Chapter 12

High voltage bushings

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12.1 Introduction

A bushing is a device for carrying one or more high voltage conductors through an earthed barrier such as a wall or a metal tank. It must provide electrical insulation for the rated voltage and for service overvoltages and also serve as mechanical support for the conductor and external connections. The requirements for bushings are specified in IEC 60137 1995 [1].

12.2 Types of bushings

Bushings are used to carry conductors into all types of electrical apparatus, e.g. transformers, switchgear and through building walls. Their form depends on the rated voltage, insulating materials and surrounding medium. Bushings can be broadly grouped into two types; noncondenser and condenser graded bushings.

12.2.1 Noncondenser bushings

In its simplest form a bushing would consist of a conductor surrounded by a cylinder of insulating material, porcelain, glass, cast resin, paper, etc. as shown in Figure 12.1. The radial thickness a is governed by the electric strength of the insulation, and the axial clearance b by that of the surrounding medium.

As shown in Figure 12.2, the electric stress distribution in such a bushing is not linear through the insulation or along its surface. Concentration of stress in the insulation may give rise to partial discharge and a

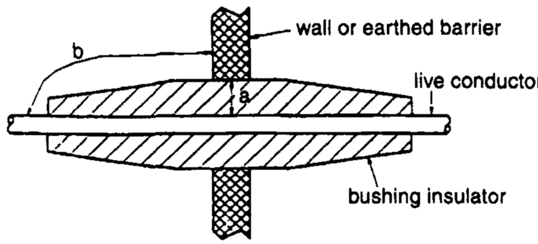

Figure 12.1 Noncondenser bushing

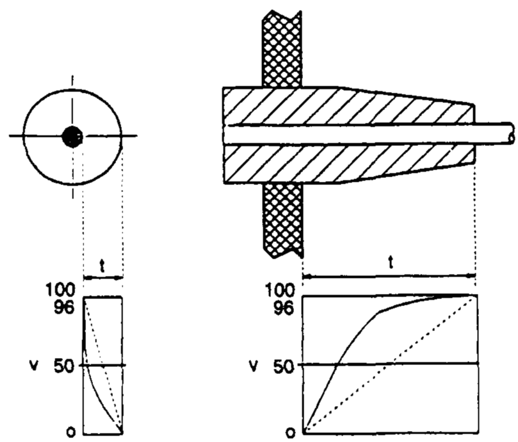

Figure 12.2 Stress distribution in noncondenser bushing

reduction in service life. High axial stress may result in tracking and surface flashover. As the rated voltage increases, the dimensions required become so large that this form of bushing is not a practical proposition.

Partial discharge can be reduced by including in the bushing design a stress control mechanism. With cast resin insulation a control electrode, electrically connected to the mounting flange, can be embedded in the insulation, reducing the stress at the flange/insulation interface.

Stress control methods have been developed for power cable terminations using heat-shrinkable stress control tubing which can also be applied to bushings. The heat-shrinkable stress grading tube is installed over the exposed solid insulation and overlapping the flange. The tube reduces the voltage gradient at the flange and along the surface of the bushing (Figure 12.3). It is important that air is eliminated from the interface using a void filling mastic to prevent partial discharge.

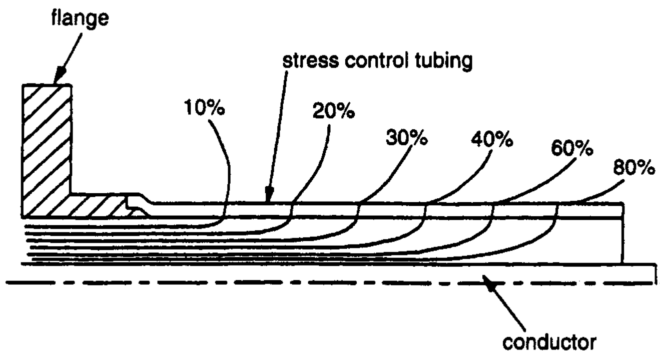

Figure 12.3 Stress control using heat-shrinkable stress control layer

12.2.2 Condenser bushings

At rated voltages over 52 kV, the condenser or capacitance graded bushing principle is generally used, as shown in Figure 12.4. The insulation material of such a bushing is usually treated paper with the following the most common:

- resin bonded paper (RBP)
- oil impregnated paper (OIP)
- resin impregnated paper (RIP).

