Bridge Methods for Locating Resistance Faults on Cable Wires

By T. C. HENNEBERGER and P. G. EDWARDS

In this paper are discussed bridge methods for locating resistance faults on cable wires, with special reference to the theory of methods for (1) locating insulation faults which cause complete cable failure, (2) locating insulation faults of high resistance, and (3) locating series resistance unbalances.

The methods described are better adapted to the toll than to the exchange telephone cable plant, since they require that the conductor resistances of the wires used for measurements be equal and, in general, that measurements be made from each end of the faulty cable.

IN the toll telephone plant, insulation faults such as "grounds" and "crosses" are usually located by the "Varley loop" method, which involves essentially the measurement of the d.-c. resistance of the faulty wire between the point of fault and one end of the cable, and the comparison of this resistance with the total conductor resistance of the wire to obtain the "percentage location" of the fault on a resistance basis. Corrections are then applied to account for such factors as the resistance of the leads between the cable and the bridge, the resistances of loading coils, and non-uniformity of conductor resistance caused by temperature differences between underground and aerial sections of the cable. After all corrections are applied the corrected percentage location is converted into distance from one cable end to the fault.

In general, the most troublesome insulation fault to locate is a "wet spot" due to absorption of moisture by the insulation through a defect in the lead covering of the cable, which results in low insulation resistance between wires and to ground. Standard apparatus now available for locating grounds and crosses is sufficiently sensitive to permit accurate locations of wet spots up to about five megohms in resistance. The Varley loop methods ordinarily employed in connection with the apparatus will give accurate results provided a wire of very much higher insulation resistance than the faulty wire is used as the "good" wire for measurements. These are the conditions which usually are found when wet spots occur. Cases occur occasionally, however, in which a "good" wire having sufficiently high insulation resistance as compared to the faulty wire cannot be obtained, either because all of the wires available for measurements are affected by the fault or because the fault resistance is high. The methods for locating insulation faults discussed in this paper are especially applicable to such cases.

Resistance unbalances on cable wires are of relatively infrequent occurrence and are usually difficult to locate. A method frequently employed for locating such faults is to measure the impedance unbalance at various frequencies of a circuit containing the faulty wire and to analyze periodic impedance-frequency curves plotted from the measurements.[1] The methods for locating series resistance unbalances discussed in this paper involve the use of ordinary Wheatstone bridges, are simple to apply, and give results which are believed to be comparable to those obtained by the impedance-frequency method.

Normal Insulation Resistance of Cable Wires

The values of insulation resistance obtained by measurements on cable wires which are not faulty are dependent on the circumstances in which the measurements are made. In the case of paper-insulated telephone cable the most important factors affecting insulation resistance are electrification period and temperature.

The following discussion of normal insulation resistance refers particularly to measurements between wires of pairs in a typical repeater section of aerial toll cable approximately 50 miles long, the wires being at ground potential at the time of application of the testing potential. Insulation resistance to ground is also of interest, but is difficult to measure accurately in long lengths of cable because of interfering potentials. As a rough approximation, normal insulation resistance between a wire and ground can be considered to be about two thirds as great as normal insulation resistance between wires.

A curve illustrating the variation of insulation resistance between wires of a typical cable pair over a 30-minute electrification period is shown in Fig. 1. In general, the electrification periods necessary for obtaining reasonably constant values of insulation resistance differ appreciably for different pairs, and for the same pair at different times. The usual period ranges from 15 minutes to an hour for a pair 50 miles long. Routine measurements are generally made, however, using electrification periods of one minute.

The paper used for insulating the wires of telephone cable has an appreciable negative temperature coefficient of insulation resistance. This is indicated by the curve of Fig. 2 which shows variations of average insulation resistance with temperature. The points for the

[1] "Telephone Circuit Unbalances," by L. P. Ferris and R. G. McCurdy, A. I. E. E. Transactions, 1924, Volume XLIII, page 1331.

curve were obtained by averaging, for each five-degree range of temperature, the insulation resistances obtained by measurements made

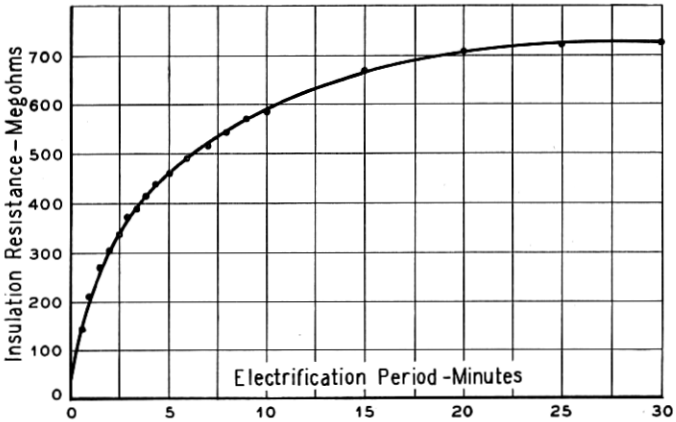

Fig. 1—Variation of insulation resistance with electrification period—typical 50 mile aerial cable pair.

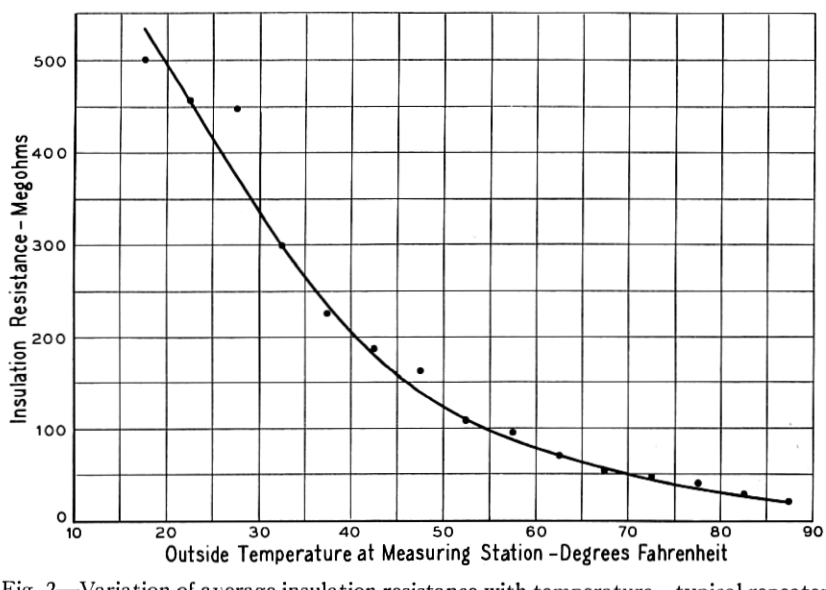

Fig. 2—Variation of average insulation resistance with temperature—typical repeater section of aerial cable.

daily over the course of a year on representative pairs in a repeater section, using electrification periods one minute long. It has been found that the percentage change in insulation resistance per degree change in temperature differs widely for different cable sections and even for the individual pairs in a particular section. The average change per degree Fahrenheit is probably about four per cent, for the temperature range encountered in the plant.

