capacitor C, the non-inductive resistors P and Q being adjusted to give a balance of the bridge, when

$$\frac{\text{Capacitance of cable-length to the fault}}{\text{Capacitance of standard capacitor}} = \frac{Q}{P}.$$

The distance to the fault is then obtained, as described above,

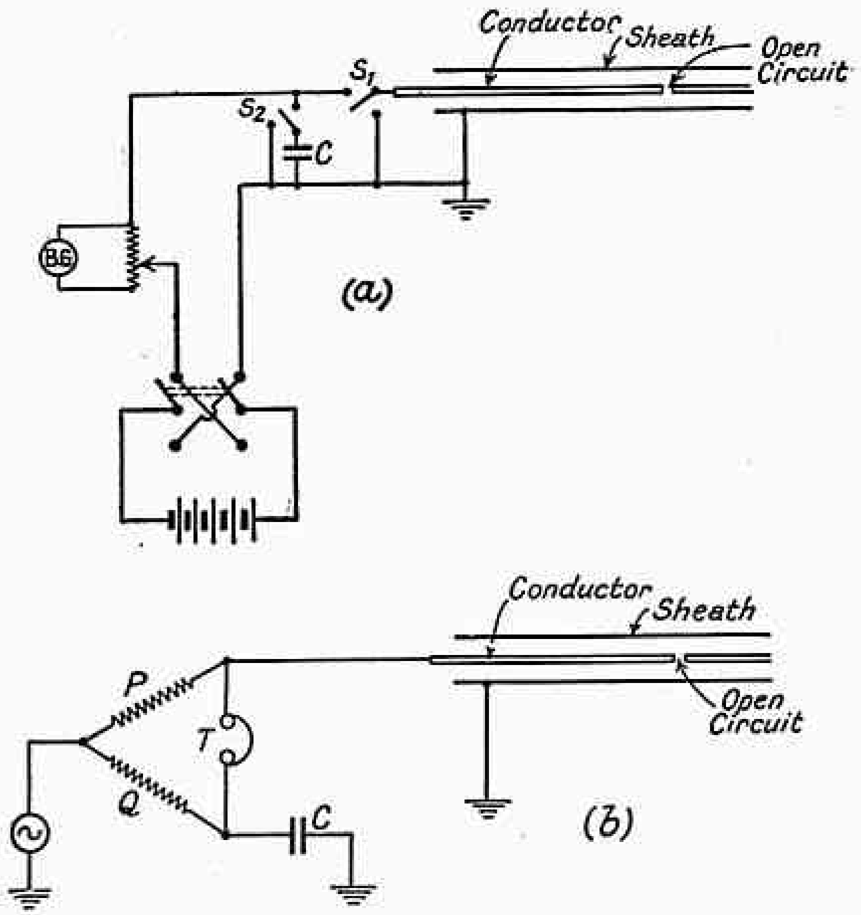

FIG. 302. TEST FOR AN OPEN CIRCUIT FAULT

from this measured value of the capacitance, up to the fault, compared with the capacitance of the whole cable.

An open-circuit fault locator operating on this principle is manufactured by Messrs. H. W. Sullivan, Ltd. A Kelvin-Varley slide wire is used for the ratio arms P and Q.

Induction Method of Testing. This method, which is used for the localization of ground faults in cables, can only be successfully employed when the cable has no metallic sheath or armouring. It is, however, useful for the localization of such faults in vulcanized bitumen cables, and has the merit of discovering the fault directly without reliance having to be placed upon calculations, or upon assumptions as to cable resistance.

A battery and interrupter are used to send an interrupted direct current through the faulty cable. An exploring, or search coil, to the terminals of which a telephone receiver is connected, is then placed with its plane parallel to the direction of the cable as shown

in Fig. 303. This coil consists of about two hundred turns of 26 or 30 S.W.G. wire, wound on an equilateral triangle former of about 3 ft. side.* The intermittent current in the cable induces an e.m.f. in the coil, and a note is thus heard in the telephone receiver. If the search coil is moved along the cable in the direction of the fault, this note will cease immediately the fault is passed, since the testing current there passes to earth, and from thence passes to the earthed terminal of the testing battery. The position of the fault is thus directly determined from the cessation of the telephone note.

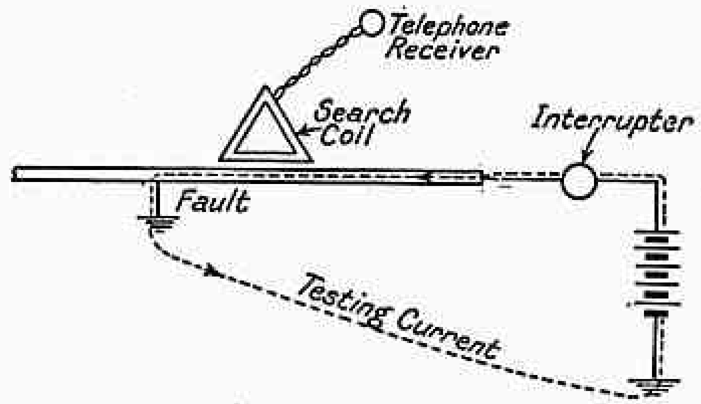

FIG. 303. INDUCTION METHOD OF LOCATING A GROUND FAULT

If the cable is lead-covered or is armoured, the method is rendered uncertain, owing to the currents flowing in the sheath (which is connected to the cable at the fault) and to the magnetic shielding effect of the steel armouring in the latter case.

A test set on this principle, containing an impulse generator as well as two different forms of search coil, is the "P & B" Cable Tracer and Fault Locator, made by Price and Belsham, Ltd. From the point of view of tracing the run of an underground cable the magnetic shielding effect of the armouring is negligible.

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* These dimensions are taken from Raphael's *Localization of Faults*.

CHAPTER XI

HIGH-VOLTAGE MEASUREMENTS AND TESTING

General Classification. The rapid advance in the use of high voltages for transmission purposes, during the last few years, has necessarily been accompanied by extensive research upon high-voltage phenomena. The subject of high voltage testing is, therefore, a very important one at the present time, and includes a large variety of testing methods.*

These may be classified as follows—

1. Sustained low-frequency tests.
2. Constant direct-current tests.
3. High-frequency tests.
4. Surge, or impulse tests.

Purpose of Various Test Methods. 1. SUSTAINED LOW-FREQUENCY tests are the commonest of all high-voltage tests. The frequency used is almost always the standard frequency—50 cycles per second in Britain and most European countries, and 60 cycles per second in America.

Voltages of 2 or 3 kilovolts (50 cycles) are used for routine pressure tests upon motors, switchgear, and other apparatus after manufacture, and in some cases after installation, in accordance with specifications of the British Standards Institution.

British Standard Specification 116 : 1952, "Oil Circuit Breakers for Alternating Current Systems," states that when such apparatus is tested at the maker's works, the test-voltages for the various components shall be as given in Table XI.

"The test voltage shall be alternating, of any frequency between 25 and 100 cycles per second, and approximately of sine-wave form."

Other tests are specified for the apparatus after erection on site.

Low-frequency tests are made upon specimens of insulation material for the determination of their dielectric strength and dielectric losses, for the routine testing of supply mains, and for works tests upon high-voltage transformers, porcelain insulators, and other apparatus. Voltages of 2,000 kilovolts and upwards are used for research work and for the testing of porcelain insulator strings and of high-tension cables.

2. CONSTANT DIRECT CURRENT TESTS. To transmit large amounts of power efficiently, high transmission voltages are necessary. Overhead lines have been erected with a working pressure of 380 kV, while cables for 275 kV have been made and tested.

The electricity supply regulations state that no extra-high-pressure main shall be brought into use "unless, after it has been

* Owing to the impossibility of covering, fully, the whole ground of the subject in a single chapter, an extensive list of recent papers on high-voltage measurements is given at the end of the chapter. These should be referred to for more detailed information.

TABLE XI

Component	Rated Service Voltage	Test Voltage: All Circuit Breakers for Systems up to 88 kV	Test Voltage: Circuit Breakers for Non-effectively Earthed Systems of 110 kV and above	Test Voltage: Circuit Breakers for Effectively Earthed Systems of 110 kV and above
	kV	kV	kV	kV
Circuit-breaker including any series coils	Up to 0·66	2	—	—
	3·3	9·5	—	—
	6·6	17	—	—
	11	27	—	—
	22	52	—	—
	33	76	—	—
	44	100	—	—
	66	150	—	—
	88	200	—	—
	110	—	250	200
	132	—	300	250
	165	—	365	300
	220	—	485	400
	275	—	—*	485
Neutral earthing circuit breaker	1·91	6·5	—	—
	3·81	10·5	—	—
	6·35	16	—	—
	12·7	31	—	—
	19·1	45	—	—
	25·4	60	—	—
	38·1	88	—	—
Operating coils and small wiring	—	2	2	2
Operating motors	In accordance with B.S. 168 and B.S. 170.			

* All 275-kV systems are considered for this specification to be effectively earthed.

placed in position, and before it is used for the purposes of supply, the insulation of every part thereof has withstood the continuous application, during half an hour, of pressure exceeding the maximum pressure to which it is intended to be subjected in use, that is to say, in the case of every electric line to be used for a pressure not exceeding 10,000 volts, twice the said maximum pressure, and in the case of a line to be used for a pressure exceeding 10,000 volts, a pressure exceeding the said maximum pressure by 10,000 volts; and the undertakers shall record the results of the tests of each main or section of a main."

If such pressure tests were carried out with an alternating high-tension supply, the transformer for the purpose would have to be of inconveniently large capacity, owing to the heavy charging current taken by such lengths of cable. Transport difficulties would be encountered, also, in moving the testing transformer to the site of the cable system, and for this reason high-tension direct current is used for testing purposes. The plant for such a supply need only be of small capacity, and may be constructed in a portable form.

High-tension direct current is also used in research work upon insulation and upon X-rays and electrical precipitation.

3. High-frequency Tests. Such tests, at frequencies varying from several thousand cycles per second to a million or more cycles, are important in work upon insulators for wireless purposes where such frequencies are usual. It has been found, also, that in the case of porcelain insulators in service on transmission lines, breakdown, or flashover, occurs in most cases as a result of high-frequency disturbances in the line, these being due either to switching operations or to external causes. Thus, insulators which may be satisfactory under high voltage of low frequency are not necessarily

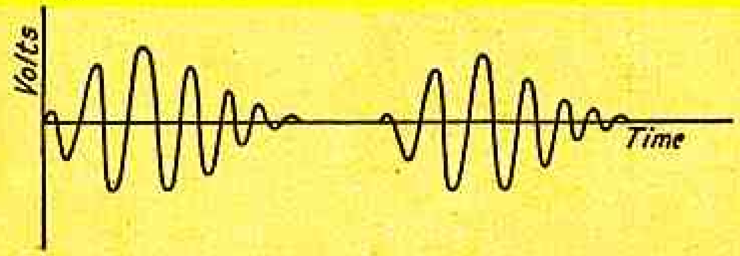


Fig. 266. Damped Oscillations

satisfactory under the different conditions existing when the frequency is of a much higher order.

It has been found that undamped high-frequency oscillations—i.e. oscillations of approximately constant amplitude—cause failure of insulators at comparatively low voltages, due to high dielectric loss and heating. Such oscillations do not, however, occur in power systems in practice. Damped high-frequency oscillations having a waveform such as that shown in Fig. 266 do occur in practice, due to switching operations, or to arcing grounds.

For this reason, high-voltage tests at high frequencies are made in insulator manufacturing works, in an endeavour to obtain a design of insulator which will satisfactorily withstand all conditions in service.

4. Surge, or Impulse Tests. These tests are carried out in order to investigate the influence of "surges" in a transmission line upon breakdown of the line insulators, and of the end turns of transformers connected to the line. In order to appreciate the importance of such tests and to realize what are the requirements of the testing plant, the nature of these surges must be understood.

Such surges are usually produced by lightning in the neighbourhood of the transmission line, and are the result of the sudden discharge of the electricity on the suspended particles of a thunder cloud, which takes the form of a lightning stroke. A direct lightning stroke on the line is comparatively rare, but a charged cloud above, and near to, the line, will induce charges, of opposite sign to that of its own charge, in the line. These charges are "bound" (i.e. held in that portion of the line nearest the cloud) so long as the cloud remains near without discharging its electricity by a lightning stroke.

If, however, the cloud is suddenly discharged—as it is when the lightning stroke occurs—the induced charges in the line are no longer bound, but travel, with the velocity of light, along the line to equalize the potential at all points of the line.

This means that a steep-fronted voltage wave travels along the line, its form being as shown in Fig. 267.* Due to this travelling wave the potential of any point along the line will rise very suddenly from its normal value by an amount equal to the amplitude of the wave. The time taken for this voltage rise is of the order of one millionth of a second. The effect is to impose very severe stresses upon the line insulators and upon the transformer windings (if

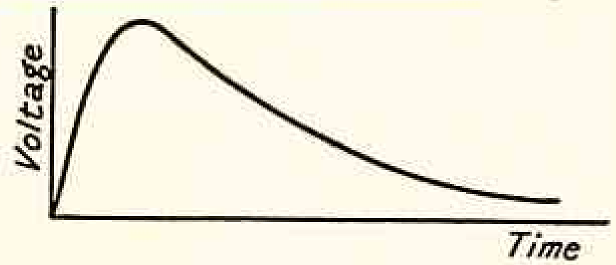


FIG. 267. SURGE WAVEFORM

the wave is allowed to reach them), the stresses depending upon the steepness of the wave front.

Violent rupture of insulators is often caused by such surges, and the investigation of their eff[illegible] upon different types of insulators and other apparatus, as w[illegible] the testing of surge-absorbers designed for transformer prot[illegible], is obviously of great importance.

The shapes of voltage waves for impulse testing have now been standardized in several countries. Thus in Britain, in B.S.S. 923 : 1940 the standard testing wave is expressed as "1/50 microsec." which indicates that it is to rise to its peak in 1 microsecond and is to fall to one half of its peak value in 50 microseconds.

The testing plant for this purpose must be capable of producing a high, uni-directional voltage, suddenly applied to the apparatus under test.

Testing Apparatus. Certain apparatus is common to all types of high-voltage tests. Special apparatus is required, in addition, for direct current, high frequency, and impulse tests. For all tests, the following apparatus is usually essential.

(*a*) A high-voltage transformer.
(*b*) Apparatus for voltage regulation.
(*c*) Control gear and high-tension connections, including safety protective devices.
(*d*) Apparatus for voltage measurement.

(*a*) HIGH-VOLTAGE TRANSFORMERS. Such transformers, for testing purposes, require careful design, owing to the fact that they are

* See also Refs. (8), (9), (10), (11), (12).

subjected to transient voltages and surges during their normal operation when the insulation under test breaks down. To withstand the internal stresses set up by such disturbances the transformer insulation must be carefully proportioned. The transformers are usually single-phase, core type, and are oil-immersed, Bakelite cylinders being used for insulation between high- and low-tension windings. Transformers for cable testing, and certain other purposes, may also be required to give a considerable current, and the question of regulation and cooling must therefore be carefully considered. In insulation testing the current taken from the transformer, when the test specimen breaks down, is limited by the insertion of water resistances in the test circuit, so that for such purposes the transformer need not have a large kVA capacity. The following table gives the order of the capacities required for various purposes, and also the approximate values of maximum voltage used.

TABLE XII

Purpose of Transformer	Approximate Capacity (kVA)	Maximum Voltage (kV)
Routine pressure tests upon motors and switchgear	Small	2 or 3
Insulation testing	10 to 20	50
Routine testing of cables	50	10 to 30
High-voltage transformer and porcelain insulator testing and research	20 to 50	100 to 200
Research and testing of strings of insulators	½ to 1 kVA per kilovolt	500 to 2,000
High-voltage cable testing	100 to 500	100 to 500

Equipments giving a maximum high-tension voltage up to 500 kV have usually a single high-voltage transformer. For the higher voltages—1,000 kV and upwards—two or more transformers are generally used, connected *in cascade*—a method of connection due to Prof. Dessauer. This arrangement is found to be more convenient than the single transformer for very high voltages, owing to the very large size and high cost of a single transformer for the purpose. A common method of connecting transformers in cascade is shown in Fig. 268. The low-tension supply is connected to the primary winding of transformer I, the tank of which is earthed. One end of the h.t. secondary winding of this transformer is connected to the earthed tank. From the other end of the secondary winding, a lead passes through a high-voltage bushing, which provides insulation for the full secondary voltage between this lead and the tank. Through this bushing also runs a second lead from a tapping point on the secondary winding, the voltage between this tapping point and the high-voltage end of the secondary winding being that required for the primary winding of transformer II. One end of the secondary winding of transformer II is connected to its tank, which is insulated from earth for the full secondary voltage of transformer I. The other end of the secondary winding provides the high voltage terminal of the equipment, the total voltage—to earth—obtainable being approximately the sum of the secondary voltages of the two transformers.

(b) Voltage Regulation. In order to avoid surges on the high-tension side of the transformer, and also for accuracy of voltage

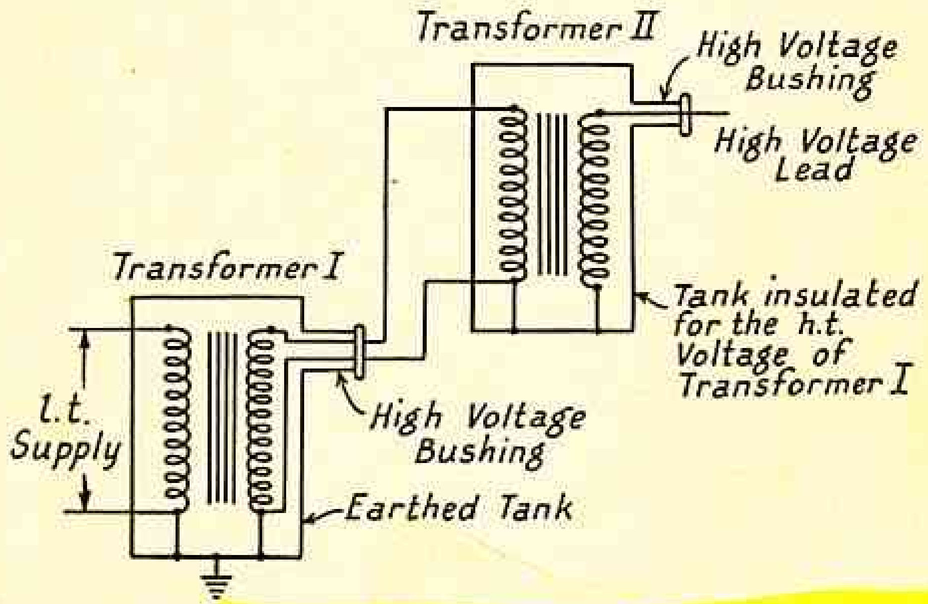


Fig. 268. Cascade Connection of Transformers

measurement, it is essential that the regulation of voltage shall be smooth. Sudden variations of the testing voltage *must* be avoided in most tests. Another requirement of voltage-regulating apparatus is that it shall not cause distortion of the voltage waveform.

The transformer secondary voltage is regulated by variation of the voltage applied to its primary winding. This may be done either—

(i) By variation of the alternator field current, or
(ii) By insertion of either resistance or inductance in the supply circuit from the alternator, or
(iii) By means of an induction regulator, or
(iv) By means of a tapped transformer.

(i) *Variation of the Alternator Field Current.* This method can only be used, of course, when a separate alternator is used for the supply to the testing plant. Except in the case of comparatively small plants for routine testing, a separate alternator is generally used. The alternator should have a voltage waveform which is as nearly as possible sinusoidal on no load, and the distortion under load conditions should be small. This is achieved by making the

air gap of the alternator large; by special design of the armature windings; and by suitable regulation of the number, and shape, of the slots.

This method of voltage regulation has the advantages of smooth control of the voltage from zero to the full voltage, absence of impedance for regulation purposes in the transformer primary circuit (which may produce waveform distortion), good waveform, convenience, simplicity, and freedom from appreciable disturbance by frequent short-circuiting of the transformer during testing.

