No. 192

The Institution of Post Office Electrical Engineers.

The Location of Faults in Lines and Cables

Capt. A. C. TIMMIS, B.Sc., M.I.E.E.

A Paper read before the London Centre of the Institution on 6th January, 1948, and at other Centres during the Session.

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CONTENTS

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Introduction.

Although there are many reasonably simple methods of determining the position of a fault by measuring resistance or capacitance at one end of the circuit too many faults are still dealt with, in practice, by methods which should nowadays be regarded as obsolete.

The loss of revenue while a trunk circuit is out of order, is not the only consequence of such methods. The value of the manhours wasted can easily amount to several times the cost of testing equipment and the skilled staff to use it.

It is the main object of this paper, therefore, to present those fault-location tests which have been found most useful in practice for overhead lines and underground cables. The location of submarine cable faults is a specialised subject, but two particularly useful tests of this kind are included in Appendix III.

Pulse fault location, or Radar applied to lines, is still in the development stage but has progressed far enough to show that it is the ideal method where speed is the foremost requirement, as for military lines. The technique has already been applied to coaxial cables, both underground and submarine.

Many of the fault-location tests which are listed under Section 4 have been described in a previous paper—Telephone Cable Testing—read in 1931 by Palmer and Jolley(1)*, but they are included here for convenience of reference, with the grateful acknowledgements of the author.

1. INSULATION FAULTS.

1.1. D.C. Methods of Fault Location.

It seems to be a characteristic of faults on overhead lines that very often they are not simple faults, such as a full earth on one wire of a pair, or a short circuit, which can be located by an ordinary Varley test. An intermittent fault, such as a tapping contact is almost impossible to locate by any bridge method. With pulse location equipment, however, there is no difficulty provided that the fault is severe enough to have a serious effect on the circuit. Generally, speed is more important than accuracy on aerial lines.

Cables are not so liable to intermittent faults, but once water has entered a paper-insulated cable all wires may become faulty if the trouble is not detected in the early stages, by regular insulation measurements. It is quite practicable by means of a Varley test, to locate an insulation fault of 200 or 300 megohms, so that the leak can be repaired long before the insulation has fallen to a figure comparable with the characteristic impedance, when it would have a noticeable effect on the working circuits. In general, it can be said that on aerial lines the first requirement is to ascertain the nature of the faults—their position can always, in the last resort, be found by inspecting the line—but with cables the nature of the fault is usually obvious. It should be located by electrical methods before it affects the working of the circuits.

1.1.1. *Varley Loop Test.*

For the accurate location of earth or contact faults the well-known Varley loop test is undoubtedly the best. If a good wire (*i.e.*, a wire having an insulation resistance high compared with the fault) is available this is joined to the faulty wire at the far end of the line and a Wheatstone bridge is connected as shown in Fig. **1**.

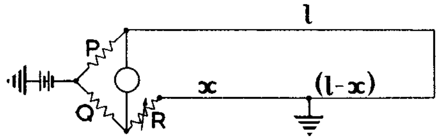

FIG. 1.—VARLEY LOOP TEST.

For all D.C. tests described here x represents the resistance of one wire to the fault and l, a, b, etc., the resistance of a wire from end to end.

If the gauge and material of a wire is known, resistance can easily be converted into length. For instance, 40 yds. of 40 lbs. copper loop = one ohm. But these figures may be in error to the extent of 1% or more, depending on temperature, deviations from nominal wire diameter, and the lay of the wires if in a cable.

When maximum accuracy is required resistance should be assumed proportional to length. For example in Fig. **1**, distance to fault $= \frac{x}{l} \times$ total length. When the loop consists of the two wires of a telephone pair it is usually safe to assume that they are of equal resistance.

The fault resistance, being in series with the battery has no effect on the balance, for which the condition is

$$\frac{P}{Q} = \frac{2l - x}{R + x}$$

whence
$$x = \frac{2l - \frac{P}{Q}R}{1 + \frac{P}{Q}}$$

If the loop consists of a pair of similar wires and P = Q, as it generally does in practice,

$$\left.\begin{array}{l}\text{Loop resistance to fault from} \\ \quad\text{near end}\end{array}\right\} = x = \frac{2l - R}{2}$$

$$\left.\begin{array}{l}\text{Loop resistance from fault to} \\ \quad\text{far end}\end{array}\right\} = l - x = \frac{R}{2}$$

When using this simple formula testing leads, or leading-in cables at the testing station, provided they are symmetrical, need not be measured.

1.1.2. *Three-wire Varley Test.*

If a good wire has to be provided by temporary means, as for instance, with a short length of cable with all wires "full earth," it is convenient to lay two

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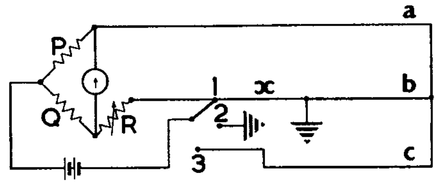
* Numerical references are to the Bibliography at the end of the Paper.

temporary wires, connecting both to the faulty wire at the far end. Three bridge measurements are then made and the distance to the fault is obtained directly, as a fraction of the cable length. In Fig. **2** the resistance of the three wires are a, b and c and x is the resistance of the faulty wire up to the fault.



$$\frac{x}{b} = \frac{R1 - R2}{R1 - R3}$$

FIG. 2.—3-WIRE VARLEY TEST.

$$\text{Switch position } 1, \frac{P}{Q} = \frac{a+b}{R_1}$$

$$\text{,, ,, } 2, \frac{P}{Q} = \frac{a+b-x}{R_2+x}$$

$$\text{,, ,, } 3, \frac{P}{Q} = \frac{a}{b+R_3}$$

$$\text{Whence } \frac{x}{b} = \frac{R_1 - R_2}{R_1 - R_3}$$

Since $\frac{P}{Q}$ does not appear in the formula any convenient ratio such as $\frac{P}{Q} = \frac{1}{10}$ or $\frac{1}{100}$, may be used.

The order of switching shown is most convenient when a bridge megger is being used. For position 3 put C on Varley terminal.

Let $\frac{Q}{l} = n$. Then the resistances x, b, and $b-x$ are given by:—

$$x = \text{resistance out} \quad = \frac{R_1 - R_2}{n+1}.$$

$$b-x = \text{resistance back} \quad = \frac{R_2 - R_3}{n+1}$$

$$b = \text{total} \quad = \frac{R_1 - R_3}{n+1}$$

The readings are easily checked, since x and $b-x$ should add up to b.

Sensitivity. If an ordinary Wheatstone bridge is used with separate battery and galvanometer the ratio arms should be low for short loops and high for high-resistance loops, but the most important factor in practice is the resistance of the fault. Accurate measurement is possible with fault resistances exceeding 300 megohms, but only with a high battery voltage and a sensitive reflecting galvanometer.

The bridge megger is the most convenient portable form of Wheatstone bridge, and its sensitivity can be improved by putting a 200 or 300V battery in series with the Varley earth connection, so adding to the generator voltage. The positive end of the battery must be connected to earth.

An improved bridge megger is arranged to apply 500 volts instead of 250 volts when in use for bridge measurements and increases the sensitivity for Varley tests as shewn in the Table:—

CHANGE OF RESISTANCE IN OHMS WHICH CAN JUST BE DETECTED.

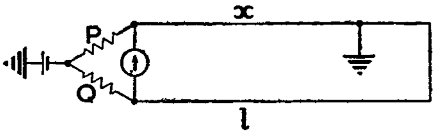
Fault resistance.	With normal bridge megger.	With 500V Model or additional battery.
½ megohm	under 2	under 1
1 ,,	2	1
2 ,,	5	3
3 ,,	10	5
6 ,,	—	10

Reasonably accurate locations can therefore be expected up to ½ megohm, or 1 megohm with the improved megger.

1.1.3. *Murray Loop Test.*

On telephone cables the Varley loop test is usually more convenient than the Murray. The latter is preferred on heavier conductors, such as coaxial and power cables and for this reason later patterns of the bridge megger include facilities for the Murray test.

The principle will be evident from Fig. **3**.



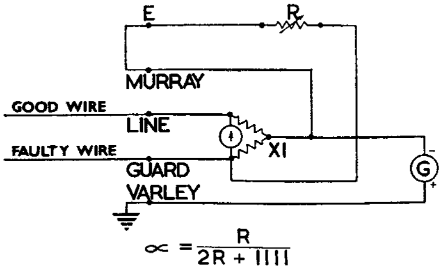
$$\alpha = \frac{P}{P+Q}$$

FIG. 3.—MURRAY TEST.

If the ratio $\frac{P}{P+Q}$ is called α, the resistance P + Q may be regarded as a slide-wire with a ratio of α, which is less than ½.

Since the balance involves only the ratio of P and Q these resistances need not be variable in small steps, even when the loop is of very low resistance. This is the main advantage of the Murray test.

Assuming both wires are of the same gauge, $x = \alpha \times 2l$. The bridge megger is made to act as a slide wire by using the guard terminal as shown in Fig. **4**. The variable resistance shunts one of the ratio arms and the slide-wire ratio α is given by $= \frac{R}{2R + 1111}$, the ratio switch being at X1.



$$\alpha = \frac{R}{2R + 1111}$$

FIG. 4.—MURRAY TEST WITH BRIDGE MEGGER.

In telephone work the Murray arrangement of the bridge megger is useful as part of the special bridge required for locating a complete insulation breakdown by Poleck's method. This method is described later on.

The Murray test is sometimes useful on short lengths of telephone cable, as well as on moderate lengths of power cable. The heaviest gauge normally met with is 40 lbs. per mile (80 yds. per ohm) in the former, but in the latter conductors measuring 300 yds. per ohm are not unusual. Since the smallest convenient reading on the variable arm of a bridge is 1/10 ohm, it is evident that a Varley test would only be accurate to 80 or 100 yds. on these heavy conductors, and to 4 or 5 yds. on 40 lb. conductors.

The Murray test, on the other hand, depends on the ratio of two resistances, which may both be of the order of 1000 ohms, and it is sufficient if one of the resistances is variable in steps of one ohm. Two modifications of the original Murray test, useful for short lengths of cable when the good wire is not of the same gauge or length as the faulty wire are therefore included here.

1.1.4. *Murray-Fisher Test.*

Fig. **5** shows the Murray-Fisher test(10). To allow for the resistance (m) of the good wire a balance is made with the switch in position 2.

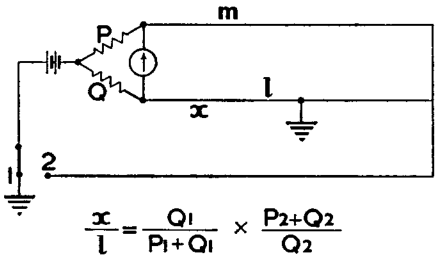


FIG. 5.—MURRAY-FISHER TEST.

Then $P^1/Q^1 = \frac{m}{l}$,

and the formula for x becomes

$$\frac{x}{l} = \frac{Q}{P + Q} \times \frac{P' + Q'}{Q'}$$

P and Q being the readings with the switch in position 1. A bridge megger with " Murray " terminal can be used for this test.

1.1.5. *Hilborn Test.*

When two good wires are available the Hilborn test (Fig. **6**) gives the answer from a single balance, if one of the good wires is of low resistance (r), so that it may be neglected in comparison with P or roughly estimated.

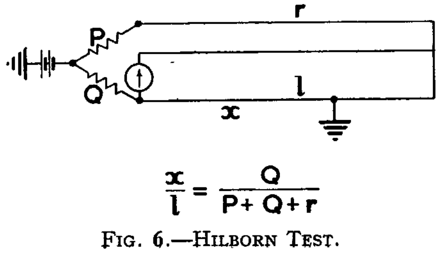


FIG. 6.—HILBORN TEST.

As will be seen from the diagram r forms part of the P arm, and the other good wire is in series with the galvanometer, so that its resistance is immaterial.

The formula is $x/l = \frac{Q}{P + Q + r}$

A bridge megger cannot be used for the Hilborn test(10).

1.1.6. *Varley Loop Test for a Contact.*

The Varley loop test may be applied to a contact fault when a third wire, free of earth or contact is available. One of the faulty wires is joined to the E terminal and the contact is then treated as an earth fault.

A useful modification of this method enables a contact between two overhead wires to be located without using a third wire. One wire is earthed at the far end, and a bridge or bridge-megger connected as shown in Fig. **7**.

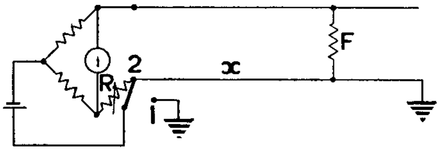


FIG. 7.—VARLEY TEST FOR A CONTACT.

The Varley measurement (with equal ratio arms) gives

$$R_1 = F$$

and the loop measurement

$$R_2 = 2x + F$$

Hence $x = \frac{1}{2}(R_2 - R_1)$

The change from Varley to loop measurement should be made as rapidly as possible, so that the fault resistance does not have time to change. As this method only applies to a pure contact it is more useful on overhead lines than cables.

1.1.7. *Overlap Test.*

The majority of earth or contact faults vary considerably in resistance with the magnitude and direction of the testing current. Any fault location method which does not eliminate the fault resistance is therefore liable to be inaccurate, but when the testing equipment is limited to a bridge or voltmeter for measuring loop resistance a very rough location can be made from one end by measuring the resistance through the fault. If several faulty wires are measured the lowest resistance will indicate something more than the true distance of the contact, depending on the resistance of the fault. In submarine cable testing various methods are used to allow for the fault resistance (which depends on the magnitude and direction of the current), but they do not apply to land lines or cables. There the fault resistance, if lower than the loop resistance of the line, can be eliminated by testing from both ends. The simplest method is known as the " overlap test "

Assume that the loop resistance from A to the fault = X and from the fault to B = Y, and let the fault resistance itself = F.

Measuring from A we have $R_A = X + F$

,, ,, B ,, ,, $R_B = Y + F$

The total loop resistance X + Y being estimated or recorded

$$R_A + R_B = (X + Y) + 2F$$

$$F = \frac{R_A + R_B - (X + Y)}{2}$$

$$\text{and} \quad X = R_A - F$$

The measurements at A and B should be made within as short a time as possible to reduce the error which nearly always arises from changes in the fault resistance.

1.1.8. *Blavier Test.*

When the fault resistance is low and fairly constant a location can be made from one end by the Blavier test. Loop resistance is measured through the fault with the far end open ($=R_f$) and then with the far end closed ($=R_c$).

Let X = loop resistance to fault

L = whole loop resistance

Then $X = R_c - (R_f - R_c)(L - R_c)$

The Blavier is less accurate than the overlap test, though it has the advantage of requiring measurement from one end only.

Both tests may obviously be applied to an earth fault, but the terminal earth resistances may cause further errors.

1.1.9. *Tests for use when a good wire is not available.*

1.1.9.1. *Corrected Varley Test.*

Generally when water penetrates a paper-insulated cable the insulation of all the wires is affected. At first some wires show an insulation of perhaps 1 megohm, while others show 50 or 100 megohms. One of the latter could be regarded as a " good " wire for the purpose of a Varley test without serious error. As the water spreads, however, the worst wires may fall to 1/10 megohm or less, and the best to a megohm or so. The insulation of the " good " wire being then comparable with that of the faulty wire, the simple theory of the Varley test no longer holds but correction factors can be applied, based on the insulation figures. Better still, by making tests from both ends of the line it is possible to eliminate these inconstant quantities from the final equation(2, 3, 4).

