencies and the setting of field current used, the general effect is an increase in sensitivity as the length of line increases, and a decrease in sensitivity with decrease in frequency. This decrease is due to the decrease in reactance with increase in length of line (Fig. 10).

It would appear that provision should be made for shifting the phase of the field current through ninety degrees, its two positions being respectively in phase with the bridge potential and ninety degrees leading. Thus the two components, r and X_B, could be balanced independently except for the shift in phase with different line lengths. This phase shift is small with a frequency of testing potential of four cycles.

A frequency of four cycles was selected as the optimum as regards the size of hyperbolic error discussed above, the sensitivity available, and the amount of phase shift with increase in length of line. The curve showing the change of hyperbolic error with variation in frequency (Fig. 7) shows four cycles to be at or near the critical point of the curve. The sensitivity at four cycles has the advantage of being sufficient but not excessive. To a large extent, the condition of phase shift (with increase in length of line) governs the ease of securing a balance over the range of line lengths. The ideal arrangement would be one in which the field current could always be placed in phase with the component of the bridge unbalance current it was desired to eliminate. Such a quality is not characteristic of the type of bridge used; however, a desirable approximation of such an arrangement is obtained when a four-cycle frequency of testing potential is used.

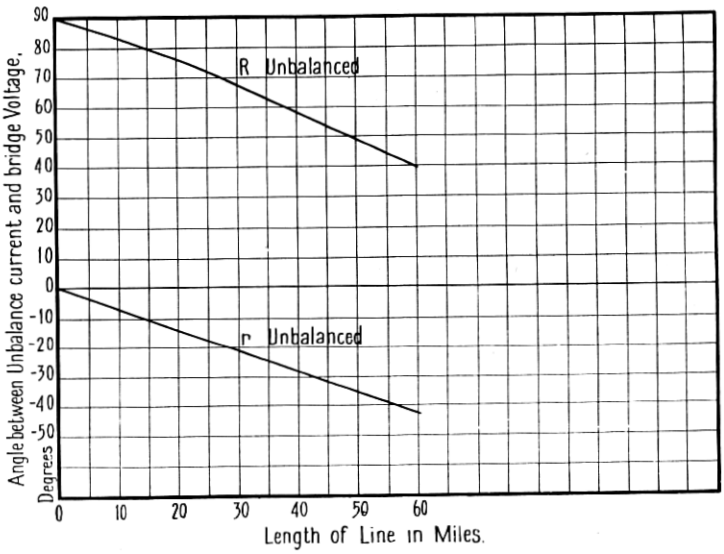


Fig. 14—Calculated variation in the angle between unbalance current and bridge voltage for unbalance in the capacitance component R and for unbalance in the resistance component r of the impedance of non-loaded 19-gauge cable. Testing potential of 4-cycles.

In order to check the assumption (stated above) that the bridge could also be balanced by keeping X_B constant and varying R and r, without materially changing the conditions of balance, another set of galvanometer unbalance currents was calculated with X_B constant and R and r varied respectively 10% from the condition of balance.

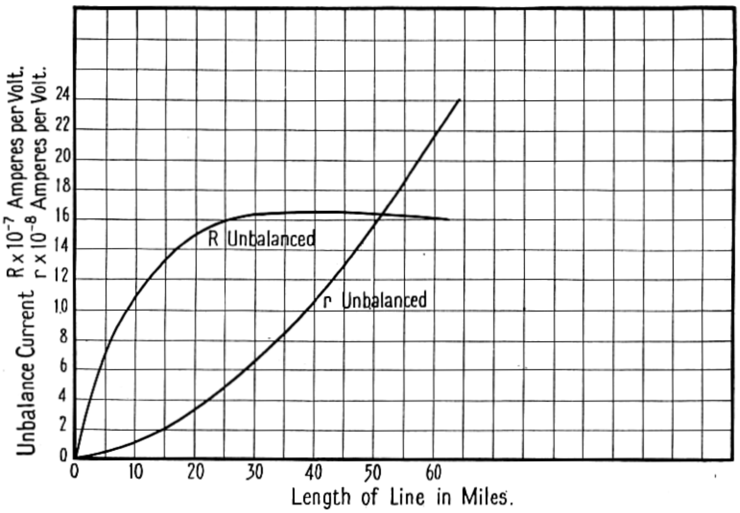


Fig. 15—Calculated magnitude of the unbalance current for unbalance in the capacitance component R and unbalance in the resistance component r of the impedance of non-loaded 19-gauge cable. Testing potential 4-cycles.