The field current of the alternator is varied directly in the case of fairly small machines, but when a large alternator is used the field

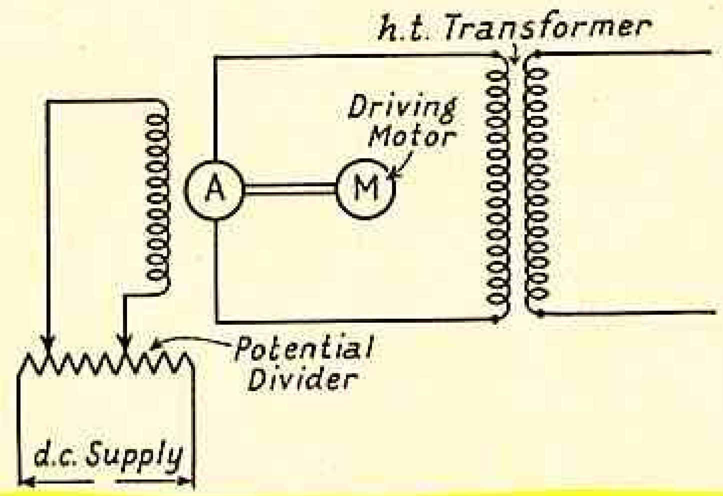


Fig. 269. Alternator Field Current Method of Voltage Control

current of the exciter may be varied, thus varying the alternator field current indirectly. Fig. 269 shows the connections for direct variation of the alternator field current. A potential divider, connected across a steady d.c. supply, is used, and the connections are arranged so that a small field current in a reverse direction to the normal one, may be obtained. By this arrangement zero voltage may be obtained by neutralization of the residual magnetism in the field. Smooth and gradual voltage regulation is obtained by a special design of the potential divider, which should have a large number of turns and some provision for very gradual and steady movement of the sliding contact.

(ii) *Resistance, or Inductance, Control.* When a separate alternator is not used—in the case of small equipments—resistance or inductance must be inserted in the a.c. supply circuit for voltage regulation.

If resistance is used, it is better to make the connections as in Fig. 270, using the resistance as a potential divider, than to insert it in series with the transformer primary winding. Zero voltage can be obtained in this way. A slider resistance should be used for smooth voltage regulation.

The disadvantages of the resistance method are the loss of power in the resistance and the impracticability of its use for high powers, owing to the very large size and great cost of resistances for the purpose. For small equipments (2 or 3 kVA) it has the advantages of cheapness, convenience, smooth voltage variation, and small distortion of the voltage waveform.

A choke coil, connected in series with the transformer primary, may be used instead of resistance. Voltage regulation is then obtained by the withdrawal or insertion of the iron core of the coil. This method has the advantage of greater efficiency than the resistance method, on account of its low power factor, but has several serious disadvantages. These are—

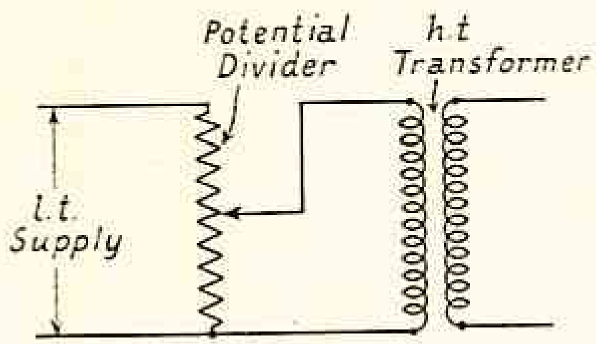


FIG. 270. POTENTIAL DIVIDER CONTROL

(*a*) the large size of coil required if the power to be dealt with is high;

(*b*) the distortion of waveform owing to the iron core;

(*c*) the fact that increase of its inductance will *increase* the primary voltage of the transformer instead of decreasing it if the power factor of the load on the secondary side of the testing transformer is leading, as is often the case.

(iii) *Induction Regulator Method.* This method of voltage regulation has the advantage of smooth regulation from zero to full

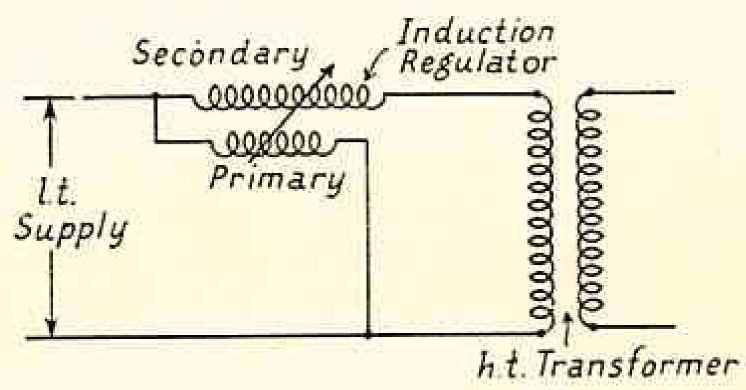


FIG. 271. INDUCTION-REGULATOR CONTROL

voltage, and may be used for all loads and power factors. It is, therefore, much to be preferred to the resistance and inductance methods described above.

An induction regulator is, essentially, a transformer, or mutual inductance, the secondary voltage of which can be varied by the rotation of the primary through any required angle up to 180°. The connections are shown in Fig. 271. If the primary and secondary have equal numbers of turns, by rotation of the primary winding the voltage induced in the secondary may be varied from $-E$ to $+E$ (where E is the low tension supply voltage). Thus the voltage

applied to the h.t. transformer primary may be varied from zero to $2E$.

Careful design, with distributed windings on the rotor, are necessary to prevent waveform distortion. This method of regulation is often used in cable-testing equipments, since its gradual voltage variation at loads of any magnitude is advantageous for such work.

(iv) *Voltage Variation by Means of a Tapped Transformer.* Fig. 272 gives the connections of this method of regulation. An intermediate regulating transformer is used, having its primary supplied from the l.t. supply. The secondary winding of the transformer

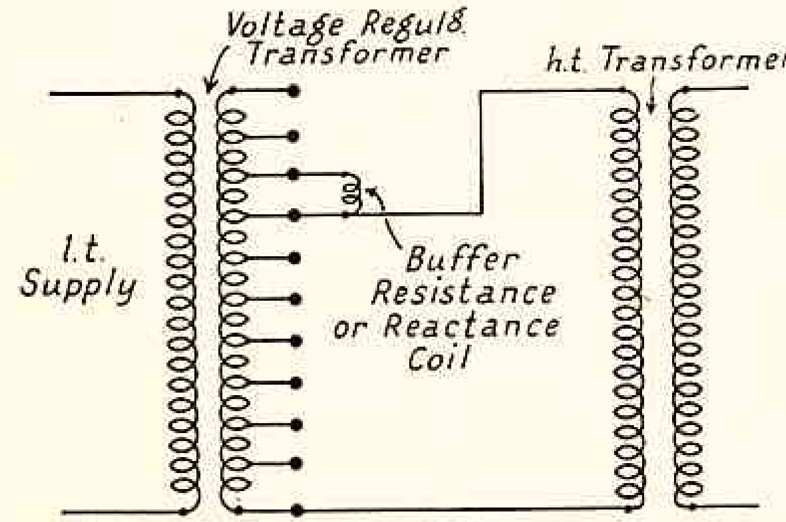


FIG. 272. TAPPED-TRANSFORMER REGULATION

has a large number of tappings whereby the voltage applied to the primary of the h.t. transformer may be varied. In order to avoid surges, due to the opening of the secondary circuit of the regulating transformer when the tapping switch is moved, two contact brushes are used, making contact with adjacent studs, and with a "buffer" resistance or reactance coil between them to prevent short-circuit of a section of the transformer winding. An auto-transformer may be used instead of the double-wound transformer shown in the diagram. The operation is similar to that in the case of the double-wound transformer.

For gradual regulation a number of coarse tappings are used together with fine tappings. The method has the advantages of high efficiency and small waveform distortion, but the regulation is not smooth unless a very large number of tappings is used and, when the power of the equipment is large, the switchgear must be large and is expensive.

(*c*) CONTROL GEAR AND CONNECTIONS. On the low tension side —i.e. in the primary circuit of the h.t. transformer, there should be—

A *main switch*, to isolate the testing apparatus from the supply.

Fuses.

A *circuit breaker*, with arrangements for tripping the breaker over a wide current range, and having a no-volt coil in order to protect apparatus from damage in the event of failure of the supply.

An *over-voltage relay*, which short-circuits the no-volt coil of the circuit breaker if the supply voltage exceeds a predetermined value.

Interlocks. These are arrangements which guard against the supply to the transformer being switched on except at a low value, or which make it impossible for the operator to pass inside the screen-work surrounding the high-tension testing area while the supply is on. The latter takes the form of a switch on the gate of the screen.

Earth connections. Both for safety and for the protection of apparatus it is necessary that all metal parts, forming part of the testing equipment, which should be at earth potential, should be definitely earthed. This applies to the framework of switchgear and to the guard screen, transformer tanks (except where a cascade arrangement is used), and to one end of each of the transformer windings.

On the high-tension side care must be taken in deciding the size and shape of the leads and connections, in order to avoid "corona" loss, which may distort the voltage waveform and may influence the breakdown or flash-over voltages measured, on account of the surges in the circuits, and because of ionization of the air in the test room, which it may produce. "Corona" is the name given to the luminous glow which surrounds a high-tension conductor when the potential gradient at its surface exceeds the disruptive strength of air. Breakdown of the air at the conductor surface occurs first of all, and this spreads outwards, ionizing the air immediately surrounding the conductor, and producing both a glow and a hissing sound. The result of such corona is a loss of power, with the possible effects mentioned above. The voltage at which corona occurs depends upon the diameter of the high-tension conductor, the voltage increasing with increasing diameter. Thus, to avoid such effects the conductors in the high-voltage circuit should be made much larger than is necessitated by current-carrying considerations.

E. T. Norris and F. W. Taylor (Ref. (13)) recommend for the diameters of high-tension conductors "1 in. for 100 kV and about 12 in. for 1,000 kV, if the atmospheric conditions are normal and the high-tension clearances are ample." High-tension conductors are almost always bare, the surrounding air forming the principal insulation. The supports for these conductors are usually Bakelite tubes or rods, or porcelain insulators. Since the current to be carried is usually very small, good contact at joints is not often essential, mere touch being sufficient. Sharp edges, which produce concentration of electrostatic field, must be avoided throughout the circuit. Terminals are usually fitted with spherical metal caps, and sharp bends in conductors are fitted with spherical elbow pieces to distribute the electric stress.

As a protection from surges which may be produced when a

sphere-gap, or the apparatus under test, breaks down, a high resistance (about $\frac{1}{2}$ ohm per volt), or choke coil, is inserted in the main high-voltage circuit. A sphere-gap is also connected across the high-voltage winding as a protection in the event of excessive voltage being applied to the circuit. This may be the same gap as is used for voltage measurement. A water resistance, consisting of a glass tube or tubes containing water, with some common salt added, is connected in the sphere-gap circuit to prevent pitting of the sphere surfaces by limiting the current flowing at breakdown. These resistances should be about 1 ohm per volt to limit the current to 1 amp.

Fig. 273 gives a simplified diagram of connections for a high-voltage testing equipment having a separate supply alternator.

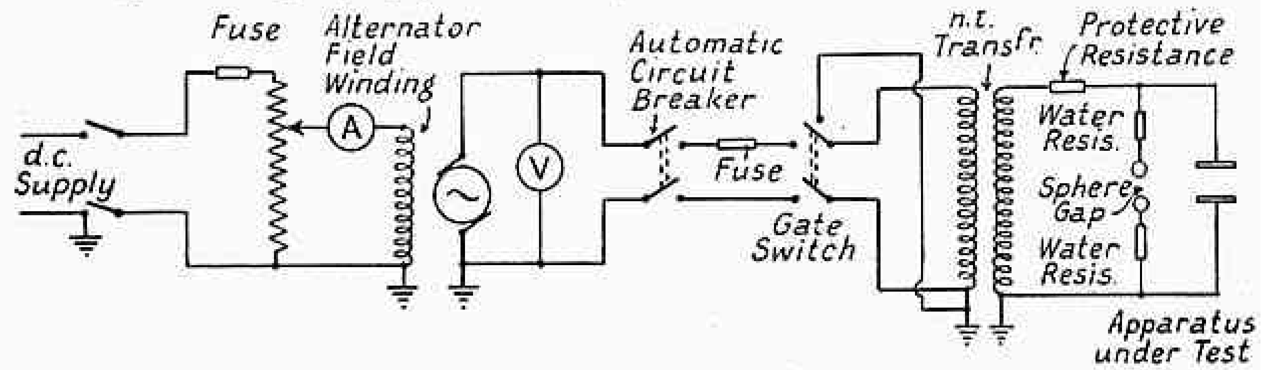


FIG. 273. CONNECTIONS OF TESTING EQUIPMENT

(*d*) APPARATUS FOR VOLTAGE MEASUREMENTS. Owing to the difficulty of designing electrostatic voltmeters, for the measurement of extra high voltages, which will be free from errors due to corona effects within the instrument, and to external electrostatic fields, a number of special methods of measurement have been devised for the purpose. Some method must be available, also, for calibrating such voltmeters when constructed. Work by the British Electrical and Allied Industries Research Association (Ref. (14)), and the American Institute of Electrical Engineers, led to the standardization of the sphere-gap method as the most reliable one.

(i) *Sphere-gap*. Two metal spheres are used, separated by an air gap. The potential difference between the spheres is raised until a spark passes between them. The value of the potential difference required for spark-over depends upon the dielectric strength of air, the size of the spheres, their distance apart, and upon a number of other factors. As a result of the research work already mentioned, the British Standards Institution has drawn up a list of "British Standard Rules for the Measurement of Voltage with Sphere-gaps" (No. 358-1939). Some years ago the American Institute of Electrical Engineers drew up a list of rules for the measurement of voltages up to 50 kV, using needle points for a spark-gap, instead of spheres as at present used. The disadvantages of this form of gap were the errors caused by variation in sharpness of the needles; by variation of the humidity of the atmosphere; and by the corona which formed at the points before the gap actually sparked over.

In B.S. 358-1939, twelve sizes of spheres are to be used to cover a range of voltage from 2 to 2,500 kV, namely, of diameters 2, 5, 6·25, 10, 12·5, 15, 25, 50, 75, 100, 150 and 200 cm. The following are extracts from these rules—

1. "A spark-gap may be used for the determination of the peak value of a voltage-wave, and for the checking and calibration of voltmeters and volt-measuring devices for high-voltage tests.

2. "Peak voltages may be measured from about 2 kilovolts to about 2,500 kilovolts by means of sphere-gaps used in conjunction with the calibrations provided herewith."

3. "The appropriate Tables may also be used for the measurement of impulse voltages of either polarity and of the standard wave forms, having fronts of at least one microsecond and times-to-half-value of at least 5 microseconds."

4. "The length of any diameter shall not differ from the correct value by more than 1 per cent for spheres of diameter up to 100 cm., or by more than 2 per cent for larger spheres."

5. "One sphere may be earthed or both may be insulated, the voltages being symmetrical with respect to earth in the latter case."

Subject to certain specified conditions,
"no conductor or body having a conducting surface (except the supporting shanks) shall be nearer the sparking point of the high-voltage sphere than the distance given by the expression $\left(0{\cdot}25 + \frac{U}{300}\right)$ metres, where U is the voltage in kV (peak) which is to be measured."

6. "It is recommended that spheres of brass, bronze, steel, copper, aluminium or light alloys be used, and that the surface of the spheres should be cleaned immediately before use. A high degree of polish should be avoided."

The rules provide that the current at spark-over shall be limited to about 1 amp. and that the interval between consecutive discharges shall be great enough to prevent appreciable heating of the spheres.

The density of the air affects the spark-over voltage for a given gap-setting. The "relative air density," is given by

$$d = \frac{p}{760} \cdot \frac{273 + 20}{273 + t} = 0{\cdot}386 \left(\frac{p}{273 + t}\right) \quad . \quad . \quad (230)$$

where p = barometric pressure in millimetres of mercury

t = temperature in degrees Centigrade

A correction factor, by which the spark-over voltage for a given gap-setting, under the standard conditions (760 mm. pressure and 20° C.) must be multiplied, in order to obtain the actual spark-over voltage, may be obtained from a table given in the B.S.I. rules. This factor is approximately equal to d for values of d above 0·9.

With regard to humidity, the rules state that over the sparking distances covered by the calibration tables, the breakdown voltage of the sphere-gap is independent of the humidity of the atmosphere

but deposited dew on the surface of the spheres lowers the breakdown voltage and invalidates the calibrations.

For the calibration of a spark-gap from a standard sphere-gap the two gaps should not be connected in parallel. "Equivalent spacings should be determined by comparing each gap in turn with a suitable indicating instrument."

F. W. Peek (Ref. (15)), Russell (Ref. (16)), and others have obtained formulae by which the spark-over voltage for a given gap-setting and sphere-diameter may be calculated, but the use of the calibrations given in the B.S.I. rules is to be recommended instead of the use of such formulae, the application of which is limited.

The spark-over voltages given in the rules are in terms of r.m.s. (sine-wave) voltage. To obtain the corresponding peak values—which are important since it is the peak value of the voltage, rather than the r.m.s. value, which determines the flash-over, or breakdown of insulation—the r.m.s. values given must be multiplied by $\sqrt{2}$.

A disadvantage of the sphere-gap method of measurement is that it cannot be used to give a continuous record of voltage. It is generally used to calibrate some indicating instrument, or other apparatus, which does give such a continuous record. In the following methods of measurement, wherever calibration is referred to, it is to be understood that the sphere-gap method is implied unless otherwise stated.*

(ii) *Transformer Ratio Methods of Measurement.* In this method the primary voltage of the high-tension transformer is measured by a calibrated voltmeter, and this is multiplied by the turns ratio of the transformer to obtain the secondary voltage. The assumption is made that the transformer ratio is unaffected by the transformer impedance and by variations in the load. The method also gives r.m.s. values of voltage, and the secondary voltage waveform must be determined in order that peak values of voltage may be obtained from the "crest factor" of the wave, i.e. the ratio

$$\frac{\text{Peak voltage}}{\text{r.m.s. voltage}}$$

Some high-tension transformers carry a separate voltmeter-coil having a number of turns which is a definite fraction of the number of turns on the secondary winding. The voltage induced in this coil (measured by a low-voltage voltmeter), when multiplied by the turns-ratio, gives the secondary voltage of the transformer. This method cannot be used with the cascade arrangement of transformers and may only be relied upon to within 1 or 2 per cent.

* The calibration of the sphere-gap itself is described by S. Whitehead and A. P. Castellain (Ref. (14)), who used a number of different methods for the purpose, and obtained consistency between them.

(iii) *Potential Divider Methods.* In such methods, either a high resistance, or air capacitor, must be used, connected across the high-voltage winding, a definite fraction of the total secondary voltage being measured by means of a low-voltage electrostatic voltmeter.

High resistances for this purpose have the disadvantage of residual phase-angle errors due to the effects of distributed capacitance, unless special precautions are taken in their design (Ref. (17)). Such resistances have been constructed, however, and are used in several high-voltage equipments.

The advantages of capacitors as compared with resistors are: their comparatively simple construction, their freedom from heating, and the fact that they are much more easily shielded from extraneous capacitance effects than are high resistances. B. G. Churcher and C. Dannatt (Refs. (18), (19)) have described the construction and use of such capacitors.

In the capacitor method an electrostatic voltmeter, whose capacitance is large compared with that of the high-voltage standard capacitor, is connected in series with the latter, and is shunted by a capacitance of much greater value than its own. The capacitance of the standard capacitor must be accurately known, and it is important that it shall be free from dielectric loss. For the latter reason air capacitors are always used for this purpose, their capacitance usually being from 50 to 100 $\mu\mu f$.*

If C is the capacitance of the standard capacitor, and C_1 that of the capacitor which shunts the electrostatic voltmeter (see Fig. 274), then the voltmeter reading v is given by

$$v = \frac{i}{\omega C_1}$$

where i is the current passing through the capacitors and $\omega = 2\pi \times$ frequency.

Neglecting the capacitance of the voltmeter, the effective capacitance of C and C_1, in series, is $\frac{CC_1}{C + C_1}$, and the voltage V of the high-tension circuit, is

$$V = \frac{i}{\omega\left(\frac{CC_1}{C + C_1}\right)}$$

Thus,

$$V = \frac{C + C_1}{C} \cdot v \quad . \quad . \quad . \quad . \quad (231)$$

This method measures r.m.s. voltage values.

Other methods utilizing a standard impedance involve the measurement of the current which flows through the impedance—either a standard air capacitor or high resistance—when it is connected across the high-tension winding of the transformer. The

* The effect of humidity of the atmosphere and of dust deposits, upon the purity of capacitors is given by B. G. Churcher and C. Dannatt (*loc. cit.*).

current may be measured by means of a thermo-junction and galvanometer; by measuring the voltage drop across a known resistance, in series with the standard high impedance, using an electrometer; or by a valve-voltmeter method described by S. Whitehead and A. P. Castellain (*loc. cit.*).

A *thermo-junction* consists of a small "heater" of fine wire, through which the current to be measured is passed. To the centre of this heater is attached a thermo-junction of two dissimilar metals, the attachment being by means of a small bead of a material which, while being electrically insulating, is a good thermal conductor.