The principle underlying all these methods is the correction of the Varley test to allow for the insulation of the good wire being comparable with the fault and (when insulation is very low) the loop resistance being comparable with the insulation of the " good " wire. It is assumed that, apart from the fault, the cable insulation is high enough to be regarded as infinite.

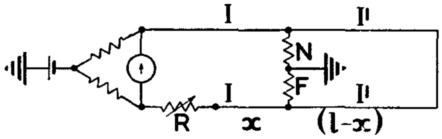


FIG. 8.—CORRECTED VARLEY TEST.

In Fig. **8** a bridge with equal ratio arms is shown, and the line wires are assumed to be of the same gauge.

x = single-wire resistance to the fault

l = ,, ,, ,, ,, ,, far end

N = insulation resistance of " good " wire

F = ,, ,, ,, faulty wire

R = Varley resistance

I, I^1 = currents at balance

When the bridge is balanced,

$$Ix + (I - I^1)N = I(R + x) + (I + I^1)F$$

$$I^1.2\,(l - x) + (I + I^1)\,F = (I - I^1)N$$

Hence $I(N - F - R) = I^1\,(F + N)$

and $I(N - F) = I^1\,[2(l - x) + F + N]$

dividing $\dfrac{N - F - R}{N - F} = \dfrac{N + F}{2(l - x) + N + F}$

Hence $2(l - x) = R \times \dfrac{N + F}{N - F} \times \left(1 + \dfrac{2(l - x)}{N + F}\right)$

or, loop resistance beyond fault

— Varley resistance × correction factor for insulation of good wire.

× correction factor for loop resistance being comparable with insulation.

In Appendix I the idea of " equivalent faults " from which correction factors for this and other conditions may be derived, is explained.

If N is infinite both correction factors = 1, and we have the usual formula for the Varley loop test. For incipient faults of the order of 100,000 ohms, the *second* correction factor may be neglected. Assuming, for example, that $2(l - x) = 2000$, corresponding to a fault in the middle of a 40-mile length of 20 lbs. cable, and that F = 100,000 and N = 300,000 the correction

$$\text{factor} = 1 + \frac{2{,}000}{400{,}000}$$

$$= 1.005$$

The *first* correction factor, however, depends on the ratio of the insulation resistances. It may be written $1 + 2\dfrac{F}{N}$, when $\dfrac{F}{N}$ is small, and in this case = 1.7 approx. If the insulation resistances could be measured with the same currents that flow during the Varley test the correction factor could be calculated with reasonable accuracy; but in practice the insulation resistance measured with a megger or testing voltmeter may be very different. If $\dfrac{N}{F} = 100$, for instance, the correction factor = 1.02 and a change in the ratio $\dfrac{N}{F}$ to 50 or 150 merely changes the factor to 1.04 or 1.013. On the other hand, when the " good " wire insulation is only 3 or 4 times that of the faulty wire it is obvious that the correction factor cannot be regarded as more than a rough guide. It is then necessary to use one of the more elaborate tests which eliminate the correction by testing from both ends of the line. The most accurate of these is the double-ended Varley test.

1.1.9.2. *Double-ended Varley Test.*

A Varley loop test is made first at one end and then at the other, before the insulation resistances have time to change, and preferably with the same total current through the bridge.

Let R_a = Varley resistance measured from *a*

R_b = ,, ,, ,, ,, *b*

Assuming that the insulation resistances are constant

$$2(l - x) = R_a \frac{N + F}{N - F} \text{ and } 2x = R_b \frac{N + F}{N - F}$$

Eliminating the factor $\frac{N + F}{N - F}$ we find that the distance of the fault is given by the following expression, which does not contain the insulation resistances ;

$$x = \frac{R_b}{R_a + R_b} l$$

If the ratio $\frac{F}{N}$ varies by a certain percentage between the two tests the result is affected, but the percentage error is much less.

The effect of the second correction (which depends on the ratio of F + N to the loop resistance) is not completely cancelled out by testing from both ends but it is reduced, especially if the fault is near the middle, or either end, of the line.

1.1.9.3. *Behrend's Test.*

Another modified Varley test⁽⁴⁾ ⁽⁵⁾, which eliminates the insulation resistances from the formula, is due to Behrend. (Fig. **9**). A Varley test is made from one end, first with the wires looped at the other end in the ordinary way, and then with a suitable resistance S at the far end. In practice S is made roughly equal to half the total loop resistance, and provided with a short-circuiting switch, so that a quick change-over can be made.

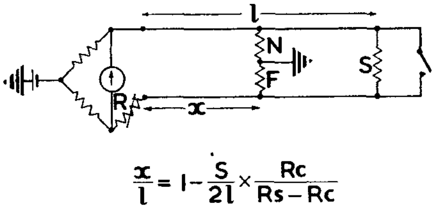


FIG. 9.—BEHREND TEST.

If R_c = the Varley resistance with the end short-circuited

R_s = the Varley resistance with S in series

and F + N is at least 120 times the total resistance (error due to neglecting second correction factor less than 1% unless the fault is near testing end when it is just over 1%)

$$\text{then } x = l\left(1 - \frac{S}{2l} \times \frac{R_c}{R_s - R_c}\right) \text{ ohms}$$

The effects of the second correction factor, which modifies R_s and R_c appreciably if the above condition is not satisfied, do not in general cancel out, but the method is suitable for high insulation faults, such as a ½ megohm faulty wire with a 1 megohm "good" wire. Unless testing facilities are available at both ends of the line the Behrend method is much easier than a double Varley, no expert assistance being required at the far end.

The double Varley test can be used when the insulation of the two wires apart from the fault is comparable with F and N, provided that it has the same value (M) for each wire, as might be the case if the insulation of the whole cable was low at some point. The first correction factor, $1 + \frac{2F\ (N + M)}{M\ (N - F)}$ cancels out. In the Behrend test the correction factor tends to cancel out if the insulation resistances M_1 and M_2 are unequal. (See Appendix II.)

1.1.9.4. *Poleck's Test.*

When the insulation of all wires is very low, measured in hundreds or thousands of ohms, as in a cable breakdown, the best method is that of Hans Poleck⁽⁶⁾. Like the modified Varley tests it requires two wires whose insulation resistances differ in a ratio of at least 2 to 1, but no corrections are needed, and at the far end a short circuit has merely to be put on and off.

The arrangement is shown in Fig. **10**. When the slide wire and *r* have been correctly adjusted the bridge is balanced whether the short circuit is on or off. In practice it is not difficult to achieve this balance, if the slide wire is first adjusted with the short circuit off and then *r* with the short circuit on. The settings are finally checked by having the short put on and off two or three times. The distance to the fault, in ohms, is given by

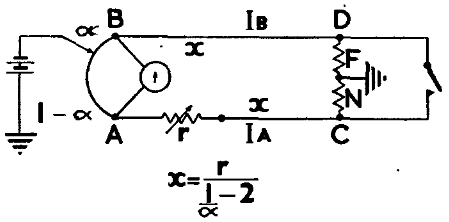


FIG. 10.—POLECK TEST.

$$x = \frac{r}{\frac{1}{a} - 2}$$

Both wires must be of the same gauge, at least up to the fault. The derivation of the formula, and conditions for sensitivity are given in Appendix I.

A bridge-megger provided with a "Murray" terminal may be used for the Poleck test as shown in

Fig. **11** (*a*). Any convenient variable resistance will serve for " *r*." After balancing its value is measured

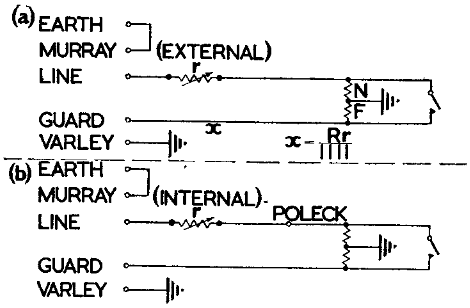


Fig. **11**.—Poleck Test with Bridge Megger.

with the instrument. The formula for x reduces to

$$x = \frac{rR}{1111}$$

Where R = reading of bridge-megger with ratio switch at X1.

In a later model a terminal marked " Poleck " is provided, which enables an internal rheostat to be used as " *r*," the good wire being connected to the Poleck terminal as shown in Fig. **11** (*b*). This rheostat is continuously variable from 0 to 10,000 ohms.

1.1.9.5. *Graf's Test.*

Another test$^{(7,8)}$ which is applicable to a cable breakdown when the insulation is very low is due to Graf. In its simplest form two reasonably accurate milliammeters are required, one at each end as shown in Fig. **12**.

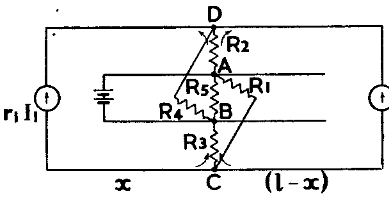


Fig. **12**.—Graf Test.

If r_1 and r_2 are the milliammeter resistances, it is evident that $\frac{2x + r_1}{2(l - x) + r_2} = \frac{I_2}{I_1} = n$, say.

Hence $x = \frac{n}{n+1}\,l + \frac{nr_2 - r_1}{2(n+1)}$ ohms. The two meters should be calibrated in series but this does not strictly give the true ratio $\frac{I_2}{I_1}$. A more accurate result can be obtained by adding a variable resistance (R) to the shorter loop until $I_1 = I_2$, according to the calibration.

Then $R + 2x = 2\,(l - x)$

and $x = \frac{l}{2} - \frac{R}{4}$ ohms.

The four wires should be selected so that R_5 is high (because it shunts the battery) and the battery voltage should be high enough to swamp variations of current due to voltages arising from the fault.

Further, if $\frac{R_1}{R_2} = \frac{R_3}{R_1}$, CD is one diagonal of a balanced bridge (AB being the other) and no current flows through the milliammeters. This is unlikely to happen in practice however.

The Graf test is convenient on account of its simplicity, but can only be used for low-resistance faults.

1.1.10. *Fall of Potential Test for Earth or Contact in Short Lengths of Cable.*

The principle of this test will be obvious from the diagram, Fig. **13**. It may be used on a coil of cable, or cable in situ.

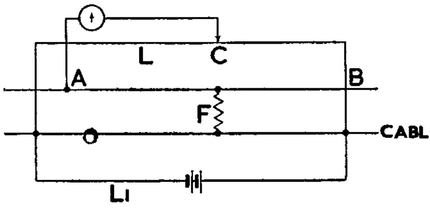


Fig. **13**.—Fall of Potential Test.

Three lengths of insulated wire are required, one being rubber or PVC covered so that a pin or prong can be used to make contact at C. With an earth fault the tapping wire is connected to earth at A. The lead must be uniform along its length. Where there is no deflection, $\frac{AC}{CB} = \frac{AF}{FB}$ and if L is laid on the ground above the cable C indicates the position of the fault.

1.2. Tests made by a lineman, or in co-operation with a lineman, to indicate whether he has passed the fault or not.

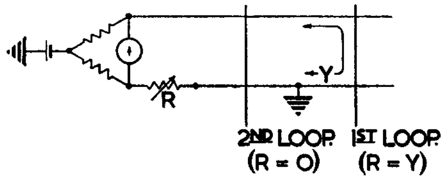
If the fault is a disconnection the lineman has only to tap in, without cutting, and if he can get the testing office it is obvious he has not passed the fault. This procedure is quite easy on overhead lines, especially if the approximate position of the fault has been determined by the testing office.

The usual method when looking for an earth or contact is to cut and test. It is objectionable, especially on overhead lines, because it leads to temporary joints, which very often give rise to disconnections or high resistance faults.

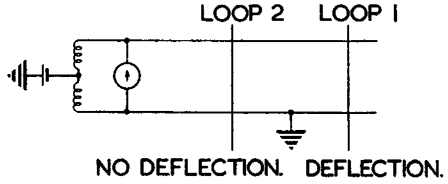
There are three simple methods which do not involve any cutting:—

1.2.1. *Varley Test.*

Assuming that the fault has been located approximately by a Varley loop test with a bridge or bridge-megger (using: 1 to 1 ratio arms) the lineman taps in and then loops the wires somewhere near the expected position of the fault. If he is beyond it, the testing station on making a Varley test will obtain a resistance reading equal to the loop resistance between the lineman's position and the fault, and should be able to tell him fairly accurately where it is. If the fault is not visible the process is repeated. Suppose that the Varley reading is zero this time. It will be obvious (from Fig. **14** (*a*)) that the lineman is now on the near side of the fault, but there is nothing to indicate exactly how far. He should, however, be near enough to find it by inspection.



(*a*) Aerial Line.



(*b*)

Fig. 14.—Varley Tests with a Lineman.

If a bridge is not available any two equal resistances (such as the windings of a differential transformer) may be used to form 1 to 1 ratio arms, with a sensitive pointer instrument as the bridge galvanometer (see Fig. **14** (*b*)). The battery should have a voltage of 50 or more according to the sensitivity of the instrument.

With loop 1, the " bridge " is unbalanced and there will be a deflection proportional to the resistance between the fault and loop 1.

With loop 2 there will be no deflection.

1.2.2. *The Listening Coil Method for Overhead Lines.*

A small coil with a jointed iron core which can be clipped over a line wire is connected to a headgear receiver. The lineman rings across the pair or between wire and earth (for a contact or an earth respectively) the wires having been left clear at both ends, and if the harmonics of the ringing current are heard the coil is on the same side of his telephone as the fault. The method is not very sensitive, but is useful on short lines.

1.2.3. *Fullerphone.*

This also is only applicable to overhead lines. The lineman rings as before, but discovers on which side the ringing current is going out by means of a temporary wire run to the next pole and tapped on the line wire. A fullerphone in series with the temporary wire makes audible the voltage due to the ringing currents in one span of the line wire. This method is more sensitive than the second and does not require any special apparatus.

1.3. A direct-reading Test Set for use on Overhead Lines.

During the war a considerable mileage of wire was erected partly on new and partly on existing lines, to serve as an emergency communication network for the R.A.F. A special test set was designed for the use of the maintenance staff, so that conductor and insulation resistances could be measured more quickly and easily than by the ordinary methods. No great accuracy is required.

The set consists essentially of a Wheatstone bridge of which the galvanometer is not brought to zero by adjusting the variable arm, but is calibrated so that its deflection is a measure of the "unknown" resistance. To cover a wide range of resistances several ratio arms are provided, and the ganged switches which select them also indicate the appropriate scale for reading the galvanometer. Because of war-time difficulties a separate set of scales with a cursor (lined up with the pointer by hand) was used instead of a multi-scale instrument.

A slide wire is used for locating earth or contact faults by the Murray method, the galvanometer being brought to zero in the usual way. A key was provided to enable the galvanometer to be used for ballistic measurements, so that disconnection faults could be approximately located but, as explained in Section 2 (*a*) the ballistic method is not satisfactory for overhead lines, unless the insulation is very high.

The simplest direct reading test set for conductor and insulation resistances is the ordinary test-desk voltmeter found in every large exchange.

