14 *High-voltage Bushings*

By H. BARKER

14.1. Types of bushing

THE problem of taking high-voltage conductors through earthed barriers such as walls, floors, metal tanks, etc. exists in many forms. The insulators which are used to fulfil requirements of this type are referred to as 'bushings' and may take many varied forms. One example is shown in Fig. 14.1, viz. a 400-kV wall bushing. Bushings have to provide electrical insulation of the conductor for the working voltage and for the various over-voltages which occur in service and also have to provide mechanical support against various mechanical forces.

14.1.1. *Non-condenser bushings*

In its simplest form a bushing would be a simple cylinder of insulating material: porcelain, glass, synthetic resin-bonded paper (s.r.b.p.), cast resin, polythene, hard rubber etc., as shown in Fig. 14.2, with radial clearance a and axial clearance b to suit the electric strengths of the insulating material and the surrounding media. These clearances will depend on the voltage distribution which is shown in Fig. 14.3. The voltage is not at all evenly distributed through the wall thickness t or along the length of the insulation l and as voltages increase the dimensions required become so large that really high-voltage bushings of this form are not a practicable proposition.

14.1.2. *Condenser bushings*

This difficulty is overcome by the condenser bushing principle illustrated in Fig. 14.4 in which the wall thickness is divided up into a number of capacitors by concentric conducting cylinders. The comparative voltage distributions in condenser and non-condenser constructions are shown in Fig. 14.5. Other methods of grading are used, e.g. a series of concentric barriers of higher dielectric constant than oil suitably arranged in a porcelain shell filled with oil. However the condenser construction gives much more compact designs than any other construction and has been far more fully exploited. A laminated construction is obviously very suited to it—hence the successful development of synthetic resin-bonded paper (s.r.b.p.) and

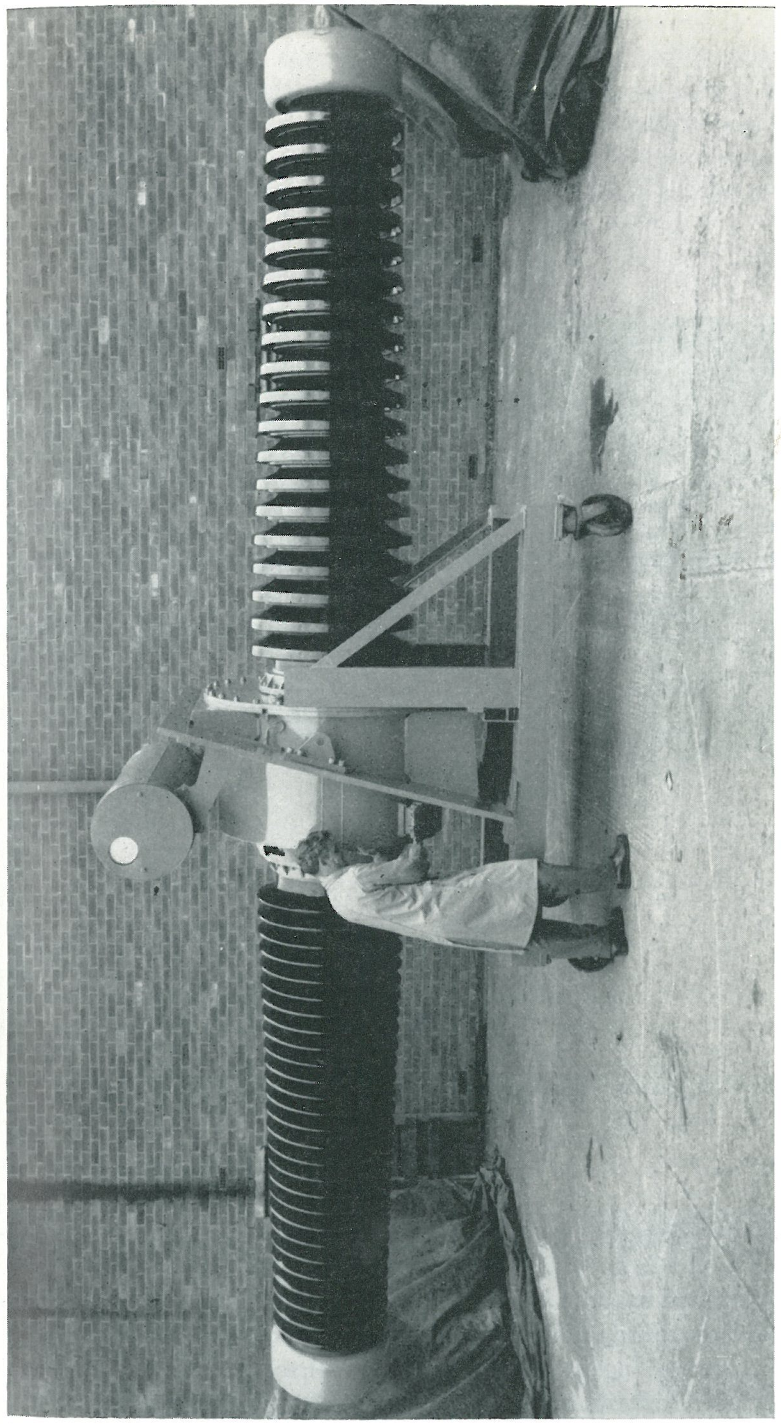

FIG. 14.1. 400-kV, 4000-A wall bushing (oil-impregnated paper).

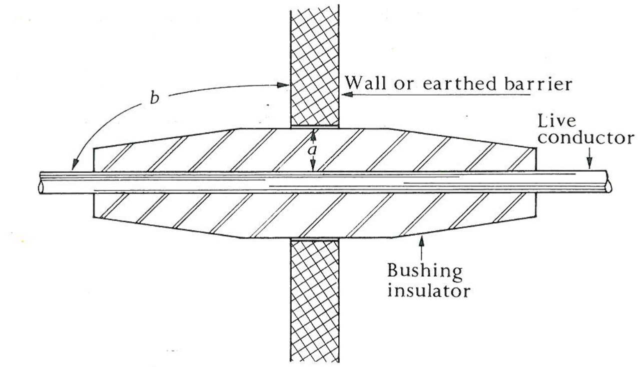

FIG. 14.2. Simple bushing.

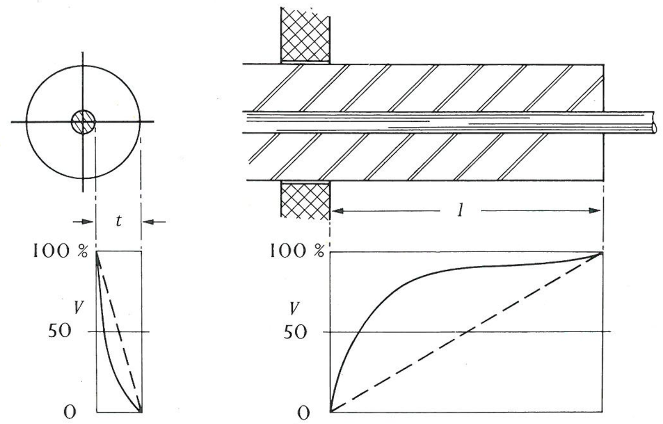

FIG. 14.3. Voltage distribution in simple bushing.