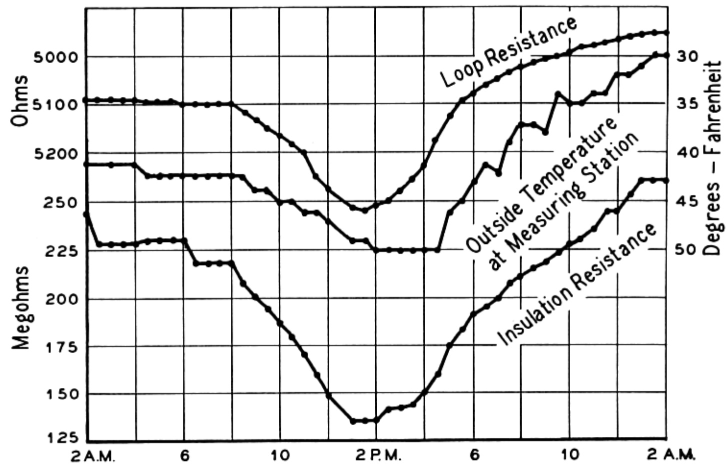

Fig. 3—Variation of insulation resistance, loop resistance and temperature over 24 hour period—typical 50 mile aerial cable pair.

The curves of Fig. 3 illustrate comparative variations of insulation resistance between wires of a representative cable pair, conductor resistance of the pair, and outside temperature, during a 24-hour period which included a sunny summer day. The curves were plotted from measurements made every half hour, one-minute electrification periods being used when measuring insulation resistance. It is not uncommon to find that the insulation resistances of particular pairs vary by factors of three to one during the course of a day.

Comparative variations of average insulation resistance between wires of pairs and of mean outside temperature over the course of a year are illustrated by the curves of Fig. 4. The points for the insulation resistance curve were obtained by measuring the insulation resistances of a number of pairs each working day during the year, using one-minute electrification periods, and averaging the measured values for each day.

In general, average insulation resistance is likely to vary by a factor of 15 to one during the course of a year. Individual pairs are, of course, subject to much wider seasonal variations in insulation resistance. During winter it is not uncommon to find particular pairs in a 50-mile repeater section with insulation resistances between wires

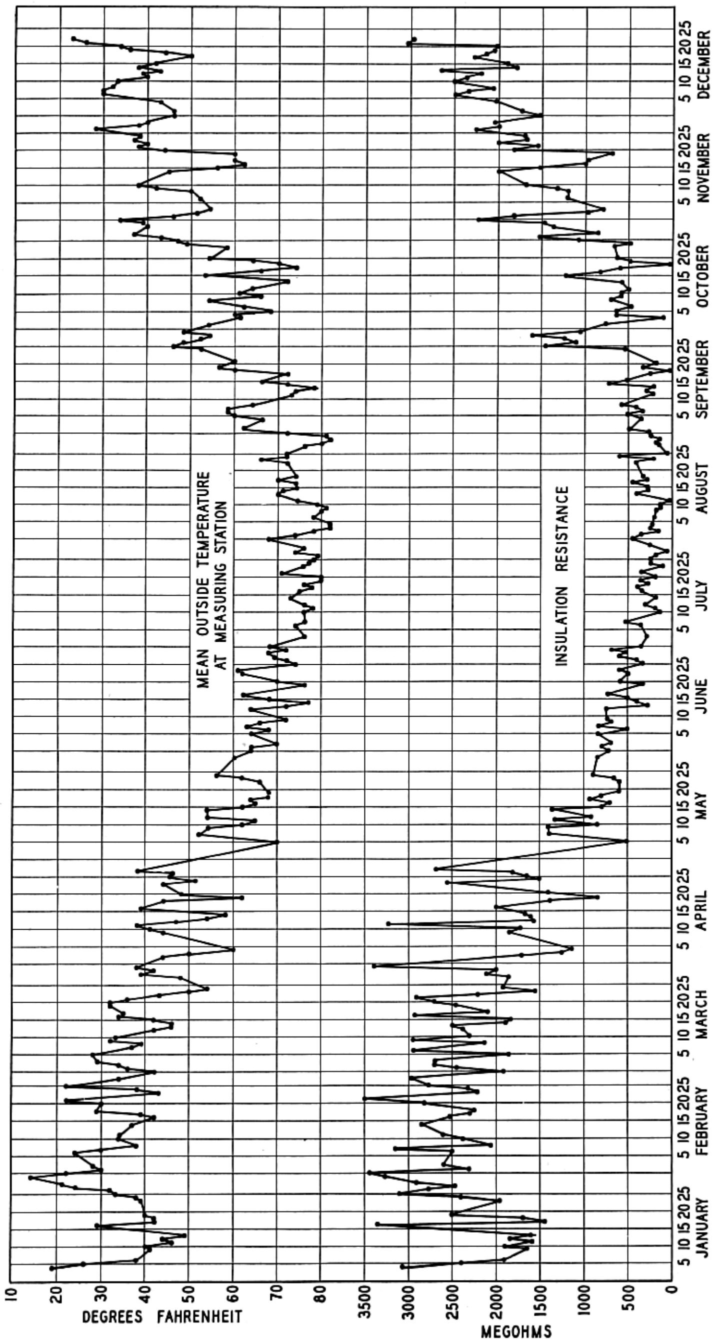

Fig. 4—Seasonal variation of average insulation resistance—typical repeater section of aerial cable.

of several thousand megohms, while during summer, especially in cables which have been in service for a number of years, the insulation resistances between wires of some pairs in a 50-mile repeater section may be as low as 25 megohms (1250 megohm-miles).

Varley Loop Method

The Varley loop circuits which are used ordinarily for locating grounds and crosses on wires of toll cable are illustrated in Figs. 5 and 6. The Wheatstone bridge has equal ratio arms, A. The "good"

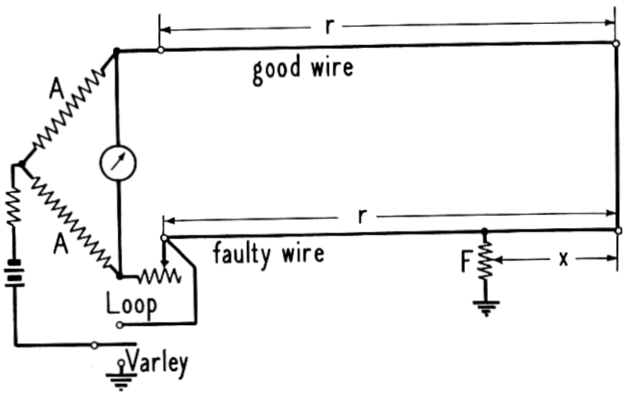

Fig. 5—Varley loop for grounds.

and faulty cable wires have equal conductor resistances, r, and are connected together at the distant end of the cable. F is the resistance of the fault, and x is the conductor resistance of the faulty wire between the fault and the distant end of the cable.

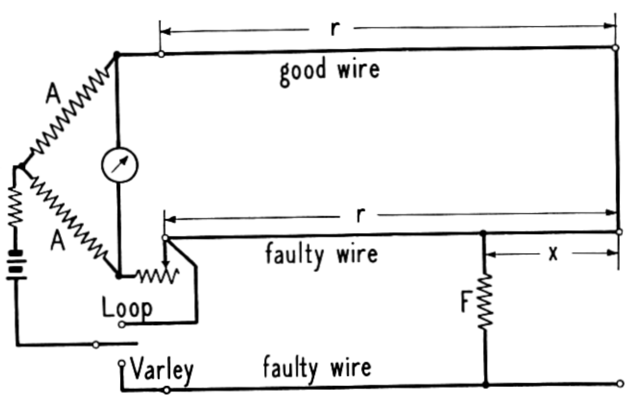

Fig. 6—Varley loop for crosses.