It is curious that these voltmeters are not provided with scales for reading resistances directly like an ohmeter.

1.4. Methods of overcoming inductive interference during Varley or other loop tests.

When two wires in the same cable are connected at the far end for an earth fault location any difference in potential between the fault and the earth connection at the testing end is effectively in series with the battery, and if variable it may cause deflections of the galvanometer which it is difficult to separate from those due to changes made in the bridge rheostat during the balancing process. This type of interference is usually not serious, and may be reduced either by increasing the battery voltage, so that the random deflections are swamped by those due to changes in the bridge resistance, or if there is another faulty wire in the cable, connecting this to the bridge in place of earth. Thus there is only one earth on the loop, and the fault is treated as a contact instead of an earth. The second method is most useful when a modified Varley test has to be made, because several wires, including the "good" wire, are more or less faulty at the same point.

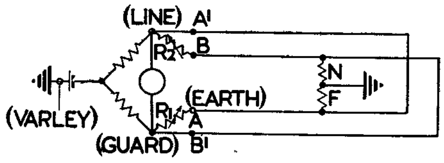
Interference from telegraphs, D.C. signalling currents, telephone circuits, etc., is much more serious, however, when the faulty wire is in one cable and the good wire in another. The inductive effects in the two wires do not balance out, and produce large random deflections which make balancing difficult.

The earth connection cannot be avoided, but the induction can be almost completely neutralised by using an arrangement described by L. Simon in " Annales des Postes, Telegraphes et Telephones," September, 1935. A second loop and bridge network exactly similar (except the battery) to the testing circuit is set up, and connected to the second winding of the differential galvanometer.

The disturbing currents picked up by the two loops oppose and cancel each other in the differential galvanometer which responds normally to unbalance currents due to the battery in the first loop. The Simon method was given a practical trial in London and proved very effective. It was found unnecessary to use a duplicate bridge network, even with the galvanometer and universal shunt fitted on precision test-desks, and the problem is simpler with the Bridge-Megger.

The current coil is duplicated to make the instrument differential and a variable resistance, adjustable between 0 and 10,000 ohms, is connected in series with the neutralising coil (shunted with 2222 ohms) and the second loop. A suitable resistance has been fitted to an experimental megger, which is used in the London cable-test room.

Another method of neutralising induction when a good wire is taken in another cable, to enable an accurate Varley test to be made, was described by J. M. Allan in the P.O.E.E.J., of July, 1946(9). It has the advantage that a differential galvanometer is not required. Two pairs are used, one in the good and one in the faulty cable, as shown in Fig. 15. An ordinary Varley bridge or bridge megger with the addition of a variable resistance R_2 is sufficient, but the insulation resistances of the two faulty wires must be different. R_1 and R_2 must be kept equal, and therefore the uncalibrated "Poleck" resistance cannot be used. Bridge megger terminals are shown in Fig. 15. If the insulations are nearly equal the balance is indeterminate, and the Simon method is the only one capable of giving reasonable accuracy. It is evident that a Behrend or Poleck test could not be used in these conditions.



R1 = R2 = VARLEY RES.

FIG. 15.—ALLAN TEST.

2. CONDUCTOR FAULTS.

2.1. Methods of locating disconnections when the insulation is high.

Measurement of the capacitance of a disconnected wire, either in terms of a known capacitance or of a known length of a similar wire, enables the position of the break to be determined. Provided that the insulation is high the well-known ballistic methods are satisfactory for any type of line, loaded or unloaded. An audio-frequency source, in conjunction with a slide wire and telephone receiver, is also quite satisfactory when the inductance of the line is negligible at the testing frequency. In practice this method is used on local cables up to about three miles, but the inductance is too high on aerial lines and loaded cables.

2.1.1. *Ballistic Tests.*

The best of these is the "Method of mixtures" shown in Fig. 16. It can be used for long cable circuits with high conductor resistance and inductance, and high insulation, but with moderately low insulation it is impossible to get a reliable balance. The same thing applies to the simple ballistic tests in which deflections of a meter are compared, or a slide wire and galvanometer are used (Fig. 17), but in addition false "kicks" at charge or discharge make balancing difficult except on short lines.

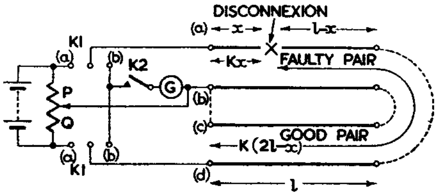


FIG. 16.—METHOD OF MIXTURES.

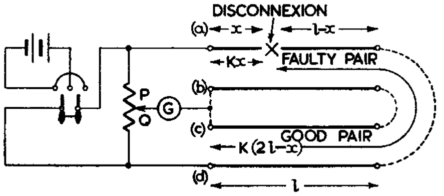


FIG. 17.—SIMPLE BALLISTIC TEST.

Two ingenious ballistic tests, one applicable when the faulty wire has low insulation on the far side of the break, the other for use when there is low insulation on both sides of the break, were described by Graf in "Telegraphen Praxis" (1940)(7).

Both methods are intended for cable faults, and require two good wires. The principle of the first will be evident from Fig. 18. The wire-to-earth capacitances C_x and C_z are proportional to the lengths x and z. Referring to the equivalent circuit, C^1_y is shunted by P, a much lower impedance, so that C^1_y may be disregarded. As h is joined to the battery

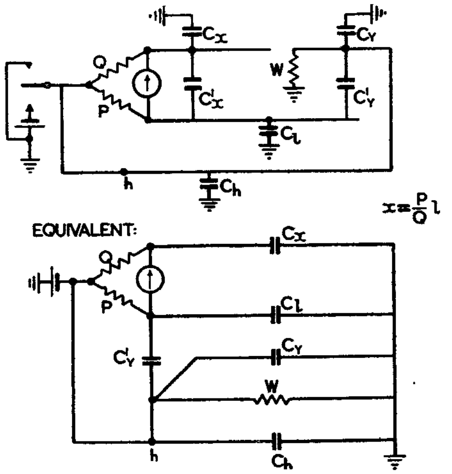


FIG. 18.—GRAF BALLISTIC TEST (1).

end of the bridge C_h, C_y and W, being in parallel between this point and earth, do not affect the balance.

When the bridge is balanced therefore,

$$\frac{x}{l} = \frac{P}{Q} \text{ and } x = \frac{P}{Q} l$$

The value of W is immaterial provided it is not low enough to shunt the whole bridge and seriously reduce the sensitivity.

The second method, shown in Fig. **19**, requires the

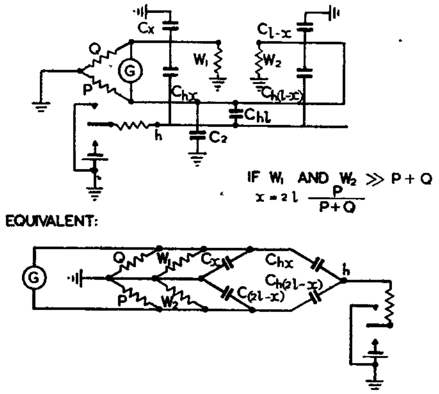


FIG. **19**.—GRAF BALLISTIC TEST (2).

insulation resistances W_1 and W_2 to be known, unless they are very much greater than P and Q.

From the equivalent diagram it will be seen that W_1 and W_2 are in parallel with Q and P. The effect is to multiply the ratio

$$\frac{P}{Q} \text{ by } \left(1 + \frac{Q}{W_1} - \frac{P}{W_2}\right)$$

When the bridge is balanced $\frac{x}{2l - x} = \frac{Q}{P}$, neglecting the correction for W_1 and W_2 and $x = \frac{2l \quad P}{P + Q}$

If n = the corrected value of $\frac{P}{Q}$

$$x = \frac{2l}{1 + \frac{1}{n}}$$

Instead of a battery and galvanometer low-frequency A.C. and a suitable type of detector could be used for both these tests, but (as will be shown later) there is no advantage because low-frequency A.C. can be used in a simpler way for the location of a disconnection accompanied by low insulation.

2.1.2. *Audio-frequency Capacitance Measurement.*

The best-known method of comparing two capacitances is to use a slide-wire, buzzer and telephone. When the two capacitances are respectively the good and the disconnected wire of a local cable pair, and the slide-wire resistances are P and Q the distance to the break (expressed as a fraction of the whole length) is $\frac{P}{Q}$, *i.e.*, $\frac{x}{l} = \frac{P}{Q}$

A simple test-set of this type was designed for use on local (subscriber) cables and is designated "Tester 9004." The circuit diagram is shown in Fig. **20**.

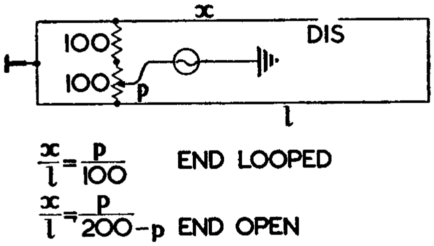


FIG. **20**.—TESTER 9004.

In order to make use of a linear potentiometer calibrated to read the distance to the break as a percentage of the whole length it is necessary to loop the good and faulty wires at the far end.

If they cannot be looped, the formula $\frac{x}{l} = \frac{p}{200 - p}$ applies, p being the dial reading. At the buzzer frequency of about 500 c/s the wire-to-earth impedances of the wires may be regarded as pure capacitances, up to a length of about three miles, which is sufficient to include nearly all subscribers' lines.

When both wires of a pair are disconnected, as with a " lost " pair, which does not appear at the D.P. where it should terminate, a good pair as near to the faulty one as possible should be bunched and used as the good wire, the other pair being bunched to form the faulty wire. It has been found that the wire-to-earth capacitance per mile of adjacent wires is reasonably uniform in local cables, so that a break in a joint can generally be located at the first or second attempt. It is best to open a joint on the exchange side of the position indicated by the test, so that the pair can be identified by testing with the exchange. The fault will not be far beyond this joint, and it will be an easy matter to locate it by making a second test from the opened joint.

If a " lost " pair has been misrouted, having been connected to the wrong branch cable for instance, it is sometimes possible to deduce what has happened by testing from the exchange and the D.P., but in such cases an instrument which measures capacitances, instead of comparing them, is much to be preferred, especially when there are teed pairs.

2.2. Low-Frequency A.C. method of locating disconnections with high or low insulation.

2.2.1. *The Disconnection Locator.*

The normal ballistic and audio-frequency methods described in Section 2.1 both fail unless the insulation of the wires, whose capacitance is to be measured, is high. This condition is the exception rather than the rule, on long aerial lines where a quick and simple method of locating a break is particularly valuable. During the War a disconnection locator capable of being used on army lines and field cables, the insulation of which is often quite low, was required and an instrument known colloquially as the " dislocator " was produced$^{(11)}$.

In principle it is a resistance-capacitance bridge designed to measure the capacitance of lines and cables, loaded or unloaded, at very low frequency. The effect of inductance (which precludes the audio-frequency method on aerial lines and loaded cables) is overcome by using a frequency between 15 and 20 c/s, and of low insulation by the use of a variable resistance in shunt with the condensers against which the line capacitance is compared. In order to detect the low frequency output from the bridge it is made audible in a telephone receiver by chopping it at an audio frequency, using the principle of the Army Fullerphone. In its original form, dating from about 1917, the Fullerphone uses a battery-driven buzzer, vibrating at about 400 c/s, with a chopping contact in series with the receiver. A later model has a metal rectifier modulator which, being fed from a source of 800 to 1000 c/s current, replaces the chopping contact. This arrangement has the advantages of no contact adjustment and a higher frequency, at which the telephone receiver is most efficient. The Fullerphone method is probably the most sensitive, and certainly the simplest method of detecting very low-frequency A.C. In the war-time model (Fig. **21**) the Fullerphone buzzer was used, but the commercial instrument (Fig. **22**) incorporates a rectifier-modulator and a microphone-receiver type of tone-generator which is enclosed in a sealed, nearly sound-proof box and produces a note of about 1000 c/s. The old model requires an external source of low frequency such as a portable telephone, but in the new model a hand generator is included, together with a transformer which may be connected to an earthed supply, such as the ringing machine of an exchange.

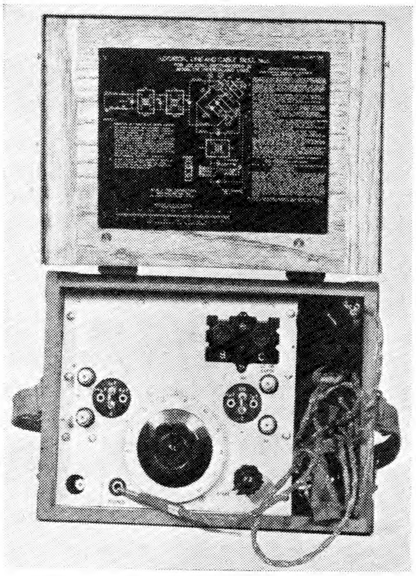


FIG. **21**.—THE "DISLOCATOR." WAR-TIME MODEL.

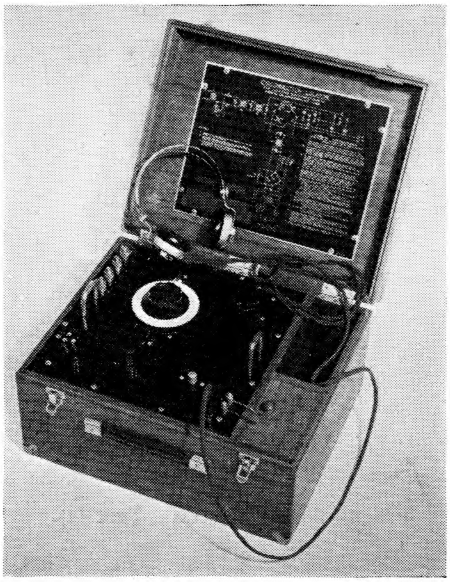
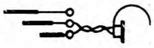


FIG. **22**.—THE "DISLOCATOR." COMMERCIAL MODEL.

The essential circuit of the dislocator is shown in Fig. **23**. The low frequency from a ringing supply



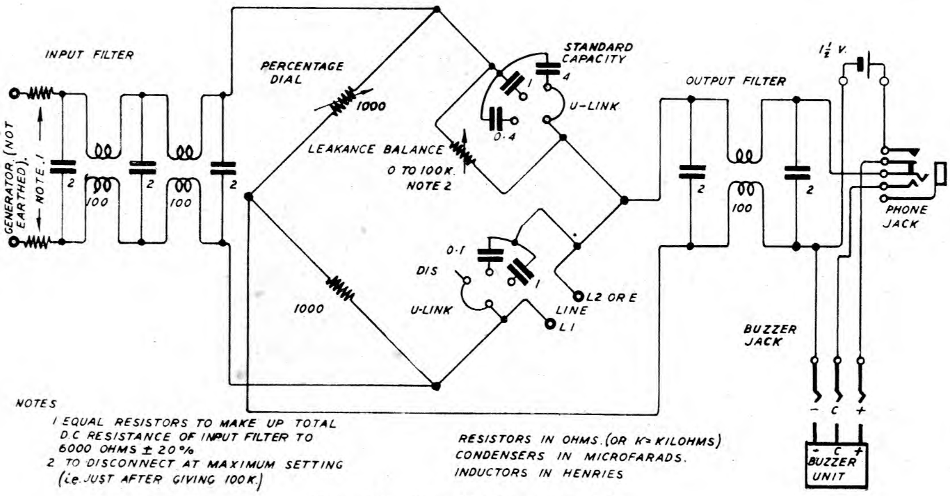


FIG. **23**.—THE "DISLOCATOR."

enters the bridge through current-limiting resistances and a L.P. filter cutting-off at about 30 c/s, to reduce harmonics which sometimes make balancing difficult. The line, which at very low frequency is equivalent to a condenser shunted by a resistance, is connected to L_1 L_2 and a U link enables one of three condensers (0.4, 10 or 4.0 μF) to be selected. The line capacitance is balanced against this condenser by adjusting the 1000 ohm variable arm, the dial of which gives the answer as a percentage of the capacitance selected. At the same time the nominal log-law 100,000 ohm resistance is adjusted to balance the leakance. This resistance is not calibrated, since its value bears no simple relation to the line insulation, but when the line is short and there is no appreciable leakance it should be infinite. For this reason the sliding contact is disconnected in the " START " position, and the resistance falls as the knob is turned clockwise.