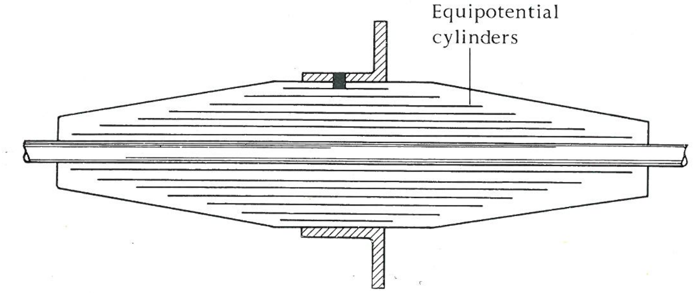

FIG. 14.4. Bushing with capacitance grading.

oil-impregnated paper (o.i.p.) bushings on a greater scale than others, and this chapter is mainly devoted to bushings of this type.

In s.r.b.p. bushings paper is first coated with synthetic resin then wound into a cylindrical form under heat and pressure, inserting conducting layers

at appropriate intervals. The conducting layers, of metallic foil or metal-coated paper, each form a complete cylinder. In practice s.r.b.p. bushings are limited in length by coating-machine widths which set a limit to the maximum flashover voltages attainable whilst thermal instability produced by the dielectric losses of synthetic resins may limit the maximum radial thicknesses which can be used. Thus s.r.b.p. bushings are not at the present time being made in this country above 275 kV.

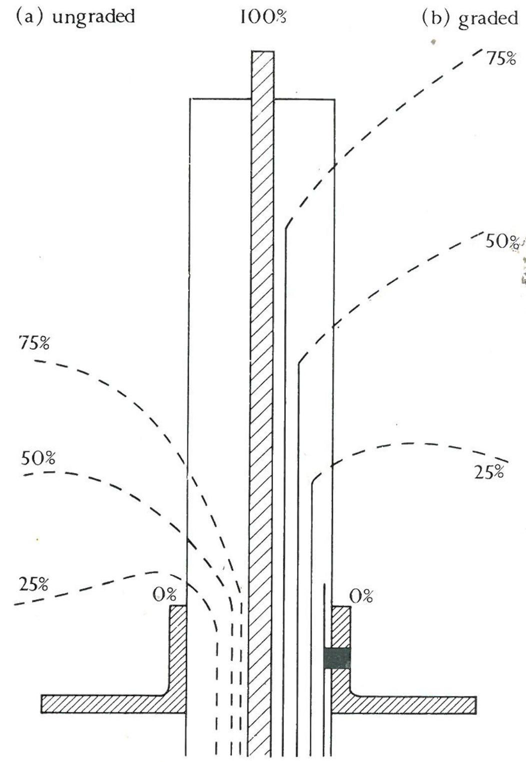

FIG. 14.5. Voltage distribution with and without capacitance grading.

O.i.p. bushings are made by similarly winding raw paper, inserting equipotential layers in the appropriate positions, afterwards impregnating the winding with oil after vacuum drying. For o.i.p. bushings the winding may be spirally wound with paper tape thus allowing longer bushings to be made than with s.r.b.p. Some manufacturers use autoclaves for the processing whilst others use the porcelain shell of the bushing as its own vacuum vessel. Dielectric losses are less than for s.r.b.p. and o.i.p. bushings are already being made for a maximum working voltage of 750 kV.

Unprotected s.r.b.p. is not suitable for outdoor use and o.i.p. obviously needs a container for its oil. Both types therefore may be enclosed in porcelain which is the only material available to date for continuous use outdoors. Glass would be suitable but the cost and complexity of manufacture of large shedded shells have precluded its use. Where s.r.b.p. bushings are used indoors, or immersed in oil or compound, enclosure in porcelain is not necessary.

14.2. Bushing applications

14.2.1. *Alternator bushings*

Alternators require bushings up to 33 kV but 22 kV is more usual (13·8 kV actual maximum working). Alternator bushings may be of porcelain or s.r.b.p. and in more recent years Duresca and Copar (types of material described later) have been found particularly suitable for the gas-tight bushings required for hydrogen-cooled alternators.

14.2.2. *Transformer bushings*

Transformers require terminal bushings for both primary and secondary windings. High-voltage terminals of large transformers are usually in air and outdoors and the bushings usually work with the lower end in oil and the upper end outdoors. In some cases a high-voltage cable is connected directly into a transformer via an oil-filled cable box.[1] A bushing then provides the connexion between the cable box and the transformer winding; such bushings have been made in s.r.b.p. for voltages up to 275 kV. Alternatively the cable insulation may be terminated by means of a condenser bushing. In both these cases of cable-connected transformers the bushings work with both ends in oil.[2]

Bushings consisting only of a porcelain shell, with or without oil filling, are used for voltages up to 66 kV but transformer bushings for 66 kV upwards are usually s.r.b.p., o.i.p., or barrier type. The bushings are mounted in localized projections from the transformer tank known as turrets and current-transformers are often housed in the turrets around the flange-barrels of the bushings.

Some transformer manufacturers prefer re-entrant bushings. The principle of the re-entrant bushing is shown in Fig. 14.6, where it will be seen that at the lower end about two-thirds of the total voltage is uniformly distributed over the surface from B to C and the lead from the winding through the bushing, usually termed the pigtail, has to be insulated in the re-entrant portion for one-third of the total voltage. The lower extremity of the bushing tube A which is at full voltage is relieved of stress concentration and all metallic parts at high voltage are buried in insulation. The re-entrant

bushing thus requires less clearance to the turret wall than the conventional bushing. With oil-impregnated paper bushings however the necessity for a re-entrant porcelain lower shell, which considerably increases the bore diameter of the bushing, and the relatively extravagant radial stress distribution in a re-entrant bushing result in an increase in diameter which tends to offset the reduction in required clearance. Whilst re-entrant bushings have been used exclusively in 275 and 400 kV transformers[3] working in this country this practice has not been generally followed abroad, and at higher voltages conventional bushings seem to be preferred.

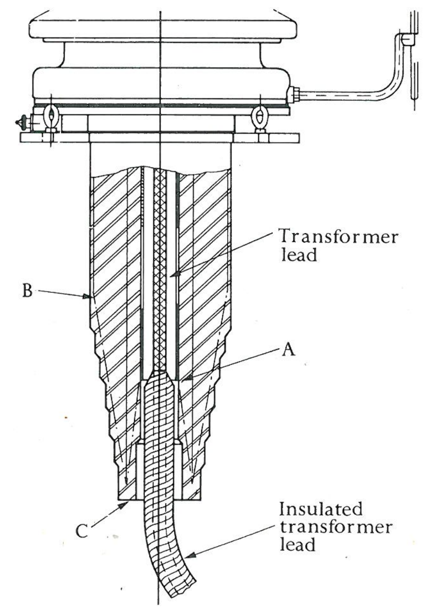

FIG. 14.6. Cross-section of re-entrant end of a 275-kV s.r.b.p. bushing.

14.2.3. *Bushings for switchgear*

In a large proportion of switchgear the actual circuit interruption is effected by an oil circuit-breaker. This may be of an outdoor type (e.g. Fig. 14.10) in which the bushings which carry the conductors through the tank wall and support the switch contacts are porcelain clad at the outdoor end, or the oil circuit-breaker may form part of a complete switch unit which is entirely encased in metal as in Fig. 14.7.

Indoor switchgear enclosed in a metal case, i.e. metal-clad switchgear, has been made for voltages up to 132 kV but the majority of this type of switchgear is within the range 3·3 to 33 kV.

Bulk type, i.e. not condenser graded, bushings made of porcelain, s.r.b.p.