With the battery switch in "Varley" position, a Varley measurement is made by balancing the bridge to a rheostat value, V, at which there is no galvanometer current. Then:

$$\frac{A}{A} = \frac{r + x}{r - x + V},$$

$$x = \frac{V}{2}. \tag{1}$$

It will be noted that the fault resistance, F, is in series with the battery and has no effect on the measurement except to limit the sensitivity of the bridge.

With the battery switch in "loop" position, a loop resistance measurement is made by balancing the bridge to a rheostat value, L. Then:

$$r = \frac{L}{2}.$$

From these Varley and loop measurements the percentage location of the fault, on a resistance basis, can be calculated as follows:

From the distant end: $\frac{V}{L}$(100 per cent).

From the measuring end: $\frac{L - V}{L}$(100 per cent).

Corrections for resistances of bridge leads, loading coils, etc., are then made, the corrected percentage location is converted into feet, and the location of the fault is determined by reference to cable records.

These Varley circuits and formulas are well adapted to the toll cable plant where wires are usually well balanced in conductor resistance, and the resistance of the leads between the bridge and the cable is small compared to the conductor resistance of the cable wires. In exchange cable work, modified forms of the Varley loop, which do not require that the "good" and faulty wires be of equal conductor resistance and which correct automatically for the resistance of bridge leads, are frequently used.

Total Cable Failures

In the case of total cable failure, due, for instance, to a wet spot, there are no wires in the cable which are unaffected by the fault, and the fault resistances of a large number of the wires are low, i.e., of the same order of magnitude as the conductor resistances of the wires.

Two methods by which such faults can be located are discussed below: A "Corrected Varley" method which may be used provided two wires having fault resistances to ground differing by at least 25 per cent are available for measurements; and a "Straight Resistance" method which does not require that the two wires have faults of unequal resistances.

Corrected Varley Method

Consider a cable in which all wires have low insulation resistance to ground because of a wet spot, and assume that from among the faulty wires two wires are selected for a Varley measurement. Assuming a bridge having equal ratio arms, A, the Varley network can be represented as shown in Fig. 7, where M and F are the effective resistances of the faults on the two wires, r is the conductor resistance of either wire, and x is the resistance of that portion of either wire which is between the distant end of the cable and the faults.[2]

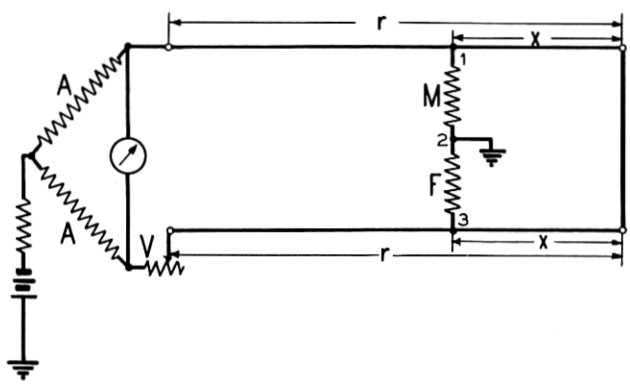

Fig. 7—Schematic circuit—corrected Vaıley method.

The Varley circuit of Fig. 7 is equivalent to the Varley circuit of Fig. 8, where the "π" type network formed by the three resistances, M, F and $2x$, has been replaced by a "T" type network having resistance values as indicated. When the bridge is balanced by adjustment of the rheostat to a resistance, V, at which there is no galvanometer

[2] The actual faults form a "π" type network consisting of a resistance between wires and a resistance between each wire and ground. The "π" type network has been replaced by a "T" type network having resistances, M and F, between the two wires and the branch point of the network, and a third resistance connecting the branch point to ground. This third resistance is in series with the bridge battery and its only effect is to limit the sensitivity of the bridge. To simplify discussion the resistances, M and F, are shown connected directly to ground, and the third resistance is considered to form a part of the resistance shown connected between the battery and the junction point of the ratio arms of the bridge.

current:

$$r - x + \frac{2Mx}{M + F + 2x} = r - x + \frac{2Fx}{M + F + 2x} + V.$$

Solving for x:

$$x = \frac{V}{2} \frac{(M + F)}{(M - F - V)}. \tag{2}$$

Comparison of this formula with Formula (1) indicates that the factor $V/2$, as determined by Varley measurement, represents the

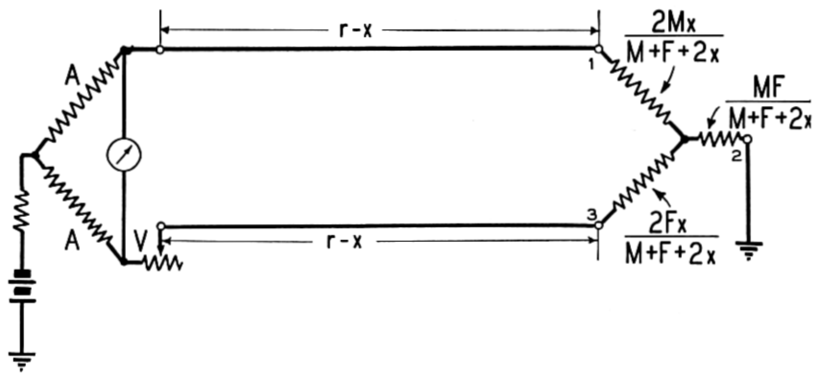

Fig. 8—Equivalent circuit—corrected Varley method.

apparent rather than the true resistance between the distant end of either wire and the location of the faults. The factor $\frac{(M + F)}{(M - F - V)}$ is a correction factor and expresses the relation between $V/2$ and the true resistance, x. If the fault, M, is very much higher in resistance than either the fault, F, or the balancing resistance, V, the correction factor becomes practically equal to one and $V/2$ becomes practically equal to x. In these circumstances the wire having the fault, M, can properly be called a "good" wire and Formula (1) will give accurate results.

Since the apparent resistance, $V/2$, can be determined by Varley measurement the faults can be located if the value of the correction factor can be determined. The correction factor can be evaluated by additional measurements made on the two faulty wires from the end of the cable opposite to that used for the Varley measurement, as described below.

Referring to Fig. 7, the resistance of either wire between the faults and the end of the cable opposite to that used in making the Varley measurement is x. If a loop resistance measurement is made from this opposite end, using a bridge having equal ratio arms, *with the distant ends of the wires open*, and the resistance in the bridge rheostat at balance is designated L_0:

$$M + F = L_0 - 2x.$$

If a Varley measurement is made from the same end, using a bridge having equal ratio arms, *with the distant ends of the wires open*, and the resistance in the bridge rheostat at balance is designated V_0:

$$M - F = V_0.$$

Substituting these values of $(M + F)$ and $(M - F)$ in (2):

$$x = \frac{V}{2} \frac{L_0}{V_0}. \tag{3}$$

Application: To apply the Corrected Varley method, an ordinary Varley measurement is made from one end of the cable, and additional loop resistance and Varley measurements, as described above, are made from the opposite end. The values of balancing resistance thus obtained are substituted in Formula (3). The location of the trouble on a resistance basis, x/r, can then be calculated, and the location can be converted into feet in the usual manner.