It can be shown that, at ringing frequencies (of 10 to 25 c/s) any line having reasonably good insulation is equivalent to a condenser, equal to its total capacitance, shunted by a resistance which depends on the distributed resistance, leakance and capacitance of the line. This shunt resistance varies with frequency, but fortunately the capacitance indicated on the dial does not. Hence the frequency of the supply is not critical, but if the hand generator is turned slowly the harmonics may not be sufficiently attenuated by the filter (which does not cut-off sharply) and this makes balancing difficult on some lines. The handle should therefore be turned reasonably fast. The frequency of exchange ringers lies between 16 and 25 c/s.

The unbalance current from the bridge is taken through another 30 c/s L.P. filter, whose purpose is to cut off 50 c/s induction from power lines, to the chopper contact and the headgear receiver.

When the bridge is balanced,

let R = resistance variable arm
C = capacitance selected
C_x = ,, of line
Q = resistance of leakance balance
M = apparent leakance of line

For reactive balance, $\frac{C_T}{C} = \frac{R}{1000}$

,, resistance ,, $\frac{R}{1000} = \frac{Q}{M}$

When the dial reads 100, $R = 1000$ and the reading therefore gives C_x as a percentage of C.

Frequency does not enter into the equations, except in so far as it affects the valve of M and therefore of Q.

When a short line is being measured, the reactances of the capacity arms of the bridge are very high compared with the resistance arms. The balance therefore depends chiefly on resistance and a dial setting may be found which gives minimum sound in the headphones but is not a true reactive balance. Such false balances can be avoided by adding to the line a capacitance of 0.1 or 1.0, selected by means of the second "U" link. This also keeps the operative part of the dial above 25% where readings are more accurate. The added capacitance must, of course, be subtracted from that indicated to obtain the capacitance of the line. These two condensers provide a simple means of checking the correctness of the instrument. For instance if $C = 4.0$ μF and 1.0 μF is put across L_1 L_2 the balance should be found at 25%, with the leakance balance at START. Similarly, balancing 0.1 against 1.0 μF should give a reading of 10%.

The three values of C—0.4, 1.0 and 4.0 μF—were chosen for use with short overhead lines or cables, long overhead lines, and trunk cables respectively. Since the capacitance per mile of an overhead pair is about .008 μF and of a cable pair about .07 μF, the instrument will deal with cable up to nearly 60 miles, and overhead lines up to 250 miles or more. It has been tested on lines approaching this length, with artificial insulation faults. When short local cables, or aerial lines having very good insulation, are being measured it is sometimes found that the leakance resistance, at its maximum of 100,000 ohms is not high enough, while infinity (START position) is too high, for a sharp balance on the dial. This is seldom important, in practical cases, but the balancing process can be made easier by connecting a high resistance (50 to 100 thousand ohms) across the line terminals. This brings the leakance balance into range without affecting the capacitance of the line.

2.2.2. *Capacitance per Mile of Various Types of Line.*

Although the capacitance of an overhead or underground trunk circuit changes very little along its length, this does not apply to local (subscribers) cables or military cables laid partly on the ground.

Generally, wire-to-wire capacitance is much more uniform than wire-to-earth on an aerial line. The latter depends on the condition of other wires, whether they are earthed or not, and in a cable wires near the sheath have considerably higher capacitance to earth than those in the centre. The following table gives typical values in μF per mile for overhead lines and for cables.

TABLE 1.

	Wire-to-Wire.	Wire-to-Earth.
Overhead lines up to 200 lb.	.008	.012 to .015
,, ,, ,, 400 lb.	.0085	.013 to .016
Paper insulated cables, trunk	.066	.09 to .13
,, ,, ,, local	.072	.09 to .14

It is obviously best to measure and record the capacitance of a line when in good order, so that when a break occurs the ratio of the faulty wire (or pair) capacitance to that of the good one gives the ratio of lengths directly, provided that the line is uniform throughout. The two cases where this is not so are discussed in the next paragraph.

2.2.3. *Non-uniform Lines.*

(*a*) When the line consists of different sections, *e.g.*, an overhead line containing short lengths of cable, the capacitance of line and cable must be known and the total worked out section by section.

(*b*) On local cables, or military field cables, the capacitance may vary from length to length to the extent of ± 10% or more and the first measurement is liable to an appreciable error. The cable should therefore be opened at a joint well on the exchange side of the place indicated, where the faulty pair can be identified by the usual methods. A measurement from this joint will then give the position of the break within a very short distance.

If both wires of a pair are disconnected it is best to measure the capacitance of each wire to earth. If both wires are disconnected at the same point the readings will be very nearly the same. The wire-to-wire capacitance should then be measured and compared either with the nominal capacitance or, better still, with the measured capacitance of an *adjacent* good pair.

If one wire only is disconnected its capacitance should be compared with that of the other wire in the pair. The earth capacitances (per unit length) of the two wires of a pair are very closely equal.

2.2.4. *Long Overhead Lines.*

(*a*) It frequently happens that a broken wire makes contact with earth or another wire on one side of the break. It will only show a clean disconnection when tested from the other side. The capacitance to earth should be measured from that side and the distance estimated from recorded wire-to-earth capacitance of the actual wire, or failing this, by reference to Table 1. If the measurement cannot be made on the clear wire, and the other wire of the pair is free of earth or contact, a measurement can be taken through a loop at the far end.

(*b*) If a pair is found to be "dis" but co-operation cannot be obtained at the far end to test each wire separately, a location can be made with the dislocator provided that the circuit is clear of earth and known to be looped (through a line transformer, for instance) at the far end. A low-resistance termination will not affect the capacitance measurements, made between each wire and earth.

If they are equal, either the break is in one wire at the far end, or both are broken at the same point. A measurement of the wire-to-earth capacitance will help to decide what has happened. If, however, the capacitances to earth are unequal (C_1 and C_2), it is easy to show that $\frac{x}{l} = \frac{2C_1}{C_1 + C_2}$

(*c*) If both wires of a pair show disconnection, their capacitances to earth should first be measured and if this indicates that both are dis. at the same point a wire-to-wire measurement should be made, since there is less risk of telegraphic induction interfering with the test.

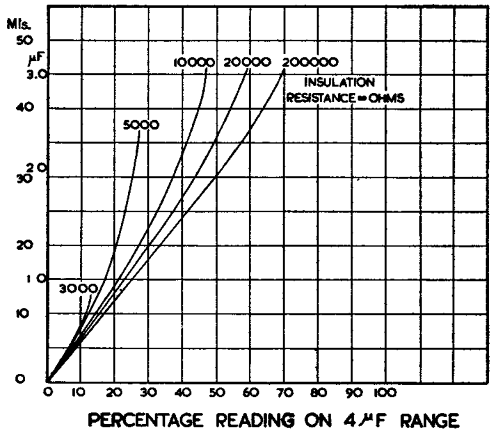
(*d*) Low Insulation. The variable resistance Q enables the line leakage to be balanced even when it is bad enough to be regarded as an earth fault rather than low insulation. The balance is unreliable, however, if the insulation resistance is less than three or four thousand ohms. A broken wire lying on the ground may have a lower insulation resistance. The method described in (*a*) should then be used. When the insulation is, say, 30 thousand ohms which would be normal in wet weather for a long line, the capacitance measurement will be accurate to about 1%, as it is in dry weather. When the insulation is very low the measured capacitance is somewhat less than the true capacitance. A correction could be applied based on the measured insulation, but it is scarcely worth while on aerial lines, where speed is generally more important than accuracy. A more serious effect of very low insulation, especially when the capacitance is low, is that it makes balancing difficult. The resistances tend to swamp the effect of the capacitances, in balancing the bridge, and there is a risk of obtaining a false balance.

The additional condensers facilitate balancing in such cases by increasing the line capacitance.

2.2.5. *Main Underground Cables.*

At the low testing frequency used the inductance of loading coils has no effect on capacitance measurements, at least up to 60 miles of loaded cable.

In main cables a disconnection is rarely accompanied by a definite insulation fault, but the insulation may be low enough to make the well-known ballistic methods useless. If the insulation resistance exceeds 20,000 ohms the error in a capacitance measurement with the dislocator is slight for 40 lbs. conductors. It is appreciable for 20 lbs., as will be seen from the curves of Fig. **24**, and still more for the lighter conductors used on local cables, but no long lengths are here involved and the great majority of disconnections are due to errors in jointing, so that the preparation of correction curves is not justified.



Effect of poor insulation, wire-to-wire (approx. balanced to earth) 20 lb. P.C. Quad Cable (loaded or unloaded). Assuming nominal capacitance 0.066 μF/mile.

FIG. 24.—DISCONNECTOR LOCATOR.

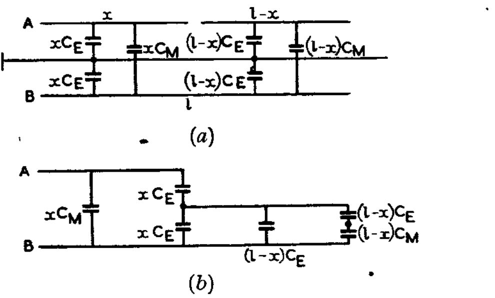
When a cable is completely broken, by an explosion for instance, all the wires should be tested for earth and contact, in order to find one clear wire, or better still a clear pair, whose capacitance can be measured. This will generally give a more reliable location than any D.C. resistance measurement. It should be noted that a contact with another wire will greatly increase the apparent capacitance of the wire or pair under test, and as a precaution, if there are several apparently clear wires, they should all be measured.

2.2.6. *Low-frequency Interference.*

When one wire of a cable pair is disconnected, and wire-to-earth capacitance measurements are impracticable because of interference from D.C. telegraphs, etc., a wire-to-wire measurement corrected by a factor depending on the formation of the cable (star quad, twin or multiple twin) may be used to give a fairly accurate location. Interference is much reduced, although the pair is unbalanced.

Assuming that the A wire is broken at a distance x, and the length of the cable is l, the wire-to-wire capacitance per mile being C, if the capacitance of the pair is measured it will be greater than xC because of the capacitance to earth and other wires of the B wire beyond the fault.

The various capacitances may be represented by condensers as shown in Fig. **25** (*a*).



(*a*)

(*b*)

FIG. 25.—LOCATION OF A DISCONNECTION WITH LOW FREQUENCY INTERFERENCE.

Wire-to-wire capacitance is composed of the direct mutual capacitance C_M, in parallel with the two wire-to-earth capacitances (C_E) in series.

Thus $C = C_M + \frac{1}{2} C_E$.

The line capacitances are equivalent to the network of Fig. **25** (*b*) from which it is evident that the apparent capacitance between A and B, if both wires were disconnected at the same place,

$$= x\,(C_M + \tfrac{1}{2} C_E).$$

The addition of $(l-x)\,C_E$, and the two capacitances in series, increases the apparent capacitance by an amount chiefly depending on $(l-x)\,C_E$, for C_M is small compared with C_E.

If the ratio of C_E to C_M is known a correction factor may be determined which will convert the fraction

$$\frac{\text{Capacitance measured at A B with A wire dis.}}{\text{,, \quad ,, \quad ,, ,, when line is good.}}$$

to the required fraction, $\frac{x}{l}$

This was done for the war-time model, and a scale was provided showing the correct ratio $\frac{x}{l}$, for any capacitance ratio.

The accuracy of the correction, however, depends on C_E which is a somewhat variable quantity (especially in cables) and the scale was necessarily a compromise. It has been omitted from the commercial model, and the wire-to-earth measurement is recommended, unless induction is exceptionally heavy. Then the "artificial earth" arrangement shown in Figs. **18** and **19** (ballistic tests) will generally reduce the interference to such a low level that balancing is not difficult. This arrangement can be used on an aerial line, by taking a second pair.

It proved effective on a line subject to very severe power induction.

The 50 c/s power noise between wire and earth, even after passing through the filter (which has not a sharp cut-off) caused an appreciable background of noise, making the balance rather blunt. A sharper, more accurate balance was obtained with the " artificial earth," but whether this would justify the complication and delay depends on conditions, such as the length and accessibility of the line.

2.2.7. *Split Pairs.*

The dislocator provides a quick method of making the capacitance measurements required in locating a joint where cable pairs have been incorrectly jointed, or " split."

Sometimes, by an error in jointing, the wires ABCD in a quad are joined, for instance, to ACBD or DBCA. The formation is upset and crosstalk results. The wire-to-wire capacitance measured on the pairs AB or CD is increased in a star quad cable (or decreased in a multiple twin cable) in proportion to the length of the incorrect formation. At the same time the capacitances A to C and A to D are reduced in the same ratio. Hence the length of the split pairs can be calculated by measuring the three capacitances:—

$$\left.\begin{array}{l} \text{A to B} = K_1 = \text{C to D} \\ \text{A to C} = K_2 = \text{B to D} \\ \text{A to D} = K_3 = \text{B to C} \end{array}\right\} \begin{array}{l} \text{Star quad, } K_2 < K_3 \\ \text{Multi twin, } K_2 > K_3 \end{array}$$

If x is the split length and l the total length, then

$$\frac{x}{l} = \frac{K_2 - K_3}{K_1 + K_2 - 2K_3}$$

When the cable is loaded, or more than a few miles in length, audio-frequency measurement is impracticable and the dislocator provides the most convenient method. The uniformity of modern trunk cables is such that the length of split formation can be estimated within 1 or 2%.

A similar formula applies to the other "split pair" conditions:

ABCD joined to CBAD (or ADCB)

Measure the capacitances

$$\left.\begin{array}{l} \text{A to B} = K_1 = \text{C to D} \\ \text{A to C} = K_2 = \text{B to D} \\ \text{A to D} = K_3 = \text{B to C} \end{array}\right\} \begin{array}{l} \text{Star quad, } K_2 > K_3 \\ \text{Multi twin, } K_2 < K_3 \end{array}$$

Then $\frac{x}{l} = \frac{K_3 - K_2}{K_1 + K_3 - 2K_2}$

If the split has been rectified at another joint so that it is only evidenced by crosstalk the relative magnitudes of K_2 and K_3 will show which type of split has been made, and the length (though not of course the position) of the split formation can be estimated from the formula.