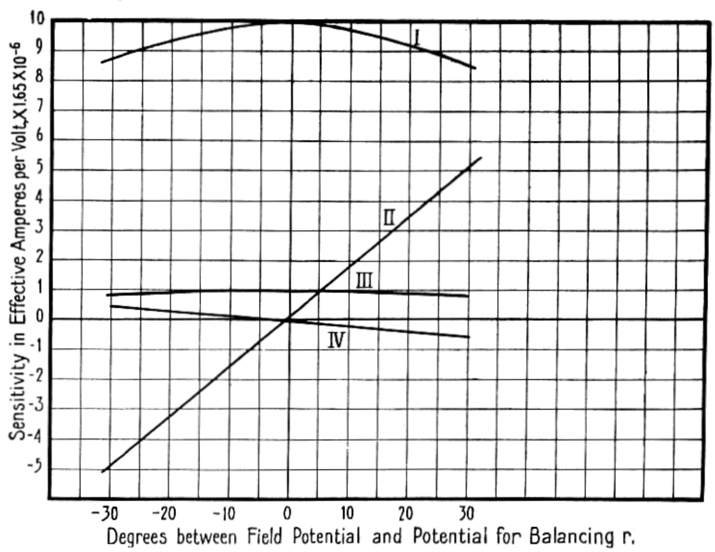


Fig. 16—Calculated sensitivity of the bridge at four cycles on a 50-mile length of non-loaded, 19-gauge cable. Sensitivities for unbalance in the component:

I—R with the phase of testing potential applied for balancing R.

II—R with the phase of testing potential applied for balancing r.

III—r with the phase of testing potential applied for balancing r.

IV—r with the phase of testing potential applied for balancing R.

The chosen frequency of four cycles was used in this calculation. These curves of phase angle and current magnitude are shown in Figs. 14 and 15, and correspond to those shown in Figs. 11 and 12, calculated by the other method.

Since R increases with increase in length of line, the sensitivity per ohm change in R will be better throughout the range of lengths if the sensitivity for a given change in R is a maximum when R is a maximum. Taking fifty miles as the average total length of line, and

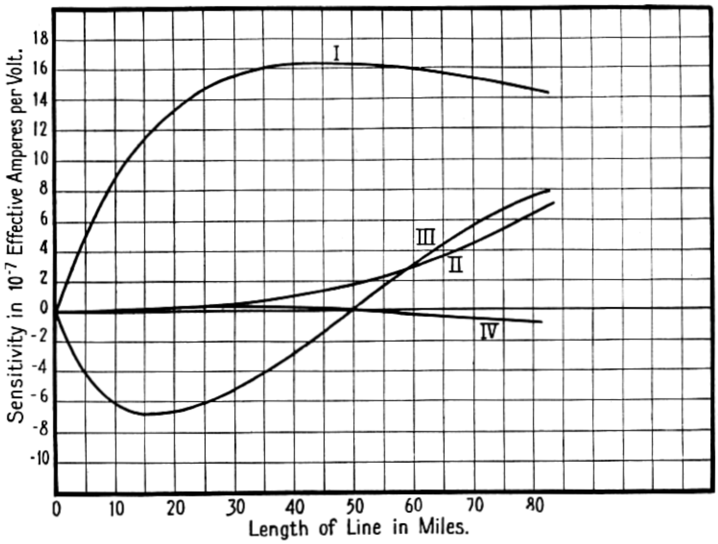


Fig. 17—Calculated sensitivity for lengths of non-loaded 19-gauge conductor using the impedance bridge arrangement which gave the maximum sensitivity for curve I in Fig. 16. Sensitivity for unbalance in the component:

I—R with the phase of testing potential applied for balancing R.
II—r with the phase of testing potential applied for balancing r.
III—R with the phase of testing potential applied for balancing r.
IV—r with the phase of testing potential applied for balancing R.

assuming two bridge potentials ninety degrees apart, a set of sensitivity curves was calculated for this length of line, the phase of the field potential being varied on either side of the bridge testing potential. The lag of the field current from the field voltage calculated from the field inductance and resistance was found to be about forty degrees. The resulting sensitivity curves are shown in Fig. 16, and these indicate a maximum sensitivity for R and r with the field potential in phase with the potential used to balance r.