As the paper is wound onto the central tube, conducting layers are inserted to form a series of concentric capacitors between the tube and the mounting flange. The diameter and length of each layer is designed so that the partial capacitances give a uniform axial stress distribution and control radial stress, within the limits of the insulation material (Figure 12.5).

12.2.2.1 Resin bonded paper bushings

RBP bushings were previously used extensively, up to 420 kV, for transformer applications but are now limited to low voltage use, particularly in switchgear, due to technical limitations. In RBP bushings, the paper is first coated with a phenolic or epoxy resin then wound into a cylindrical form under heat and pressure, inserting conducting layers at appropriate intervals. The use of RBP bushings is limited by the width of paper available and by the danger of thermal instability of the insulation due to the dielectric losses of the material. RBP bushings are designed to operate in service at a maximum radial stress of approximately 20 kV/cm.

The RBP insulation is essentially a laminate of resin and paper. The bushing therefore contains a considerable amount of air distributed between the fibres of the paper and at the edges of the grading layers.

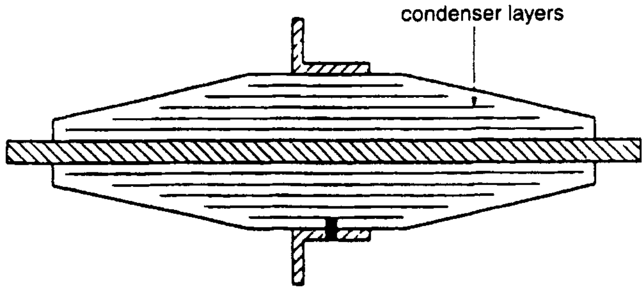

Figure 12.4 Condenser bushing

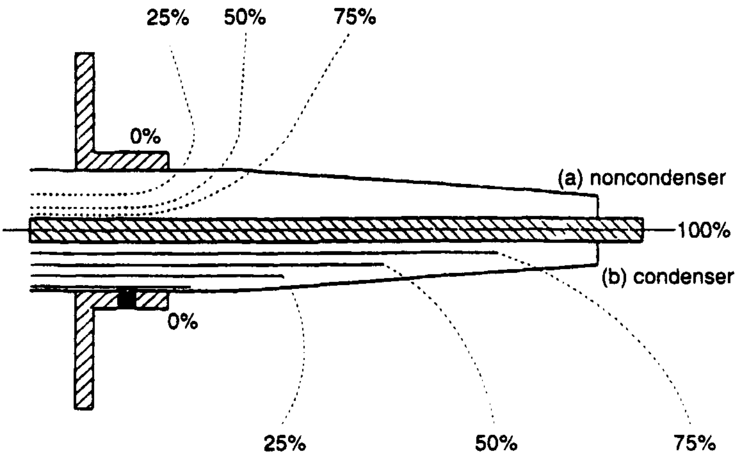

Figure 12.5 Field distribution in noncondenser and condenser bushings

Where internal faults exist, as the voltage applied to the bushing is raised, partial discharge inception can occur at the layer ends where the stress is greater than the radial stress between the layers. During manufacture, incorrect winding conditions may result in circumferential cracking produced by shrinkage or weak resin bonding. Here, in the voids produced, the electric stress is enhanced and partial discharge may occur at low levels of stress.

In service, ingress of moisture into RBP bushings can cause delamination and increased and unstable dissipation factor or tangent delta. Discharges at the layer end produce carbon treeing, extending axially, while discharges in voids may produce breakdown between layers. Both forms of discharge are progressive and ultimately lead to failure over a long period by overstress or thermal instability in the residual material [2, 3].

Overvoltages that occur in service are usually surges produced by switching or lightning. Breakdown of a bushing under this type of stress would normally be initiated axially from the ends of the layers due to breakdown of air in the winding. Complete failure may be a combination of axial and radial breakdown.