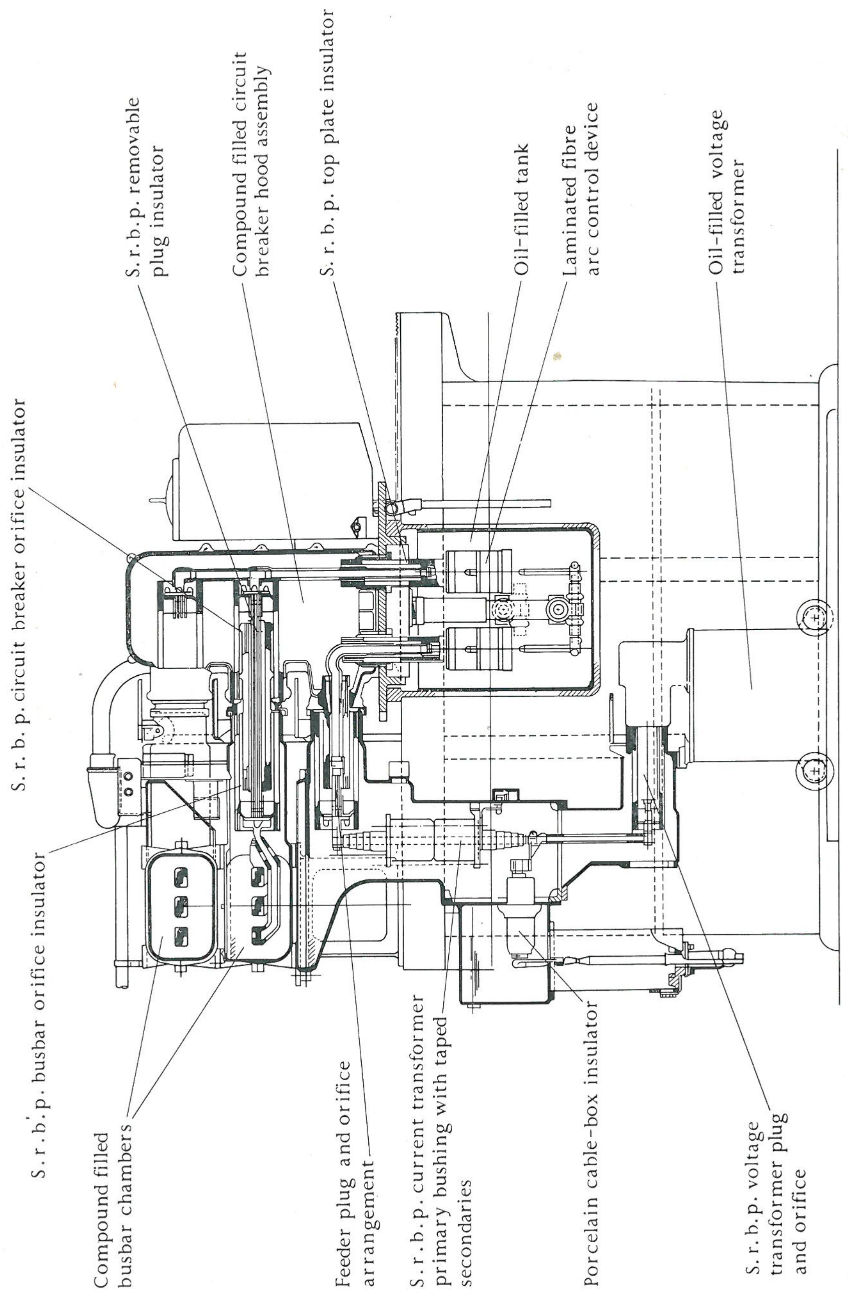

FIG. 14.7. 33-kV metal-clad switchgear.

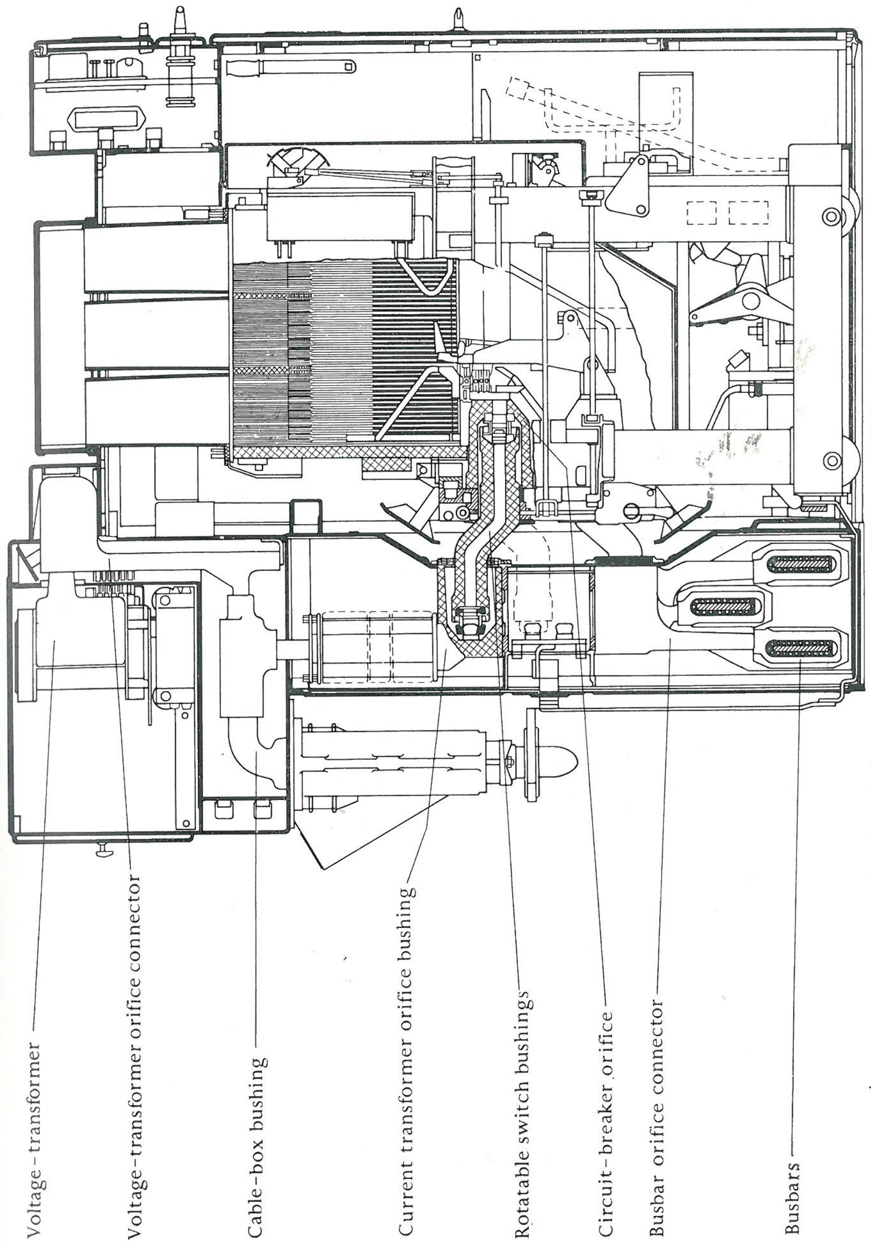

FIG. 14.8. Indoor air-break switchgear unit, 1600 A 11 kV 500 MVA, showing cast resin parts.

or cast resin are suitable for switchgear up to 22 kV but for higher voltages condenser bushings are invariably used and where size is important they offer advantages at lower voltages. An example of a 33-kV metal-clad switch is shown in Fig. 14.7 where cable box, plug and orifice, current-transformer primaries, and the oil circuit-breaker top-plate insulators of condenser construction in s.r.b.p. are illustrated.