Usually it will be necessary to determine the loop conductor resistance, $2r$, of the faulty wires from cable records rather than by measurement at the time the location is being made. A measurement of loop conductor resistance would be in error because of the low resistance shunt $(M + F)$ on the portion of the loop between the faults and the short-circuited ends of the wires. The accuracy of location is dependent, therefore, on the accuracy to which conductor resistance can be estimated.

In cases where it is desirable to use the Corrected Varley method the fault resistances will be low, so that usually the balancing resistance, L_0, will not exceed 10,000 ohms. If L_0 is too high to measure using a bridge with equal ratio arms, unequal ratio arms, A and B, may be used and the quantity $\frac{A}{B} L_0$ substituted for L_0 in Formula (3). Measurement of V_0, however, should be made using a bridge with equal ratio arms.

The Corrected Varley method will give accurate results only under the following conditions:

(1) Both faults must be at the same point along the cable.
(2) The fault resistances must remain constant throughout the test.

(3) The resistance of the fault on one wire must be higher than the resistance of the fault on the other wire.
(4) The conductor resistances of the faulty wires must be equal.

In the practical application of the method, care must be exercised in selecting the wires to be used for measurements. The resistance, M, of the fault on the wire which is connected to the ratio arm of the bridge when measuring V should be appreciably higher (at least 25 per cent higher) than the resistance, F, of the fault on the wire connected to the rheostat arm of the bridge. This can be understood by considering that as M and F approach each other in value the correction factor becomes larger and the Varley balancing resistance, V, approaches zero, i.e., the apparent location of the trouble approaches the distant end of the cable. Errors in measurement become increasingly important as V and V_0 become smaller.

Accurate results will not be secured if the resistances of the faults vary while a set of measurements to determine V and the correction factor is being made. It is advisable, therefore, to make a number of separate sets of measurements, and to base the location on those sets which appear to be consistent.

Straight Resistance Method

In many cases of complete cable failure the faults on all of the wires are of practically equal resistance, and the Corrected Varley method cannot be used successfully. The Straight Resistance method described below has the advantage that the wires used for measurement need not be unequal in fault resistance.

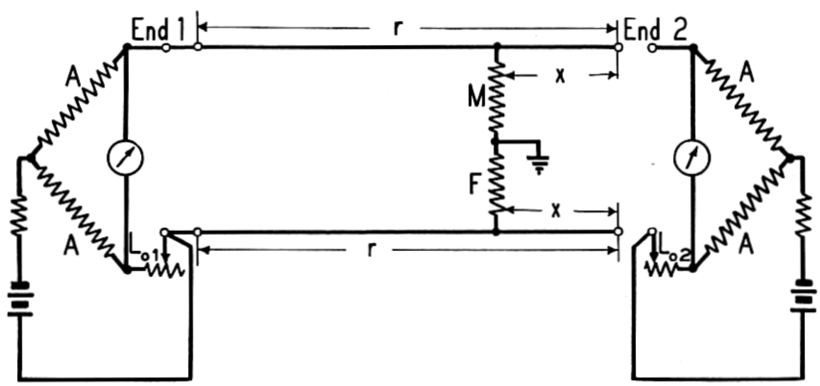

Fig. 9—Schematic circuit—straight resistance method.

The Straight Resistance method is based on the assumptions that the wires on which the tests are made are of equal conductor resistance, that the fault resistances are comparable in magnitude to the conductor resistances, and that the fault resistances remain constant while a set of measurements is being made.

Referring to Fig. 9, assume that, from among the faulty wires, two wires are selected having a fault of low effective resistance, $(M + F)$, between wires. Let r be the conductor resistance of either wire between cable Ends 1 and 2; and let $(r - x)$ and x be the conductor resistances of either wire from Ends 1 and 2, respectively, to the fault.

With the wires open at End 2, the resistance between wires is measured at End 1 by means of a bridge having equal ratio arms and arranged for an ordinary loop resistance measurement. Calling the rheostat resistance at balance, L_{01}:

$$L_{01} = 2(r - x) + (M + F).$$

Similarly, with the wires open at End 1, the resistance between wires is measured at End 2. Calling the rheostat resistance at balance, L_{02}:

$$L_{02} = 2x + (M + F).$$

Combining the equations for L_{01} and L_{02}:

$$L_{02} - L_{01} = 4x - 2r.$$

and therefore:

$$x = \frac{2r + (L_{02} - L_{01})}{4}, \tag{4}$$

$$(r - x) = \frac{2r - (L_{02} - L_{01})}{4}. \tag{5}$$

Application: The Straight Resistance method involves only simple resistance measurements, L_{01} and L_{02}, from the two ends of the cable. The loop conductor resistance of the faulty wires is obtained from cable records. The values thus secured are substituted in Formula (4) or (5), and the location, x or $(r - x)$, is converted into feet in the usual manner.

Since the conductor resistances of the faulty wires must be equal, measurements should be made on the two wires comprising a pair when practicable. The effective fault resistance between wires should be low; otherwise slight errors in measurement might cause large errors in calculated location. However, in cases where the fault resistances are too high to be measured using bridges with equal ratio arms, unequal arms, A and B, may be used and the quantity $\frac{A}{B}(L_{02} - L_{01})$ substituted for $(L_{02} - L_{01})$ in the formulas.

In connection with both the Corrected Varley method and the Straight Resistance method, it is possible to modify the measuring schemes and obtain somewhat more complicated formulas for the location of the faults. The specific measuring schemes which have been described are those which it is felt are most practicable for fault locating work on toll cable.

Insulation Faults of High Resistance

In order to locate faults of high resistance, sensitive galvanometers and highly insulated bridges must be employed, and the fault locating methods must correct for factors peculiar to the locating of such faults. If the resistance of the fault is high enough to be comparable in magnitude to the normal insulation resistance of the faulty wire, the effect of normal insulation resistance must be taken into account. In the case of a high resistance wet spot, it may happen that all wires in the cable are affected to some extent by the fault so that no wire of high insulation resistance compared to the selected faulty wire is available for measurements.

The solutions of the Varley networks for high resistance faults are more readily obtained by approximate than by exact mathematical reasoning, and will be worked out by the process of combining all of the "effective faults" on the wires into a single resultant fault and then solving the bridge network for this fault. The approximate solution is based on a principle which for the purposes of the present discussion can be stated as follows:

> Any two shunt faults of high resistance along a wire can be replaced by a single resultant shunt resistance located between the two faults at a point the distance of which from either fault is directly proportional to the fault resistances.

Thus, if M and F are the resistances of two faults at separated points along a wire, and m and f are their respective distances from the resultant, then:

$$\frac{M}{F} = \frac{m}{f}\,.$$

The application of this "Rule of Resultant Faults" to Varley measurements can be shown as follows: Let M and F be the effective resistances of the faults on two cable wires at the same point along the cable; let r be the conductor resistance of either wire between the cable ends, and x the resistance of that portion of either wire which is between End 2 of the cable and the faults. Let V be the value of balancing resistance for a Varley measurement made from End 1, using a bridge with equal ratio arms, as indicated in Fig. 10.