12.2.2.2 Oil impregnated paper bushings

OIP insulation is widely used in bushings and instrument transformers up to the highest service voltages. OIP bushings are made by winding untreated paper inserting conducting layers at the appropriate positions and impregnating with oil after vacuum drying.

The paper used is generally an unbleached kraft which is available in widths of up to 5 m. This width is adequate for most applications but, for ultra high voltage bushings, various methods of extending the condenser length by multi-piece construction or paper tape winding have been used. It is important that the paper be sufficiently porous to allow efficient drying and impregnation while maintaining adequate electric breakdown strength.

The oil used is a mineral oil as used in power transformers and switchgear [4]. Prior to impregnation, processing is carried out to ensure low moisture and gas content and high breakdown strength [5]. In certain applications, other properties may be important; for example, low pour point for low temperature installations and resistivity and fibre content for DC bushings.

Processing of the bushing may be carried out by placing the whole assembly in an autoclave or by applying vacuum directly to the bushing assembly before impregnation. Manufacturing defects are generally detected in routine tests. In the case of properly processed OIP bushings, there are no gaseous inclusions in the material. Internal discharge inception therefore occurs at much higher stress levels than with the RBP bushings. OIP bushings are therefore being designed to operate at radial stresses of typically 45 kV/cm. Discharges can occur at the layer ends (due to misalignment) of the layers at the high stress levels associated with lightning impulse and power frequency tests. If this stress is maintained, gassing of the oil and dryness in the paper can be produced, and eventually carbonisation at the layer ends may occur which, due to the high radial component of the stress, tends to propagate radially, leading to breakdown.

12.2.2.3 Resin impregnated paper

RIP insulation was developed in the 1960s for use in distribution switchgear and insulated busbar systems. In recent years, development has increased its utilisation to 800 kV.

In the manufacturing process, creped paper tape or sheet is wound onto a conductor. Conducting layers are inserted at predetermined positions to build up a stress controlling condenser insulator. The raw paper insulator is dried in an autoclave under a strictly controlled heat and vacuum process. Epoxy resin is then admitted to fill the winding. As a 525 kV bushing may have a core greater than 6 m in length, it is important that the resin has low viscosity and long pot life to ensure total impregnation. During the curing cycle of the resin, shrinkage must also be controlled to avoid the production of cracks due to internal stresses. The resulting insulation is dry, gas tight and void free, giving a bushing with low dielectric losses and good partial discharge performance.

During manufacture, the conducting layer follows the shape of the creped paper. The spacing between individual layers varies between the peaks and troughs of the creping. The layer spacing with RIP is therefore coarser than with RBP and OIP bushings, and full advantage of the high intrinsic strength of the resin cannot be taken. RIP bushings are designed to operate with a radial stress of about 36 kV/cm.

12.3 Bushing design

It is essential that a bushing be designed to withstand the stresses imposed in test and service. These are summarised in Table 12.1. Condenser type bushings are used predominantly at high voltages and their design and application will now be considered.

Electrical stresses act both radially through the insulation and axially along its surface. The maximum allowable stresses for each material have been determined by experience and test to give a minimum service life of 40 years.

The condenser design controls these stresses to a safe level. The stress distribution is dependent on five principal factors (Figure 12.6):

r_o, radius of conductor
r_n, radius of outer layer
l_l, length of first condenser
l_n, length of last condenser
U_n, rated voltage.

A typical OIP bushing, one end operating in air and the other in oil, as shown in Figure 12.7, will be considered to describe the procedures of bushing design [6]. Figure 12.8 shows 420 kV OIP bushings installed on a transformer supplied by VA Tech Peebles, Edinburgh, UK, to NGC UK.

In Figure 12.7 the condenser winding (1) is enclosed in air side (2) and oil side (3) insulators which are pressed against the mounting flange (4), the underside of which may be extended to provide current transformer accommodation, by springs contained in the head of the bushing (5) acting to tension the central conductor or tube (6). The assembly is sealed by a gasket to prevent oil leakage.