With the assumed conditions as determined by this calculation,

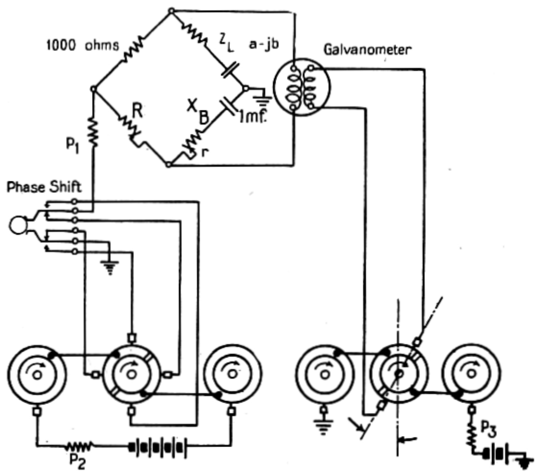


Fig. 18—Impedance bridge circuit showing the arrangement used in applying testing potentials in quadrature.

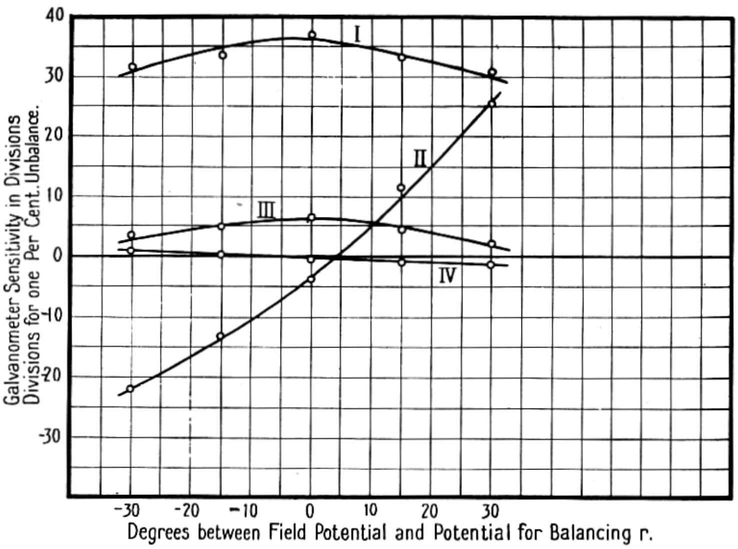


Fig. 19—Observed galvanometer sensitivities which are comparable to the calculated sensitivities of Fig. 16. Sensitivity for unbalance in the component:

I—*R* with the phase of testing potential applied for balancing *R*.
II—*R* with the phase of testing potential applied for balancing *r*.
III—*r* with the phase of testing potential applied for balancing *r*.
IV—*r* with the phase of testing potential applied for balancing *R*.

viz., two bridge potentials ninety degrees apart and a field current lagging one bridge potential forty degrees, a complete set of sensitivity curves was calculated for different lengths of line from zero to eighty miles. These are shown in Fig. 17. It should be noted that the sensitivity for detecting an unbalance in R is a maximum at the desired length of fifty miles. The sensitivity for an unbalance in r