Applying the Rule of Resultant Faults, the apparent location of the faults as determined by the Varley measurement will be at a point between the two faults, and at a distance from either fault which is directly proportional to the fault resistances. Let c be the resistance

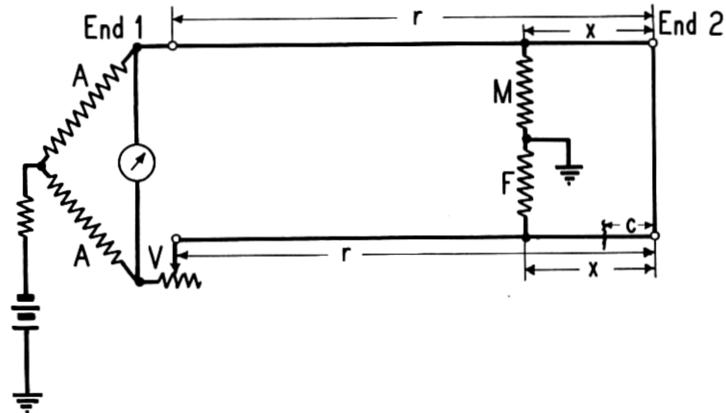

Fig. 10—Location of a resultant fault.

of the portion of the wire between the distant end of the cable and the apparent location. Then:

$$\frac{M}{F} = \frac{x + c}{x - c},$$

$$c = x\frac{M - F}{M + F}.$$

When the bridge is balanced for the Varley measurement:

$$c = \frac{V}{2}.$$

Equating the two values of c and solving for x:

$$x = \frac{V}{2}\frac{M + F}{M - F}. \qquad (6)$$

Comparison of Formula (6) with the more exact Formula (2) for the same case indicates that the Rule of Resultant Faults will give accurate results only if the fault resistances are high compared to the conductor resistances, and if M is of appreciably higher resistance than F.

If M equals F, the location will be indeterminate: The two faults will have no effect on the balance point of the bridge and V will be zero.

Double Varley Method [3]

The distributed normal insulation resistances of cable wires can be considered, in so far as fault locating measurements are concerned, as though they were single resistances concentrated at some point along the wires (Rule of Resultant Faults). Consider two wires having equal and correspondingly distributed normal insulation resistances, N, which appear to be concentrated at some point b ohms from End 2 of the wires, and assume faults of effective resistances, M and F, on the wires at a point x ohms from End 2. Let r be the conductor resistance of either wire, and V_1 and V_2 the balancing resistances for Varley measurements from Ends 1 and 2 of the wires, respectively, using bridges with equal ratio arms as indicated in Fig. 11.

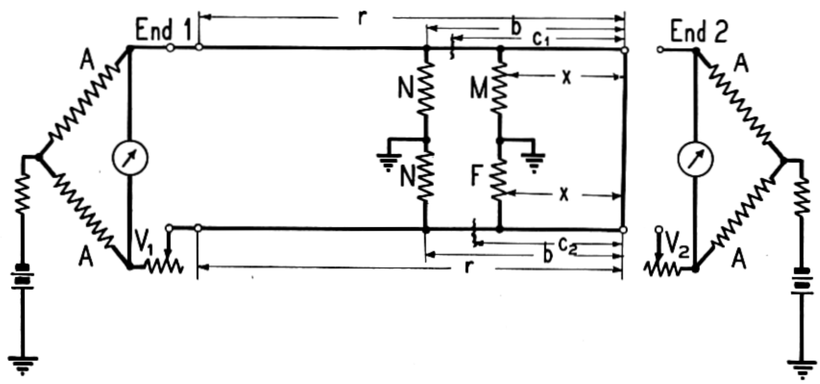

Fig. 11—Schematic circuit—double Varley method.

Applying the Rule of Resultant Faults, let c_1 be the apparent location, in ohms from End 2, of the resultant of M and N, and let c_2 be the corresponding location of the resultant of F and N. Then:

$$\frac{M}{N} = \frac{c_1 - x}{b - c_1},$$

$$c_1 = \frac{Mb + Nx}{M + N},$$

and correspondingly:

$$c_2 = \frac{Fb + Nx}{F + N}.$$

The equivalent resistance of the resultant of M and N is $MN/M + N$, and of the resultant of F and N is $FN/F + N$. Let c_3 be the apparent

[3] The Double Varley method has been described in "Cable Testing," a paper read by E. S. Ritter before the Nottingham Centre of the Institute of Post Office Electrical Engineers (British), May 25, 1922. In that paper it is stated that the method is due to Mr. H. T. Werren.

location, in ohms from End 2, of the resultant of these two resultants, as indicated in Fig. 12.

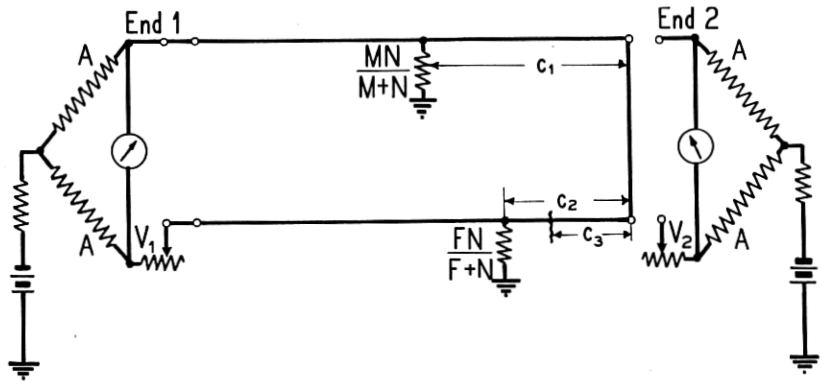

Fig. 12—Equivalent circuit—double Varley method.

Again applying the Rule of Resultant Faults:

$$c_3 = \frac{Nx(M - F)}{M(F + N) + F(M + N)}.$$

For the Varley measurement from End 1 of the cable:

$$c_3 = \frac{V_1}{2}.$$

Equating these two values of c_3 and solving for x:

$$x = \frac{V_1}{2}\left[\frac{M + F}{M - F} + \frac{2MF}{N(M - F)}\right]. \qquad (7)$$

Likewise, for the Varley measurement from End 2 of the cable:

$$x = r - \left\{\frac{V_2}{2}\left[\frac{M + F}{M - F} + \frac{2MF}{N(M - F)}\right]\right\}. \qquad (8)$$

By equating the two values of x found in (7) and (8), the value of the "correction factor" for the Varley measurements can be determined:

$$\frac{M + F}{M - F} + \frac{2MF}{N(M - F)} = \frac{2r}{V_1 + V_2}.$$

Substituting this value of the correction factor in Formula (7):

$$x = \frac{rV_1}{V_1 + V_2}. \qquad (9)$$

Likewise, the resistance of one wire between End 1 of the cable and the faults is:

$$(r - x) = \frac{rV_2}{V_1 + V_2}. \tag{10}$$

Application: To apply the Double Varley method, ordinary Varley measurements, V_1 and V_2, are made from the two ends of the cable, using bridges with equal ratio arms, and the loop resistance, $2r$, of the wires is measured. The location, x or $(r - x)$, can be calculated from Formula (9) or (10), and then converted into feet in the usual manner.