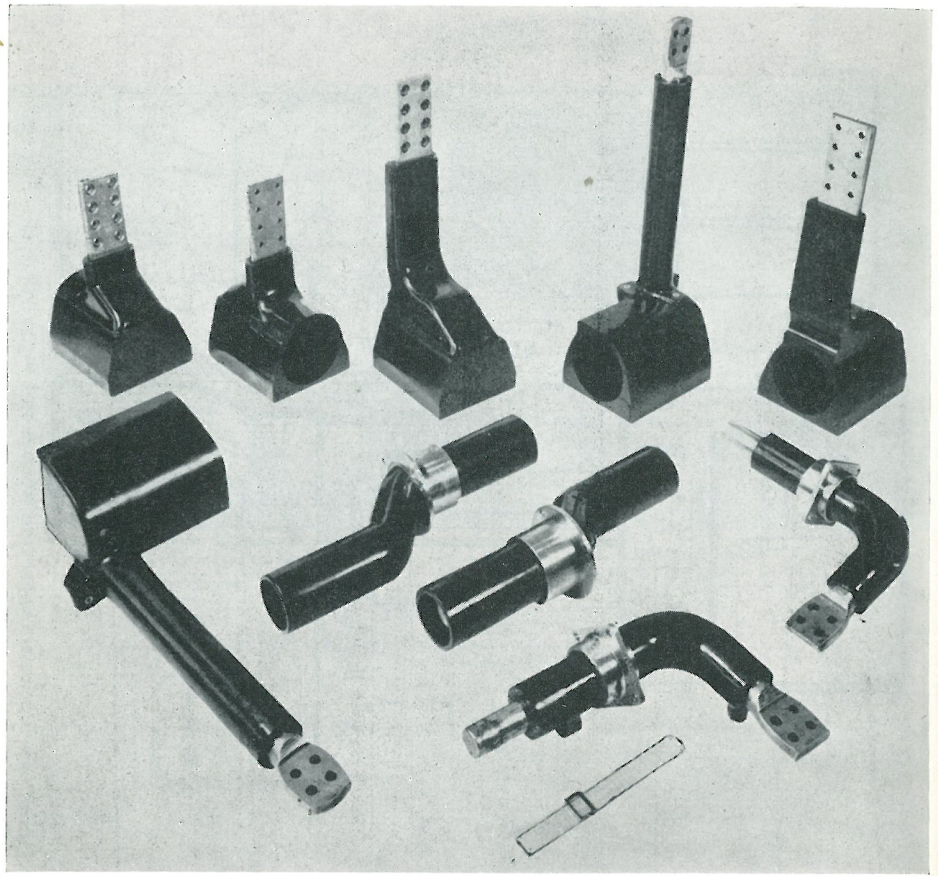

FIG. 14.9. Cast resin insulators for air break circuit-breaker shown in Fig. 14.8.

In recent years switchgear designs have been developed which use cast epoxy-resin insulation[4] instead of porcelain or s.r.b.p. This material allows more complicated shapes of bushing which can be used with advantage to simplify the construction of the switchgear. Fig. 14.8 shows an 11-kV air break switch fully insulated with cast resin and a group of insulators for this type of switch is shown in Fig. 14.9.

Oil circuit-breakers for outdoor use range from 11 to 330 kV. The

bushings may be entirely porcelain at the lower voltages where condenser grading is not essential. At the higher voltages s.r.b.p. bushings with porcelain protection at the outdoor end and sometimes at the lower end for protection against carbon contamination of the oil, oil-impregnated paper bushings, and barrier bushings are used.

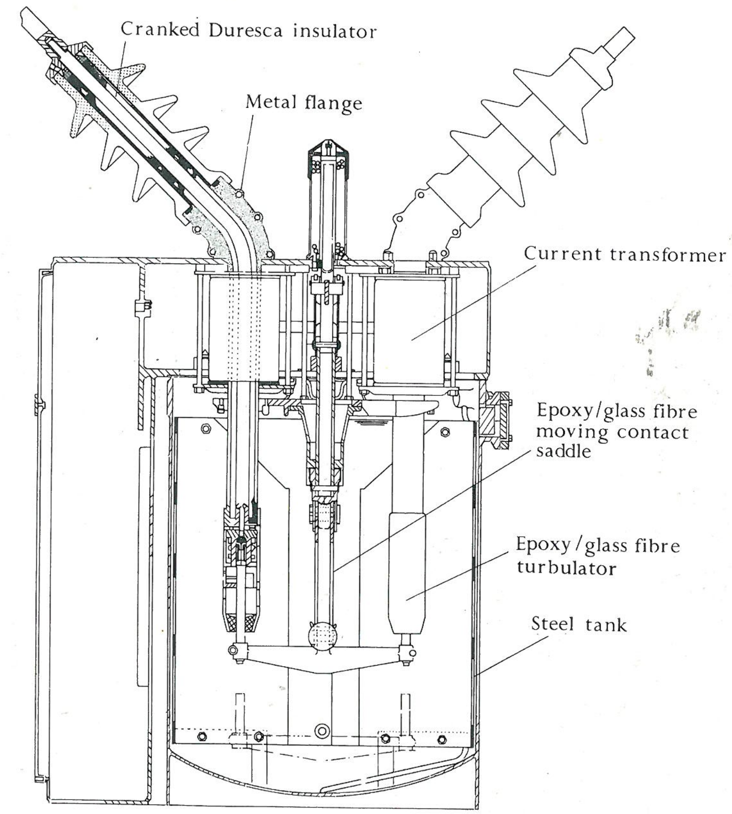

FIG. 14.10. 33-kV outdoor oil circuit-breaker with 3 phases in one tank.

The development of a modern material, Duresca, has made possible the manufacture of fully condenser-graded bushings of a bent shape; this in turn has made possible the construction of a 33-kV outdoor circuit breaker with three phases in one tank, as shown in Fig. 14.10. Duresca is a material made from crepe paper tape impregnated with epoxy resin and incorporating metallic grading layers. Due to its high resin content (about 70 per cent) Duresca is gas-tight at high pressures.

Air blast circuit breakers which split the circuit interruption into a number of breaks in series demand bushings which are gas-tight at pressures of some hundreds of lb/in^2 and of high mechanical strength (see Section

13.2 and seq.). Whilst porcelain can be used a condenser construction is of advantage both from the point of view of graded clearances and capacitance across the individual breaks. Duresca bushings, previously described, and Copar, a cast resin construction embodying condenser layers, find an application in this type of equipment. Copar is basically a mineral-loaded cast epoxy-resin with its condenser grading built up on a corrugated paper

FIG. 14.11. Copar insulators for a 400-kV air blast interrupter—36 are used in a complete 3-phase circuit-breaker.

skeleton. A group of Copar bushings for a 400-kV air-blast circuit breaker is shown in Fig. 14.11.

14.2.4. *Wall and roof bushings*

The biggest problem in working high-voltage equipment outdoors is to overcome the effects of pollution. One effective way of overcoming this problem is by greasing the porcelain insulators but this is a very costly business. In recent years many substations for 132 kV and above in unfavourable situations have been put inside a building. Buildings such as this need wall bushings which at 132 kV invariably have an s.r.b.p. core with outdoor porcelain at one end and indoor porcelain at the other. For the reasons stated in Section 14.1.2 275 kV is the largest rating of wall bushings made in s.r.b.p. At 400 kV o.i.p. is used. Fig. 14.1 shows a 400-kV, 4000-A wall bushing[3] as used for indoor substations in this country.

Wall bushings are usually fitted with current-transformers so that there is no need for separate post-type current-transformers.