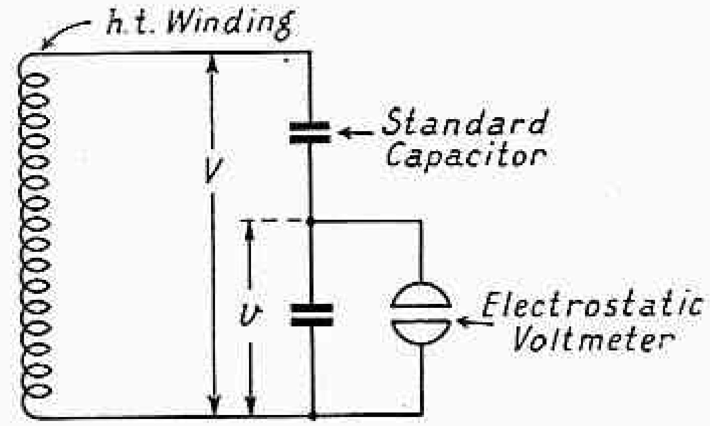


FIG. 274. CAPACITOR POTENTIAL DIVIDER

An e.m.f. is set up, in the circuit containing the thermo-junction, when a current is passed through the heater. This e.m.f. depends upon the magnitude of the heating effect of the current, and thus the r.m.s. value of a small alternating current may be measured by comparison with a known direct current. The thermo-junction, which may be of the vacuum type—in which the heater and junction are enclosed in a small evacuated glass bulb with terminals brought out—or air type, is used in conjunction with some form of galvanometer. The arrangement is calibrated with direct current, and is then used for the measurement of alternating currents of the same order of magnitude as the direct, calibrating current. Such thermo-junctions may be obtained for either 2·5 mA, 5 mA, 10 mA, and so on, up to 10 amp. Below 1 amp. they are vacuum type, and above 1 amp. air type.

From the measured value of the current flowing through a standard impedance, the r.m.s. values of the high-tension voltage may be obtained by multiplication by the value of the impedance.

(iv) *Measurement of Peak Voltage.* Owing to the fact that the *maximum* or *peak* value of the applied voltage is that which produces the actual breakdown stress in the material under test, it is important that this value should be known in most cases. If methods of voltage measurement which give r.m.s. voltage values are used, the peak voltage may be obtained from the crest-factor of the voltage wave. It is often more satisfactory, however, to use some method of voltage measurement which gives the peak value of the voltage directly. From the fact that the breakdown of air is involved in the sphere-gap method, this is obviously one method which depends upon the peak values, and the calibration curves for sphere-gaps, already referred to, give such peak values.

Other methods of measurement of peak voltage have been devised and are as follows—

1. *Rectified Capacitor Charging-current Method.* This method depends upon the fact that the peak voltage value is proportional to the average charging-current of a standard air capacitor. The charging-current is therefore rectified, either by a mechanical rectifier, by specially designed thermionic valves or metal rectifiers, and its average value is then measured by a d.c. moving-coil, permanent-magnet milliammeter, or by a d'Arsonval galvanometer.

The valves used depend for their action upon the fact that if two electrodes are enclosed within a highly evacuated tube, one of these electrodes—the plate—being comparatively cold, whilst the other—the filament—is heated, current is passed only in the direction plate to filament. The amount of current which it is possible to rectify by this means is dependent upon the filament temperature.

One-half of each wave must be entirely suppressed by such a valve. In order to prevent ripples in the output current wave, two valves are used with a suitable proportioning of inductance and capacitance in the circuit.

The capacitor used may be either of the type already mentioned, the capacitance being calculated from the dimensions of the capacitor—when the method is an absolute one—or it may take the form of a capacitor bushing, fitted to the transformer, in which case calibration is needed.

Theory. If v is the voltage across the capacitor, of capacitance C, at any instant, and Q is the quantity of electricity in the capacitor at that instant, we have

$$\int i dt = Q = Cv$$

where i = charging current and t = time.

Now, during one whole period, the voltage rises to a positive maximum, falls to zero, rises to a negative maximum, and falls again to zero, thus giving a total change in voltage, during the cycle, of $4V_{max}$, where V_{max} is the peak, or maximum, value. Meanwhile, the quantity of electricity supplied to the capacitor during this period is $\int_0^T i dt$, T being the periodic time.

Thus
$$\int_0^T i dt = C \,.\, 4V_{max}$$

or
$$\frac{1}{T}\int_0^T i dt = \frac{C \,.\, 4V_{max}}{T}$$

Now, $\frac{1}{T}\int_0^T i dt$ is the average value of the charging-current, i_{av}. Hence,

$$i_{av} = \frac{4CV_{max}}{T} = 4Cf \,.\, V_{max}$$

where f is the frequency.

Thus
$$V_{max} = \frac{i_{av}}{4Cf} \quad . \quad . \quad . \quad . \quad . \quad (232)$$

which gives the peak voltage value if the capacitance of the capacitor and the frequency (which must be kept constant throughout the test) are known.

Fig. 275 shows the connections of an arrangement for peak voltage measurement using full-wave rectification (see Ref. (20)).

This method of peak voltage measurement was first described by Chubb and Fortescue, and its accuracy is considered by R. Davis, G. W. Bowdler, and

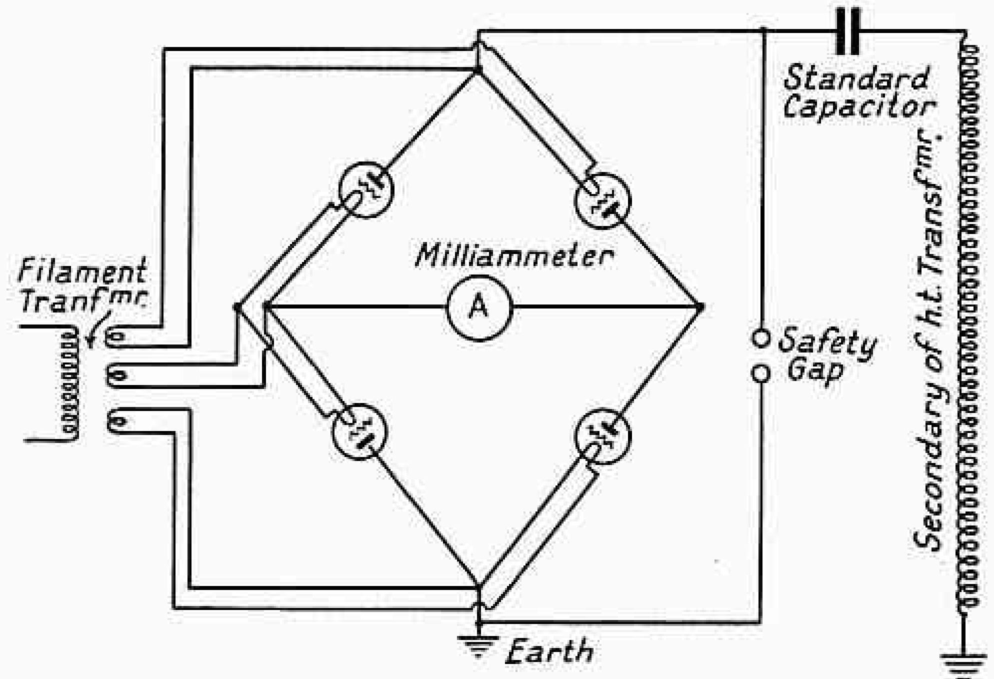


FIG. 275. CIRCUIT FOR PEAK VOLTAGE MEASUREMENT BY RECTIFIED CONDENSER CHARGING CURRENT

W. G. Standring (Ref. (21)), who state that, for a sine wave of voltage, the method is accurate provided that the impedance of the rectifier is negligibly small compared with that of the capacitor; that the rectifier is efficient in entirely suppressing one-half of the alternating wave; and that the milliammeter, or galvanometer, indicates the mean current correctly.

With regard to wave-form, the same authors state that: "the method . . . is satisfactory for all wave-shapes with the exception of (1) wave-shapes with different positive and negative maxima, and (2) wave-shapes with more than one peak in each half cycle."

2. *Ryall Crest Voltmeter.* L. E. Ryall (Ref. (22)) has developed a simple form of crest voltmeter which is independent of frequency. It consists of a neon lamp, used in conjunction with a capacitor potential-divider. Two capacitors, one—a variable one—of much greater capacitance than the other, are connected in series across the voltage whose peak value is to be measured. A neon lamp of a specially chosen type, is connected across the variable capacitor (see Fig. 276). Neon lamps have the characteristic that they only

commence to glow when the voltage applied to them reaches a certain definite value, called the "striking" voltage.

In this method of peak voltage measurement the variable air capacitor, across which the lamp is connected, is adjusted until the lamp "strikes." Then the peak value of the h.t. voltage is given by

$$V_{max} = V_{a.c.s.}\left(1 + \frac{C_1}{C_2}\right) \quad . \quad . \quad . \quad (233)$$

where $V_{a.c.s.}$ is the a.c. striking voltage of the lamp (which is a constant quantity if the type of lamp is suitably chosen), and C_1

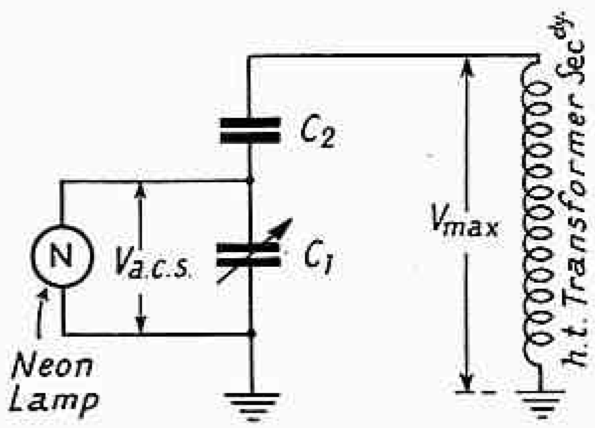


Fig. 276. Connections of Ryall Crest Voltmeter

and C_2 are the capacitances of the variable and fixed capacitors respectively.

Ryall found that the a.c. striking voltage for a neon lamp "is constant for all frequencies above 25 cycles per second, and can be measured to within $\pm \frac{1}{2}$ per cent if about 5 min. is allowed to elapse between successive flashes of the lamp, so that the lamp can return to its original ionized condition.

"The a.c. extinguishing voltage, $V_{a.c.e.}$, is also constant for all frequencies above 25 cycles per second, and can be measured to within $\pm \frac{1}{4}$ per cent."

The accuracy of the method obviously depends upon the accuracy with which $V_{a.c.s.}$ may be determined, and upon the accuracy with which the capacitances C_1 and C_2 are known.

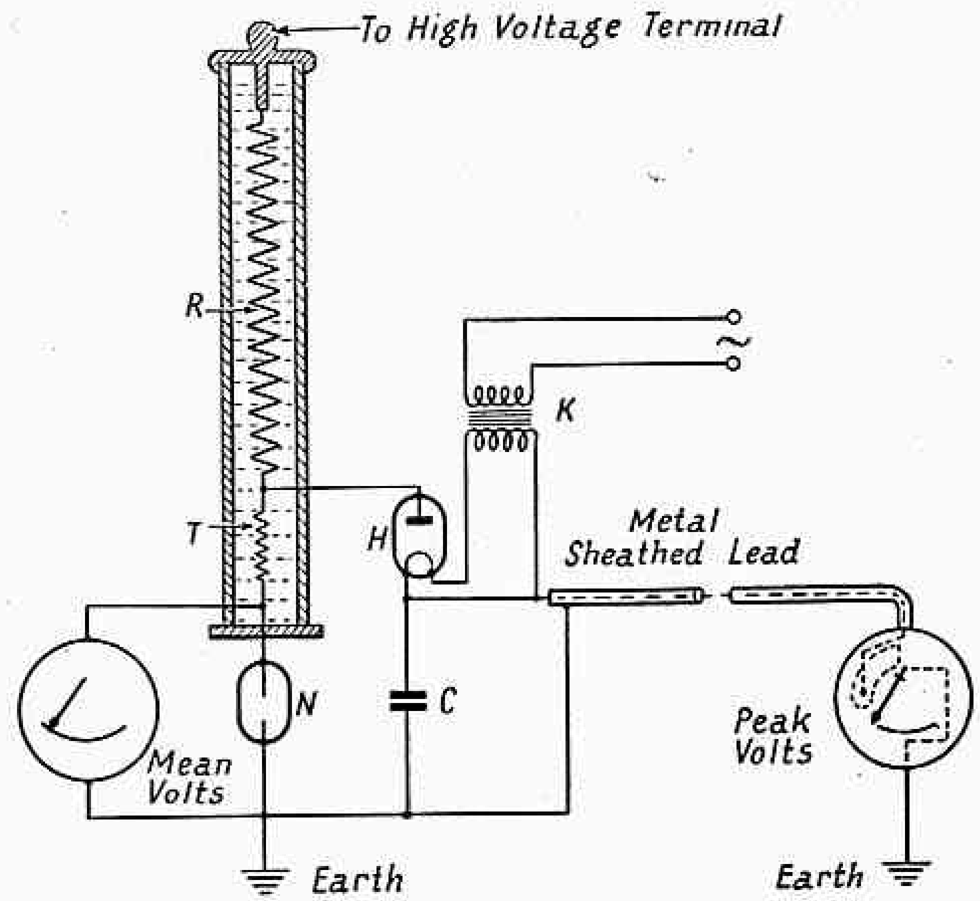
Both the lamp and capacitor C_1 are enclosed within metal boxes for screening purposes, and the lamp, in addition, is screened by a wrapping of lead foil, which is earthed, as the lamp glows when placed in a strong electrostatic field. A design of such a crest voltmeter for 150 kV (max.) is given by Ryall (*loc. cit.*).

Fig. 277 shows the principle of the Everett-Edgcumbe peak voltmeter for high-voltage measurements up to 500 kV (peak). This instrument gives a direct and continuous indication of the peak voltage under all conditions of loading and its readings are independent of waveform.

A resistor R is connected between the high-voltage terminal and earth. Across a section T of this resistor is joined a high-voltage rectifying valve H in series with a capacitor C and an electrostatic voltmeter reading direct in peak volts. For safety, the connecting leads are enclosed in an earthed flexible metal sheathing.

In the diagram of connections a mean voltmeter is also included.

(v) *High-voltage Voltmeters.* For the measurement of voltages up to about 200 kV, several forms of voltmeter have been designed which may be connected across the high-voltage circuit directly,



(*Everett Edgcumbe & Co., Ltd.*)

Fig. 277. Everett Edgcumbe Peak Kilovoltmeter

without any potential-dividing device. Most of these are of the "attracted-disc" type, based on Lord Kelvin's volt balance. The latter is an absolute instrument. It consists of two flat discs, one fixed, and the other suspended from one arm of a balance. The fixed disc is insulated from the case of the instrument and is charged to a high potential. The pull between the two discs is given by

$$\mathrm{F} = \frac{\kappa . A . V^2}{8\pi d^2} \quad . \quad . \quad . \quad . \quad (234)$$

where A is the area of the moving disc, V the voltage between the discs, d the distance between them, and κ the permittivity of the medium. This force is balanced by weights on the balance arm, the magnitude of the weights giving the force F, and hence V.

Fig. 278 shows the construction of the Siemens and Halske instrument, based on the above principle, while Fig. 279 shows the Abraham voltmeter, the latter being commonly used in high-voltage testing equipments.

In the former instrument the high-tension plate is in the form of a hollow metal spheroid, suspended, by means of an aluminium rod and metal filament, in oil. The oil tends to prevent the formation of an arc between the high-tension plate and the earthed plate, and by enabling the two plates to be brought nearer together, increases the working forces of the instrument. The earthed plate is in the form of a shallow metal pan, which also screens the instrument from

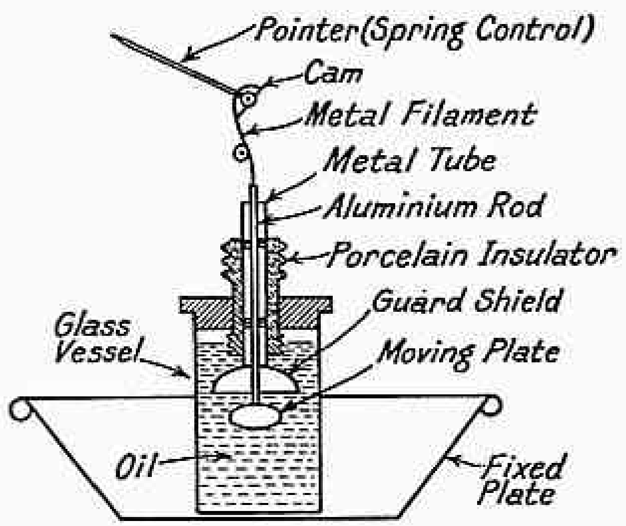


FIG. 278. SIEMENS AND HALSKE HIGH-TENSION VOLTMETER

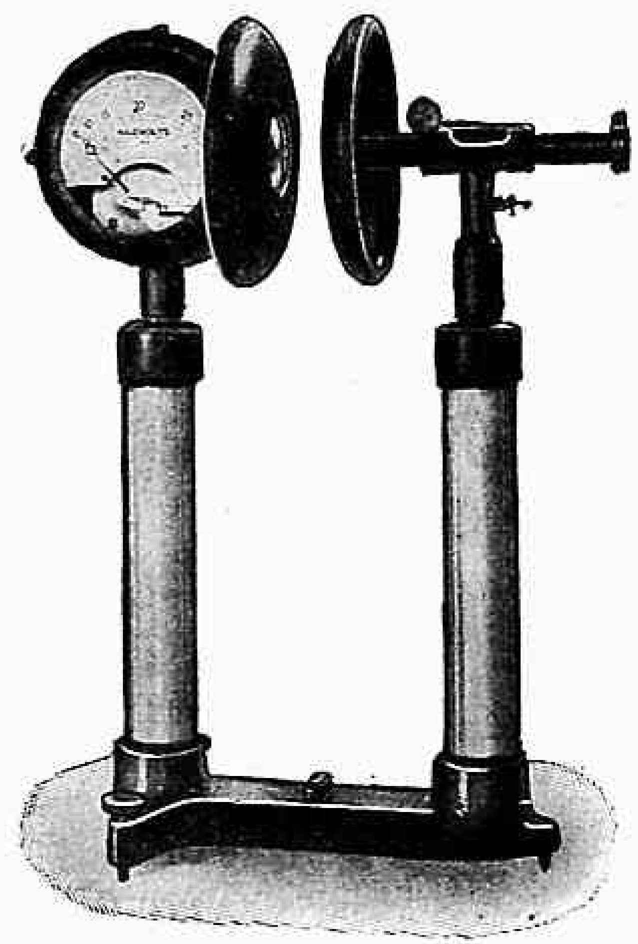
external electrostatic effects. Another guard screen is provided in the oil just above the high-tension plate, as shown.

Control of the instrument is by a spiral spring on the pointer spindle, and damping is by fluid friction of the high-tension plate in the oil. The cam on the pointer spindle gives a scale which is almost uniform over the upper 70 per cent of its range.

In the Abraham instrument—manufactured by Messrs. Everett-Edgcumbe—there are two hollow metal mushroom-shaped discs arranged as shown. The right-hand disc forms the high-tension plate, while the centre portion of the left-hand disc is cut away and encloses a small disc which is movable and is geared to the pointer of the instrument. The two mushroom-shaped discs are fixed in position except that the right-hand one may be set to different distances from the other, to alter the range of the instrument. A scale is provided, for this setting, on the right-hand support. The two large discs form adequate protection for the working parts of the instrument against external electrostatic disturbances. This instrument is made in six sizes covering the range of voltage 3 kV to 500 kV.

Most of the high-voltage electrostatic voltmeters which are absolute instruments depend upon a direct measurement of the forces brought into play by the voltage applied. But there is another class of absolute instrument for this purpose which operates through the indirect action of these forces, i.e. through their influence upon the period of oscillation of a conducting body. The best known example of such an instrument is the ellipsoid voltmeter (see Ref. (66)) but E. Bradshaw, S. A. Husain, N. Kesavamurthy and K. B. Menon (Ref. (87)) have discussed their general theory and have considered their scope and limitations.

Ionic Wind Voltmeter. When a highly-charged point is situated



(Everett-Edgcumbe & Co., Ltd.)

FIG. 279. ABRAHAM-VILLARD VOLTMETER

in air or other gas, a movement of the air surrounding the point is observed. This is referred to as the "electric wind," and is brought about by the repulsion of ions from the surface of the point by the intense electrostatic field. These ions, colliding with uncharged molecules of air in the neighbourhood of the point, carry the latter with them and set up the "electric wind." If an earthed electrode is placed near to the highly-charged one, an intense electric field exists, of course, between the two, and a similar wind is observed also at the earth electrode.

This phenomenon has been investigated by W. M. Thornton and by M. Waters and W. G. Thompson, and has been put to a useful purpose in their Ionic Wind Voltmeter (Ref. (23)).