Similarly, using the Rule of Resultant Faults, it can be shown that Formulas (9) and (10) also apply when only one of the wires used for Varley measurements is faulty. In this case the resistance, x, of the portion of the faulty wire between the distant end of the cable and the fault is:

$$x = \frac{V}{2} + V\frac{F}{N},$$

where V is the balancing resistance for a Varley measurement made from one end of the cable. This formula indicates that, where the ordinary Varley method (Figs. 5 and 6) is used, the insulation resistance of the "good" wire should be at least several hundred times as high as the fault resistance of the faulty wire. If this condition does not obtain the Double Varley method should be used. It will be clear, however, that the Double Varley method may be used, if desired, instead of the ordinary Varley method in cases where a wire of sufficiently high insulation resistance to be a "good" wire is available. In such cases the sum of the Varley balancing resistances obtained by measurements from the two ends of the cable will be equal to the loop resistance and Formula (9) will reduce to Formula (1).

The Double Varley method is workable only if the conductor resistances of the two wires used for measurements are equal. It can be shown that, if the conductor resistance of the wire having the fault, M, is r_m and that of the wire having the fault, F, is r_f, and if the normal insulation resistances of the wires are equal and uniformly distributed so that they may be regarded as concentrated at the middle of each wire, Formula (9) becomes:

$$x = r_f\left\{\frac{\frac{V_1}{2}[2MF + N(M + F)] + \frac{r_f - r_m}{2}[MF + N(M + F)]}{\frac{V_1 + V_2}{2}[2MF + N(M + F)] + (r_f - r_m)[MF + N(M + F)]}\right\}.$$

As indicated by the above discussion, the limitations of the Double Varley method are as follows:

1. There must be only one actual fault on any one cable wire.
2. The fault resistances must remain constant throughout a set of measurements to determine V_1 and V_2.
3. If both of the wires used for the Varley measurements are faulty, the faults must be at the same point on each wire, the resistances of the faults must be unequal, and the resistance of the fault on at least one of the wires must be high compared to the conductor resistance of the wire.
4. If the fault resistances are high enough to be comparable in magnitude to the normal insulation resistances of the faulty wires, the normal insulation resistances must be equal, and correspondingly distributed along the wires.
5. The conductor resistances of the wires must be equal.

It will be understood that since the Double Varley method is applicable only when the resistance of the fault, M, is high compared to the conductor resistances of the wires, the Corrected Varley method or the Straight Resistance method should be used in cases where M is comparable in magnitude to the conductor resistances.

Series Resistance Unbalances

The methods for locating series resistance unbalances discussed in this paper involve essentially the balancing of the faulty wire against a "good" wire of equal capacitance by adding resistance to the "good" wire at the testing end until the effective impedances of the two wires are equal. A simple relationship then exists between the balancing resistance required, the resistance of the fault, the length of the faulty wire between the distant end of the cable and the fault, and the total length of the faulty wire. The circuit arrangement used depends on whether the cable under test is long or short.

The circuit arrangement for applying the test to short cables is shown in Fig. 13.

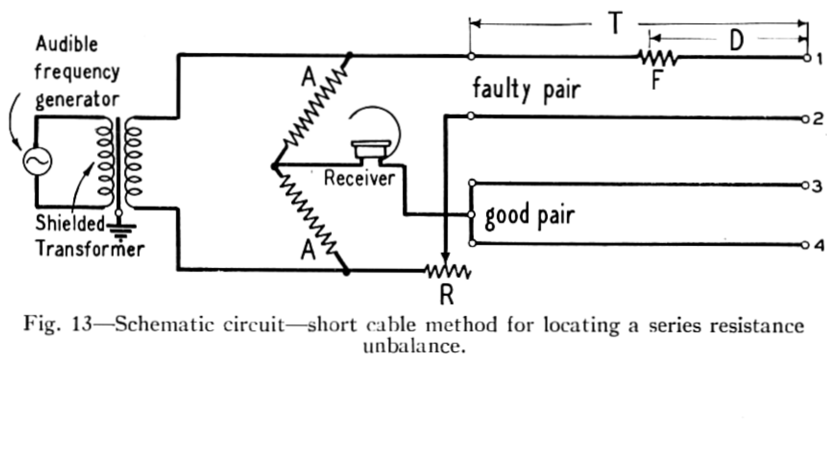

Fig. 13—Schematic circuit—short cable method for locating a series resistance unbalance.

The wires 1–2 and 3–4 form the pairs of a quad containing a series unbalance of resistance, F. The total length of the faulty wire is T, and the length of the portion of the faulty wire between the distant end of the cable and the fault is D. The bridge has equal ratio arms, A, and a balancing resistance, R. The audible frequency generator is a buzzer or other source of relatively low frequency current.

The bridge is balanced first with the distant ends of wires 1, 2, 3 and 4 open, and then with the distant ends of wires 1, 2, 3 and 4 connected together. The location of the unbalance from the distant end can be calculated from the formula:

$$D = T\sqrt{\frac{R_0}{R_c}},$$

where R_0 and R_c are the balancing resistances for the measurements with the distant end open and the distant end short-circuited, respectively. This test is suitable for use only on non-loaded cable, up to a few miles in length.

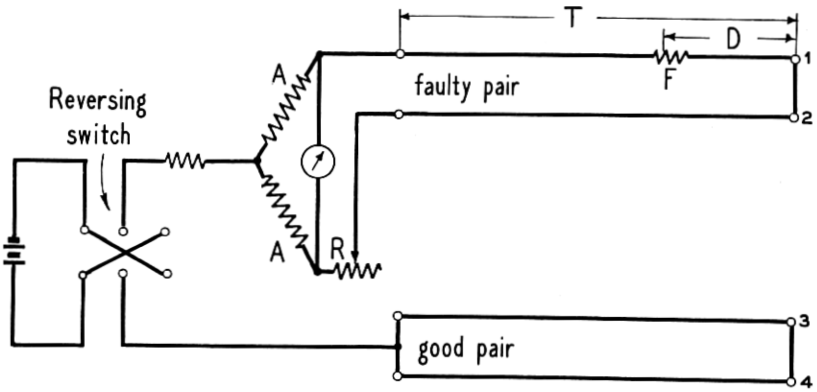

Fig. 14—Schematic circuit—long cable method for locating a series resistance unbalance.

The bridge arrangement for applying the test to long (either loaded or non-loaded) cables differs from that for short cables in that the wires of each pair, 1–2 and 3–4, are connected together at the distant end when measuring R_0, and a testing current of very low frequency is used. A battery, reversed either manually or by means of a motor-driven commutator, provides a satisfactory source of current, as indicated in Fig. 14.

With the wires of each pair, 1–2 and 3–4, connected together at the distant end as shown, the balancing resistance is adjusted to a value

R_0 at which no deflection of the galvanometer occurs when the battery is reversed. The two short-circuited pairs are then connected together at the distant end, the reversing switch is left in one position, and the rheostat is adjusted to a value R_c to balance the bridge. The location of the unbalance from the distant end is:

$$D = T\frac{R_0}{R_c}.$$

As will be clear from the following discussion, both the formula for the short cable method and that for the long cable method are based on the assumption that the wires under test are of short electrical length. Theoretically, either method could be used with cables of any physical length provided the testing frequency were chosen properly. The specific measuring schemes described here are well adapted to practical application, however.