14.2.5. *Cable-end and joint-box bushings*

A variety of bushings are used in cable-end boxes ranging from 3·3-kV porcelain bushings bringing the cores of a low-voltage cable out from an insulating compound filled box, to oil-impregnated paper bushings formed on site on the end of a high-voltage single-phase cable from sheets of pre-impregnated paper basted with hot oil and finally vacuum-filled.

S.r.b.p., cast resin, and Duresca bushings are used in stop joints which are used for connecting a high-pressure gas-filled cable to an unpressurized solid cable.

14.3. Service conditions and specifications

14.3.1. *Power-frequency voltages*

In solidly earthed neutral systems the power frequency voltage cannot rise above the normal phase-to-earth voltage which in this country may be 10 per cent above the nominal (5 per cent in the U.S.A.). With some systems of earthing the voltage may rise under fault conditions as high as the line voltage but these conditions are not allowed to persist for more than a few hours. Bushings designed for continuous working at the normal voltage will usually meet the latter conditions without damage but it is necessary with higher voltage bushings (above 132 kV) to check that they will not fail due to thermal instability. For unearthed neutral systems, where under fault conditions the working voltage may rise to the line voltage for long periods, bushings of higher rating are used.

14.3.2. *Surges*

Over-voltage surges may be generated in service by switching operations or induced in the system by lightning. The former are usually complex waves lasting some hundreds of microseconds, often accompanied by oscillations, whilst the latter are of much shorter duration, only a few microseconds. Switching surges can be limited by the design of the switchgear; lightning surges have to be limited by protective gaps or surge divertors.

In the 1930s when system voltages were limited to 132 kV, and before that time, surges were catered for in specifications by power frequency over-voltage tests. Towards the end of the 1930s impulse tests were introduced the standard wave-shapes being $1/50\ \mu s$[5] in this country and $1\frac{1}{2}/40\ \mu s$[6] in the U.S.A. Since that time both power-frequency tests and impulse tests have been used, with gradually more emphasis being placed on impulse tests.

In the last three or four years further changes have occurred. It has become evident from tests in various laboratories that, with switching surges of the values which occur in systems above 275 kV, the clearances required become disproportionately high and for impulse waves with wave-fronts of the order of 200 μs the breakdown value of an air gap is considerably lower than that for the same peak value on a short-fronted wave (1–$1{\cdot}5\ \mu$s) or even a 50 c/s wave. This has led to the introduction of long-wave impulse tests (in some cases under wet conditions) in some foreign specifications, and to a momentary power-frequency test of relatively higher value than previously specified for 400-kV bushings for the C.E.G.B. Tests carried out on a 400-kV wall bushing[3] have indicated that condenser grading appears to be beneficial in reducing the clearances required for long-wave surges. The flashover voltage also appears to be reduced under wet conditions.

14.4. Breakdown of bushings

A satisfactory bushing is one which has been so designed that it will withstand without breakdown during its life the maximum working voltage plus any over-voltages it may be subjected to either in service or during testing.

The former requisite demands the consideration of long-term breakdown which in the cases of both s.r.b.p. and o.i.p. is usually due to internal discharges though by somewhat different mechanisms.

14.4.1. *S.r.b.p. bushings*

S.r.b.p. for high-voltage bushings consists of discrete layers of paper bonded together with thin films of resin. It, therefore, contains a consider-

able amount of air uniformly distributed between the fibres of the paper. When the voltage on a bushing is raised a value is reached at which the minute pockets of air in the regions of highest stress begin to discharge. These regions are at the ends of the equipotential layers where the stress reaches several times the radial stress between the layers, depending on the spacing between the layers. In addition the hazards of bushing manufacture may result in circumferential cracking due to the stresses set up by the differential between radial and circumferential shrinkage or to weak resin-bonding due to incorrect winding conditions. In the discrete voids formed in this way the electric stress is increased considerably due to the low dielectric constant of air compared with the rest of the material. The magnitude of a discharge which occurs in a void is limited by the surface resistivity within the void. Thus discharges in voids in contact with metallic layers or conductors are more intense and more damaging.

The effects of discharges occurring in s.r.b.p. are well known though the exact mechanism by which the material is destroyed locally is not. The effects may be chemical, due to the formation of oxides of nitrogen or ozone in the discharge on the cellulose, or they may be due to temperature or ionic bombardment. Some discharges produce a carbonless 'erosion' which gradually extends in a radial direction until a layer is punctured. This effect occurs mainly at the ends of equipotential layers. An example of erosion at the end of a layer in a bushing, produced in about 30 years of continuous stressing at 24 kV/cm is shown in Fig. 14.12. In other cases the discharge extends axially from the end of a layer forming a carbonized 'tree-like' path and some examples have occurred of a discharge in a localized void progressing radially through the wall of the insulation. All the above forms of discharges are progressive and ultimately result in a breakdown over a long period. Final breakdown may occur due to residual over-stressed material being unable to withstand a surge or becoming thermally unstable. Breakdowns due to discharges at working voltage thus occur from periods of several weeks upwards to several years.

Over-voltages which occur in service are usually surges due to switching or lightning. In normal designs of condenser bushing the breakdown is axial from the ends of the layers; it occurs in a very short time (a few microseconds) and is no doubt the result of breakdown of the air in the paper. The complete breakdown of a bushing may be complex e.g. the axial breakdown of the material over some distance may so increase the radial stress locally that it punctures radially, again by breakdown of the air in the paper. Localized circumferential cracking or poor bonding may complicate the breakdown by providing an air path of low dielectric strength in which the breakdown in initiated.

Purely localized radial breakdown can occur at high stresses due to local weakness such as local mechanical puncture due to a small 'foreign body' being wound in.

During testing of bushings high-power frequency voltage are applied and instantaneous breakdown along the laminations may occur by the same mechanisms as for surges. There is also the possibility of local high-intensity discharges producing a thermal breakdown in times ranging from seconds to hours.

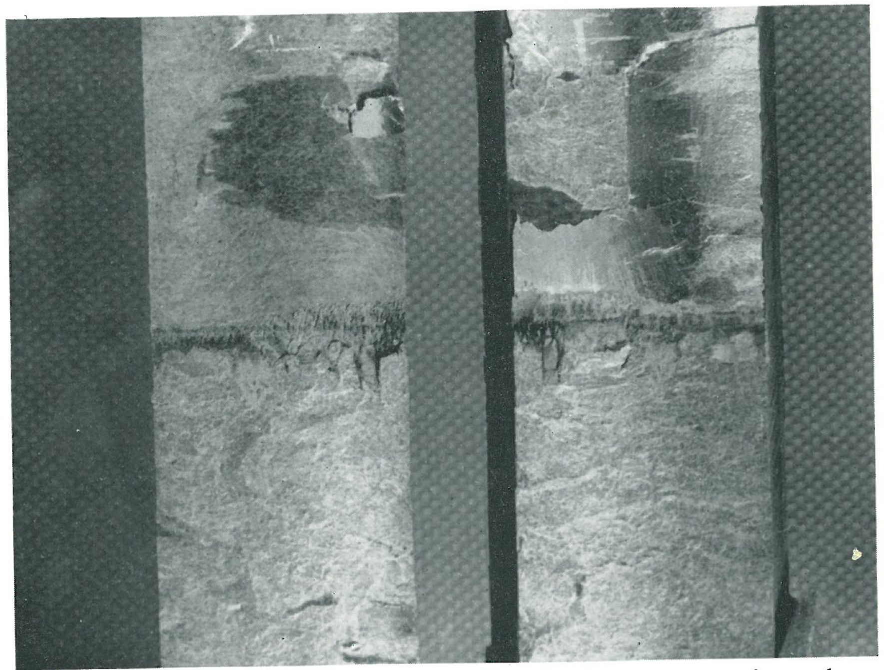

FIG. 14.12. Erosion of s.r.b.p. by discharges as a result of overstressing at the end of a foil layer.