2.3. D.C. and A.C. Methods of locating High-Resistance Faults.

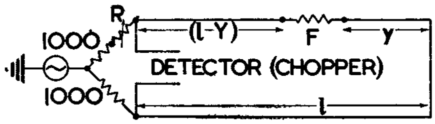
A badly made joint in a cable pair, having a resistance of a few ohms may unbalance the pair sufficiently to cause crosstalk, especially if phantom circuits are in use. Occasionally a length of small gauge cable is inserted in a trunk cable, as a temporary repair, and not recorded.

In both these examples there is a high resistance fault, and it can be located by bridge measurement, if the fault resistance is steady. The method generally used is the Reid test, with an improvement introduced by Stevens. The principle of the method is:—

Having looped the faulty wire to a good wire at the far end, compare the " wire-to-earth " impedances at the far end (measured by D.C. reversals or low-frequency A.C.) of the faulty wire and the rest of the loop in the same way as the capacitances would be compared if the fault were a complete disconnection.

At very low frequency the impedances may each be represented by an earthed condenser equal to the capacitance of the wire (assumed uniform) at the centre of a resistance equal to that of the wire.

Details are given, with a proof of the formula, in Palmer and Jolley's paper. The bridge circuit is shown in Fig. **26**. x and l are the wire resistances.



$$\frac{Y}{l} = \frac{R}{F} \times \frac{2l + F}{2000 + R}$$

FIG. 26.—STEVENS TEST.

The formula

$$\frac{l - x}{l} = \frac{R}{F} \times \frac{2l + F}{2000 + R}$$

may be written $\dfrac{l - x}{l} = \dfrac{R}{2000 + R} \cdot \dfrac{2l + F}{F}$

The two 1000 ohm resistances and R may be replaced by two resistances, one fixed and the other variable.

Moreover low - frequency A.C. and a suitable detector may be used instead of a reversible battery and ballistic galvo, and we may interchange the " battery " and " galvo " connection of the bridge. The dislocator can easily be adapted, as shown in Fig. **27**, to provide the requisite bridge. The leakance balance is not used.

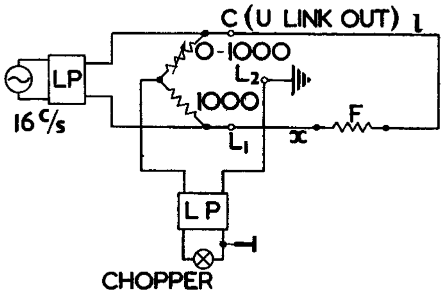


FIG. 27.—STEVENS TEST WITH DISLOCATOR.

If n = the dial reading at balance

$$\frac{l - x}{l} = \frac{1000 - 10n}{1000 + 10n} \times \frac{2l + F}{F}$$

No great accuracy is attainable, especially when F is less than 40 or 50 ohms, but the whole test can be made with portable apparatus—a bridge megger being used for the resistance measurements. Otherwise it is necessary to set up a special bridge with batteries and a sensitive galvanometer, or a ringing generator and Fullerphone detector. Both these arrangements will give accurate results, if the fault resistance is steady.

3. A.C. METHODS.

3.1. A.C. Methods applicable to insulation and conductor faults or to any changes of line impedance.

When an A.C. is transmitted over a line of uniform impedance no reflection occurs until the impedance changes. If the end of the line is open, for example, the current is reflected in phase, voltage being doubled as compared with a characteristic impedance (Z_0) termination, and on returning to the sending end increases or decreases the current there according to the phase-change it has suffered in transit. Thus the sending end impedance, which is $\frac{\text{voltage}}{\text{current}}$, is increased or decreased. If the far end is short-circuited total reflection again takes place, but with 180° phase-change. Similar effects, reduced in magnitude, are produced by terminal resistances greater or less than (Z_0).

At certain frequencies the reflected wave is exactly in phase, and the impedance is a minimum; at others in opposition, when the impedance is a maximum. The impedance-frequency characteristic will therefore be a wavy curve and the phase shift between successive maxima is 2π. Let the two frequencies be ω_1 and ω_2 radians and x the length of the line. Then the total phase-shifts are

$$2x\beta_1 \text{ and } 2x\beta_2$$

$$\text{and} \quad 2x(\beta_1 - \beta_2) = 2\pi$$

$$x = \frac{\pi}{\beta_1 - \beta_2}$$

On loaded lines, for which this effect is most useful, $\beta = \frac{\omega}{V}$, where V, the velocity, $= \frac{1}{\sqrt{LC}}$ approx.

Hence it is easy to show that

$$x = \frac{V}{2(f_1 - f_2)}$$

The distance to any impedance change may therefore be found from two peaks on the impedance-frequency curve. But it is unnecessary to draw a curve derived from the usual bridge measurements—a rather slow process.

With the aid of a constant-output heterodyne oscillator and a rectifier voltmeter it is an easy matter to observe the frequencies at which maximum or minimum readings occur.

Portable equipment of this type was made for the Royal Corps of Signals, during the war. Correction tables were supplied, to take account of the error involved in the approximate formula for V, in the case of a coil-loaded line. If the cut-off frequency = ω_0 radians,

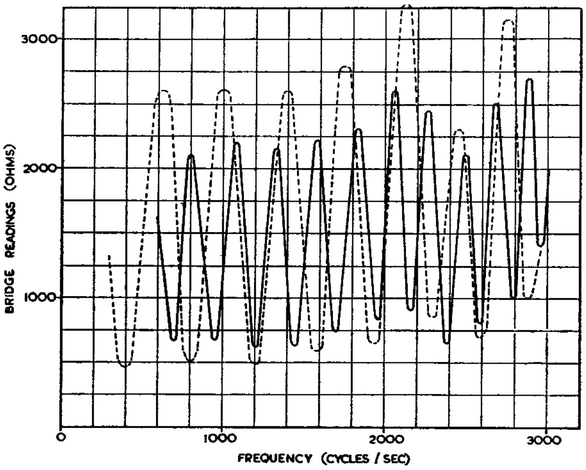
$$\beta = \omega\sqrt{LC} \times \frac{\arc\sin\frac{\omega}{\omega_0}}{\frac{\omega}{\omega_0}}$$

and the correct frequency

$$(f^1) = \text{observed frequency } (f) \times \frac{\arc\sin\frac{\omega}{\omega_0}}{\frac{\omega}{\omega_0}}$$

The correcting factor is nearly unity at frequencies remote from ω, increasing at higher frequencies. For example, on the 88 mH loaded cable whose characteristic is shown in Fig. **28**,

when $f = 800$, $f^1 = 806$ c/s
and when $f = 2490$, $f^1 = 2706$ c/s



Dotted line = Fault of 100 ohms at 17.04 miles.
Full line = Fault of 100,000 ohms at end.

FIG. 28.—EFFECTIVE RESISTANCE/FREQUENCY CHARACTERISTIC ON 25.56 MILES 40 LB. P.C.Q.T. LOADED 88 MH/2000 YARDS.

Since practically all the phase-change takes place at the loading coils, this method is liable to an error of one loading section.

The method can be applied to aerial lines, for which V = 180000 m/sec. approx. at audio and carrier frequencies.

If the fault is 10 miles away, $f_1 - f_2 = 18000$ c/s ; if 60 miles $f_1 - f_2 = 3000$ c/s. It is evident that high frequencies must be transmitted without excessive loss if any peaks are to be detectable. This is the case on heavy-gauge aerial lines, but not on unloaded cables, for which V = 120000 m/sec. approx.

The nearer the fault the greater the frequency difference between the peaks, so that even for a complete short or disconnection the attenuation of the reflected wave is severe. This does not apply to coaxial cables which have moderate attenuation at high frequencies.

In practice, therefore, the method is limited to aerial lines, loaded cables and coaxial cables. The great advantage is that any type of fault—earth contact or disconnection—can be located, provided that it does not present a resistance approximating to the characteristic impedance of the line, and does not vary rapidly. The impedance-frequency method was, until recently, the only means of locating a complete breakdown in a cable, when no good wire was available for a loop test. It cannot be used when the fault is nearer than, say, two miles on a loaded cable, because no peaks will occur below cut-off frequency, but this is not very serious in practice. If a breakdown is within two miles it can generally be found by inspection.

Another limitation is set by the uniformity of the line. If a loading coil is missing, for instance, a number of peaks will be found when the line is good, and it might be impossible to distinguish them from those due to a fault without drawing the curves for both conditions.

A similar difficulty may be met on an aerial line if its uniformity is broken by a section of cable. The impedance mismatch will produce peaks in the characteristic, and if these are comparable with the peaks due to a fault it may be impossible to separate them. These difficulties can be overcome by using the pulse reflection method, which is described in Section 3.2. This also depends on the velocity of propagation, but it can be used to locate intermittent or even multiple faults, since the echoes from any changes of impedance are seen simultaneously on the time base of the cathode ray tube. Nevertheless, the impedance frequency method has proved very useful on long aerial lines, and continuously loaded submarine cables.

3.2. Fault location by means of pulse reflection.

The measurement of distance by observing on a cathode ray oscillograph the echo of an electrical pulse is the essence of Radar. When the same principle is applied to lines certain complications arise. For instance, the velocity varies with the type of line and on coil-loaded cables a rectangular pulse (containing frequencies above cut-off) cannot be transmitted completely. The possibility of locating any type of discontinuity (earth, contact, disconnection, missing loading coil, etc.) provided that it is comparable with the characteristic impedance of the line, by testing from one end only makes the pulse method ideal for military purposes. A further advantage over other methods is that double faults, or intermittent ones, can be located without difficulty. The method is applicable to any type of line, civil or military, from overhead wires to coil-loaded or coaxial cables(12, 13, 14).

Suitable equipment is in course of development by the Post Office and the Royal Corps of Signals.

The velocity on overhead lines and U.L. cables is about 180,000 and 120,000 m/sec. respectively. On carrier quad (a loaded aerial cable used by the Army) it is about 25,000 and on ordinary loaded cables it varies from 10,000 to 20,000. Overhead lines therefore require a pulse not much more than 5 μS wide. Then a fault 1/2 mile away giving a reflection time of 5.5 μS would just be visible. If the pulse is approximately rectangular there is no difficulty in obtaining a visible reflected pulse on the C.R.O. Carrier quad, having a 30 kc. cut-off requires a pulse with much less band width, that is to say a duration of about 40 μS. As the velocity is only 25,000 m/sec, however, faults within 1/2 mile can be detected.

Any coil-loaded cable, being equivalent to a low-pass filter, exhibits a complex transient effect, when subjected to a pulse containing frequency components in the neighbourhood of cut-off and above. The effect appears as a damped sine wave beginning at the same time as the pulse. It is not troublesome on very lightly loaded cables such as carrier quad, but on heavily loaded cables it completely masks the picture. The remedy is to use a pulse shape which involves only frequencies below cut-off. The error-function or streamline pulse meets this requirement. It is rather like a $(\text{sine})^2$ curve but smoother, and when adjusted to a width of 400 μS (at $\frac{1}{e}$ amplitude) produces no damped wave effect whatever, on an ordinary coil loaded cable. The streamline pulse can be produced by applying a rectangular pulse to a circuit containing only one valve.

A rectangular pulse generator, designed by Kosacki at Dollis Hill, uses essentially three valves and the pulse width can be varied from about 5 μS to 300 μS, or more. The O.P. stage is a cathode follower, and the pulse amplitude is varied by a sliding contact on the O.P. resistance (Fig. **29**).

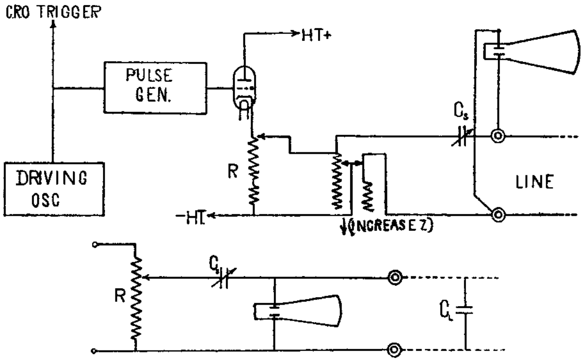


Fig. 29.—Pulse Fault Locator.

The interpretation of the trace on the C.R.O. requires a simple and accurate time-scale of some kind. A method used in Radar and in the American Lookator (designed for U.S. Army carrier quad) is simple and convenient. It consists in sliding back the picture by means of the X shaft until the reflection coincides with the starting line—the beginning of the pulse. The X shift dial may be calibrated in time or in miles of a particular line. Accuracy depends on the driving frequency to which the pulse generator and the C.R.O. are both locked. This may be the 50 c/s mains or an oscillator. The time scale can, of course, be checked by testing the line when it is in good order, either to the far end or to a short at an intermediate point ; but if a line or cable is completely broken down and one cannot get in touch with the other end a pulse test is the only reliable means of estimating the distance. The instrument must therefore have a time scale from which distance can be obtained, knowing the velocity. The velocity for any type of line can be calculated with sufficient accuracy and moreover time measurement need not depend on the driving frequency as in the method already mentioned. Double beam C.R.Os. are commercially available, and using one of these, a fraction of the pulse may be tapped off to act as a marker on the second beam. By means of a variable delay network this marker pulse may be shifted between pulse and reflection and the time interval read on a dial. Any departure from linearity in the time base of the C.R.O. being the same for both beams, will be neutralised. There are, however, difficulties in this scheme where the delay time is long and one or two quite satisfactory methods of time measurement are now available in commercial C.R.Os.

The driving frequency, which triggers off the pulse generator and thus fixes the repetition frequency of the picture, is best supplied from an oscillator. For loaded cables, when the reflection time may be 5 mS or more a driving frequency of 150 c/s has been found suitable, and for unloaded cables or overhead lines the shorter pulse and reflection time require about 1500 c/s.

3.2.1. *Application to Overhead Lines.*

An overhead line, unless it contains an unusual number of cable sections (at power crossings, etc.) has a low attenuation at frequencies up to 100 kc. or more. A pulse of 5 μS will therefore give a reasonable amplitude of reflection over the full length. The short cable sections will show as inverted (shunt type) reflections. Changes of gauge also show, because at the lower component frequencies in the pulse the characteristic impedance depends on resistance. The far end of the line shows as an erect or inverted reflection according as it is open or looped, and the fault gives a reflection whose amplitude depends on the fault impedance in relation to Z_0, and its distance. If it is within a mile or so, line attenuation will be negligible and the narrowest pulse can be used. On the other hand, if it is some distance away and the line attenuation seriously reduces the size of the reflection a wider (more powerful) pulse may safely be used. There is little advantage in this, however ; doubling the pulse width increases the amplitude of the reflection, but it does not reduce the line attenuation to a value corresponding with half the frequency.

Owing to the relatively low attenuation of aerial lines multiple reflections are often seen, especially when the fault is not far away. These secondary reflections are liable to confuse the observer. For example, a disconnection five miles away on an aerial line produces a fairly high peak, above the line on the screen. If the impedance of the pulse generator happens to be lower than that of the line the first echo, returning from the fault, is reflected as at a shunt fault, and inverted. Thus a smaller peak (below the line) appears at twice the distance (corresponding to 10 miles) and a third echo, still more reduced and above the line this time, may be seen at 15 miles, and so on.

It is important to recognise these secondary echoes, particularly as they may be superimposed on the normal picture of the line if the fault is a partial one and does not cut off all transmission beyond itself.