Fig. 280 shows the principle of the instrument. A hot wire, of platinum-gold alloy, included in one arm of a Wheatstone bridge network, is used as the earthed electrode of a high-tension gap. Before the high voltage is applied to the gap the bridge network is balanced—i.e. the galvanometer G is set to zero. When the voltage across the gap exceeds a certain value—called the "threshold voltage"—the electric wind cools the hot wire and hence reduces its resistance. A reduction of 25 per cent in resistance is obtainable

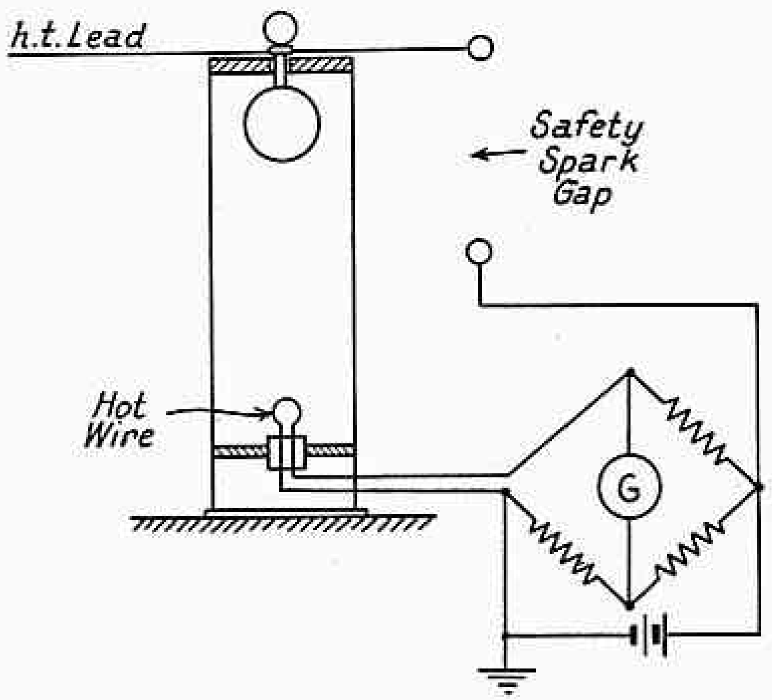


FIG. 280. IONIC WIND VOLTMETER

under suitable conditions, and this is sufficient to cause an appreciable out-of-balance voltage in the bridge network, as indicated by the galvanometer deflection. The cooling, and hence the galvanometer deflection, depends upon the potential gradient (and hence upon the applied voltage), as well as upon the temperature of the electrode, the nature and pressure of the gas in which the electrostatic field exists, and upon the frequency.

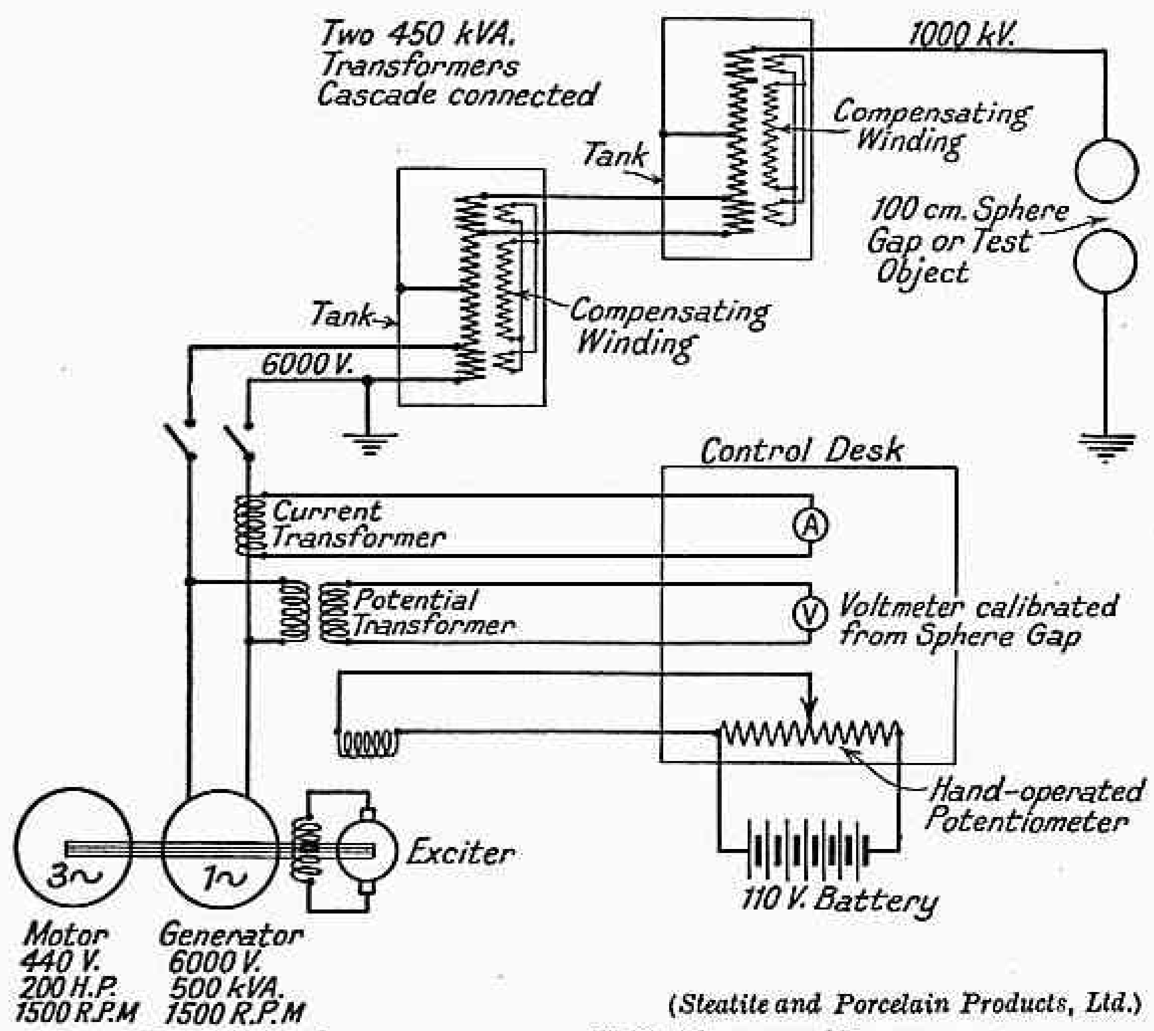
The "threshold voltage" is the voltage which is required before the potential gradient is sufficient for ionization to commence. When the applied voltage is alternating, therefore, only that portion of the voltage-wave which lies above the threshold value is effective from the point of view of cooling of the hot wire. The area of the effective portion of the voltage-wave—and hence the cooling—varies for different wave shapes, even though the waves have the same r.m.s. value. Voltage waveform, therefore, influences the instrument readings, but the authors have shown how this influence may be predetermined. Calibration of the instrument is on a sine waveform.

The voltmeter can be used to indicate either crest or r.m.s.

alternating voltages, or direct voltages. Several forms of the instrument have been constructed, both for out-door and laboratory use, and for voltages up to 300 kV.

The principle advantages are that the high voltage may be measured by an observer at some distance from the charged conductors, and the robust construction, and freedom from disturbance by weather and temperature conditions which make it suitable for outdoor use.

A description of the vacuum-enclosed electrostatic voltmeters



(Steatite and Porcelain Products, Ltd.)

FIG. 281. LOW-FREQUENCY H.T. TESTING EQUIPMENT

recently developed by Metropolitan-Vickers Elec. Co., Ltd. is given in Chapter XVIII, p. 661.

Special Apparatus for Tests other than Low-frequency Alternating Current Tests. The apparatus described in the foregoing pages is, to a great extent, common to all methods of high-voltage testing. Except for a few special pieces of apparatus which may be required in individual cases, according to the purpose for which the equipment is to be used, no further apparatus is required for sustained low-frequency high-voltage tests. A complete diagram of connections for an equipment of this type is shown in Fig. 281.

Apparatus, in addition to that already described, is required however, for the other types of test—namely, constant direct current tests, high-frequency tests, and surge tests.

CONSTANT DIRECT CURRENT TESTS. As previously mentioned, high-voltage direct current is chiefly used for the testing of high-voltage cables after installation. For the generation of high-tension direct current a number of comparative low-voltage generators can be connected in series. A specially designed machine, called a "transverter" (Ref. (24)), can also be used to obtain d.c. from a three-phase a.c. supply. Both of these methods are, however, only of use when a large amount of power is to be dealt with, and cannot

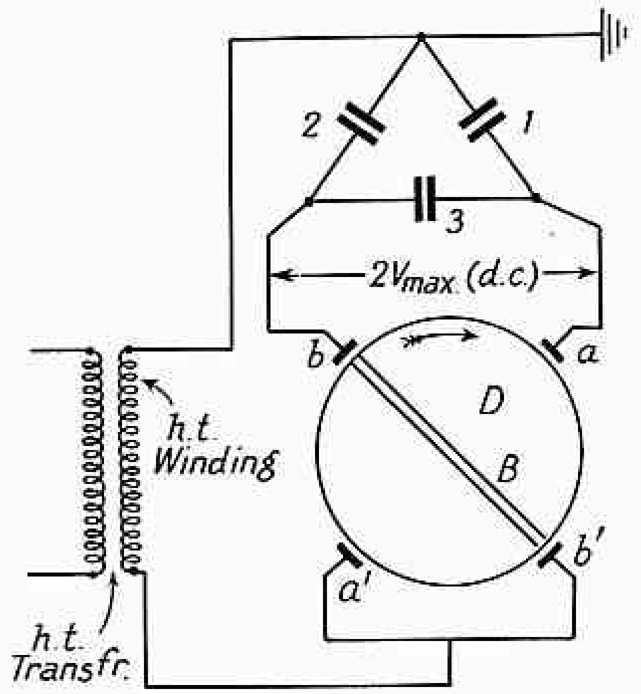


FIG. 282. DELON MECHANICAL RECTIFIER

be adapted to a small power-testing set, which, for the purpose of cable testing, should be portable.

The methods of obtaining the direct current now used is by the rectification of high-voltage alternating current, the latter being obtained from a high-voltage transformer.

The rectification may be done either by a mechanical rectifier, by a thermionic valve rectifier or by selenium or copper oxide rectifiers. Metal rectifiers are now in common use.

Delon Mechanical Rectifier. Fig. 282 illustrates the principle of this apparatus. An insulated disc D carries a conducting bar B, the ends of which come, in turn, opposite to one pair of the collecting brushes aa' and bb'. This disc is driven in synchronism with the alternating current supply, so that the rotating bar B is opposite to collecting brushes bb' (say) at the instant when the high voltage wave is at its positive maximum point, and opposite aa', when the voltage is negative maximum. Sparks pass between the collecting brushes and the connecting bar at these instants, the result being

that the capacitor 2 is charged to a voltage of $+E_{max}$ (above earth) and capacitor 1 to a voltage of $-E_{max}$ (below earth). Thus the potential across capacitor 3 is $2E_{max}$ and this voltage is *direct* not alternating. The high-tension d.c. is thus obtained from capacitor 3, and since the charging is taking place continuously, direct current can be supplied to a circuit under test.

In tests upon cables the internal capacitance between the cable cores, and from cores to ground, form the capacitors 1, 2, and 3 but the spark-over which takes place at the collecting brushes in the mechanical rectifier tends to set up surges and oscillations which,

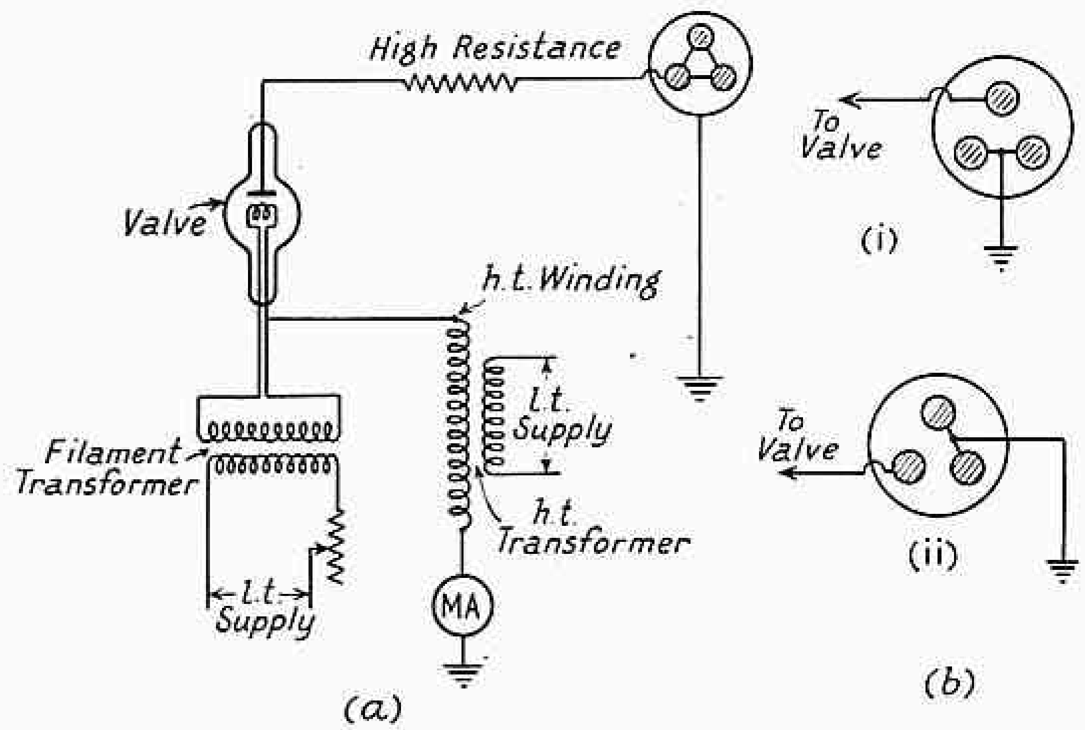


FIG. 283. CONNECTIONS FOR D.C. HIGH-VOLTAGE CABLE TESTS

by weakening the cable dielectric, may cause breakdown at a lower indicated voltage than would otherwise be obtained.

For this reason the mechanical rectifier has been largely displaced, by thermionic valves or metal rectifiers.

Tests with Thermionic or Metal Rectifiers. Fig. 283 shows the connections for a high-voltage d.c. test upon a three-core cable—cores to ground.

Current passes through the valve, or rectifier which now commonly replaces it, only during one half-wave of the voltage cycle. During this time the capacitor formed by the cable cores and the sheath is charged to a potential equal to that of the maximum value, V_{max}, of the high-tension transformer secondary voltage. When this voltage reverses—during the next half-wave—the potential of this cable-capacitor remains the same, while the potential of the valve filament rises to a maximum potential of V_{max} in the opposite direction. Thus the valve must be able to withstand a voltage of $2V_{max}$ between its plate and filament. The filament-transformer windings must, also, be insulated for a voltage of V_{max} between windings. The milliammeter MA reads the charging and leakage current through the capacitor formed by the cable.

The voltage for the valve filaments is usually 8 volts, and care must be taken that the correct voltage is used, since departure from it, by a comparatively small percentage, causes a considerable fall in the output current of the valves if the filament voltage is low. Resistances of about $\frac{1}{4}$ megohm are connected in the plate circuits of these valves for protection against surge effects.

Tests are usually made upon three-core cables with connections

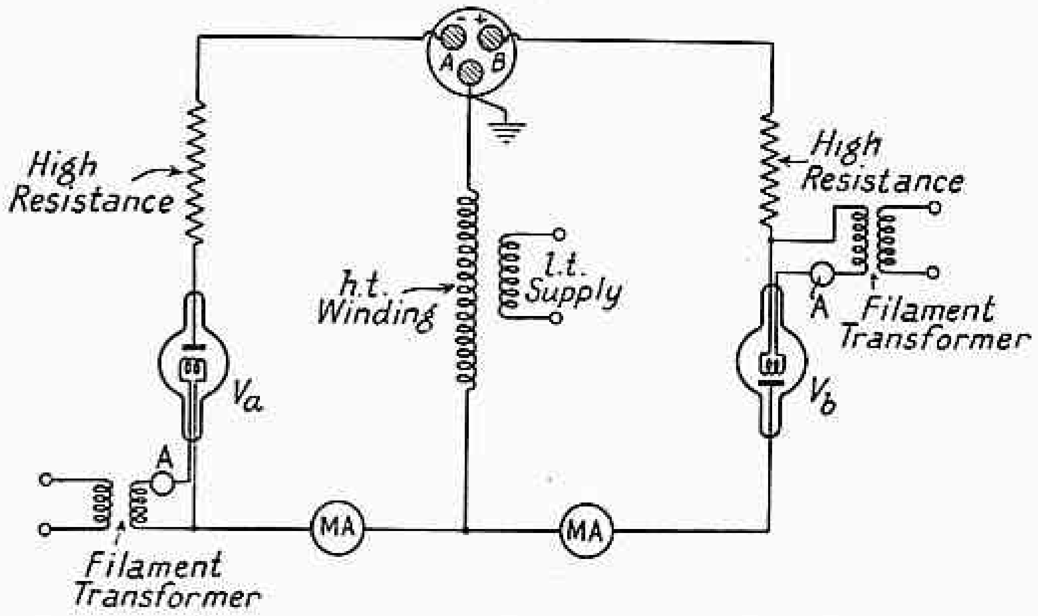


FIG. 284. CONNECTIONS FOR HIGH-VOLTAGE D.C. TEST UP TO 200 kV

as shown in Fig. 283(*b*) as well as with the connections of Fig. 283(*a*).

Two valves are used for test voltages up to 200 kV. The connections for such a test are shown in Fig. 284, the test being one between cores A and B of a three-core cable. Valve V_a allows current to flow only in the direction plate to filament. Thus, during one half-cycle current flows through it in this direction, and core A of the cable is charged to a potential V_{max} below earth, V_{max} being the maximum value of the voltage wave of the h.t. transformer secondary winding. Meanwhile, valve V_b is allowing no current to flow through it. During the next half-cycle the process is reversed, current flowing through valve V_b and charging core B to a potential V_{max} above earth. Thus the d.c. potential between cores is $2V_{max}$, and from each core to earth V_{max}.

In the case of a single-core cable, if the same pressure ($2V_{max}$) is to be applied between core and sheath as between cores in the three-core cable, two auxiliary capacitors must be used, connected, as shown in Fig. 285.

In some portable high-voltage d.c. testing sets a single-phase low-voltage alternator, driven by a petrol engine, is used for the

supply. The primary of the high-voltage transformer is supplied through an auto-transformer with a variable inductance choke-coil for fine adjustment. Voltage measurement is made by an electrostatic voltmeter of the Abraham Villard type, directly connected across the cable cores under test, although a sphere-gap is often included. In order to avoid trouble from surges, which may cause breakdown of apparatus, it is advisable to increase the testing pressure to its full value gradually, and also to discharge the cable through a high resistance. Owing to dielectric absorption it is necessary, also, to maintain the discharging connection for a con-

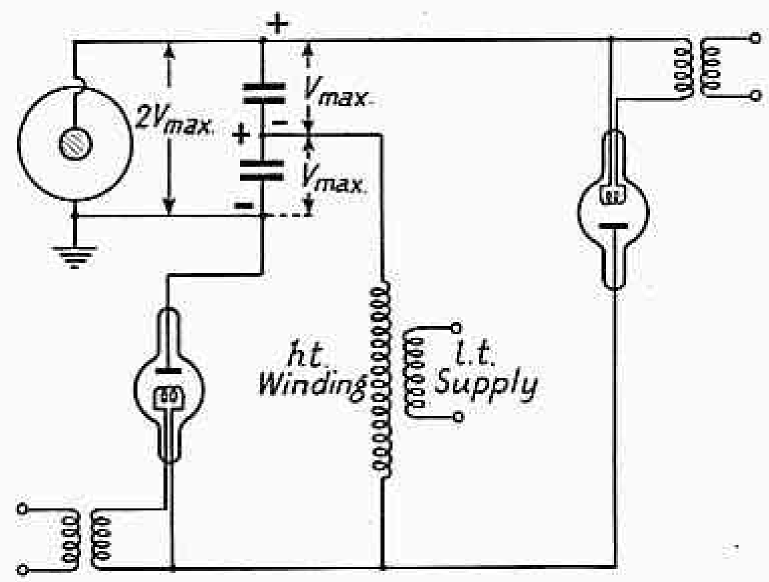


FIG. 285. CONNECTIONS IN THE CASE OF A SINGLE-CORE CABLE

siderable length of time, in order to avoid a subsequent dangerous rise of voltage.

Other connections for high-voltage d.c. cable-testing are given by J. Urmston (Ref. (25)).

Equivalence of D.C. and A.C. Test Voltages. Owing to the "electric osmosis" effect, any moisture which may exist within the cable dielectric tends to move towards the negatively-charged electrode (the sheath or one of the cores, depending upon the test), when a d.c. voltage is applied. Although the amount of such moisture is usually small, it may yet be sufficient to cause breakdown due to its concentration near the negative electrode. If the applied voltage is alternating, no such movement of moisture occurs, the moisture remaining uniformly distributed. Again, breakdown may occur when testing cable-samples due to surges which are produced by spark-discharge and corona effects at the cable ends. These effects are more severe with a.c. than with d.c.