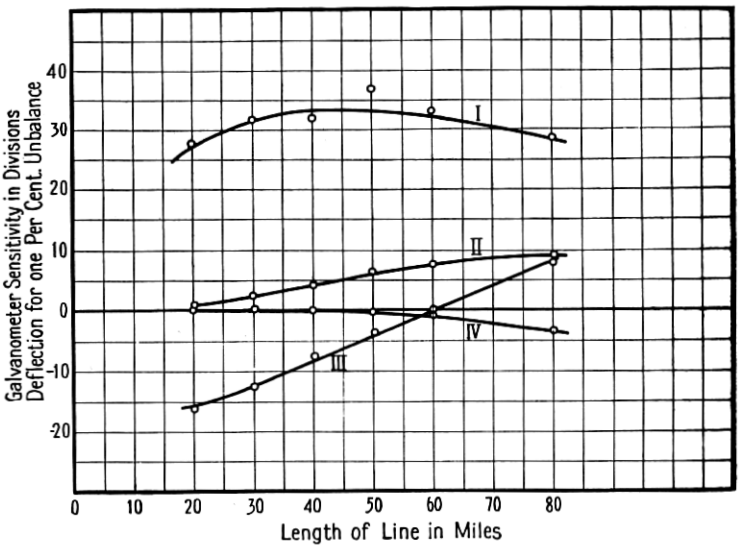


Fig. 20—Observed galvanometer sensitivities which are comparable to the calculated sensitivities of Fig. 17. Sensitivity for unbalance in the component:

I—R with the phase of testing potential applied for balancing R.
II—r with the phase of testing potential applied for balancing r.
III—R with the phase of testing potential applied for balancing r.
IV—r with the phase of testing potential applied for balancing R.

is low at the shorter lengths of line, but increases as the length of line increases. It may be noted that in both Figs. 16 and 17 the sensitivity curve for changes in R passes through zero when the testing potential is applied for balancing r. Likewise the sensitivity curve for changes in r passes through zero when the testing potential is applied for balancing R. This point is where the field current and galvanometer unbalance current are ninety degrees out of phase. Naturally this point coincides with the point of maximum sensitivity for the normal potential arrangement. As stated above, it would be ideal if these "reverse sensitivities" could be zero and the "true sensitivities" could be maximum throughout the entire range of lengths. Reference to Fig. 17 will show that the reverse sensitivity for r is practically zero throughout the range of lengths. This fact in itself is significant. Assuming r to be set on zero, R could be varied to secure an approximate balance, using the proper testing potential. This balance would be fairly accurate since the reverse sensitivity for r is quite low throughout. Shifting bridge potentials ninety degrees, r could be adjusted almost to the proper point since R is practically

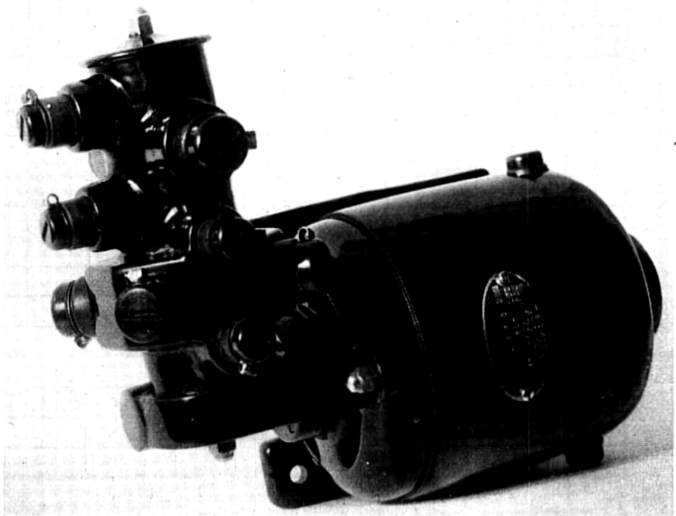


Fig. 21—Commercial design of motor-driven commutator which is used to supply 4-cycle alternating potentials for the impedance bridge.

correct. The balance of R and r can then be refined as often as is necessary to secure a perfect balance. Since r is not used in any calculation, and since its effect on R is small once an approximate balance of R and r is obtained, the need for an accurate balance of r is small.

A series of observations made with experimental apparatus arranged as shown in Fig. 18 gave the sensitivity curves shown in Figs. 19 and 20. The observed sensitivity characteristics shown by these curves agree very favorably with the theoretical values shown by the curves of Figs. 16 and 17.

By way of summarization, it may be observed that in the process of developing a suitable method for the location of faults in telephone cables a definite sequence of steps has been taken to provide an effective treatment of the problem:

1. In establishing requirements for a suitable method, a study was

made of the historical development of the art. The effectiveness of the art was compared with the needs of present practices.