To enable an inexperienced observer to recognise and eliminate the secondary echoes, the generator impedance is made continuously adjustable. In the case now being considered increasing the impedance would make the secondary peaks fall to zero and then appear above the line. If the fault were a short circuit they would appear alternately above and below the line. It is only necessary, therefore, to turn the impedance up and down until the secondaries disappear, leaving the first or true echo to indicate the position of the fault.

The first secondary peak can be recognised as it always changes sign when the impedance is changed over. Hence, if the true peak cannot be seen clearly it may be assumed to be halfway between the pulse and the first secondary peak.

Some oscillograph pictures taken on an overhead trunk line, of the old continuous twist type, at Banbury are reproduced in Figs. **30** to **34**. Two pairs were looped back at 10.8 miles, making a circuit of 21.6 miles, with both ends at Banbury exchange.

The line is led in through .05 miles of cable, and there is about the same length of cable at 8.8 miles where a power line crosses.

Fig. **30** is the C.R.O. trace with the line " open circuit " and a sent pulse about 10 μS wide. Unfortunately in this case the sent pulse occurs on the fly-back, but measurement on another trace checks the position of the power crossing in each pair, the velocity being 183,000 miles/sec. or a reflection time of 11 μS per mile of line. At the first power crossing the reflection is downwards, as for a shunt fault or decrease of impedance, followed by an upward peak. The latter is due to the rise of impedance from the far end of the cable to the overhead line, but the time interval between the peaks is much greater than the transit time of the cable. As with the sent pulse and the end-of-line reflection, time measurements are made to or from the beginning of the slope. This is the usual practice in Radar, when a rectangular pulse is used.

Fig. **31** shows the effect of an earth fault put on by a lineman at 4.6 miles from Banbury. It will be seen that the downward reflection is the same as would be given by a partial short. The far end disconnection

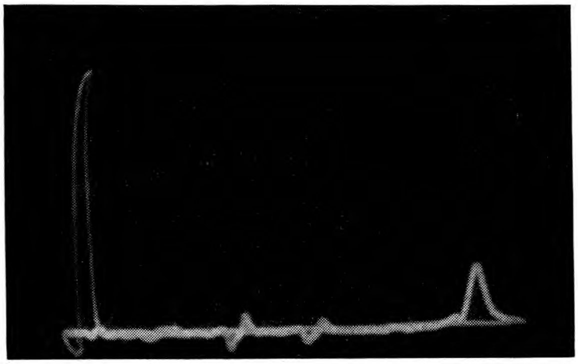


FIG. 30.

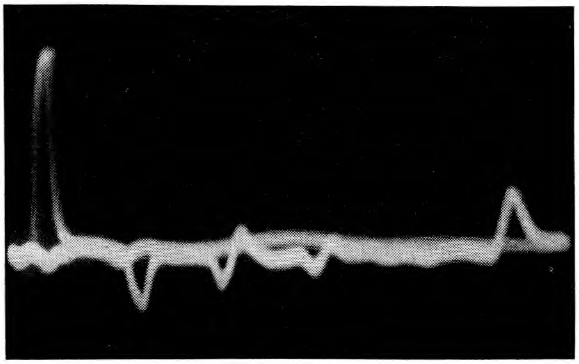


FIG. 31.

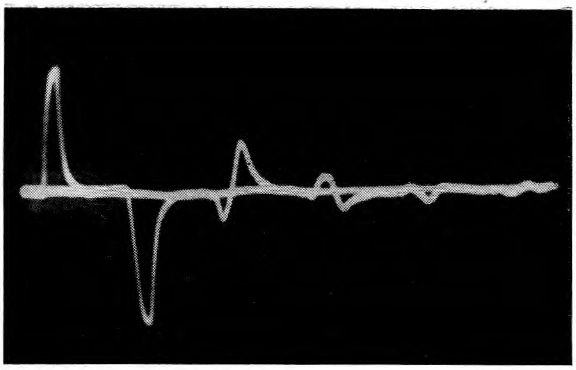


FIG. 32.

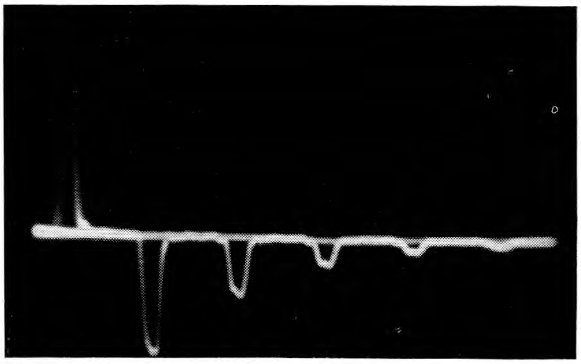


FIG. 33.

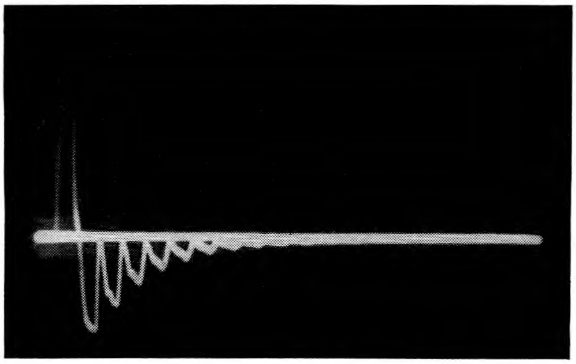


FIG. 34.

and the power crossings are visible as before, but the line is blurred. This is due to induction (ringing, etc.) picked up through the unbalance of the earth fault.

Figs. **32** and **33** show the result of a short at the same point. In Fig. **32** the (adjustable) impedance of the pulse generator was made higher than the line characteristic impedance (Z_0), which is around 600 ohms. When the first reflection comes back it is reflected (in phase) at the pulse generator, again reflected (but reversed) at the fault and so produces a second peak, upwards, separated from the first by the same time interval as that between the pulse and the first peak. The process is repeated until the reflection peaks are damped out. In Fig. **33** the impedance of the pulse generator has been reduced below Z_0, and the first secondary, or false reflection is reversed. In practice when the false reflections have been separated from the primary or true reflection marking the position of the fault by observing this reversal, the generator impedance is adjusted until the false peaks disappear. This was done for Fig. **31** because of the small attenuation between the sending end and the fault but was unnecessary for Fig. **30**.

The positions of the earth (and short circuit) fault indicated by the pulse test was 4.7 miles from the exchange. This and the distance of the power crossings, etc., checks closely with the mileage records.

Fig. **34** was obtained by putting a short circuit on the line at about 1½ miles. It shows that when a fault is so close that its reflection is partly coincident with the pulse the distance can be estimated by measuring to (say) the 8th reflection and dividing by 8.

It appears from these tests on a working trunk line, subject to 50 c/s mains induction and interference from D.C. signalling circuits, that interference voltages are not troublesome, provided that a reasonably strong pulse is used.

When the fault has been located approximately, the lineman is sent to put a short on the line near the location. This is seen on the C.R.O. and the distance from the fault estimated from a knowledge of the intervening line. The lineman is then told how far to go, and no great accuracy is required as the distance should be quite short. At the worst, if the first location was very incorrect (because the line mileage was not known, for instance) a third attempt should suffice to find the fault.

3.2.2. *Application to Unloaded Cables.*

Unless it is a coaxial type an unloaded cable is somewhat inconvenient for pulse location. Both attenuation and velocity are high. The same remarks apply, as regards width of pulse, as with overhead lines, but a rather striking effect occurs (on loaded cables also to a less extent) due to the capacitance of the cable discharging through the O.P. resistance of the pulse generator after the cessation of the pulse, when the O.P. valve (being negatively biased to get the right pulse shape) is non-conducting. As will be seen from Fig. **29** the remedy is simple. The condenser C_S in series with the O.P. resistance R, and C_L the effective capacitance of the line, acts like the " signalling condenser " used in D.C. telegraphy. It modifies the shape of the (D.C.) pulse entering the line somewhat, but when C_L discharges through R, the voltage across the C.R.O. is dropped by C_S and the trace can be brought on to, or below, the zero line by varing C_S. Any reflections will appear on the curved line, but it is preferable that they should appear on the base line as measurement is somewhat easier.

A variable condenser is therefore provided in the generator O.P. circuit. This phenomenon has not been noticed on coaxial cables, no doubt because of their low capacitance.

Tests were also made at Banbury on unloaded cable pairs.

Figs. **35** and **36** were taken on a 40 lb. (paper core, lead covered) aerial cable. Fig. **35** shows the effect of short and open circuit at the end of a four mile line, formed by looping back two pairs at a D.P. The pulse-width was about 10 μS, as before, and the velocity works out at 16 μS per mile. This agrees very closely with a previous measurement on a 40 lb. trunk cable, about eight miles long.

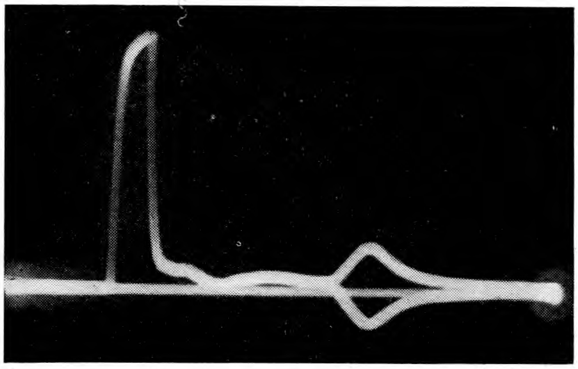


Fig. 35.

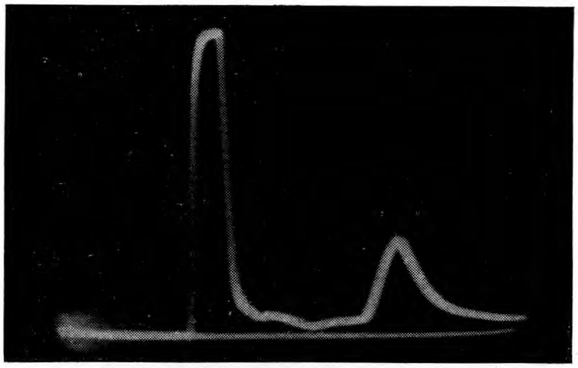


Fig. 36.

The measurement is taken from beginning of pulse to beginning of reflection. When one wire was earthed the " disconnection " peak was reduced to about half its height, without any change of position. This was not quite conclusive evidence that the wire-to-earth transmission (discussed later on) causes no error in the time measurement, however, because the pair was looped back.

A single pair was therefore used, 2.8 miles long, and the picture appears in Fig. **36**. In this case also an earth on one or both wires made no difference to the position of the reflection, proving that even on short length of unloaded cable the velocity is the same for an earth as for a loop fault. No series condenser was required to cut out the discharge effect, the lines being very short.

3.2.3. *Application to Loaded Cables.*

Continuously loaded cables, having no cut-off, present no special difficulty. Velocity may be calculated from $v = \frac{1}{\sqrt{LC}}$ m/sec. Coil-loaded cables, on the other hand, give rise to " overshoot " if the pulse contains any components above the cut-off frequency, defined as $f_0 = \frac{1}{\pi \sqrt{L_S C_S}}$ where L_S and C_S refer to the loading sections.

The overshoot effect shows as a damped wave following the pulse and is formed by the reflection from the first few loading sections of all components which exceed or " overshoot " the cut-off frequency. A cable loaded for carrier working such as carrier quad with $f_0 = 30$ kc. gives a noticeable amount of overshoot, with a rectangular pulse.

The heaviest loading in general use is type MH, 176 mH at 2000 yds., with $f_0 = 2.9$ kc. A rectangular pulse is quite useless on this or any other audio type of loading, but the streamline pulse mentioned above gives a picture free of all overshoot effects. Its general appearance will be seen in Fig. **37**. The pulse is of necessity some 400 μS wide, and this corresponds to four or five miles of line.

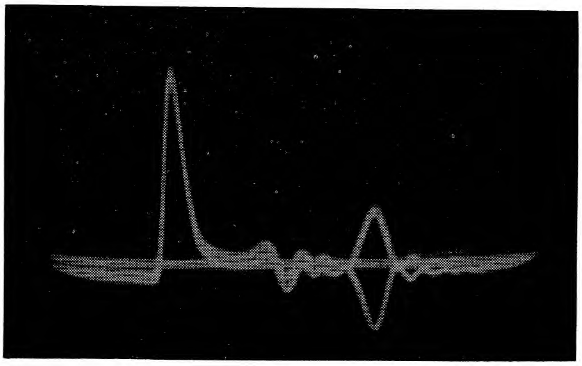


Fig. 37.

To enable faults near the testing end to be detected a network simulating a few miles of cable can be inserted, but this refinement may not be worth while for fault location. Since practically all phase shift occurs at the loading coils this method also is liable to an error of one loading section.

The shaped or " streamline " pulse has been used on various loaded cables with satisfactory results. Results confirm that the velocity of propagation of the pulse is approximately $\frac{1}{\sqrt{LC}}$ on a pair (wire-to-wire) circuit, but when the pulse travels on a wire-to-earth circuit, as it does to some extent with an earth fault, L is very much less, and therefore velocity is higher than on the pair.

With an aerial line, where the velocity approaches that of light it must be approximately the same on the pair as on the wire-to-earth circuit, so the reflection from an earth appears at the same point as that from a short or disconnection, which travels entirely on the pair. But on a loaded line the reflection due to an earth on one wire is made up of two parts: (*a*) the reflection travelling on the pair, from the impedance change in the pair circuit caused by the fault itself, and (*b*) the reflection which travels on the wire-to-earth path. Of these (*b*) travels faster but suffers more attenuation. The result is, putting it in general terms, to make the peak of the reflection occur sooner than with a short or disconnection. If the fault is only a few miles away (*b*) suffers little extra attenuation and the reflection may consist of a double peak. For greater distances (*b*) is almost wiped out and merely distorts the main reflection, making its peak slightly earlier.

It was intended to earth the centre point of the pulse generator, but this idea has been abandoned as it has proved unnecessary and increases the earth effect. The error due to this effect will generally be reduced in practice because the type of fault for which pulse location is most useful—complete breakdown—means that all wires will be showing earth and contact. If the breakdown is more than 10 miles away the error, on an ordinary loaded cable, will be negligible. At five miles it might be a mile, or a loading section whichever is greater.

The same effect takes place on unloaded cable pairs, but is much less marked. In fact, it was quite undetectable on the 40 lb. cable tested at Banbury. The trace shown in Fig. **37** was taken on a loaded cable circuit, formed by looping back two 88 μH loaded pairs in the Banbury-Brackley cable. At the latter place the end section is .3 mile instead of .57, so that in the middle of the 20 miles line there was only half the normal spacing between two coils. This means half the capacitance, or a high shunt impedance, which shows on the trace as an upward peak. It is followed by a downward peak, the whole effect being the inverse of that shown at the power crossings on the overhead line. Owing to the cut-off at 4000 c/s it was necessary to use a shaped pulse about 300 μS wide.

The velocity agrees very closely with the calculated figure of 14 miles per mS. To get both disconnection and short on the same photograph, each condition was put on for half the exposure time. The vertical displacement of the trace is due to changes in the D.C. component of the pulse, with terminal conditions.