For these reasons it is obvious that there are other considerations beyond mere equivalence of potential gradient, which must determine to what alternating voltage a given direct voltage is equivalent from the point of view of insulation breakdown.

N. A. Allen, to whom the author is indebted for much of his information upon cable-testing with direct currents, gives (Ref. (24)) a table showing the ratios of d.c. to a.c. test voltage, quoted by various authorities as giving an equivalent breakdown-test upon cables and dielectrics. For paper-insulated cables, although a d.c./a.c. ratio of 2·5 has been used, Allen suggests that a ratio of 1·5 to 2·0 would be more satisfactory. Owing to the fact, also, that this ratio increases with increasing insulation thickness, he suggests the adoption of a ratio 1·5 for cables up to 33,000, and a ratio of about 2·0 for voltages above this. The following table—taken from the same paper—gives the d.c./a.c. ratios usually adopted by English cable makers.

TABLE XIII

Working Voltage	Standard Test-voltage		Ratio D.C./A.C.	Average Thickness of Dielectric
	A.C.	D.C.		
11,000	20,000	30,000	1·50	0·30 in. (7·62 mm.)
22,000	44,000	75,000	1·71	0·40 in. (10·2 mm.)
33,000	66,000	100,000	1·52	0·50 in. (12·7 mm.)

Localization of Faults in High-voltage Cables. Another application of the rectifying valve, is in the localization of faults in long lengths of high-voltage cable. Such faults are often of very high resistance and cannot easily be located, with accuracy, by the ordinary methods of fault localization given in the following chapter.

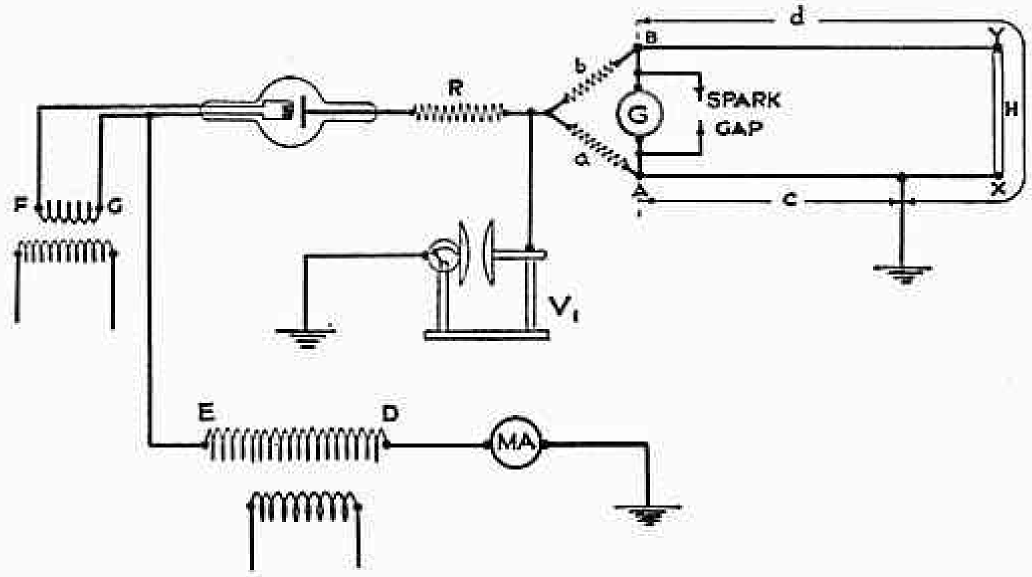
In high-voltage cables the large amount of oil present in the cables and joints causes faults in the cable (which may be obvious—owing to their low resistances—when the high testing voltage is applied) to seal up rapidly when this voltage is withdrawn, resulting in their having, again, a high resistance. One method of dealing with such a fault is to reduce its resistance by the continued application of a high testing voltage which "burns out" the fault, and enables location to be made by ordinary methods.

The method which has been largely adopted, as being more satisfactory than this, is to use a valve rectifier high-tension d.c. testing set for the supply of current for a "Murray loop" test. This and similar h.t. tests are described by Allen (Ref. (24)) and by Urmston (Ref. (25)).

Fig. 286 gives the connections for such a test, using a single-valve d.c. high-voltage testing set whereby a testing voltage of about 60 kV—which is usually sufficient for the purpose—can be obtained. A two-valve set may be used, if necessary, for higher testing voltages.

A loop is made by connecting together (by means of a short-circuiting strap) the two distant ends of a sound cable and the

faulty one. A highly insulated slide-wire, having a sliding contact which can be operated by a long insulating handle, is connected across the near ends of the loop, and a galvanometer and spark-gap —the latter for protection of the galvanometer—are also connected across these ends as shown. The d.c. testing voltage is applied to an intermediate point on the slide-wire, and an Abraham voltmeter is used to indicate the applied voltage. A high resistance and milliammeter are connected in the supply circuit for the limitation and measurement, respectively, of the supply current—i.e. of the fault current.



(*Watson, London*)

FIG. 286. CONNECTIONS OF AN EQUIPMENT FOR LOCALIZATION OF FAULTS IN HIGH VOLTAGE CABLES

The procedure, as given by Urmston (Ref. (25)) is as follows: "Pressure is then applied, and when the breakdown occurs the fault current is limited to 3 or 4 mA., and a preliminary balance made. The current is then increased to 40 or 50 mA., and the balance readjusted."

The cable voltage is usually low when the fault is fully broken down, but the voltage may rise very suddenly if the fault clears, and this necessitates the precautions regarding insulation of the slide-wire in order to safeguard the operator. The spark-gap, which is set to about 0·01 in. by micrometer, is for the protection of the galvanometer and slide-wire when the fault resistance falls, at breakdown, resulting in the discharge of the cable. The inductance of the galvanometer and bridge circuit cause this discharge current to pass across the spark-gap rather than through them.

If a and b are the resistances of the slide-wire ratio arms at balance (see Fig. 286), and c and d are the resistances of the cable lengths to the fault, then

$$\frac{b}{a} = \frac{d}{c}$$

or

$$\frac{a+b}{a} = \frac{c+d}{c}$$

$$\therefore c = \frac{a(c+d)}{a+b}$$

Thus, assuming the resistance of the cable-loop, per unit length, to be uniform, and calling the total length of the loop L, we have—

$$\text{Distance of fault from point } A = \frac{aL}{a+b}$$

The resistance and length of the short-circuiting strap may be assumed negligible.

HIGH-FREQUENCY TESTS. It has been stated already that the behaviour of insulating materials at high frequencies is very different from that at ordinary commercial frequencies. This is largely due to the very much greater dielectric power loss, within the material at the high frequency. The heat produced by this power loss tends to produce breakdown of the insulation at voltages which are smaller than those at which breakdown occurs when the frequency is low. Such tests are useful, also, in the detection of lack of homogeneity in compound-filled porcelain insulators.

Two kinds of high-frequency high-voltage tests are carried out—

(a) Tests with apparatus which produces undamped high-frequency oscillations.

(b) Tests with apparatus producing damped high-frequency oscillations.

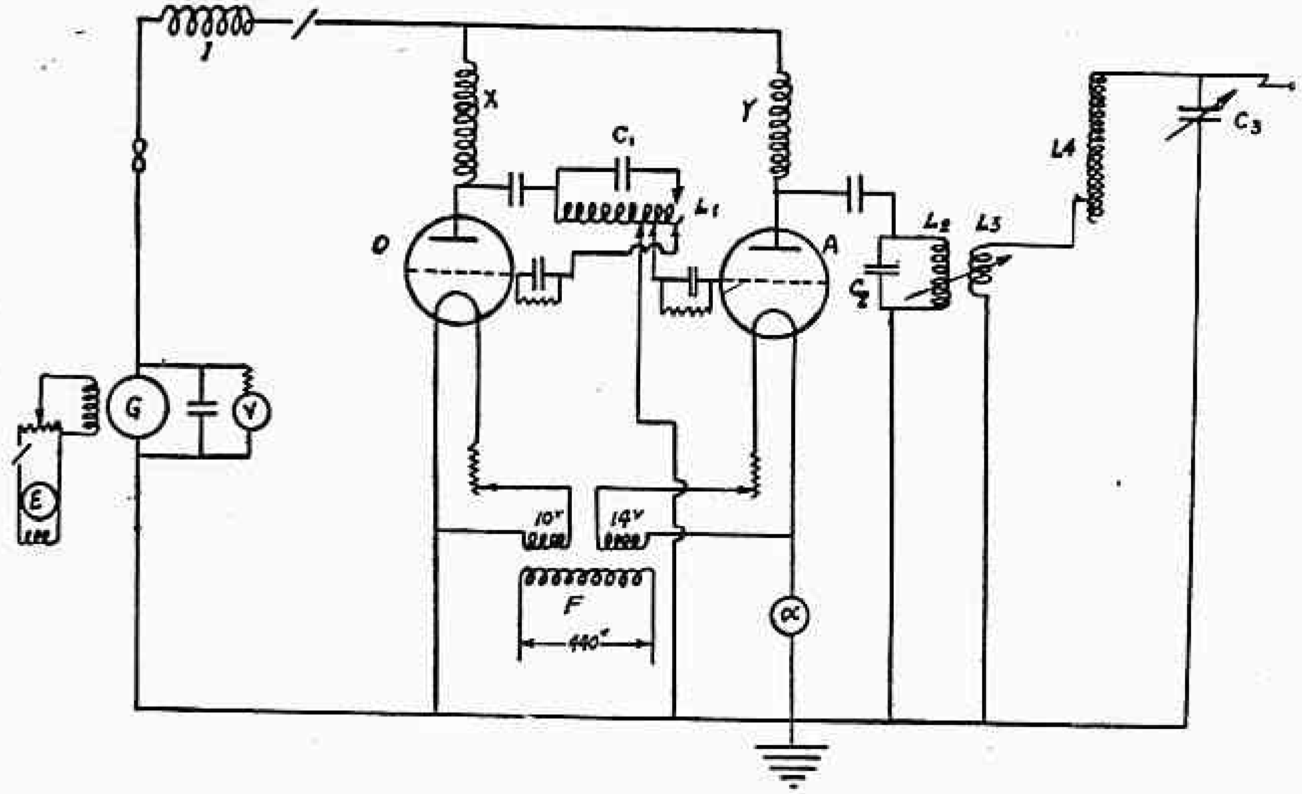
(a) *Undamped oscillations* do not occur in power systems, but are useful for insulation testing purposes, especially for insulation to be used in radio work.

High-frequency alternators have been used for frequencies up to 30,000 cycles per second, and high-frequency arc generators have also been used, but these have the disadvantage that smooth voltage variation is difficult.

Fig. 287 shows a valve circuit used by the Metropolitan-Vickers Electrical Co., Ltd., for such tests. Voltage variation is effected by variation of the coupling between the anode circuit of the main valve, and the secondary circuit, by means of the variometer, or by variation of the anode voltage of the valves. The voltage obtainable is 150 kV, and the frequency 100,000 cycles per second.

(b) *Damped high-frequency oscillations* are obtained by the use of a Tesla coil, together with a circuit containing a quenched spark-gap, as shown in Fig. 288. The Tesla coil constitutes the high-voltage transformer. It consists of two air-cored coils which are placed concentrically. The high-voltage secondary coil has a large number of turns, and is wound on a frame of insulating material, the insulation between turns being air, or in some cases, oil. If the Tesla coil is oil-immersed, the spacing between turns can be made smaller

than when air is the insulation. The primary winding has only a few turns, wound on an insulating frame. The supply is usually 50 cycle a.c. to the primary of a high-voltage testing transformer,



(*Metropolitan-Vickers Elec. Co., Ltd.*)

FIG. 287. HIGH-FREQUENCY TESTING EQUIPMENT FOR 150 kV

although a valve rectifier may be used on the secondary side of this transformer to give a d.c. supply to the primary side of the Tesla transformer. Two capacitors, C_p and C_s are connected in the

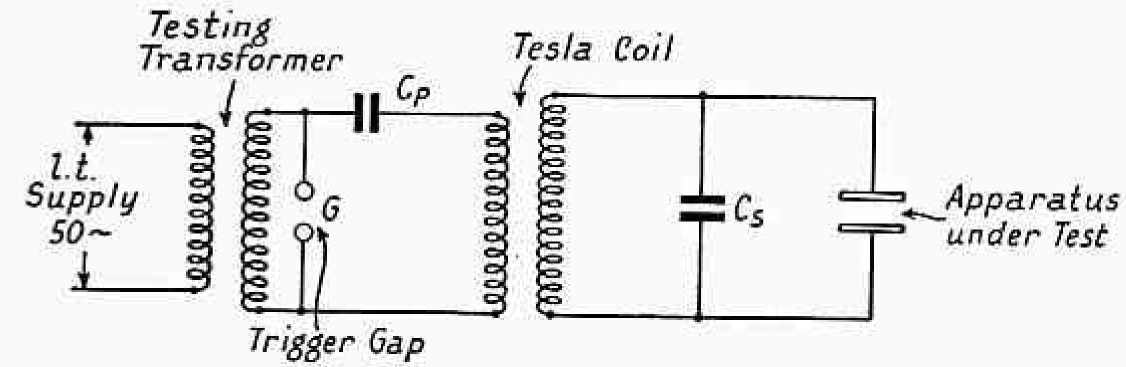


FIG. 288. CIRCUIT FOR HIGH-VOLTAGE TESTS WITH DAMPED HIGH-FREQUENCY OSCILLATIONS

primary and secondary circuits respectively, of the Tesla transformer. C_p is an air capacitor. C_s is usually made up of a sphere-gap, for voltage measurement purposes, the internal capacitance of the secondary winding of the Tesla coil, and the capacitance of the apparatus under test, the latter being usually small in comparison with the other two. The primary circuit of this transformer also contains a trigger spark-gap.

Assuming the supply to the primary of the Tesla transformer to be alternating—as it usually is—the capacitor C_p is charged to some maximum voltage, which depends upon the voltage on the secondary side of the supply transformer, and upon the setting of the "trigger-gap." At this voltage value the trigger-gap breaks down, the capacitor C_p discharges, and a train of damped oscillations, of high frequency, is produced in the circuit containing C_p, the spark-gap, and the primary winding of the Tesla transformer. During the time taken for this train of oscillations to die away (this time being a very small fraction of a second), the spark-gap is conducting, due to the formation of an arc across it.

This charge and discharge of capacitor C_p takes place twice in one voltage cycle—i.e. in $\frac{1}{50}$ sec. for 50 cycle supply. Thus there will be 100 of these trains of damped oscillations per second.

The frequency of the oscillations themselves is very high—100,000 cycles per second being a usual value—its actual value depending upon the inductance and capacitance of the oscillatory circuit.

B. L. Goodlet (Ref. (26)) states, in connection with the test frequency to be adopted, that "to the author's knowledge the highest frequency oscillation from which any serious trouble has been experienced on any transmission system is 80,000 cycles." He also gives results of tests which show that the spark-over voltage of an insulator is very little higher at about 600,000 cycles than it is at 100,000 cycles, and suggests that 100,000 cycles per second is therefore the maximum required for testing purposes.

The frequency is given approximately by the expression

$$f = \frac{1}{2\pi\sqrt{L_pC_p}} \quad . \quad . \quad . \quad . \quad (235)$$

where L_p is the inductance of the primary circuit of the Tesla transformer.

Oscillations are induced in the secondary circuit of the Tesla transformer by oscillatory current in the primary, and these will be of the same frequency as those in the primary circuit if the secondary inductance and capacitance are adjusted so that the two circuits are in tune—i.e. if $L_pC_p = L_sC_s$—L_s and C_s being the inductance and capacitance of the secondary oscillatory circuit. In this way a series of trains of damped oscillations are applied to the apparatus under test, connected as shown.

To prevent the energy of the oscillatory discharge from surging backwards and forwards between the primary and secondary circuits of the Tesla transformer, the trigger spark-gap must be quenched by air-blast cooling. This is helped by using a rotating spark-gap.

A sphere-gap is used for voltage measurement, and if the waveform of the Tesla secondary voltage is required a cathode-ray oscillograph must be used. Accurate measurements of the high-frequency voltage are not always required, as such tests are often

carried out by allowing high-frequency discharge to take place across the surface of an insulator for a certain time, and observing its effect upon the insulator. The frequency of the discharge is obtained from the constants of the oscillatory circuits.

Voltage and Frequency Values in the Oscillatory Circuits. The voltage relationships in the primary and secondary circuits of the Tesla transformer can be determined approximately as follows (Ref. (26))—

Let V_p = maximum voltage to which the primary capacitor C_p is charged.
„ V_s = maximum voltage to which the secondary capacitor C_s is charged.

Then,

$$\text{Energy in primary capacitor at breakdown of trigger-gap} = \frac{1}{2}C_pV_p^2$$

This energy is passed on to the secondary circuit, with some loss due to resistance and dielectric losses, and to the fact that the electromagnetic coupling between the two circuits is not perfect.

Energy given to secondary circuit $= \frac{1}{2}C_sV_s^2$. If ε is the efficiency of the energy transfer, then

$$\frac{1}{2}C_sV_s^2 = \varepsilon \cdot \frac{1}{2} \cdot C_pV_p^2$$

or

$$\frac{V_s^2}{V_p^2} = \varepsilon\frac{C_p}{C_s}$$

Thus,

$$\frac{V_s}{V_p} = \sqrt{\varepsilon \cdot \frac{C_p}{C_s}}$$

To determine the oscillation frequencies in the two circuits, let M be the mutual inductance between the two windings of the Tesla transformer. Let I_p and I_s be the currents in the primary and secondary oscillatory circuits, respectively. Then neglecting the resistances of the two circuits, since these are usually small compared with the other impedances in the circuits, we have—

For the primary circuit,

$$I_p\left(j\omega L_p - \frac{j}{\omega C_p}\right) - j\omega MI_s = 0 \quad . \quad . \quad . \quad . \quad . \quad (236)$$

(ω being $2\pi \times$ frequency).

In the secondary circuit,

$$I_s\left(j\omega L_s - \frac{j}{\omega C_s}\right) - j\omega MI_p = 0 \quad . \quad . \quad . \quad . \quad . \quad (237)$$

Then

$$\frac{I_p}{I_s} = \frac{j\omega M}{j\omega L_p - \frac{j}{\omega C_p}} = \frac{j\omega L_s - \frac{j}{\omega C_s}}{j\omega M}$$

Hence,

$$\omega^2M^2 - \omega^2L_pL_s - \frac{1}{\omega^2C_pC_s} + \frac{L_s}{C_p} + \frac{L_p}{C_s} = 0$$

or

$$\omega^2(M^2 - L_pL_s) + \frac{L_s}{C_p} + \frac{L_p}{C_s} - \frac{1}{\omega^2C_pC_s} = 0$$

Let $\frac{M^2}{L_pL_s} = K^2$ or $K = \frac{M}{\sqrt{L_pL_s}}$

(K is the "coefficient of coupling" of the circuits.)

Then $\omega^2 (K^2L_pL_s - L_pL_s) + \dfrac{L_s}{C_p} + \dfrac{L_p}{C_s} - \dfrac{1}{\omega^2 C_pC_s} = 0$

or $$\omega^2(1-K^2) - \frac{1}{L_pC_p} - \frac{1}{L_sC_s} + \frac{1}{\omega^2 L_pL_sC_pC_s} = 0$$

Factorizing, we have,

$$\left[\omega(1-K) - \frac{1}{\omega L_pC_p}\right]\left[\omega(1+K) - \frac{1}{\omega L_sC_s}\right] = 0$$

since $L_pC_p = L_sC_s$ when the two circuits are tuned.

Thus, $\omega^2 = \dfrac{1}{L_pC_p(1-K)}$

or $f_1 = \dfrac{1}{2\pi\sqrt{L_pC_p(1-K)}}$ (f_1 being one value of the frequency)

or $\omega^2 = \dfrac{1}{L_sC_s(1+K)}$

or $f_2 = \dfrac{1}{2\pi\sqrt{L_sC_s(1+K)}}$ (f_2 being another value of the frequency)

Now, K is usually small compared with L_pC_p and L_sC_s, so that as previously stated, the frequency is given, approximately, by

$$f = \frac{1}{2\pi\sqrt{L_pC_p}} = \frac{1}{2\pi\sqrt{L_sC_s}} \quad . \quad . \quad . \quad (238)$$

With regard to the closeness of the coupling between the two circuits of the Tesla transformer, Goodlet (*loc. cit.*) points out that if this is very close an impulse effect will be obtained rather than an oscillatory one, and, if the coupling is very loose, the conditions existing with undamped oscillations will be obtained.

Surge or Impulse Tests. In surge tests it is required to apply to the circuit or apparatus under test, a high direct voltage whose value rises from zero to maximum in a very short time and dies away again comparatively slowly—i.e. a voltage having a very steep wave-front and a flat tail is to be applied. This is done by means of a circuit due to Prof. E. Marx (Refs. (88), (89), and (90)) and called the Marx circuit after him. To illustrate the principles of the method the connections of a multi-stage surge generator are given in Fig. 289. Many modifications of the circuit have been used.