2. Preliminary to the development of a suitable method, an analysis was made of the errors which may enter into the determination of an open location. These errors were classified for treatment or correction during the development.

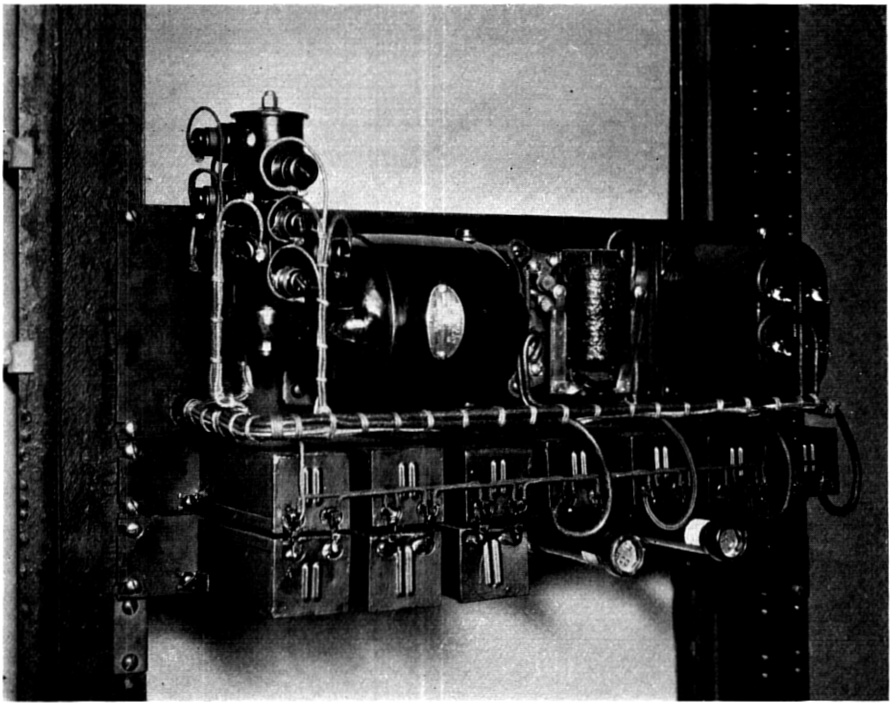


Fig. 22—4-cycle motor-driven commutator with associated equipment.

3. A mathematical analysis was made of the electrical characteristics of the circuits on which open locations may be required.

4. A suitable method was devised and an associated impedance bridge circuit was developed which, in the light of the recent research, most consistently and economically met the requirements for the determination of open locations.

After having completed an analysis of the problem and demonstrated the practicability of the proposed methods, it remained to develop applications of these methods for practical use. Equipment was designed to develop a low frequency source of alternating potential by reversing a testing battery. The device developed for this purpose is a 4-cycle, motor-driven commutator shown in Fig. 21. By studying the curves used in the selection of a suitable frequency of testing potential, it may be observed that the selected value of four cycles is not critical, in fact a variation of $\pm$ 25 per cent may be allowable in