To sum up the position as regards pulse fault location ; any type of fault, intermittent or steady, or even two simultaneous faults, can be located provided (*a*) that the line attenuation is moderate and (*b*) that the fault is severe enough to affect the working of the circuit. Incipient insulation faults require the ordinary D.C. methods.

LIST OF BRIDGE TESTS FOR THE LOCATION OF LINE FAULTS

(To be applied after the usual D.C. tests have indicated the nature of the fault)

4.1. Overhead Lines.

	Type of Fault.	*Suitable Test.*	*Reference Para.*
1.	Earth, one good wire available	Varley (1 to 1 ratio)	1.1.1.
2.	(*a*) Contact, one good wire available	,, ,,	1.1.6.
	(*b*) Contact, no other wire available	Loop and Varley combined	1.1.6.
3.	All wires " earth and contact "	(*a*) Overlap test	1.1.7.
		(*b*) Impedance frequency, with carrier frequency oscillator	3.1.
		(*c*) Poleck test	1.1.9.4.
4.	Complete breakdown. All wires broken, some " dis " others " earth and contact "	(*a*) Loop resistance	—
		(*b*) If one wire can be found not in contact with another and having an insulation exceeding 5000 ohms, measure its capacitance with the " dislocator." For an accurate location either the impedance - frequency or the pulse method must be used	2.2.1.
5.	One or both wires of a pair disconnected	(*a*) Measure wire-to-wire or wire-to-earth capacitance with the " dislocator." Insulation must be better than 5000 ohms	2.2.1.
		(*b*) If the insulation is very good capacitance may be measured reliably by ballistic methods, but a sensitive milliammeter or galvanometer is necessary	2.1.1.

4.2. Cables, Paper-Core.

	Type of Fault.	*Suitable Test.*	*Reference Para.*
6.	Earth. Fault resistance low compared with normal insulation and good wire available	(*a*) Varley	1.1.1.
		(*b*) Murray, for short lengths of heavy conductors	1.1.3.
7.	Contact, third wire available	Varley	1.1.1.
8.	Contact, no other wire available	(*a*) Loop and Varley combined, as in 2(*b*)	1.1.6.
		(*b*) Overlap test from both ends	1.1.7.
		(*c*) Blavier test—rather unreliable	1.1.8.
9.	Insulation breakdown, all wires " earth and contact," good wire available on another route	Varley	1.1.1. 1.4.
10.	Ditto, no good wire available, fault resistance a few hundred ohms on all wires	(*a*) Overlap test from both ends, or	1.1.7.
		(*b*) Poleck test, provided two wires with insulation resistances in ratio of at least 2 to 1 can be found	1.1.9.4.
		(*c*) Graf test, if no bridge available	1.1.9.5.
11.	Ditto, but faults just developing, as when water seeps into cable through slight crack in sheath. Worst insulation a few thousand ohms, best 5 or 10 times higher	(*a*) Poleck test	1.1.9.4.
		(*b*) Double-ended Varley	1.1.9.2.
		(*c*) If best wire plus worst wire exceeds 120 times loop resistance—Behrend's test is accurate	1.1.9.3.
12.	Low insulation on all wires. Worst 1 or 2 megohms, best 10 or 20 times higher. (Ratio of best to worst wire is generally variable in this case)	(*a*) Double-ended Varley	1.1.9.2.
		(*b*) Behrend test	1.1.9.3.
		(*c*) Poleck test	1.1.9.4.
		(*d*) Varley with correction—if ratio best/worst exceeds 20 and balance is steady. *Note*: High testing voltage is required with all methods, for reasonable sensitivity	1.1.9.1.

Type of Fault.	*Suitable Test.*	*Reference Para.*
13. Disconnection, one wire	Measure capacitance to earth and compare with that of adjacent (good) wire.	
	(*a*) If insulation is high ballistic methods reliable in expert hands. Dislocator is quicker.	2.1.1. 2.2.1.
	(*b*) When insulation is low measure capacitance with the dislocator. If below 20,000 ohms correction may be applied.	2.2.1.
14. Disconnection, both wires of a pair	Verify that both wires are dis. at same point by measuring capacitance to earth, as in 13 (*a*) or (*b*). Then measure wire-to-wire capacitance and estimate distance either by comparison with a good pair or on basis of .066 μF per mile for trunk cables. .072 μF per mile for local cables.	2.1.1. 2.2.1.
15. Whole cable broken	(*a*) If one pair can be found with wire-to-earth insulation better than 10,000 ohms, measure its capacitance and proceed as in 14 (above).	2.2.1.
	(*b*) If all wires are in contact—due to cable-end being in water, etc.—a rough location may be obtained by measuring the loop resistance of several pairs and taking the lowest value. The fault will be somewhat nearer than the position thus indicated. [*Note*: A steady resistance value usually indicates a metallic contact of negligible resistance.] For an accurate location either the impedance-frequency or the pulse method must be used.	3.1. 3.2.

5. SEARCH COIL AND SIMILAR METHODS

(*a*) The use of a search coil to find the track of a buried cable, by picking up the induction from a buzzer tone applied to the cable, has long been known.

It is comparatively easy to find a cable, but to find a fault (other than a complete break) by means of a search coil has so far been found impracticable, on lead-covered cables at any rate. During the war many cables were laid directly in the ground, and records were sometimes rather vague. Search coils were therefore in demand and an improved outfit, including a portable amplifier, was developed at Dollis Hill. The chief defect of pre-war search coil outfits is that the noise heard in the telephone receiver is liable to be masked by the sound of road traffic, wind or mains induction. For example, the cable search apparatus known as Tester S.A.9001 has a buzzer which produces a tone very like the noise of a low-power motor cycle. Its range is very limited because no amplifier is used. Another example is a German Army equipment in which a continuous tone is used, picked up by means of an iron-cased coil, and there is a compact portable amplifier but this outfit is not very effective.

It is of prime importance to select a suitable frequency for the tone applied to the cable. When A.C. passes along the conductors or sheath of a cable, returning via the earth, a magnetic field is created around the cable, which has maximum linkage with the search coil when the plane of the coil is vertical and parallel to the cable.

The induced voltage is proportional to frequency, to the mutual inductance between cable and coil, and to the current in the cable. Both mutual inductance and the current decrease with frequency. The former depends on the resistivity of the ground, the latter on the longitudinal attenuation of the cable. Experiments indicated that the best compromise between these factors was given by a frequency of 600 to 1000 c/s. As the telephone receiver is most sensitive at about 1000 c/s this was chosen for the tone to be applied to the cable. To enable it to be recognised in spite of various electrical or other noises, the tone is produced by an oscillator which gives a continuous tone interrupted at a rate adjustable between two and several hundred pulses per sec. The output impedance is adjustable from ½ ohm to several hundred ohms, enabling the full power to be used either on a single wire or the sheath of a cable, which has very low impedance to earth.

The coil itself is wound on a two-foot-square wooden frame, with 4000 turns of 40 SWG wire, electrostatically screened and sprayed with suitable protective dope. It is resonant at about 1000 c/s, and when in use is connected to a portable three-stage amplifier, tuned broadly to 1000 c/s.

As will be seen from Fig. **38**, this is carried in a haversack with the necessary batteries.

Search coils of the type discussed here are not suitable for the location of faults in lead-covered cables. If a number of wires are earthing due to penetration of water for instance, and tone is put on between wires and sheath, it is easily picked up with a search coil but no definite change in sound can be detected when the fault is passed.

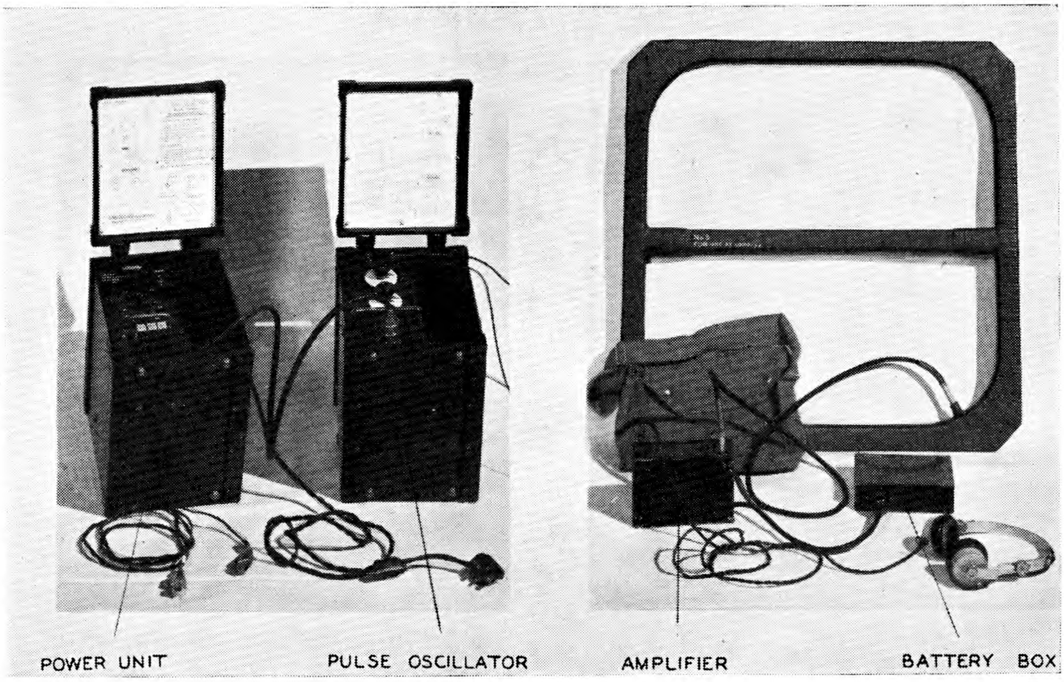


FIG. 38.—SEARCH COIL OUTFIT.

In tracing a cable the oscillator is at one end. If the other end is not available tone is applied between sheath and an independent earth connexion, such as a water main which does not run near the cable. If the other end is available tone is applied between the sheath and two or more conductors, bunched and earthed at the far end. If a long length of cable is involved ten or more pairs should be bunched to reduce attenuation. The impedance of the oscillator is adjusted to give maximum output by listening with the search coil, and then the rate of impulsing is set in accordance with the local conditions. When electrical disturbance is experienced from AC or DC mains a slow impulsing rate is best.

Armoured cables or cables in ducts, buried at a depth of two or three feet, can be traced with this apparatus for 1 to 1½ miles when the tone is applied to the sheath only.

When several pairs of conductors can be used, earthed at the far end, distances greater than 25 miles may be covered.

In 1945 the apparatus was used between Berlin and Potsdam to trace a damaged cable which was buried 18 feet deep in clay soil. The depth was estimated by observing the inclination of the coil for maximum pick-up when held at a measured distance on either side of the cable track.

Apparently the impedance of all wires (which are effectively bunched at the fault) to earth is low compared with the fault resistance, at middle audio frequencies. It would be possible to raise this impedance by using a low frequency, with suitable means of detection, but then the current induced in the coil would be so much reduced that the whole arrangement would have a poor signal-to-noise ratio.

A more promising method of locating faults is to use a small iron-cored coil placed on the cable at a joint box. The tone is connected to a pair, and the magnetic field, which rotates every few inches according to the lay of the wires, can be detected easily with the aid of the amplifier.

The method has proved very useful as a means of tracing unrecorded pairs in subscribers' cables, but it is not suitable for tracing faults, in lead-covered cables at least.

A filter is advisable in front of the amplifier to cut out 50 c/s induction which may sometimes overload the amplifier and seriously reduce its gain.

If one wire of a pair is disconnected a capacitance measurement should be made to find the distance of the fault. The pair can be traced, if necessary, with the search coil but no definite change is heard as the coil is moved past the fault.

6. THE LOCATION OF SUBMARINE CABLES BY MEANS OF TOWED ELECTRODES

The electrode gear, used by the P.O. cable ships since 1932, depends on the potential gradient near the surface of the sea, over a cable carrying 16 to 20 c/s A.C. (from an earthed generator) which returns via the sea water. The far end of the cable must be earthed, either deliberately or through a fault. As the current returns partly through the sheath and partly through the sea water, regarded as a conductor of very large cross-section and moderate resistivity, the current density at the surface is greatest immediately over the cable. Two metal plates, or electrodes, just under the surface and in line with the cable, will therefore pick up an alternating voltage proportional to the distance between them. If they are in any other position the voltage will be less, and when they are at right angles to the general direction of the cable (disregarding sharp bends) practically no voltage will be observed.

In practice two brass electrodes, streamlined in shape, rather like the recording log used by many ships, are towed in line astern by the cable ship. They are spaced 20 yds. apart, and rubber-covered leads connect them to a tuned amplifier-detector and micro-ammeter on board. Various frequencies were tried in the early experiments and it was found that a low frequency was best, although it made the tuning of the amplifier somewhat blunt. Ringing frequency was chosen because an exchange ringing machine, battery driven, could be conveniently installed in a cable hut and would provide sufficient power. The shape of the electrodes will be seen from Fig. **39**. They are made of polished brass to reduce the contact E.M.F.'s which produce erratic deflections of the meter at any but the slowest speeds. In a choppy sea the electrodes sometimes break surface and the flapping of the two lines in the earth's field may also cause false deflections.

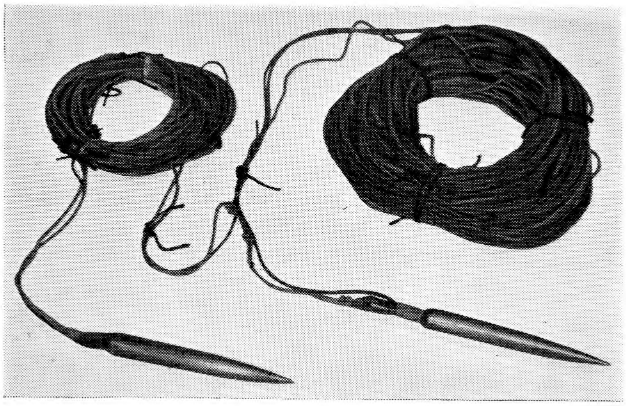


FIG. 39.—ELECTRODE GEAR.

At the moment when the ship crosses over the cable, at an angle of some 30° or 40°, the deflection increases suddenly. The ship then changes course so as to cross over the cable again and by repeating the process can take a zig-zag course over the cable, until the deflections increase and then rapidly decrease. This means that the fault has been passed. By manœuvring slowly the position of the fault can be found within a few hundred yards.

It was hoped that the towed electrodes could be replaced by metal plates fixed to the sides of the ship, thus avoiding the difficulties already mentioned. Experiments were made with brass plates, carefully streamlined, mounted on wooden frames hung over the sides of a small motorship, but the results were disappointing. When the ship was moving at less than one or two knots the 16 c/s voltage produced satisfactory readings, but as the speed increased contact voltages apparently due to the rush of water along the ship's sides overshadowed the pick-up from the cable, and it was obvious that patch electrodes would be useless at any reasonable speed.

The towed electrodes have proved very useful, both for checking the position of cables thought to be in danger from naval demolitions, and in helping the cable ships to find faulty cables.

Recently, improved equipment has been designed. The electrodes have been redesigned to improve their stability at moderate towing speeds, and the amplifier has been made more selective, giving a better "signal-to-noise ratio" against the erratic disturbances due to contact potentials.