C_1, C_2, C_3, and C_4 are capacitors which are connected in parallel with high resistances, R_1, R_2, etc., between them. S_1, S_2, and S_3 are trigger spark-gaps.

The capacitors are charged, in parallel, from a high-tension transformer, through a rectifying valve. At a certain voltage, depending upon their setting, the trigger-gaps break down and connect the capacitors in series instantaneously. Thus the voltage between the point T and earth, at this instant, is the sum of the

voltages to which the capacitors were charged. The discharge takes place in so short a time that the energy loss in the resistors is negligible. Thus, the whole of the energy which is stored in the capacitors during charging, is suddenly discharged through the test circuit when the trigger-gaps break down. The gaps are set so that S_1 breaks down at a slightly lower voltage than S_2, S_2 at a slightly lower voltage than S_3, and so on. Then S_1 breaks down first and S_2 and S_3 follow instantly.

Although only three gaps are shown in the figure, the number of gaps and capacitors may be increased to give any desired multiple of the charging voltage and it has been found feasible in practice to operate a 50-stage impulse generator. The number which can be

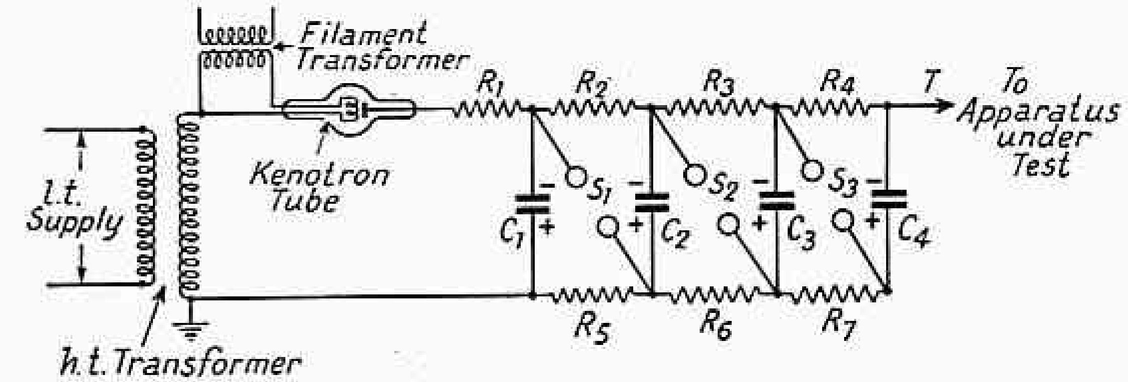


Fig. 289. Connections of Multi-stage Surge Generator

used successfully is limited to some extent, however, by the fact that the high resistance between the supply and the distant capacitors, when a large number are used, may prevent them from receiving a full charge. A large number of gaps in series also reduces the impulse voltage obtainable.

F. S. Edwards, A. S. Husbands and F. R. Perry (Ref. (87)) have reviewed subsequent developments of the Marx circuit and described the construction of impulse generators as well as their practical application. In this paper the simplified circuit shown in Fig. 290 (*a*) is given for a single-stage impulse generator. C_1 = discharge capacitance of the generator, C_2 = capacitance of the load, L_1 = internal inductance of generator, L_2 = external inductance of load and connections, R_1 or R'_1 = resistance for control of wave-tail (there are two alternative positions for this resistance), R_2 = resistance for control of wave-front. These authors state, however, that if the tail of the wave is long compared with its front—as it is for a standard wave—very little error is caused by ignoring the wave-tail resistance during the calculation of the wave-front duration. The circuit can then be further simplified to that of Fig. 290 (*b*).

The critical resistance of the circuit (see Chapter XVI) is

$$R = \sqrt{\frac{4L}{C}}, \text{ where } \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

The voltage across the load C_2, for a charging voltage E across C_1, is then given by

$$V = \frac{CE}{C_2}\left[1 - \left(1 + \frac{2t}{CR}\right)\varepsilon^{-\frac{2t}{CR}}\right] \quad . \quad . \quad (239)$$

or, if L is reduced to zero, R remaining the same,

$$V = \frac{CE}{C_2}\left(1 - \varepsilon^{-\frac{t}{CR}}\right) \quad . \quad . \quad . \quad . \quad (240)$$

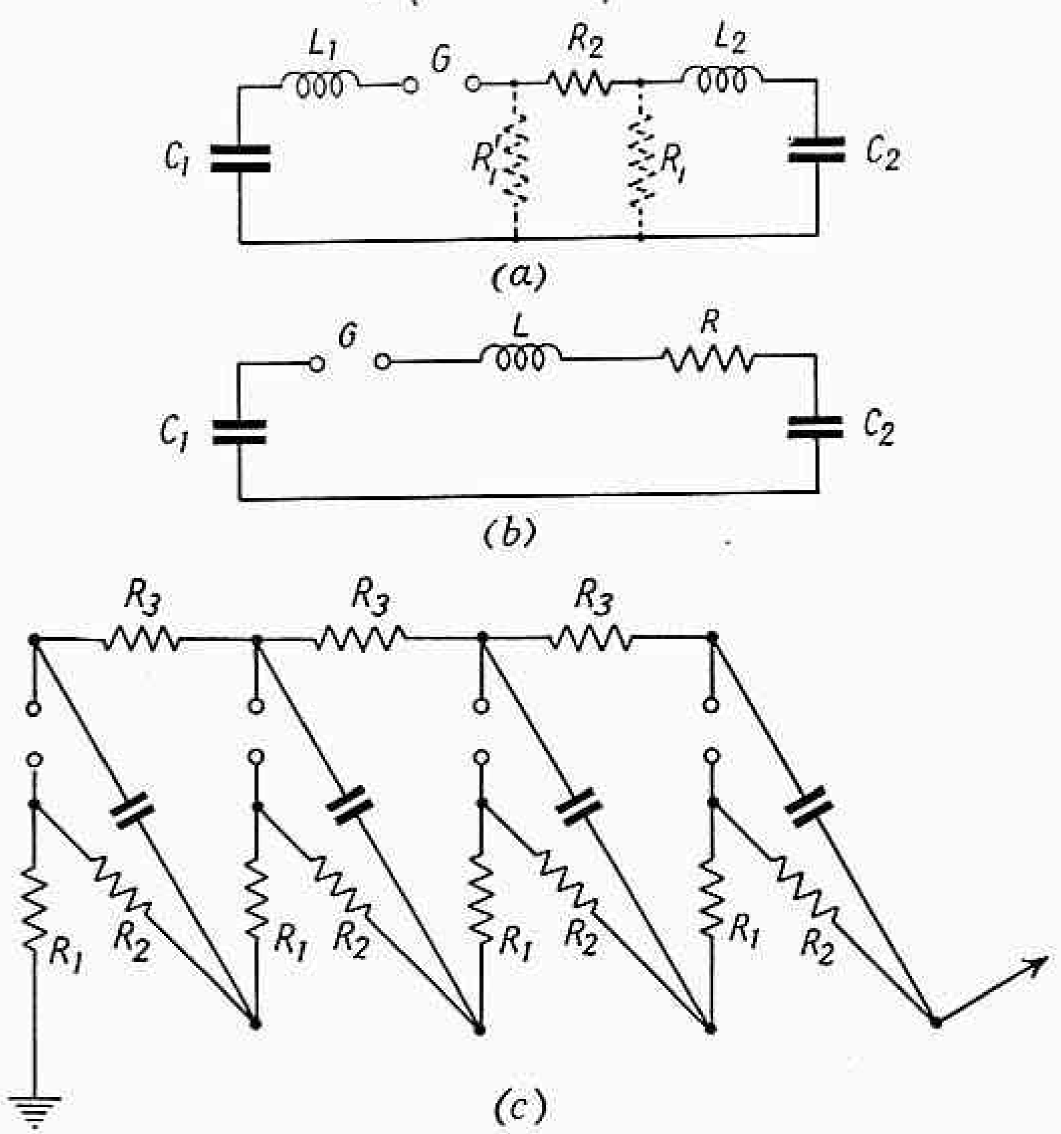


Fig. 290

V approaches $\frac{CE}{C_2}$ as t approaches infinity.

The "nominal wave-front" defined in B.S. 923 : 1940 is equal to $2{\cdot}75CR$ when L is zero, and to $2{\cdot}1CR$ when the circuit is critically damped. In calculating the resistances the value of R_2 needed to make the circuit of Fig. 290 (a) non-oscillatory with R_1 absent is obtained. Then the value of R_2 (if $> \sqrt{\frac{4L}{C}}$) required to give the desired wave-front is computed, and finally the value of R_1 to give the required wave-tail when R_1 is on the generator side of R_2.

The efficiency of the generator can then be approximately estimated as $\frac{C_1}{C_1 + C_2}$ multiplied by a factor of about 0·95 for a 1/50-microsec. wave.

Wave-front-control resistances can be connected either outside or within the generator, or partly in and partly outside. The best arrangement is probably to have about half of the resistance outside the generator. Wave-tail-control resistors can be used as the charging resistors within the generator circuit.

Fig. 290 (c) shows the connections of a widely used multi-stage circuit which combines high efficiency with distributed wave-front resistors. The value R_3 is made large compared with R_1 but R_2 is as small as is necessary to give the required length of wave-tail. Since the current through R_2 does not flow through R_1 it does not reduce the initial generator-output voltage, however small the value of R_2 or however large R_1 may be.

A sphere-gap is used for voltage measurement, and measures the peak value of the impulse wave. Owing to the fact that the sphere-gap and apparatus under test are in parallel, care must be taken in using the former for voltage measurement. The conditions of its use for this purpose are specified in B.S. 368 : 1939. This states that the accuracy of measurement is within $\pm$ 3 per cent provided that the duration of the impulse voltage is not less than that of a 1/5-microsec. wave.

A single-beam cathode-ray oscillograph is used, with a simple capacitance-type potential divider, to obtain either a visual or photographic record of the impulse wave shape. A. K. Nuttall (Ref. (91)) has described the construction of an oscillograph for the measurement of moderately high impulse voltages directly.

Impulse Ratio. The "impulse ratio" of an insulator is the ratio

$$\frac{\text{Minimum spark-over voltage when tested with an impulse voltage}}{\text{Spark-over voltage when tested at power frequency}}$$

This is not constant for any given insulator, but is always greater than unity. It depends upon—

(a) The polarity of the impulse voltage. The spark-over voltage is usually less, by some 10 per cent, when the insulator pin (in the case of a porcelain insulator) is positive, than when it is negative.

(b) The steepness of the impulse wave-front and the time of decay of the impulse voltage. The highest spark-over voltage is obtained with an impulse voltage which rises most rapidly to its crest value and also falls away again rapidly. Goodlet (*loc. cit.*) gives the figures 1·3 to 1·5 for the mean impulse ratio in the case of pin-type porcelain insulators, and 1·2 to 1·4 for suspension insulators.

Notes on the Testing of Insulators, Insulating Materials, and Cable Lengths. While impulse and high-frequency tests are carried out, as above described, for research purposes, and by manufacturers, in order to ensure that their finished products will give satisfactory performance in service, the most general tests upon insulating materials are carried out at power frequencies. Such tests may be carried out in accordance with the purchaser's specifications, and their exact nature then depends upon individual requirements. So many factors, such as barometric pressure, temperature, time of application of the testing voltage, and so on, influence the results of these tests that the British Standards Institution, and similar authorities in other countries, have drawn up standard specifications which state standard test conditions for various types of manufactured apparatus and materials.

TESTING OF PORCELAIN INSULATORS. Such insulators are designed so that spark-over occurs at a lower voltage than puncture, thus safeguarding the insulator, in service, against destruction in the case of line disturbances. Flash-over tests are thus very important in this case. Flash-over, or surface breakdown, is really due to a breakdown of the air at the insulator surface, and the voltage at which it occurs for a given insulator depends upon—

(a) The barometric pressure.
(b) The temperature.
(c) The shape of the electrostatic field.
(d) The humidity.
(e) The nature of the contact between the insulator and the electrodes.

Of these factors, the first two can be taken into account by assuming that the flash-over voltage is directly proportional to the "air density correction factor" $\left(\frac{0\cdot386p}{273 + t}\right.$, p being the pressure in millimetres of mercury and t the temperature in degrees Centigrade), provided this is not very different from unity.

If the electrostatic field has no component in a direction normal to the surface of the insulator, the breakdown voltage is simply that for the air alone, and is practically independent of the material of the insulator. Usually, however, the electrostatic field lies partly in the surrounding air and partly in the insulator, and the shape of this field becomes very important. It is thus necessary to take into account the disposition of any metal parts, used for mounting purposes, when considering results.

The flash-over voltage decreases with increasing humidity and correction factors are given in B.S. 137 : 1941. Dirt of any kind upon the surface has a similar effect to that of deposited moisture in lowering the flash-over voltage, and thus for consistent results upon a given insulator it should be both clean and dry.*

Unless the contacts between the electrodes and insulator are good, ionization of the air near the contacts will take place, and the breakdown voltage will be reduced.

The time of application of the voltage may also affect the results.

* See also Ref. (84).

If the applied voltage is high, and is maintained for some time at a value a little below the normal flash-over voltage, breakdown often occurs.

In addition to the dry flash-over test, rain tests, and tests in a misty or smoke-laden atmosphere are often carried out, the rain test being specified in British Standard Specification No. 137 : 1941, for "Porcelain and Toughened Glass Insulators for Overhead Power Lines" (3·3 kV and upwards).

The specification gives a table of standard insulator rating numbers and test voltages, the latter being separated into "Minimum dry flash-over voltage," "Minimum wet flash-over voltage," "One-minute dry test voltage," "One-minute rain test voltage" and "Puncture test voltages."

The various tests are then specified and the following notes give an indication of their nature (the specification should be referred to for full details).

POWER FREQUENCY TESTING VOLTAGE. This shall be of frequency between 25 and 100 c/s and approximately sine-wave form. The peak value, determined by sphere gap, oscillograph or other approved method, shall not exceed $1\cdot45 \times$ r.m.s. value.

FLASH-OVER TESTS. These are (i) 50 per cent dry impulse flash-over test, using an impulse generator delivering a positive 1/50-microsecond impulse wave. "The voltage shall then be increased to the 50 per cent impulse flash-over voltage, i.e. the voltage at which approximately half of the impulses applied cause flash-over of the insulator." (ii) Dry flash-over and dry one-minute test in which the test voltage given in the table (mentioned above) is applied. "The voltage shall be raised gradually to this value in approximately ten seconds and shall be maintained for one minute. The voltage shall then be increased gradually until flash-over occurs." (iii) Wet flash-over and one-minute rain test in which the insulator is "sprayed throughout the test with artificial rain drawn from a source of supply at a temperature within 10° C. of the ambient temperature in the neighbourhood of the insulator." The resistivity of the water is to be between 9,000 and 11,000 ohm cm.

SAMPLE TESTS. Specifications are given for temperature-cycle tests, mechanical tests, electro-mechanical tests, puncture tests and porosity tests.

ROUTINE TESTS. These are to be applied to all insulators and "shall be commenced at a low voltage and shall be increased rapidly until a flash-over occurs every few seconds. The voltage shall be maintained at this value for a minimum of five minutes or, if failures occur, for five minutes after the last punctured piece has been removed. At the conclusion of the test the voltage shall be reduced to about one-third of the test voltage before switching off."

POTENTIAL DISTRIBUTION ALONG A SUSPENSION INSULATOR STRING. Owing to the earth capacitances between the metal fittings (caps and pins) of an insulator string and the supporting tower or pole, the potential distribution across the various component units of the string is by no means uniform. The potentials across the units adjacent to the line conductor are much greater than those across units nearer to the supporting cross-arm. If all the units are identical, the consequence is that the "string efficiency," i.e. the ratio $\frac{\text{actual breakdown voltage of the complete string}}{\text{breakdown voltage per unit} \times \text{number of units}}$ is low.*

* For a fuller discussion of the question, see Ref. (78); also F. W. Peek, *Trans. A.I.E.E.*, Vol. XXXI, p. 907; or H. Cotton, *The Transmission and Distribution of Electrical Energy*.

Measurement of the potential distribution along such a string may be carried out in the laboratory by either (*a*) direct measurement or (*b*) a potential divider or null method. These methods may be understood from the simplified diagrams of Fig. 291, in which (*a*) shows the direct method and (*b*) the potential-divider method.

In (*a*) a small test spark-gap is employed, set to spark over at a voltage *e* across it. The potential *V* across the string is brought up to such a value as to cause the gap to spark. The connection *P* is moved from one unit to another down the string, and for each position the required value of *V* for gap spark-over is determined.

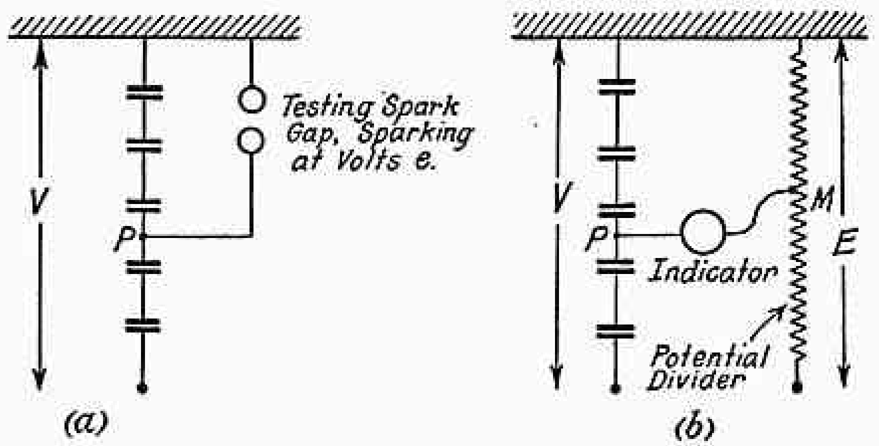


Fig. 291

The results give the percentage voltage drops e/V for the various portions of the string.*

Although this method is very simple and involves only a capacitance current, which does not cause pitting of the spheres, it is rather rough, and the presence of the exploring wire, unless this is correctly placed, may influence the electrostatic field distribution. Again, the capacitance of the gap itself may be comparable to that of the insulator units. In Method (*b*) the contact *M* is moved until the indicator shows zero, when the potentials of *M* and *P* are obviously the same, so that that of *P* is known, for a given applied voltage *V*, from the calibration of the potential divider.

The potential divider may be a resistance or capacitor, or it may be replaced by a separate source of supply. This source, either from an induction regulator† or a second alternator driven in synchronism with that supplying the insulator string, must be in the same phase and of the same waveform as the supply volts *V*.

The indicator‡ may be: (i) a spark-gap; (ii) a neon tube of special construction; (iii) an electrometer across a high resistance;

* See R. H. Marvin, *Trans. A.I.E.E.*, January and June, 1916.

† Drewnowsky, *Archiv. für Elektrotechnik*, Vol. XXVII, p. 229.

‡ See also A. Schwaiger, "Voltage Distribution for Insulator Suspension Chains," *E. and M.*, No. 50, 1919; and "Theory of the High-voltage Insulator," *E.T.Z.*, No. 43, 1920; and *E. and M.*, No. 38, 1920; also Schering and Raske, *E.T.Z.*, Vol. LVI, p. 75, 1935.

(iv) a vibration galvanometer in series with a high resistance; or (v) a triode.

The use of an electrometer for the measurement of high alternating voltages has been described by P. W. Baguley and H. Cotton.* They used a Lindemann electrometer, which is a very useful instrument for the measurement of very small currents. The instrument, described by F. A. Lindemann and T. C. Keeley,† is manufactured by the Cambridge Instrument Co.

Testing of Insulating Materials. In the case of such materials it is not the voltage which produces spark-over breakdown which is important, but rather the voltage for puncture of a given thickness (i.e. the dielectric strength). The measurements made upon insulating materials are usually, therefore, those of dielectric strength and of dielectric loss and power factor, the latter being intimately connected with the dielectric strength of the material.

The breakdown of solid insulating materials is a complex process, and does not occur simply when the applied potential gradient, or field strength, exceeds a certain critical value, regardless of other conditions.

It is found that the dielectric strength of a given material depends, apart from the chemical and physical properties of the material itself, upon many factors including—

(*a*) The thickness of the sample tested.

(*b*) The shape of the sample.

(*c*) The previous electric and thermal treatment of the sample.

(*d*) The shape, size, material, and arrangement of the electrodes.

(*e*) The nature of the contact which the electrodes make with the sample.

(*f*) The waveform and frequency of the applied voltage (if alternating).

(*g*) The rate of application of the testing voltage and the time during which it is maintained at a constant value.

(*h*) The temperature and humidity when the test is carried out.

(*i*) The moisture content of the sample.

It is obviously very necessary, therefore, that tests shall be carried out under standard conditions, and with standard sizes and shapes of both sample and electrodes if the results are to have any real significance.