Short Cable Method [4]

When the bridge measurement is made with the distant ends of wires 1, 2, 3 and 4 open, as shown in Fig. 13, the impedance of wire 1 to 3–4 is compared to the impedance of wire 2 to 3–4. Assume a

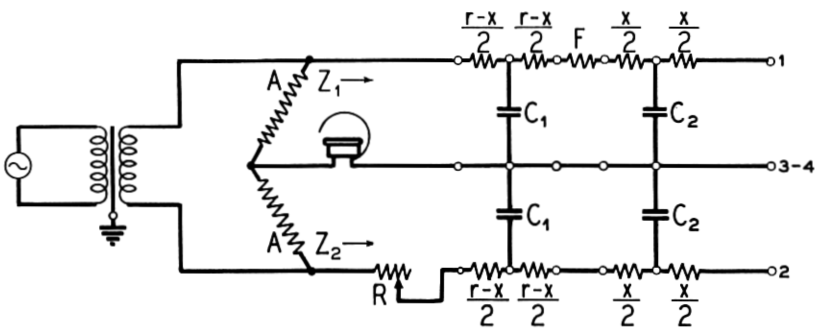

Fig. 15—Equivalent circuit—short cable method for locating a series resistance unbalance.

testing current of sufficiently low frequency that the wires are electrically short. Calling the capacitance and the conductor resistance of the length $(T - D)$ of each wire, C_1 and $(r - x)$, respectively, and of the length D of each wire, C_2 and x, respectively, the bridge circuit of Fig. 13 is practically equivalent to that of Fig. 15.

The impedance presented to the bridge terminals by the network

[4] The short cable method is described briefly in the paper, "Cable Testing," by E. S. Ritter, loc. cit.

containing F can be determined by inspection to be:

$$Z_1 = \frac{r-x}{2} + \frac{\frac{1}{j\omega C_1}\left[\frac{r}{2} + F + \frac{1}{j\omega C_2}\right]}{\frac{r}{2} + F + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}},$$

where j is the operator $\sqrt{-1}$ and ω is 2π times the testing frequency.

Likewise, the impedance presented to the bridge terminals by the network containing R is:

$$Z_2 = R + \frac{r-x}{2} + \frac{\frac{1}{j\omega C_1}\left[\frac{r}{2} + \frac{1}{j\omega C_2}\right]}{\frac{r}{2} + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}}.$$

When the bridge is balanced, these two impedances are equal, so that:

$$\frac{r-x}{2} + \frac{\frac{1}{j\omega C_1}\left[\frac{r}{2} + F + \frac{1}{j\omega C_2}\right]}{\frac{r}{2} + F + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}} = R_0 + \frac{r-x}{2} + \frac{\frac{1}{j\omega C_1}\left[\frac{r}{2} + \frac{1}{j\omega C_2}\right]}{\frac{r}{2} + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}}.$$

This equation reduces to:

$$\left[\frac{r}{2} + F + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}\right]\left[\frac{r}{2} + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}\right] = \left[\frac{1}{j\omega C_1}\right]^2 \frac{F}{R_0}.$$

For a testing current of relatively low frequency the capacitive reactances, $1/j\omega C_1$ and $1/j\omega C_2$, are much larger than the resistances, r and F, and the above equation can be written as follows, the symbol $\doteq$ being used to denote "is practically equal to":

$$\left[\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}\right]^2 \doteq \left[\frac{1}{j\omega C_1}\right]^2 \frac{F}{R_0},$$

$$\sqrt{\frac{R_0}{F}} \doteq \frac{C_2}{C_1 + C_2}.$$

Since C_2 is proportional to the length D and $(C_1 + C_2)$ to the total length, T:

$$\sqrt{\frac{R_0}{F}} \doteq \frac{D}{T}.$$

When the bridge is balanced to the value R_c, with the distant ends of wires 1, 2, 3 and 4 connected together, the amount of unbalance between wires 1 and 2 is measured. Assuming that F is the only unbalance present, and that the conductor resistances of wires 1 and 2 are equal:

$$R_c = F$$

and therefore:

$$D \doteqdot T\sqrt{\frac{R_0}{R_c}}. \tag{11}$$

Application: It will be clear from the above theory that Formula (11) will give accurate results only if the following requirements are met:

1. The resistance, F, must be the only unbalance on the wires.
2. The resistance of the unbalance must remain constant throughout a set of measurements to determine R_0 and R_c.
3. The conductor resistances of wires 1 and 2 must be equal.
4. The capacitive reactances of wires 1 and 2 to 3–4 must be large as compared to the conductor resistances of the wires and the fault resistance.
5. Capacitance unbalances of wires 1 and 2 to 3–4 must be negligible.

In general, the short cable method is suitable for locating, with a fair degree of accuracy, series resistance unbalances ranging from a few ohms to several hundred ohms on non-loaded cable not exceeding three or four miles in length. In cases of unbalances of only a few ohms resistance, however, it is essential that the wires of the faulty quad be very well balanced in conductor resistance; and the bridge rheostat should be variable in steps of 0.1 ohm. Usually, best results are secured when measurements are made from the cable end nearer the fault.

The bridge voltage used should be as small as practicable in order to minimize changes in fault resistance. A sufficient number of separate determinations of the location should be made to insure that consistent results are being secured.

The measurement with the distant ends of wires 1, 2, 3 and 4 connected together is made merely to obtain the actual value of fault resistance. The value of fault resistance can be obtained instead by a d.-c. Varley measurement, if desired. If this is done, however, arrangements should be made so that the bridge connections can be changed rapidly, as it is desirable to make measurements of R_0 and R_c in quick succession to avoid errors due to changing fault resistance.

The short cable method is applicable to paired cable as well as to quadded cable. In the case of paired cable, ground may be substituted for wires 3–4, and measurements made of impedance to ground rather than of impedance between wires. Usually in these circumstances, however, the bridge cannot be balanced very sharply.

Long Cable Method [5]

Referring to Fig. 14, assume that the wires under test are non-loaded and that a testing current of very low frequency is used so that the wires are electrically short. Calling the capacitance and the

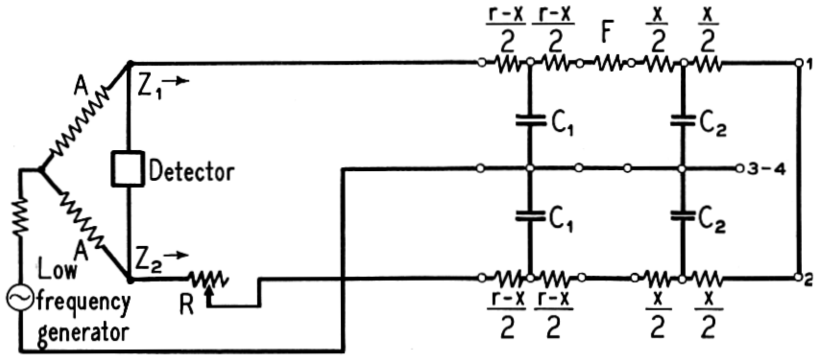

Fig. 16—First equivalent circuit—long cable method for locating a series resistance unbalance.

conductor resistance of the length $(T - D)$ of each wire, C_1 and $(r - x)$, respectively, and of the length D of each wire, C_2 and x, respectively, the bridge circuit of Fig. 14 is practically equivalent to that of Fig. 16.