14.4.2. *Oil-impregnated paper bushings*

There are no gaseous inclusions in oil-impregnated paper bushings which have been properly processed and adequately impregnated. Internal discharges do not occur therefore at the same stress levels as for s.r.b.p. The generation of gas bubbles in oil in the presence of fibrous material containing small amounts of water has been mentioned in Section 7.2.1. The stress levels required are much higher than the working stresses in bushings, even allowing for the large increase in stress at the edges of equipotential layers, but under surge or test conditions at high power-frequency voltages such high stress levels are attained.

Repeated impulse voltages giving stresses of the order of 250 to 300 kV/cm

(surface stress on a layer—not edge stress which will be very much higher) produce an effect of dryness at the edges of the layers as if the oil had been driven away from the edges. Many impulses are required to produce an effect detectable by eye. The effect is also detectable by a progressive reduction in discharge inception and extinction voltages. It appears to be reversible and after some hours the discharge inception voltage is restored to a high level.

It follows from this that an impulse imposed on a bushing already subjected to a power-frequency stress can initiate a discharge which will persist at the power-frequency stress level. Such discharges are of relatively low intensity and are no doubt similar to those which occur in oil-impregnated paper which is inadequately impregnated. Very slow progressive deterioration occurs in which polymerization of the oil into 'cable wax' can also occur, as in cables (see Section 16.2).

At high power-frequency stresses discharges occur at the edges of the layers which can propagate rapidly in oil-impregnated paper. The discharge is presumably initiated in the same manner as with repeated impulses but the high repetition rate results in rapid propagation, ranging from just perceptible spikes of carbonization at the ends of the layers (observed after one minute, say) to more extensive treemarking following paths along the laminations. At high enough stresses the destructive effect of the discharges is sufficient to extend radially through several layers of paper and local punctures occur leading rapidly to complete breakdown.

As with s.r.b.p. the stress at which discharge commences is dependent on the layer spacing, e.g. a stress of 140 kV/cm with a layer spacing of 1 mm does not produce any detectable permanent damage in 1 min but with a spacing of 1·5 mm the same stress may produce treemarking in this time due to the higher local stress at the edge of the layer.

14.5. Design of bushings

As with other forms of electrical equipment the design of bushings requires considerable knowledge and experience, especially when one considers the very numerous types required for the different applications described in Section 14.2. In this section an attempt has been made to outline the principles of the electrical design of bushings but it will be appreciated that many other considerations are involved in the detailed design of practical bushings.

The breakdown mechanisms of s.r.b.p. and o.i.p. described above and electric stresses at which they occur are important factors in the design of bushings but they are not the only factors. The breakdown characteristics of the media surrounding the bushing must also be taken into account.

In order to study the factors which influence the design of bushings it is convenient to consider a hypothetical transformer bushing, one end of which works in air and the other in oil, with dimensions as shown in Fig. 14.13. Before considering the design of the internal-condenser bushing it is necessary to consider the factors which govern the design of the air and oil ends.

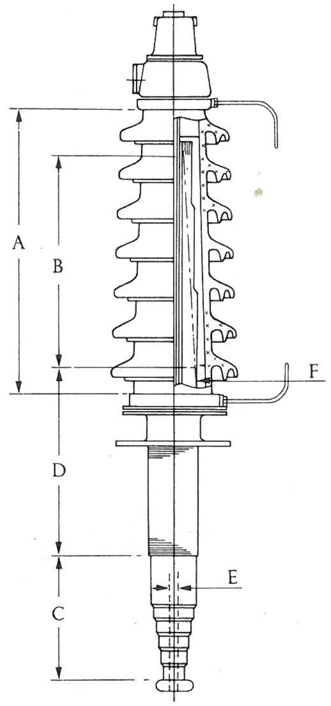

FIG. 14.13. Main dimensions.

14.5.1. *Air-end clearance*

As stated in Section 14.3 the power-frequency voltages are relatively low compared with surges and it is the latter, together with the test voltages specified to cater for them, which govern the air- and oil-end dimensions. As mentioned in that section, fashions have changed in the tests specified to cater for surge conditions from power frequency withstand in the 1930s, impulse tests for the past 30 years (both were used for 10 or 15 years), back to a 50-cycle test for 400 kV over the last 3 years and long-wave tests in recent American specifications for 500 kV and 750 kV in the last 2 or 3 years. Whichever test is specified the air-end clearance of the bushing must be made to suit it. With condenser bushings the external surface of the bushing can be fairly uniformly graded for 50-cycle and 1/50-μs impulse voltages so that the clearances required are fairly linear. The corresponding

voltage gradients are about 2·8 kV/cm and 5·5 kV/cm respectively. At the time of writing little information is available on the long-wave impulse flashover characteristics of high-voltage bushings and the clearances being provided on bushings for 500 kV and above may prove to be rather more generous than the service conditions require.

Whilst the air-end clearance has to be sufficient to meet the specified over-voltage tests it may in fact be determined by another factor—creepage path. In polluted atmospheres resistance to flashover under wet conditions even at working voltage without over-voltages is dependent on surface creepage distance, i.e. the length of the insulating surface between high tension and earth, and the proportion of it protected from rain. Porcelain manufacturers have exercised their ingenuity to produce the maximum creepage distance for a given length of porcelain. Even so the creepage may be the determining factor in the air-end clearance of a bushing.

Having determined the air-end length of a bushing (dimension 'A' in Fig. 14.13) from these considerations the air-end length of the internal condenser can be determined. It is not necessary to grade 100 per cent; in fact 70 per cent internal grading or less gives adequate surface grading for large bushings. Dimension 'B' is thus determined.

14.5.2. *Oil-end clearance*

The axial breakdown strengths of s.r.b.p. and o.i.p. are less than that of the oil external to the bushing, provided the bushing controls the external surface gradient. Internal breakdown is, unlike air flashover, destructive and final. Specifications, therefore, demand an internal breakdown with a margin (usually about 15 per cent) above the air withstand value. Both power-frequency and impulse voltage tests have been used to specify this characteristic. For both s.r.b.p. and o.i.p. the axial gradient at the oil end is designed on the basis of about 10 kV/cm for 50 c/s or about 20 kV/cm for impulse voltages.

This determines dimension 'C'.

14.5.3. *Length of earth layer*

The length of the earth layer of a bushing (dimension 'D') is usually determined by the accommodation required for current-transformers or by mounting considerations though in some cases it may be allowed to assume its optimum dimension in relation to the radial dimensions (see Section 14.5.4). Whichever is the case the following relationship between the length of the first and last condensers (l_1 and l_n respectively) holds:

$$\alpha = \frac{l_1}{l_n} = \begin{array}{l} 3{\cdot}15 \text{ for minimum thickness of insulation,} \\ 3{\cdot}29 \text{ for minimum external diameter,} \end{array}$$

4·12 for minimum volume of insulation,
4·44 for minimum total volume.

The ratio for minimum external diameter depends on the conductor diameter being optimum and this may not be the case as will become evident later. Thus minimum thickness of insulation is a more common condition.

14.5.4. *Radial gradients and diameters*

For both s.r.b.p. and o.i.p. the radial impulse breakdown gradients are so high that they need not be considered and only power-frequency voltages are involved in determining the radial gradients.