The Nature of Dielectric Breakdown. The theory of breakdown which was most generally adopted in the past was the *Thermal* theory. K. W. Wagner first attempted to give a definite mathematical theory of thermal breakdown, and Prof. Miles Walker, during a discussion on E. H. Rayner's paper on "High-voltage Tests and Energy Losses in Insulating Materials" (*Jour. I.E.E.*, Vol. XLIX p. 3) stated the essentials of the theory, which are as follows—

Dielectric losses occur in insulating materials, when an electrostatic field

* *World Power*, Vol. XIX, No. CXI, March, 1933.

† *Phil. Mag.*, 1924, Vol. XLVII, p. 577.

is applied to them. These losses result in the formation of heat within the material. Most insulating materials are bad thermal conductors, so that, even though the heat so produced is small, it is not rapidly carried away by the material. Now, the conductivity of such materials increases considerably with increase of temperature, and the dielectric losses, therefore, rise and produce more heat, the temperature thus building up from the small initial temperature rise. If the rate of increase of heat dissipated, with rise of temperature, is greater than the rate of increase of dielectric loss with temperature rise, a stable condition (thermal balance) will be reached. If, however, the latter rate of increase is greater than the former, the insulation will break down owing to the excessive heat production, which burns the material.

Now, the dielectric losses per cubic centimetre in a given material and at a given temperature, are directly proportional to the frequency of the electric field and to the square of the field strength. Hence the decrease in breakdown voltage with increasing time of application and increasing temperature, and also the dependence of this voltage upon the shape, size, and material of the electrodes and upon the form of the electric field.

Much research has been done, particularly by the British Electrical and Allied Industries Research Association, during recent years on this question of the dielectric breakdown of insulating materials. S. Whitehead (Ref. (93)) has reviewed the subject comprehensively and this work together with those mentioned in Refs. (2), (94), and (95), should be consulted by readers wishing to study the subject. H. F. Church and C. G. Garton (Ref. (95)) list five well-established causes of failure in solid insulation and state that two others are now under investigation.

Importance of Dielectric Loss Measurements. From the above it will be realized that the measurements of dielectric loss in insulating materials are very important, and give a fair indication as to comparative dielectric strengths of such materials. In the case of cables, dielectric loss measurements are now generally recognized as the most reliable guide to the quality and condition of the cable.

The measurement of dielectric losses was dealt with in Chapter IV.

Directions for the Testing of Solid Specimens. A number of reports issued by the British Electrical and Allied Industries Research Association* give directions for the study of insulating materials of all classes, including solid dielectrics, papers, fabrics, varnishes, and oils.

The following extracts from the B.S.I. Standard Specification (No. 234 (1942)) for "Ebonite for Electrical Purposes," will serve to indicate what precautions are to be taken and what methods adopted in the testing of ebonite, which may be taken as a typical solid dielectric.

"ELECTRIC STRENGTH. The ebonite shall withstand for one minute without breakdown the following r.m.s. test-voltages when applied in accordance with the method described in Appendix D—

For Grade I—2,000 volts per mil (80 kV per mm).
For Grade II—1,000 volts per mil (40 kV per mm).
For Grade III—750 volts per mil (30 kV per mm)."

Appendix D gives the following method—

"A sheet or disc of the material, not less than 4 in. (101·6 mm) in diameter, shall be taken and recessed on both sides so as to accommodate the spherical electrodes described below, with a wall or partition of the material between them 20 mils (0·508 mm) thick, as shown in Fig. 4.

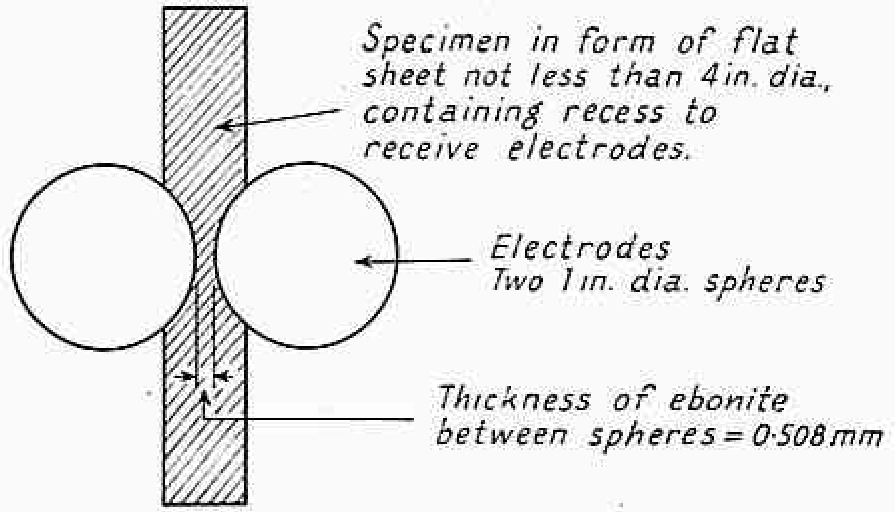
"The test shall be carried out at a temperature of from 15° C. to 25° C.

* See references at end of chapter.

"The electrical stress shall be applied to the specimen by means of two 1 in. diameter spheres fitting into the recesses without leaving any clearance, especially at the centre."

"Fig. 4," referred to in the extract, is reproduced in Fig. 292. It is further specified that the specimen shall be conditioned, before testing, by being "maintained in an ordinary room atmosphere for at least 24 hours immediately before test." The applied voltage is to be of approximately 50 cycles frequency and of sinusoidal wave-form. This voltage must be commenced at about one third the full value and increased rapidly to the full testing voltage.

It is laid down also that the power-loss factor (defined as the "product of the power factor and the permittivity which shall be determined at a frequency



(*By courtesy of the B.S.I.*)

FIG. 292. ARRANGEMENT OF ELECTRODES FOR THE TESTING OF EBONITE

from 800 to 1,600 cycles per second by the method described in Appendix E") shall not exceed

0·018 for Grade I
0·030 for Grade II
0·080 for Grade III

(Appendix E describes a Schering bridge method the operation of which is specified more fully in B.S. 903 : 1950.)

THE TESTING OF INSULATING OILS. In British Standard specification (No. 148 : 1951) for "Insulating Oil," the method of applying the testing voltage (which must be alternating, or approximately sine wave-form, of frequency between 25 and 100 cycles per second and with a peak factor of $\sqrt{2} \pm 5$ per cent) which is recommended, is shown in Fig. 293, taken from the specification.

It is specified that—

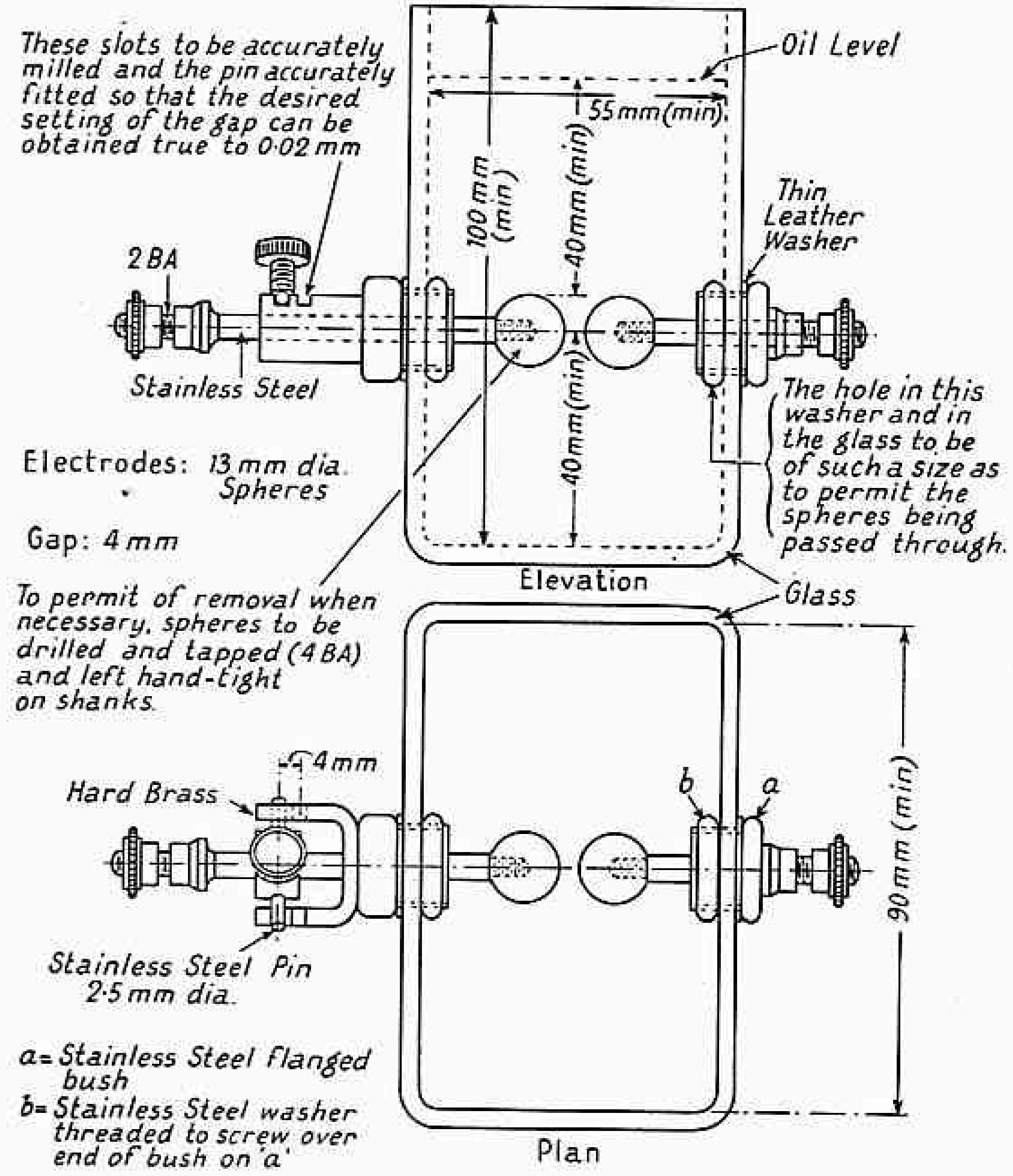
"The minimum internal dimensions of the test-cell shall be 55 mm. × 90 mm. × 100 mm. high.

"The electrodes shall be polished spheres of 12·7–13 mm. diameter, preferably of brass, arranged horizontally with their axis not less than 40 mm. above the bottom of the cell. For the test, the distance between the spheres shall be 4 ± 0·02 mm. A suitable gauge shall be used for checking the gap.

"Spheres shall be replaced as soon as pitting caused by discharges is observed."

On account of the serious effect of suspended solids and moisture in the oil, upon the electric strength, great care must be taken in preparing the oil sample for test and in cleaning the test-cell. These matters are dealt with in the specification.

Cable Testing. The cable tests which have already been described in this chapter have been tests upon cables already installed.



(*By courtesy of the B.S.I.*)

Fig. 293. Apparatus for the Measurement of the Dielectric Strength of Oil

Acceptance tests, which are tests called for by purchasers before accepting cables from the manufacturers, are also of importance. The results of such tests must be a reliable guide as to the probability of the cables being satisfactory in service.

At one time breakdown tests upon short lengths of cable with alternating voltages of commercial frequency, rapidly applied, were called for, but it was later realized that such tests gave little or no

reliable information regarding the cable, since the breakdown value, when the voltage is applied for a considerable time, is usually considerably smaller than that obtained with rapid application of voltage. Thus, tests with a voltage applied for 15 or 30 min. were carried out in addition to the rapid tests. As a development of these tests, time-voltage curves for short lengths of cable are now carried out by some manufacturers (Ref. (29), (30)). These are obtained by first determining the breakdown voltage for one length with rapid application of voltage, and then, with other lengths, finding the length of time required before breakdown occurs, with applied voltages of gradually decreasing magnitudes for each test length. For example, if 100 kV produces breakdown of sample 1, when rapidly applied, and it is found that it takes 5 min. for 90 kV to produce breakdown of sample 2, 12 min. for 85 kV to produce breakdown of sample 3, and so on, a time-voltage curve for the cable can be plotted. This method is suggested by Dunsheath (Ref. (6)). E. A. Beavis (Ref. (30)) has investigated the question of the preparation of the ends of the cable lengths for such tests, in order to avoid breakdown by flash-over instead of by puncture.

Dielectric loss and power-factor tests are regarded as giving the most reliable information as to the quality of the cable, and such tests are of greater importance than breakdown tests upon short lengths.

It is found that the dielectric losses in high-voltage cables do not increase with the square of the voltage, as is the case with most simple dielectrics, nor does the power factor remain constant. The losses increase in proportion to some power of the voltage greater than the square, and the power factor rises with voltage, these effects being due to "ionization" caused by air which is entrapped within the cable insulation. Measurements of power factor with different voltages applied to the cable are therefore made, and the power factor–voltage curve plotted. This should be practically flat if the cable under test is such as will be satisfactory in service. The variation of power factor with temperature is also of importance. In a good cable the power factor should increase very little with increase of temperature. To investigate this power factor, measurements are made at different dielectric temperatures, obtained by heating the cable by the passage of current through its cores. The power factor–voltage curve is also obtained when the cable has cooled after a heat run. This should not be appreciably different from the curve obtained before the heat run.

Live Conductor Detection. While this scarcely comes under the heading of a high-voltage measurement it is perhaps worthy of mention here.

It is very important to be able to determine whether a high voltage conductor is live or dead prior to earthing it and a difficulty arises from the fact that, if the detecting device used is defective, it may indicate that the conductor under test is dead when, in fact it is not.

The requirements for a satisfactory potential indicator have been discussed by G. F. Shotter and E. E. Hutchings (Ref. (97)). They are—

"(i) To indicate reliably if a conductor is not at earth potential.

"(ii) To discriminate whether the voltage on a conductor is due to conductive connection with a source of supply, or to electrostatic charge, or electrostatic or inductive coupling with a live circuit. This involves a quantitative indication.

"(iii) To be of a form suitable for use by a linesman either indoors or outside under all weather conditions.

"(iv) To be such that it can be tested before use to ensure that it is operating satisfactorily."

This report made recommendations for the construction of a potential indicator of the resistance type and such an instrument is now made by Everett Edgcumbe and Co., Ltd. It has a series resistor comprising a number of ceramic resistance units in a tube of Bakelized material and a robust moving-coil indicator having high sensitivity. A permanently attached flexible lead is used for earthing. The indicator reads direct in kilovolts to earth and has a scale which is closed up at higher readings. This increases the effective range and enables the detector to be checked, before use, on a medium-voltage circuit.

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CHAPTER XII

LOCALIZATION OF CABLE FAULTS

THE routine testing of cables with high voltages and the localization of faults in high-tension cables, using high-voltage d.c., have already been dealt with in the previous chapter. Only the localization of faults in cables which are in service, and for use with the lower distribution voltages, will be considered here.

The faults which are most likely to occur are: (*a*) a breakdown of the insulation of the cable which allows current to flow from the core to earth or to the cable sheath—called a "ground" fault; (*b*) a "cross" or short-circuit fault, in which case the insulation between two cables, or between two cores of a multi-core cable, is faulty; and (*c*) an open-circuit fault where the conductor becomes

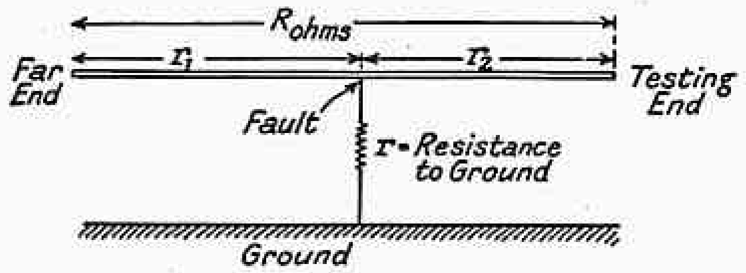


FIG. 294. GROUND FAULT ON A SINGLE CABLE

broken or a joint pulls out. The methods used for locating an open-circuit fault differ from those used in the other two cases.

The causes of such faults are numerous and need not concern us. It is important that their exact position shall be determined, however, in order that repairs may be undertaken without loss of time and effort.

In the case of multi-core cables it is advisable, first of all, to measure the insulation resistance of each core to ground and also between cores. If the fault is a "ground" this will enable the faulty core to be discovered; and if a short-circuit, the cores which are involved can be determined.

Blavier and Earth Overlap Tests. These tests enable one to find the position of a ground on a single cable—i.e. when no other cables run along with the faulty one.

The case is illustrated by Fig. 294. The total resistance of the cable, before the occurrence of the fault, is assumed to be known. Let this be R ohms. Suppose also that r is the resistance of the fault to ground, and that r_1 and r_2 are the resistances of the lengths of cable, "far end" to fault, and "testing end" to fault, respectively.

In the Blavier test the resistance between line and ground is

measured, first with the "far end" disconnected from earth, and then with the "far end" earthed.

These measurements may be made with the aid of a low-tension supply, and either an ammeter and voltmeter, or a bridge network.

Theory. Let the two measured values of resistance be M_1 and M_2.

Then
$$M_1 = r_2 + r \quad . \quad . \quad . \quad . \quad \text{(i)}$$
$$M_2 = r_2 + \frac{rr_1}{r + r_1} \quad . \quad . \quad . \quad \text{(ii)}$$
and
$$R = r_1 + r_2 \quad . \quad . \quad . \quad . \quad \text{(iii)}$$
From (i),
$$r = M_1 - r_2$$
Hence, in (ii),
$$M_2 = r_2 + \frac{(M_1 - r_2)\, r_1}{(M_1 - r_2) + r_1}$$
from which $(M_2 - r_2)(M_1 - r_2 + r_1) = (M_1 - r_2)\, r_1$

$\therefore M_1M_2 - M_1r_2 - M_2r_2 + r_2^2 + r_1M_2 = M_1r_1$

Substituting from (iii), we have, after simplifying,
$$M_1M_2 - 2M_2r_2 + r_2^2 + RM_2 = M_1R$$
or $\quad r_2^2 - 2M_2r + M_2^2 - M_2^2 + M_1M_2 = R\,(M_1 - M_2)$
$$(r_2 - M_2)^2 = (M_1 - M_2)\,(R - M_2)$$
Thus
$$r_2 = M_2 \pm \sqrt{(M_1 - M_2)\,(R - M_2)} \quad . \quad . \quad (241)$$

Since r_2 is obviously less than M_2, the negative sign in this expression is the one to be taken, i.e.
$$r_2 = M_2 - \sqrt{(M_1 - M_2)\,(R - M_2)} \quad . \quad . \quad . \quad (242)$$

In the "earth overlap" test, the two measurements made are: first, the resistance M_1 between line and ground, measured from the "testing end," with the "far end" earthed; and then the resistance M_2, line to ground, measured at the "far-end," with the "testing end" earthed.

Then
$$M_1 = r_2 + \frac{rr_1}{r + r_1}$$
$$M_2 = r_1 + \frac{rr_2}{r + r_2}$$
and, as before, $R = r_1 + r_2$.

By elimination, as in the Blavier test, we have
$$r_2 = M_1\left(\frac{R - M_2}{M_1 - M_2}\right)\left\{1 - \sqrt{\frac{M_2(R - M_1)}{M_1(R - M_2)}}\right\} \quad . \quad . \quad (243)$$
and also
$$r_1 = M_2\left(\frac{R - M_1}{M_2 - M_1}\right)\left\{1 - \sqrt{\frac{M_1(R - M_2)}{M_2(R - M_1)}}\right\}. \quad . \quad (244)$$

In each of the above tests, the distance of the fault from either end is obtained from the resistance between the fault and the end by using the known value of the resistance, per unit length, of the cable. The accuracy of these two methods is not high, mainly because it is often difficult to make connections to earth, at the ends of the cable, having a low enough resistance for this to be considered negligible—as it is in the theory of the tests (see Ref. (8)).

Voltage-drop Tests. These tests can be used when a second cable, free from faults, runs along with the faulty cable, the sound cable being used, either as part of the current circuit as in Fig. 295, or as a potential lead to the voltmeter as in Fig. 296.