When the bridge is balanced so that there is no current through the detector, the impedance Z_1 looking into the upper branch of the net-

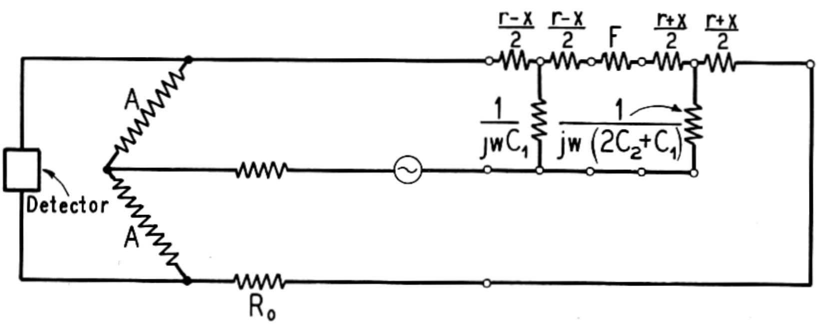

Fig. 17—Second equivalent circuit—long cable method for locating a series resistance unbalance.

work must be equal to the impedance Z_2 looking into the lower branch. At the balance point the bridge circuit is practically equivalent to that shown in Fig. 17, in which the network up to the point of fault, as seen from the bridge terminals of the lower branch, is replaced by a single resistance-capitance network.

[5] Credit for the long cable method is given to Capt. F. Reid in the paper, "Cable Testing," by E. S. Ritter, loc. cit.

The network of Fig. 17 can be replaced by the equivalent network of Fig. 18. The values of the impedances h, k and p of Fig. 18 are:

$$h = \frac{r-x}{2} + \frac{\dfrac{1}{j\omega C_1}(r+F)}{\dfrac{1}{j\omega C_1} + \dfrac{1}{j\omega(2C_2+C_1)} + r + F},$$

$$k = \frac{\dfrac{1}{j\omega C_1}\left[\dfrac{1}{j\omega(2C_2+C_1)}\right]}{\dfrac{1}{j\omega C_1} + \dfrac{1}{j\omega(2C_2+C_1)} + r + F},$$

$$p = \frac{r+x}{2} + R_0 + \frac{\dfrac{1}{j\omega(2C_2+C_1)}(r+F)}{\dfrac{1}{j\omega C_1} + \dfrac{1}{j\omega(2C_2+C_1)} + r + F}.$$

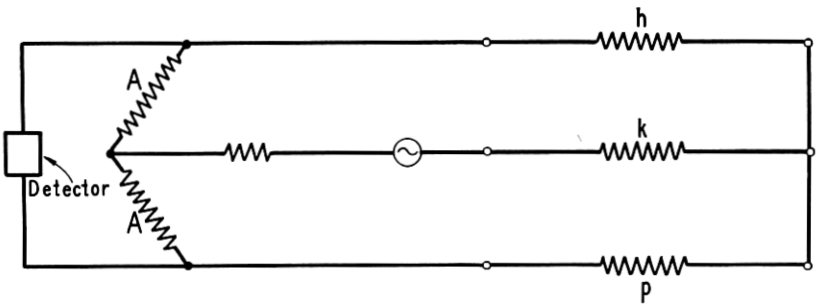

Fig. 18—Third equivalent circuit—long cable method for locating a series resistance unbalance.

It is evident from inspection of Fig. 18 that if h equals p the network is balanced so that there is no current through the detector. Equating the values of h and p, and solving gives:

$$\frac{R_0}{F} = \frac{\left[\dfrac{1}{j\omega C_1} - \dfrac{1}{j\omega(2C_2+C_1)}\right] + \dfrac{r}{F}\left[\dfrac{1}{j\omega C_1} - \dfrac{1}{j\omega(2C_2+C_1)}\right]}{\dfrac{1}{j\omega C_1} + \dfrac{1}{j\omega(2C_2+C_1)} + r + F} - \frac{x}{F}.$$

If the capacitive reactances of the wires are very high compared to the conductor resistances and the fault resistance, this last equation can be reduced to:

$$\frac{R_0}{F} \doteq \frac{C_2}{C_1+C_2} + \frac{r}{F}\left[\frac{C_2}{C_1+C_2}\right] - \frac{x}{F},$$

and since, for a testing current of very low frequency, C_2 and x are proportional to D, while $(C_1 + C_2)$ and r are proportional to T:

$$r\left[\frac{C_2}{C_1 + C_2}\right] = x,$$

and we may write:

$$\frac{R_0}{F} \doteq \frac{D}{T}.$$

When the bridge is balanced to the value R_c with wires 1, 2, 3 and 4 connected together at the distant end, the amount of unbalance between wires 1 and 2 is measured. Assuming that F is the only unbalance present, and that the conductor resistances of wires 1 and 2 are equal:

$$R_c = F$$

and therefore:

$$D \doteq \frac{R_0}{R_c} T. \qquad (12)$$

Application: The same general requirements set down for the short cable method must be met to secure accurate results with the long cable method. While Formula (12) has been developed specifically for non-loaded cable, it is clear that it applies also to loaded cable, provided the effective series impedances of the wires, including the loading coils, are very low compared to the effective shunt impedances of the wires. A testing frequency of three or four cycles per second is sufficiently low to satisfy this requirement on telephone cables up to a repeater section in length. If, however, the cable is only a few miles in length, the effective sensitivity of the bridge may be too low for satisfactory results.

In general, the long cable method is suitable for locating, with reasonable accuracy, series resistance unbalances ranging from about 10 ohms to several thousand ohms. A well insulated bridge and a fairly sensitive galvanometer are desirable, especially when working with faults of low resistance.

An essential requisite for accurate results is that the resistance of the fault remain constant while a set of measurements to determine R_0 and R_c is being made. In the application of the method, therefore, the bridge voltage used should be as low as practicable. Bridge voltages of, say, 100 volts for measuring R_0 and six volts or less for measuring R_c are usually satisfactory. In this connection it can be pointed out that if measurements R_{01} and R_{02} are made from the two ends of the cable it is unnecessary to measure R_c since $(R_{01} + R_{02})$ will equal F

and Formula (12) can then be written:

$$D \doteqdot T\frac{R_{01}}{R_{01} + R_{02}}.$$

In cases where the fault resistance appears to be affected appreciably by the testing current this scheme of measuring may be found desirable.

It has been found that, when a battery and manually operated battery reversing switch are used and the balance point of the bridge is determined by observing the galvanometer kicks as the battery is reversed, the action of the galvanometer is somewhat as follows: For settings appreciably below the balance point the galvanometer kicks are definitely in one direction while for settings which are too high the kicks are definitely in the opposite direction (assuming, of course, that the polarity of the battery is taken into account). When the rheostat setting is very close to the point of balance but slightly too low, the galvanometer gives a quick double kick, i.e., the needle moves away from galvanometer zero, then returns toward zero a short distance and again moves away from zero. When the rheostat setting is slightly too high, the galvanometer gives a single kick and then coasts toward the end of the scale. The balance point of the bridge is where the transition from double to single kick occurs.

When the value of R_0 is low a rheostat variable in steps of 0.1 ohm may be necessary if the transition point is to be accurately obtained.

Seasoned judgment is an essential adjunct to a knowledge of theory in the practical application of fault locating methods. This is especially true in the case of methods such as those discussed here, with which accurate results cannot be secured unless the fault resistances remain constant in value while a set of measurements to determine location is being made. Experience has indicated that cable faults of the types discussed are apt to be inconstant in resistance. Great care must be exercised, therefore, in interpreting the results of measurements. It is very important to make a sufficient number of separate sets of measurements to insure that consistent data are being obtained.