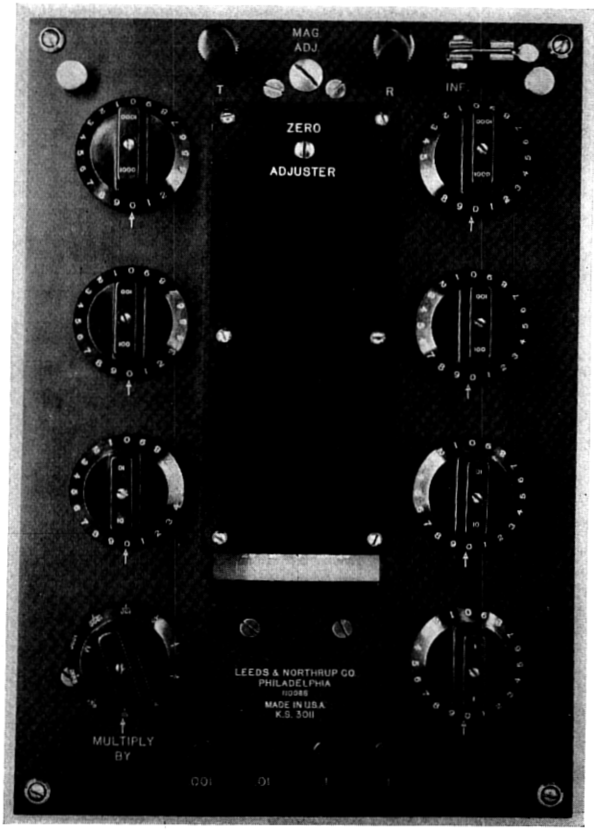


Fig. 23—Panel assembly of the impedance bridge.

different machines. However, in practical application, the accuracy of results obtained depends upon a comparison or ratio of two impedance measurements which cannot be made simultaneously. Since impedance varies with frequency, it is important that the frequency of testing potential should remain constant while the two measurements are being made. This requirement is met for the short time required for two measurements. The assembly of the 4-cycle commutator with associated apparatus is shown in Fig. 22.

The galvanometer and the equipment required in the modified form of the De Sauty bridge have been incorporated in a compact unit which is shown in Fig. 23. This bridge, while being particularly adapted to the 4-cycle impedance measurements required for open location tests, is also applicable for direct-current bridge measurements. Assembly details for the bridge arrangement are shown in Fig. 24.

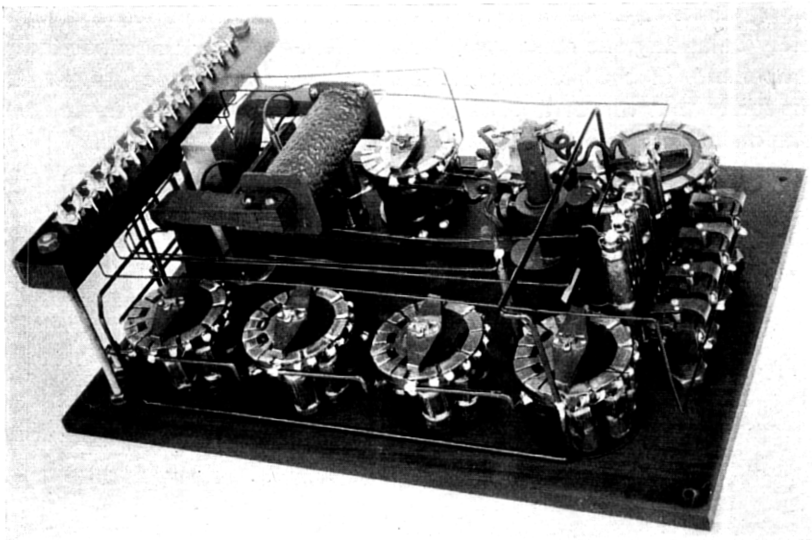


Fig. 24—Internal assembly of the impedance bridge.

The alternating-current galvanometer is sufficiently sensitive to be directly actuated by any significant unbalance of the impedance bridge, so that it is unnecessary to use an amplifier, rectifier, or other converting apparatus which may be difficult of adjustment or maintenance.

A few additional features are outlined as some of the significant results of this development of an improved open location method.

It has been shown that the error, caused by the deviation from the straight line relation between sending end admittance and physical length of line, has been reduced to a value which may be neglected as being less than the required accuracy of the open location method.

As a result of an analysis of errors which are introduced by line irregularities, methods were devised for applying corrections for all such errors which are of a magnitude sufficient to interfere with the desired accuracy.

This impedance bridge arrangement employs several features which are a distinct improvement on the methods previously utilized for this purpose. In order that the impedance angles of the impedance networks may be balanced, a variable resistance has been connected in that branch of the bridge which contains the comparison capacitance. This balance of the impedance angles of the impedance network was found to be important in obtaining a steady performance of the alternating-current galvanometer. A system has been devised for separately balancing the resistance components as well as the capacitance components of the reactive networks of the impedance bridge. It was found that this arrangement gives a maximum sensitivity to each component and permits of a very rapid balance of the bridge.