In s.r.b.p. the complete avoidance of discharges, or at any rate their restriction to what is regarded as an innocuous value, is ensured by the specification of some form of discharge test. The audible hissing test gave a breakdown free standard over a period of 25 years; it is now being replaced by more sophisticated discharge testing methods mentioned in Section 14.6.2. The generally accepted standard is a maximum of 100 pC at a voltage usually 5 per cent above the maximum working voltage.

To meet this condition a maximum radial gradient of about 20 kV/cm is suitable for bushings manufactured from high-quality s.r.b.p., provided a suitable layer spacing is chosen. The radial gradient of a bushing is not constant throughout the wall thickness and at lower gradients than the maximum the layer spacing may be increased.

At the higher power-frequency voltages used in testing, e.g. the one-minute test or the instantaneous test used to cover switching surges, discharges will occur in s.r.b.p. but the amount of damage is negligible and not detectable.

With o.i.p. the radial gradient is limited by the necessity for avoiding damage by discharges at the power-frequency test voltages whether one minute or instantaneous. This results in the gradient at maximum working voltage being limited to about 35 kV/cm, slightly less than twice that for s.r.b.p. Tests have been carried out to show that with this gradient many hundreds of superimposed impulses of the appropriate level do not initiate discharge.

The maximum gradient at a voltage V in the capacitor is given by the relationship:

$$\frac{V}{2Er_0} = \frac{\alpha \log \alpha}{\alpha + 1} \text{ where } \alpha = \frac{l_1}{l_n}, \quad r_0 = \text{radius of conductor,}$$

(if $\alpha = 3{\cdot}59$ then $\alpha \log \alpha = 1$) E = maximum gradient.

From this expression it will be seen that for a given α and a maximum gradient the radius of the conductor is proportional to the voltage. This fixes the minimum diameter of the conductor but other factors may determine its actual diameter, e.g. the current to be carried, the accommodation of a re-entrant porcelain, or mechanical considerations. From these considerations dimension 'E' is fixed.

If the ratio of the earth layer diameter to that of the conductor, r_n/r_0, is denoted by β the maximum stress E in the expression above will be at the conductor if $\beta > \alpha$, at the layer nearest to the earth layer if $\beta < \alpha$, and will be equal at both these diameters if $\beta = \alpha$.

An optimum value F for the earth layer diameter can thus be chosen. It will be seen that due to the relationship between β and α lengths and diameters are interdependent.

14.5.5. *Equipotential layer positions*

Having determined the dimensions of the inner and outer layers of the condenser the position of the layers can be calculated. For s.r.b.p. and o.i.p. bushings the basis of design usually adopted is that of equal partial capacitances which mean equal voltages on them and equal axial spacings between the ends of the layers. In practice the layer diameters are rationalized to the nearest 0·25 mm, say, for convenience in manufacture, so that partial capacitances are only approximately equal and the axial layer clearances are adjusted to compensate for this. A constant axial gradient is thus retained. With this method of design the layer spacing varies with the gradient so that if a suitable number of layers, based on experience, is chosen the correct layer spacing for the maximum gradient is automatically achieved.

For bushings where the laminating material is much thicker than paper, e.g. Duresca or Copar, it is usual to design on the basis of equal layer spacings. Constant axial gradient can still be attained but the partial capacitances are no longer equal.

It is possible to design a bushing with a constant radial gradient but this can only be at the expense of a variable axial gradient. As it is usually desirable to retain a constant axial gradient the radial gradient is allowed to vary and will be maximum either at the conductor or the earth layer. The minimum wall thickness occurs when the radial gradients at the conductor and earth layer are equal, i.e. when $\beta = \alpha$.

The calculations for the layer design of a large bushing with perhaps 150 layers or more are lengthy and tedious. Recently however computer programs for bushing design have been worked out and the time taken for the largest bushings is scarcely more than the print-out time.

14.6. Testing of bushings

A paper on high-voltage bushings would not be complete without some reference to the tests imposed on them to prove the designs and quality of manufacture. The more usual bushing tests are briefly described and comments are made on them in relation to other features described in this paper. Details of the majority of the tests referred to are given in *B.S.* 223.

Tests may be specified as type tests, i.e. tests intended to prove design features of bushings, or as routine tests which check the quality of individual bushings. Some tests may have a dual purpose and can serve as either type tests or routine tests according to circumstances.

14.6.1. *Power-factor/voltage test (power-frequency voltage)*

This test is probably the most universally applied test for all types of high-voltage bushing. For the test the bushing is set up as in service, or in

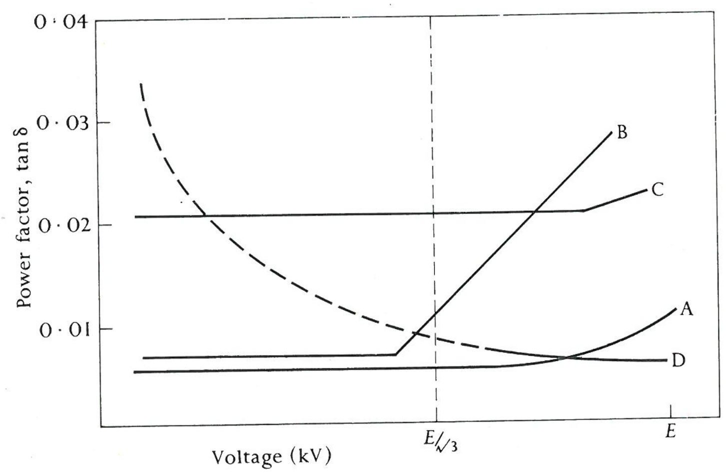

FIG. 14.14. Dependence of power factor on voltage.

some cases totally immersed in oil, connected so as to form one arm of a Schering Bridge, and voltage is applied in increasing steps up to the nominal line voltage and reduced in similar steps. Capacitance and power factor values are recorded for each voltage step on both increasing and reducing voltage. The Schering Bridge actually indicates the tangent of the loss angle δ rather than power factor, $\cos\phi$, but for the range of values usually obtained for bushings these two values may be regarded as identical. The actual value of the power factor gives an indication of degree of cure in resinous-type materials such as cast epoxy-resin, Duresca or Copar; it also gives an indication of moisture content in s.r.b.p. and o.i.p. Thus in Fig. 14.14, which shows typical power-factor/voltage curves for s.r.b.p.

bushings, Curve A would indicate a normal good bushing; the 'knee-value' which is due to internal discharge is above the working voltage. In Curve B the 'knee-value' is below the working voltage and deterioration would almost certainly occur in service. Curve C indicates high moisture content which may be due to incorrect winding conditions or in an old bushing absorption of moisture in storage. Curve D, a 'falling power factor' is indicative in s.r.b.p. of a poor connection to either first or last condenser layers or a punctured layer.

The power-factor/voltage test is almost invariably a routine test but it may sometimes be made on a percentage basis.

14.6.2. *Internal discharge tests*

From the early 1930s to the middle 1950s the audible 'hissing' test was used to assess internal discharge in s.r.b.p. bushings and when rigidly applied this test has given an excellent record of freedom from deterioration and failure in service. An insulating 'listening tube' was used to locate the position of discharge in the bushing and to determine the voltage at which 'audible hissing' ceased. Specially constructed rooms from which all extraneous noise was excluded were used for carrying out hissing tests. For the whole of a bushing to be accessible to the listening tube bushings had to be suitably supported in air for the test.