Referring to Fig. 295, a large *steady* current is passed through the loop formed by the sound and faulty cables, joined together at the

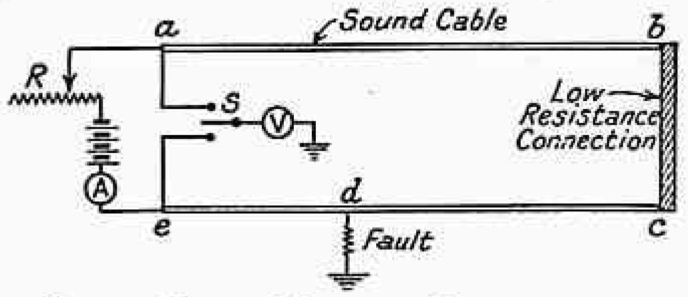


FIG. 295. SOUND CABLE USED IN CONJUNCTION WITH THE FAULTY ONE

distant end, as shown, by a low resistance connection. The current is from a number of accumulators, and is regulated and measured by the resistance R and ammeter A. By means of the throw-over switch S the voltmeter V, one terminal of which is earthed, is connected first across the section ed of the loop, and then across the section $abcd$. Let the two readings obtained be V_1 and V_2. Since the same current flows through both of these loop-sections (neglecting the voltmeter current) we have

$$\frac{V_1}{V_2} = \frac{\text{Resistance of section } ed}{\text{Resistance of section } abcd}$$

or

$$\frac{V_1}{V_1 + V_2} = \frac{\text{Resistance of section } ed}{\text{Resistance of the whole loop } abcde}$$

Now, if the cross-section of the cable is the same throughout the length, we have

$$\frac{\text{Distance of fault from } e}{\text{Length of the whole loop}} = \frac{V_1}{V_1 + V_2}$$

from which the position of the fault can be found. If the cable cross-section is not uniform, a correction must be applied to allow for the fact.

The resistance of the voltmeter should be large compared with the resistance of the fault, since the latter forms part of the voltmeter circuit. This fact constitutes an objection to the method. Another reason for the high-resistance voltmeter is that the instrument would otherwise take an appreciable current and so introduce errors in measurement.

In the circuit shown in Fig. 296, the fault resistance does not enter into the resistance of the voltmeter circuit. In this case the voltmeter measures the voltage drop across the length ed of the cable, and the resistance of this length is obtained by dividing by the current through it (as indicated by the ammeter A).

The voltmeter resistance should be high, as compared with the resistance of both the length ed, and of length $abcd$, of the cable, if corrections for voltmeter current are to be avoided. If the voltmeter is electrostatic, no corrections are, of course, necessary.

The length ed is calculated, as before, from the known resistance per unit length. Care must be taken that the current passed through the length ed of the cable is not sufficient to produce appreciable

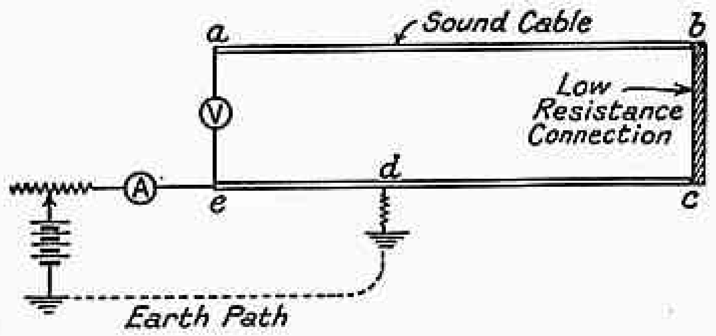


FIG. 296

heating as the resistance per unit length will then be different from that used in the calculation of length.

The same precaution must be taken in the previous method if the cable cross-section is not uniform. If the cross-section is the same throughout, however, the proportionality renders the precaution less necessary, although it is not advisable to pass such a current as will produce appreciable heating, even in this case.

Loop Tests. These tests can be carried out for the location of either a ground or a short-circuit fault, provided that a sound cable runs along with the grounded cable or with the two cables (or cores in a multi-core cable) which are short-circuited. Such tests have the advantage that the resistance of the fault does not affect the results obtained, provided this resistance is not very high. If it is high it may adversely affect the sensitivity.

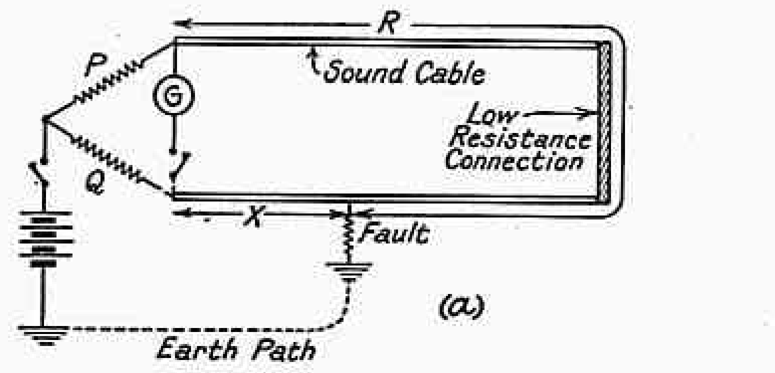
MURRAY LOOP TEST. The connections for this test are shown in Fig. 297. Connections (a) are for a test for a ground fault, and (b) for a short-circuit fault. Both circuits are essentially Wheatstone bridge networks, G being a galvanometer and P and Q resistances, or a slide-wire, forming two ratio arms. Referring to Fig. 297(a), the bridge is balanced by adjustment of P and Q until G indicates zero deflection.

Then,
$$\frac{P}{Q} = \frac{R}{X}$$

or
$$\frac{P+Q}{Q}=\frac{R+X}{X}$$

$$\therefore \frac{Q}{P+Q}=\frac{X}{R+X}=\frac{X}{2r} \quad . \quad . \quad . \quad . \quad (245)$$

where r is the resistance of one of the cables when free from faults. The value of r may be obtained from the lengths, cross-sections and temperatures, of the two cables all of which are assumed to be the same for each. The distance of the fault from the lower end of



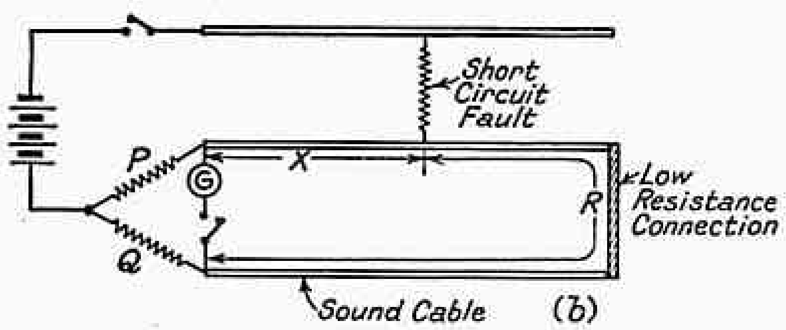


Fig. 297. Murray Loop Test

resistance Q may then be obtained from the value of X obtained as above.

It should be noted that the resistance of the fault enters only in the battery supply circuit and, provided it is not sufficiently large to reduce the sensitivity, will not affect the results.

In Fig. 297(b), the connections are practically the same as in the ground test, except that a portion of one of the short-circuiting cables is substituted for an earth path in the battery circuit. Balance is obtained as before, by the adjustment of P and Q and, at balance,

$$\frac{Q}{P}=\frac{R}{X}$$

or
$$\frac{P}{P+Q}=\frac{X}{R+X} \quad . \quad . \quad . \quad . \quad . \quad (246)$$

The total resistance $(R+X)$ of the loop is assumed to be known, so that X, and hence the distance of the fault from the upper end

of P, may be calculated. Again, the fault resistance enters only into the battery circuit.

Varley Loop Test. This test makes provision for the measurement of the total loop resistance instead of obtaining it from the known lengths of cable and their resistance per unit length. The connections are shown in Figs. 298, 299 for both the ground and short-circuit tests respectively. In this loop test the ratio arms P and

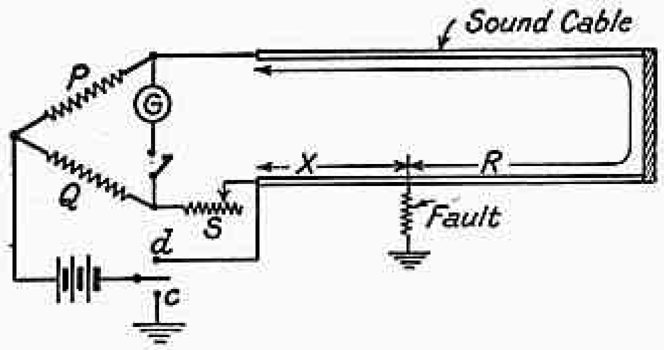


Fig. 298. Varley Loop Test for Ground Fault

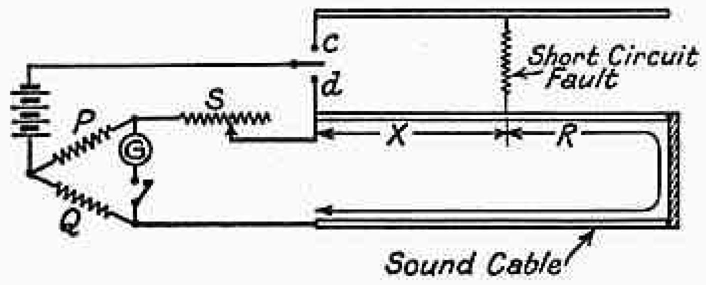


Fig. 299. Varley Loop Test for Short Circuit Fault

Q are fixed, balance being obtained by adjustment of a variable resistance S, placed in series with the section of the loop having the smaller resistance. When balance is obtained with the throw-over switch, in the battery circuit, on contact c, then, in either test, the magnitude of the resistance X may be obtained from the setting of S for balance, together with the values of P and Q and of the resistance $R+X$ (i.e. the total resistance of the loop).

At balance, in the ground test,

$$\frac{P}{Q}=\frac{R}{X+S}$$

or
$$\frac{P+Q}{Q}=\frac{R+X+S}{X+S}$$

From which,
$$X=\frac{Q(R+X)-SP}{P+Q} \quad . \quad . \quad . \quad (247)$$

In the short-circuit test,

$$\frac{Q}{P}=\frac{R}{X+S}$$

Now, P, Q, and S are known. $R + X$ may be measured by throwing over to contact d and obtaining a balance by adjustment of S as in the ordinary Wheatstone bridge network. In the ground test, as connected in Fig. 298, at balance,

$$\frac{P}{Q} = \frac{R + X}{S_1}$$

where S_1 is the new setting of S. Thus $R + X$ can be found. In Fig. 299, at balance,

$$\frac{P}{Q} = \frac{S_2}{R + X}$$

where S_2 again is the required setting of S for balance. The measured value of $R + X$ is then used in the calculation of X, from whose value the position of the fault is obtained as before. The use of the Evershed and Vignoles "Bridge-Megger Testers" for the location of cable faults was mentioned on p. 307.

FISHER LOOP TEST. In this test, developed by H. W. Fisher, two sound conductors, running from the testing end to the far end of the faulty cable, must be available. The lengths and resistances of these two conductors need not be known, but the length and resistance of the faulty cable must be known.

Two balances of the bridge network are necessary, the two connections for these being as shown in Fig. 300 (a) and (b). In the first test, one of the sound cables—of resistance R_1—is left disconnected, and in the second test it is merely used as a lead from the battery to the far end of the faulty cable. R_2 is the resistance of the other sound cable, while x and r are the resistances between the fault and the testing end, and between fault and the far end respectively.

Theory. Let P_1 and Q_1 be the balance values of P and Q in the first test, and P_2 and Q_2 their values in the second test.

Then,
$$\frac{P_1}{Q_1} = \frac{R_2 + r}{x}$$
and
$$\frac{P_2}{Q_2} = \frac{R_2}{x + r}$$

R_2 is eliminated as follows—

$$\frac{P_1}{Q_1} + 1 = \frac{R_2 + r}{x} + \frac{x}{x} = \frac{R_2 + r + x}{x}$$

$$\frac{P_2}{Q_2} + 1 = \frac{R_2}{x + r} + \frac{x + r}{x + r} = \frac{R_2 + r + x}{x + r}$$

$$\therefore \frac{\frac{P_2}{Q_2} + 1}{\frac{P_1}{Q_1} + 1} = \frac{x}{x + r}$$

$$\therefore x = (x + r)\frac{\left(\frac{P_2}{Q_2} + 1\right)}{\left(\frac{P_1}{Q_1} + 1\right)} \quad . \quad . \quad . \quad . \quad . \quad (248)$$

If the resistance per unit length of the faulty cable is uniform, we have

Distance of fault from testing end

$$= \left(\frac{\frac{P_2}{Q_2} + 1}{\frac{P_1}{Q_1} + 1}\right) \times \text{Total length of faulty cable}$$

Fault Localizing Bridges. Several forms of fault-localizing bridge,

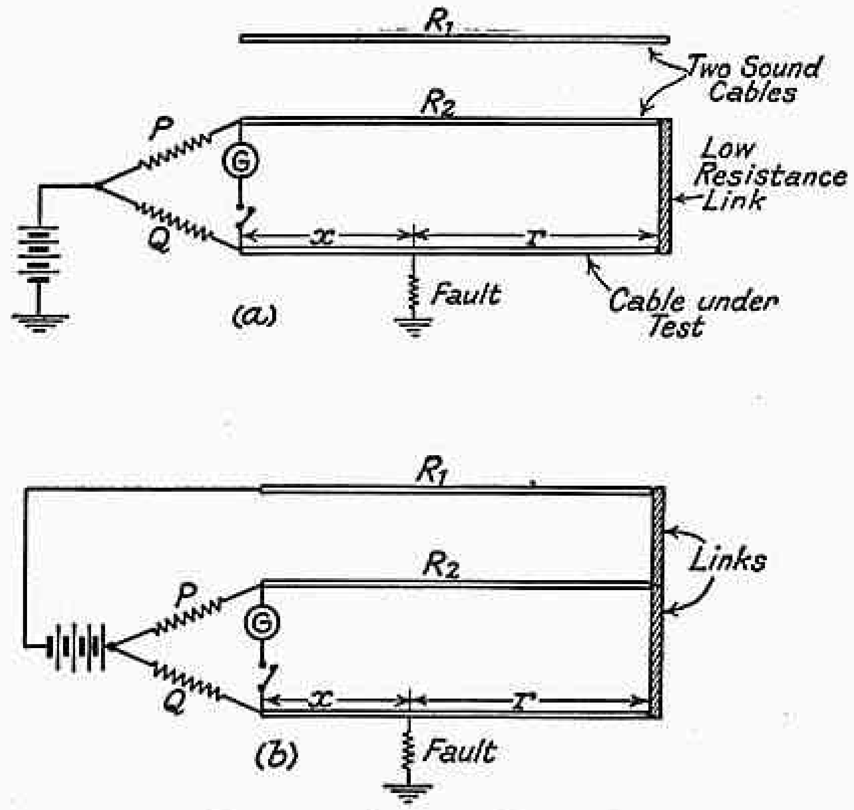


FIG. 300. FISHER LOOP TEST

which are portable and are arranged for determination of the distance of a fault from the testing end directly (i.e. without calculation), are made up by different manufacturers. Fig. 301 shows the connections and lay-out of the Raphael bridge, developed by F. C. Raphael, and manufactured by Messrs. Muirhead & Co., Ltd. It consists of a double slide-wire, with a scale, and two movable contacts S and P. The former contact connects one end of the cable loop to any point on the bridge wire, while P is the sliding contact for balance adjustment. The galvanometer and battery are connected to the cable loop, as in the Murray loop test (Fig. 297(a)).

In carrying out a test for a ground fault location, the contact S is placed in such a position on the slide-wire that the number of scale divisions of the working portion of this wire is a convenient multiple of, or is the same as, the length of the loop in yards. P is then moved until balance is obtained, when the scale reading opposite P gives the distance of the fault from the testing end, in yards, directly.

The relationship at balance is the same as in the Murray loop test, namely, $\dfrac{Q}{P+Q} = \dfrac{x}{2r}$

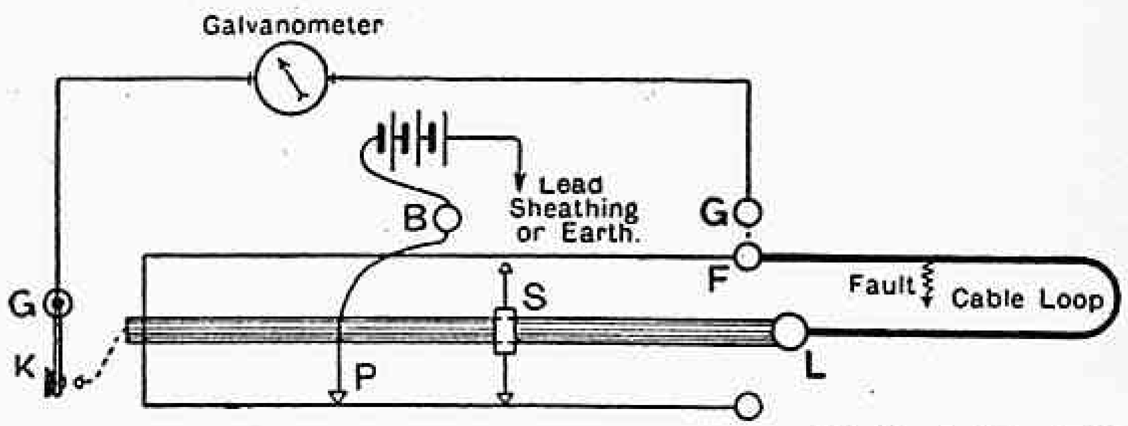
Corrections to be Applied in Loop Tests. If a ratio such as

$$\frac{\text{Resistance to fault}}{\text{Resistance of the whole loop}}$$

is, in one of these tests, determined in terms of resistances in the bridge ratio arms, it is obviously equal to

$$\frac{\text{Distance to fault}}{\text{Length of the whole loop}}$$

only if the cable section (and also the temperature) is uniform throughout the loop. If this is not so, corrections must be applied.



(*Muirhead & Co., Ltd.*)

FIG. 301 RAPHAEL FAULT LOCALIZING BRIDGE

Correction when the Cross-section and Length of both Faulty and Sound Cables are Known.

Let L_f = length of faulty cable.

" a_f = cross-section of faulty cable.

" L_s = length of sound cable.

" a_s = cross-section of sound cable.

Then, equivalent length of the whole loop is $L_f + L_s \cdot \dfrac{a_f}{a_s}$ and this length must be used in calculating the distance to the fault, instead of the actual length of loop. If resistances of the two cables, per unit length r_f and r_s, are used instead of cross-sections, the equivalent length is $L_f + L_s \dfrac{r_s}{r_f}$. Temperature corrections are applied in a similar way if the temperatures of the two cables are known or can be estimated with reasonable accuracy.

Correction when the Cross-section of the Faulty Cable is Not Uniform. Suppose the faulty cable consists of a number of sections, in series, these sections having different resistances per unit length. Let L_1, L_2, L_3, etc., be the lengths of these sections, and r_1, r_2, r_3, etc., be their resistances per unit length. Then, the first section has resistance L_1r_1, the second L_2r_2, and so on. If x is the resistance—obtained by measurement—of the cable from testing end to the

fault, it is first necessary to determine in which section the fault exists. Thus, if x is greater than $L_1r_1 + L_2r_2$, but less than $L_1r_1 + L_2r_2 + L_3r_3$, the fault is in the third section, and its distance L along this section from the point of junction with section 2 is given by

$$L = \frac{x - L_1r_1 - L_2r_2}{r_3} \quad . \quad . \quad . \quad . \quad . \quad (249)$$

As mentioned above, temperature corrections must also be applied if any appreciable difference of temperature exists between the various sections. It may be necessary, also, to correct for the resistance of joints if these are numerous.

Although other cases requiring corrections exist, enough has been said to indicate the method of applying such corrections in any particular case.

Tests for an Open-circuit Fault. If a complete disconnection occurs in a cable—either by a fault burning clear without causing a ground fault, or on account of the cable being pulled out at a joint—its position may be found by a capacitance test. The capacitance of a cable, to ground or to another parallel conductor, is proportional to the length of the cable. If the capacitance C of the whole length of the cable, when sound, is known, and the capacitance C_x of the length between one end and the fault is measured, the distance of the fault from the testing end is $\dfrac{C_x}{C} \times$ length of the whole cable. If the capacitance C is not known, tests must be carried out from each end of the cable, the sum of the two capacitances so measured giving the capacitance C. The distance of the fault from either end can then be obtained as above.

For the measurement of capacitance, either a ballistic galvanometer or an alternating current bridge method, using a high-frequency generator and telephone detector, may be employed.

Connections for the measurement of the capacitance of the cable up to the fault are shown in Fig. 302, two alternatives being given. The first method of measurement is by direct deflection, using a ballistic galvanometer. C is a standard capacitor. The galvanometer BG is shunted by an Ayrton shunt. The galvanometer throw is first observed when the capacitance represented by the cable-length is charged from the battery, the standard capacitor being then out of circuit. This capacitor is then substituted for the cable by means of the switches shown, and the galvanometer "throw" produced, when it is charged from the same battery, is observed. If D_c and D_s are these two throws—corrected if necessary for variations of the shunting powers in the two cases—we have

$$\frac{\text{Capacitance of cable-length to the fault}}{\text{Capacitance of standard capacitor}} = \frac{D_c}{D_s}$$

In the second method a capacitor bridge is employed, the supply being a high-frequency generator, and the detector T a telephone. The cable capacitance is then measured in terms of the standard