At the same time, by using two pairs of electrodes towed from the stern, one on the port and one on the starboard side, the ship is enabled to use the cable like a leader cable or a radio navigational beam. The electrodes are connected to two separate amplifier-detectors, one giving an output proportional to the difference of the voltages picked up by the port and starboard pairs, the other an output proportional to the sum of the voltages. The first amplifier operates a centre-zero meter, which is marked "port" and "starboard" on either side of the centre line. This shows the position of the cable relative to the ship.

The other amplifier operates the "proximity" meter whose deflection increases as the ship approaches the cable, provided of course that the keel of the ship is not at right angles to the cable, when no voltage will be picked up.

In order to make the amplifiers highly selective, the nominal 16 c/s A.C., whose actual frequency depends upon the speed of the ringing machine on shore, is made to lock an oscillator which feeds a ring demodulator. This converts the output of the amplifier into the D.C. which operates the indicator. In this way both amplifiers are made much more selective than is possible with ordinary tuned circuits at the very low frequency employed.

By observing the two indicators it is possible for the ship to follow the line of the cable, without steering a zig-zag course. When the ship is over the cable and in line, the pointer of the port/starboard indicator is central, and that of the proximity indicator shows a maximum deflection.

In conclusion, the author wishes to acknowledge the assistance of numerous colleagues, especially Mr. F. J. D. Taylor and Mr. F. F. Roberts, in connection with pulse fault location.

7. SUMMARY OF DISCUSSIONS.

Discussion at the various Centres produced much valuable information about the application of fault location methods mentioned in the paper, and other methods which could usefully be included. In the following brief summary it has only been possible to deal with the salient points:—

Section 1.1.

Some difficulty has been found in applying the Poleck test to a wet cable, in which the faults are less than 1000 ohms. In one case they were 200 and 500 ohms and varying so much due to electrolytic effects that no accurate balance was possible, at least with a bridge megger. This trouble may occur in a corrected Varley, or any other test which depends on the ratio of two fault resistances, and (in the absence of a good wire) the Graf seems to be the only suitable D.C. test. On the other hand, if the fault resistances are some thousands of ohms the Poleck test is quite accurate, and balancing not difficult, provided there is no great interference from signalling or other voltages on other wires in the cable.

When the fault resistances are high enough for a Behrend test (120 times the loop) there is usually no difficulty in balancing, and this test is easier than the Poleck. But the latter has the advantage that if a balance can be got (though the fault resistance may be variable) it will give the correct answer. The Behrend test depends on the ratio of the fault resistances being the same during both balances. There is, moreover, a wide range of fault resistances for which the Poleck is the only practicable bridge method and for this reason a " Poleck " terminal has been added to the bridge megger.

When dealing with insulation faults, up to 300 or 400 megohms a corrected Varley or Behrend test can be very accurate, unless there are patches of unequal low insulation comparable with the faults. The correction factor is then different according to the closing resistance and the Behrend formula no longer applies.

A good approximation to the true location of the fault can sometimes be achieved by the following method, due to Mr. Oakford (London Telecommunications Region): Take several Varley tests with various closing resistances down to zero, and plot x, the single-wire resistance to the fault against l, the half-loop resistance. The value of x is obtained by correcting the Varley reading with the factor $\frac{N + F}{N - F}$; using the measured values of N and F.

Under the conditions assumed this will give too high values of x, but the error will decrease with l. If a short circuit could be put on the loop between the end of the cable and the fault (in effect decreasing l still further) and moved nearer to the fault, the effect of the correction factor would be progressively reduced. This process can be followed, in imagination, by drawing a curve through the plotted values of x, and extending it until it cuts the line $x = l$. The value of x so obtained will generally be nearer the truth than the result of a Behrend or double Varley test.

When the insulation of a cable is very high, apart from an incipient fault at one point, experience shows that reasonably close location is possible even when F = 1000 and N = 2500 megohms.

Section 1.2.

It was suggested that the clip-on coil sold in U.S.A. as the " Westector " would be useful to overhead linesmen, both here and in the Colonies. The alternative arrangement is less interesting now that the Army Fullerphone has become obsolete.

Section 2.1. *and* 2.2.

The capacitance of main cables is very uniform and ballistic tests are found to give reliable results for disconnection faults, unless the insulation is low.

The impedance frequency method is then liable to an error up to one loading section, but the " dislocator " gives accurate results when the insulation is down to 50,000 ohms or less and has the advantage of being portable. Examples were given from various old cables, such as London-Birmingham No. 1.

Most of the disconnections in short local cables, due to jointers' mistakes, can be located with the audio-frequency " tester 9004," but when a pair does not appear at the proper D.P. according to the records an absolute measurement of capacitance, rather than a comparison, is required. This is most readily done with the dislocator.

Examples were given from a large exchange area where some of the numerous pairs which had been " lost " as a result of bomb damage have been traced in this way. When the approximate length has been determined, however, there may be nothing to indicate whether the pair branches off at a joint or not. This calls for the saddle type search coil (Section 5 (*a*)) which, when held on the cable sheath will indicate the presence of the wanted pair.

Section 2.3.

The Stevens test was used to locate an unrecorded length of small gauge cable in one of a pair of 24/40 carrier cables. This was only successful because a wire in the other cable was used as the good side of the loop, and wire-to-wire capacitance is almost exactly the same in both cables. The artificial earth arrangement of Fig. **17** was used.

Section 3.

The impedance-frequency method was defended by several contributors. In dealing with this and most of the other methods in the paper the emphasis was rather on speed and convenience than precision. There is no doubt that, as a quick method of locating a breakdown, or any fault that cannot be dealt with by D.C. methods, it compares unfavourably with pulse location.

But if an A.C. bridge with a sensitive detector is used to take the impedance characteristic of the line, first in good order and then faulty, a comparison of the two curves will give an accurate location of the fault. The oscillator-voltmeter method is quicker but less accurate, like the measurement of resistance with ammeter and voltmeter instead of a D.C. bridge.

Essentially the impedance frequency and the pulse methods are different ways of measuring the same thing—the phase shift which takes place on any transmission line concurrently with attenuation. In most cases the phase coefficient (β) depends almost entirely on reactance, and velocity $\frac{\omega}{\beta}$ is nearly constant, especially on unloaded or continuously loaded cables. A steady fault even at some distance from the testing end (giving a high return loss) may be detected by using a sensitive A.C. bridge, or a powerful pulse and high receiving amplification. But if the fault is intermittent the pulse method, being almost instantaneous, has no rival. Moreover the oscilloscope trace is a complete picture of the line, so that multiple as well as intermittent faults can be located with a minimum of calculation. Both methods, depending on the transmission of high frequencies, are limited by attenuation. The ordinary D.C. and low-frequency A.C. tests have the advantage in this respect and in simplicity of apparatus.

Pulse fault location is most useful for overhead lines, military lines and cables, and power lines(16).

Mr. F. F. Roberts described the application of D.C. and A.C. pulses (the latter being composed of a few cycles of very high frequency A.C.) to the detection of slight impedance irregularities as well as definite faults in coaxial cable. Here again attenuation determines the type of fault which can be detected. Coaxial cables, both land and submarine, have relatively low attenuation. On ordinary cables, however, the high-frequency A.C. pulse or wave train would suffer too much attenuation in a reasonable length. There is no prospect, therefore, of using a pulse test to detect incipient insulation faults.

Application to local cables is more promising. Although attenuation is high, distances are short, and velocity is nominally the same for all gauges.

Pulse location is being tried on some long overhead lines of British Railways. The method should be particularly useful on these lines, which contain numerous short lengths of cable.

Section 5.

It is evident that the search coil outfit, particularly the saddle-type coil to be used on the sheath of a cable, meets a very real need in large exchange areas. Its most valuable feature is that a pair can be followed through main and branch cables to where it ends in a short or a disconnection. But it must be realised that the search coil will *not* indicate a one-wire disconnection — no change in tone is observed when the fault has been passed. The search coil is therefore an adjunct to the dislocator and Tester 9004, not an alternative.

The sheath-drop method of tracing a fault when the cable is accessible(15) is in the same category as the search-coil and towed-electrode methods.

It may be found useful on aerial cables, which are liable to develop insulation faults when the sheath cracks or is pierced by gun-shot.

The development of a tester was mentioned which would enable one of the coaxial tubes in a cable to be identified so that the other tubes could continue to carry power and traffic while one was opened for test. The principle is to close the jaws of a super-sensitive " clip-on " ammeter around the tubes in turn noting the amplitude *and direction* of deflections due to battery pulses put on the centre conductor of the tube to be identified.

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9. APPENDICES.

9.1. Appendix I. Proof of formulæ for Poleck test.

In Fig. **10** the resistance r is in series with the " good " wire.

If the bridge is balanced whether the switch is open or closed C and D must be equipotential points, and so must A and B. Let I_A and I_B be the currents in the two wires, each of resistance x between the bridge and the fault.

Then $I_B \times F = I_A \times N$ ....(1)

and $I_B = (1 - \alpha)\, I_A$ ....(2)

hence $\frac{\alpha}{1-\alpha} = \frac{I_A}{I_B} = \frac{F}{N}$

Also $xI_B = (x + r)\, I_A$ ....(3)

hence $\frac{I_A}{I_B} = \frac{x}{x + r} = \frac{\alpha}{1 - \alpha}$

$$\alpha\,(2x - 1) = r\,\alpha$$

and $x = \frac{r}{\frac{1}{\alpha} - 2}$

From (2)

$$\alpha = \frac{1}{1 + \frac{N}{F}}$$

Thus α depends only on $\frac{N}{F}$, and if this = 1, $\alpha = \frac{1}{2}$, $r = o$ and the value of x is indefinite.

The balance is insensitive when $\frac{N}{F} < 1.5$ and it is desirable that the ratio $\frac{N}{F}$ should be at least 2. When F and N are both high one needs a high-voltage battery, or megger for reasonable sensitivity.

If $\frac{N}{F}$ exceeds 20, r may be inconveniently large, and a corrected Varley or a Behrend test may give better results.

The connections of a bridge megger for the Poleck test are shown in Figs. **11** (*a*) and **11** (*b*).

The formula $x = \frac{rR}{1111}$

is derived as follows:—

Slide wire ratio, $\alpha = \frac{R}{2R + 1111}$

Since $x = \frac{r}{\frac{1}{\alpha} - Z}$ and $\frac{1}{\alpha} = \frac{2R + 1111}{R}$

$$x = \frac{rR}{1111}$$

9.2. Appendix II. Corrected Varley Test.

The first correction factor, which is derived from consideration of the circuits shown in Fig. **8**, may be derived more simply by using the conception of the " equivalent fault." The loop of Fig. **8** may be drawn as a straight line ACB. (Fig. **8** (*a*)).

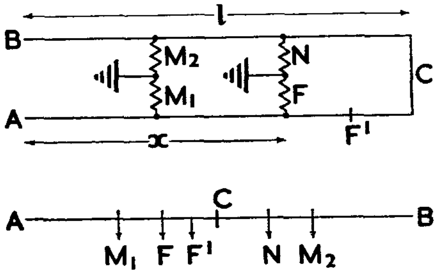

FIG. 8 (*a*).—CORRECTED VARLEY TEST.

It is obvious, by symmetry, that if F = N the Varley resistance = 0, and the apparent position of the fault is at C. Now suppose N = 4 or 5 times F, then the apparent, or equivalent, fault will be at F^1, the centre of gravity of F and N. That is to say, $\frac{FF^1}{F^1N} = \frac{F}{N}$

Hence $\frac{FC}{F^1C} = \frac{\frac{N + F}{2}}{\frac{N + F}{2} - F} = \frac{N + F}{N - F}$

and $2(l - x) = R \times \frac{N + F}{N - F}$

If there are two more faults, M_1 and M_2, the equivalent faults position can be found by taking the centre of gravity of M_1 and M_2, regarding this as the position of a fault $\frac{M_1 M_2}{M_1 + M_2}$, and again taking the centre o gravity of this fault and F^1, which $= \frac{FN}{F + N}$.

This is not a practical case, however. The values of M_1 and M_2 might be known, but not their position. Generally the normal insulation of the wires, assumed equal, is known. Thus $M_1 = M_2 = M$ and the process just described gives the correction factor:—

$$1 + \frac{2F\,(N + M)}{M\,(N - F)}$$

The position of M M does not matter, because their centre of gravity is always at C.

In the special case where N is infinite, the correction factor is:—$1 + \frac{2F}{M}$

Since all the above correction factors are independent of the position of the fault, they are readily eliminated from the equations in the Double Varley and Behrend tests. In Weber's article(4) it is shown that the Double Varley test eliminates also the second correction factor—for the shunting effect of F + N on $2(l - x)$, the loop resistance beyond the fault—when the fault is in the middle, or very near one end of the line. This does not happen in the Behrend test but this test has some advantages as regards the elimination of the first correction factor when M_1 and M_2 are unequal.

If M_1 and M_2 are high compared with F and N, and their ratio does not exceed about 2, the consequent error is usually very small in the Behrend test. It may or may not be small in the Double Varley test, according to the relative positions of the faults.

The possibility of allowing for the error, in the Behrend test, by using two or more values of S was investigated, by calculation and experimentally (on artificial lines), but the result was negative. It would appear that if a patch of low insulation is known to exist, but the insulation resistances of the wires are not known before the fault occurs, great accuracy cannot be expected. But the chances are better with the Behrend test than with the Double Varley.

9.3. Appendix III. Faults in Submarine Cables.

When a gutta-percha insulated cable is damaged, the conductor, whether broken or not, is usually in contact with the sea water. Electrolytic action between the copper, the iron sheathing wires and the sea water sets up " polarisation effects " which result in variable fault resistance. A number of tests were devised, many years ago, in which these polarisation effects are eliminated, or reduced, by measuring the resistance to earth with different voltages. These tests all depend on empirical laws relating the fault resistance to the magnitude and direction of the testing current, and generally give results differing by several ohms.

The best that can be done is to apply several different tests and then interpret the results in the light of practical experience. As few communications engineers have such experience, however, two of the simple tests, which have been found useful in the Submarine Branch, are given here:—

Mance's Test.

Measure the resistance of the conductor to earth with an ordinary Wheatstone bridge, using 100 + 100 ohm ratio arms, and positive to line. When the balance is steady, quickly change to 1000 + 1000 ratio arms and balance again. If the two bridge readings are R_1 and R_2 then the resistance to the fault is

$$x = \frac{1000\,R_1 - 100\,R_2}{900 + (R_1 - R_2)}$$

It is generally necessary to subtract the resistance of ½ mile of cable to allow for the fault resistance.

Cann's Test.

With negative to line, measure the resistance to earth with 20, 10 and 5 cells in the bridge battery, so that the ratio of currents is 4:2:1, and call the results R_1 R_2 R_3. Repeat with, say, 40, 20 and 10 cells. Then

$$x = R_1 + R_2 - R_3$$

The lowest value of x is the most likely to be correct, and it is unnecessary to allow for the resistance of the fault. This simple test gives good results in sea water.

In fresh water it is advisable also to try Mance's test, and allow about 1 mile of cable for the fault resistance.

Dorling & Co. (Epsom), Ltd., Printers. 3752