Experimental work using electronic methods of discharge detection in bushings began as early as 1937 and a considerable amount of work was done by various bushing manufacturers using the Discharge Bridge circuit developed by Armann and Starr[8] in the early 1930s. The introduction of the E.R.A. discharge detector, described in Section 9.7, gave some impetus to the work on bushings especially as it introduced a method of calibration which could be adapted to the Discharge Bridge enabling different manufacturers' results to be compared.

The E.R.A. discharge detectors use an oscilloscope as an indicator whilst the Discharge Bridge usually has a valve voltmeter, though an oscilloscope may also be used. In the BEAMA proposals for discharge measurements on bushings the charge and discharge constants of the valve voltmeter are the same as in *B.S.* 727.[9] and a calibrator is used giving a pulse every half-cycle. Under these conditions it has been shown that for internal discharge measurements in bushings the oscilloscope and the valve voltmeter give the same readings. If the discharges are completely resolved the indication will be of the maximum discharge in the bushing but due to the restricted frequency band-widths used in most discharge indicator equipments the discharges usually are not completely resolved and a degree of summation occurs.

For s.r.b.p. fairly general agreement has been reached that a level of 100 pC gives a rather better standard of acceptance than the 'hissing' test and should, therefore, ensure a not inferior performance in service.

For o.i.p. bushings much lower acceptance levels have been suggested (5 pC or less) in view of the more damaging effects of discharge in o.i.p. but agreement on the levels for this material has not yet been reached. The internal discharge test is invariably a routine test for bushings. For electronic discharge measurements the bushing is usually mounted as in service using suitable corona shields to minimize external discharges though with small bushings this may be more readily achieved by immersing the bushing completely in oil for the test.

14.6.3. *One-minute dry withstand test (power-frequency voltage)*

The oldest and most common routine test used for various classes of electrical equipment is the one-minute dry withstand test, in which a specified power-frequency voltage is applied for 1 min with the bushing mounted as in service. The current through the bushing is often measured during the test and this often gives an indication of deterioration or impending failure. There is clearly some justification for applying the test to bushings which are to be fitted to equipment which is subjected to a 1-min test or to an induced voltage test at 150–250 c/s. Properly designed bushings will withstand the test without damage but there is little can be said really to justify its retention among the much more informative tests in use nowadays.

14.6.4. *Momentary dry withstand test (power-frequency voltage)*

This test has already been referred to in Section 14.3. It is carried out with the bushing mounted as in service. It has now been virtually replaced by the impulse withstand test.

14.6.5. *Wet withstand test (power-frequency voltage)*

A test which has been the subject of much controversy over the years is the wet withstand test, usually of 30 s duration, with the bushing mounted as in service under artificial rainfall of specified intensity and water resistivity. The modern replacement for this test is the wet switching surge test referred to in Section 14.6.12.

14.6.6. *Under-oil flashover or puncture withstand test (power-frequency voltage)*

This test is intended to ensure that the internal breakdown strength of a bushing has a margin (of the order of 15 per cent) above the power-frequency

momentary dry withstand test. The test may be carried out as its title implies with the bushing completely immersed in oil but it is often possible to achieve the required voltage with one end in air as in service and this is clearly much more convenient for very large bushings. Though still retained as a type test in some specifications an under-oil impulse withstand test is now usually specified as an alternative.

14.6.7. *Thermal stability test*

With s.r.b.p. bushings the power factor at the maximum oil temperature reached by transformers, about 80°C, is high enough to produce considerable dielectric losses and with large bushings there may be a danger of thermal instability. Experience has shown that there is little danger of this with bushings below 132 kV and it has been the practice for many years in British Specifications to specify a thermal stability test as a sample test (i.e. on a small percentage of bushings) for bushings of 132 kV and above. The test is carried out with the bushing immersed in oil at the maximum temperature as in service and the voltage specified is 0·86 of the nominal system voltage. This is approximately $\sqrt{2}$ times the working voltage and the dielectric losses are thus about double the normal value. The additional losses due to the higher voltage have to cater for the conductor losses due to the current. On bushings of low current ratings (up to say 600 A at 132 kV) the conductor losses are of this order but with higher current ratings some attention has to be paid to dissipation of the heat from the conductor.

It has been considered unnecessary to specify thermal stability tests for o.i.p. bushings in view of the low dielectric losses compared with s.r.b.p. It is necessary however, in large o.i.p. bushings for heavy current, e.g. a 400-kV, 1600-A transformer bushing, to pay attention in the design to the dissipation of the conductor losses which may be several times the dielectric losses.

More sophisticated tests than the thermal stability test may be carried out therefore, by manufacturers, on bushings with simultaneous voltage and current loadings to ensure that they are thermally stable under service conditions.

14.6.8. *Visible discharge test (power-frequency voltage)*

The main purpose of this test is to determine whether a bushing is likely to produce radio interference. With the bushing mounted as in service line-to-line voltage is applied and reduced until corona is no longer visible in the dark. In the U.S.A. radio interference voltage tests have been specified for some time and are likely to be introduced into this country. This should render the visible discharge test, which is a type test, obsolete.

14.6.9. *Full wave withstand test (impulse voltage)*

This test has also been referred to previously in Section 14.3.2. For many years the full wave impulse withstand test has been specified as a type test to ensure that the air-end clearance of a bushing is adequate. The test is carried out with the bushing mounted as in service. Five impulses of both positive and negative polarities are applied though if it is known that one polarity gives a lower flashover value than the other the test may be limited to five impulses of that polarity only. If one impulse application of the five results in a flashover, five additional impulses are applied, and if a second failure occurs the bushing is deemed to have failed the test. The impulse voltage wave-shape applied is a $1/50$ μs wave in Europe and a $1\frac{1}{2}/40$ μs wave in the U.S.A. It has also been used as a routine test by some manufacturers and more recently has been specified as such for 275-kV and 400-kV transformer bushings to ensure that transformers complete with bushings can safely be subjected to impulse test.

14.6.10. *Under-oil flashover or puncture withstand test (impulse voltage)*

This test is made at a value 15 per cent above the full wave impulse withstand test. It is usually permissible to carry out this test with negative waves and as the negative flashover voltage is generally higher than the positive it is possible to carry out the test in air. Two impulses are applied and whilst air flashover is permitted no internal failure or under-oil flashover may occur. The test is specified as a type test.

14.6.11. *Chopped-wave withstand test (impulse voltage)*

In a chopped-wave test the impulse voltage is removed suddenly by causing a spark gap to flash over in parallel with the object under test. This test is no more onerous on a bushing than a full wave test but it is possible for the very high impulse current which occur with chopped waves to burn out the connexion to the first or last layers if the bushing is not adequately designed to meet this condition. The voltage value for the chopped-wave test is the same as that for transformers, i.e. 15 per cent above the full wave test and thus the same as the under-oil withstand test. It is a type test for transformers and is specified in this country as a type test for 275 kV and 400-kV bushings.

14.6.12. *Switching surge tests*

In the last three or four years some American specifications have included 'switching surge tests' in some cases under wet conditions. Where a wave shape has been specified it has usually been a $200/1000$-μs wave which is known to give the minimum flashover voltages.

There is little experience so far, in this country with long-wave tests of this nature though some experimental work has been done as mentioned in Section 14.3.2.

14.6.13. *Corrections for atmospheric conditions*

The air flashover characteristics of a bushing are affected by atmospheric air temperature, pressure, and humidity. For tests in which these characteristics are being measured or where air flashover is a possibility, (i.e. tests 14.6.4, 14.6.5, 14.6.8, 14.6.9, and 14.6.12) corrections are made to the applied voltages. The correction factors are given in *B.S.* 223[7] and similar specifications.[6, 10]

14.7. References

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