Table 12.1 Likely stresses for bushings

Electrical	Lightning impulse voltage (BIL)
	Overvoltages caused by switching operation (SIL, etc.)
	Power frequency voltage withstand
Thermal	Conductor losses
	Dielectric losses
	Solar radiation
Mechanical	Loads due to external connections
	Self-loads due to mounting angle
	Earthquake forces
	Short-circuit forces
Environment	Wind loads
	Nature of surrounding medium (air, oil, gas)
	Pollution

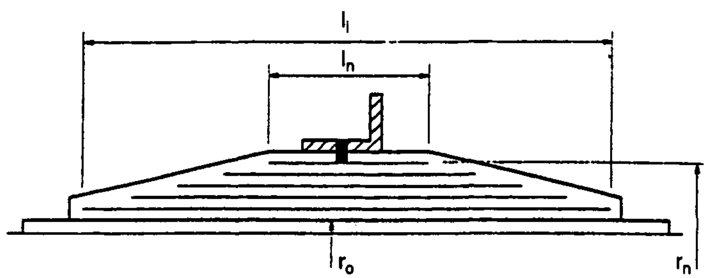

Figure 12.6 Major dimensions of condenser bushings

12.3.1 Air end clearance

For indoor use with moderate pollution and humidity, resin based insulating materials need no further protection from the environment. Oil or gas filled or impregnated bushings always require an insulating enclosure. This is commonly porcelain but modern glass reinforced plastic with rubber coatings (composite insulators) are also used.

The length of the insulator is governed by the lightning impulse and switching impulse requirements. The design of the bushings produces uniform axial stress along the surface of the insulator, and the length can therefore be less than for a simple airgap. The length of the insulator is also affected by the service environment. In polluted atmospheres, resistance to flashover under wet conditions even at working voltage is dependent on the surface creepage distance, i.e. the length of the insulating surface between high voltage and earth, and the proportion of it protected from rain. IEC 60815 [7] gives guidelines on the design of insulator profiles for use in polluted atmospheres.

From information on the site pollution severity, a minimum nominal

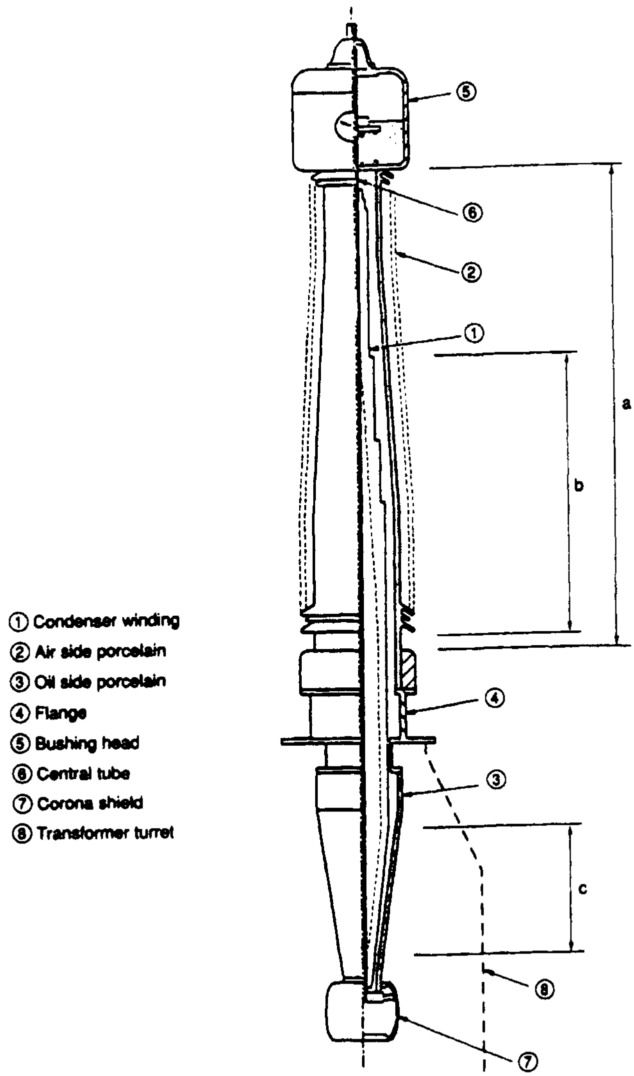

Figure 12.7 Section of typical transformer bushing

specific creepage distance l is specified for each of the pollution levels indicated in Table 12.2. The minimum total creepage distance L is given by:

$$L = K_D U_r l$$

where:

K_D = diameter correction factor to increase creepage distance with average diameter of insulator D_m

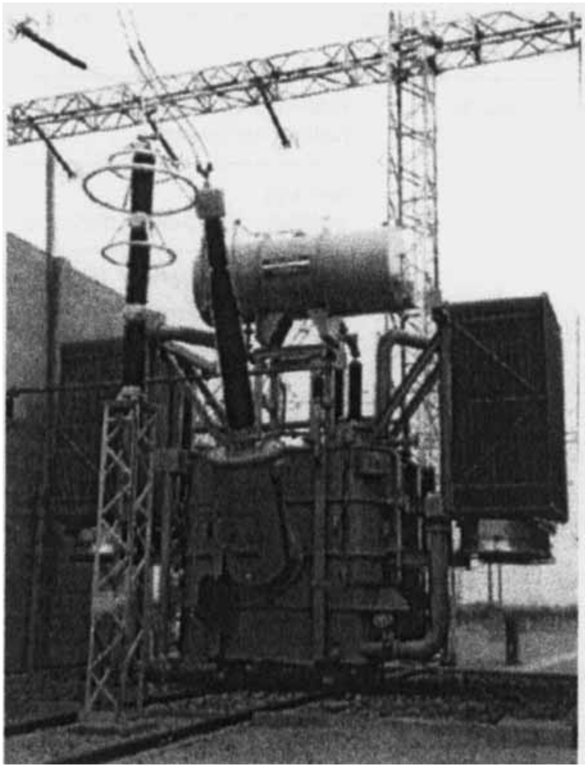

Figure 12.8 420 kV oil impregnated paper transformer/air bushing

$D_m < 300$ mm $\quad K_D = 1$
$300 < D_m < 500$ mm $\quad K_D = 1.1$
$D_m > 500$ mm $\quad K_D = 1.2$
U_r = Rated voltage of bushing (kV)

In certain desert areas, a combination of adverse climatic conditions, long periods without rain, frequent fog, sand storms, etc. has led to the accumulation of conductive pollutants and insulator flashover. To combat these conditions, enhanced creepage distances of 40 mm/kV or more have been specified.

Modern porcelain insulator designs generally use an alternate long/short (ALS) shed profile which gives superior performance to the previous antifog type. ALS profiles allow easier cleaning under natural rain and wind conditions and can be produced economically by modern turning techniques. Typical profiles are shown in Figure 12.9.

The manufacture of porcelain insulators is limited by the tendency to bend during firing if the piece has a high ratio (typically > 6) of height to bore. This is overcome by bushing manufacturers using epoxy adhesive to bond together several sections. The outdoor porcelain of a 420 kV

Table 12.2 Pollution levels, equivalent ambient severities and minimum specific creepage distance

Pollution levels and typical environments	Equivalent ambient severities (reference values)			Minimum specific creepage distance, l (mm/kV)
	Salt-fog method	Solid-layer methods		
	Salinity (kg/m^3)	Steam-fog	Kieselguhr	
		Salt deposit density (mg/cm^2)	Layer conductivity (μS)	
I Light – frequent winds and/or rainfalls – agricultural – mountainous (> 10 km from sea, no sea-winds)	5–14	0.03–0.06	15–20	16
II Average – industries without pollution smoke – dense housing with wind and/or rain, exposed to wind from sea but not too close)	14–40	0.1–0.2	24–35	20
III Heavy – high density of industries – suburbs of large cities (close to sea)	40–112	0.3–0.6	36	25
IV Very heavy – conductive dust, smoke – sea-spray, strong sea winds – desert	> 160			31

bushing may typically be assembled from three sections to give an overall height of 3.5 m with a height to bore ratio of approximately 10. The adhesive produces a high strength, oil-tight joint and the assembly is considered to be a single piece.

IEC 60815 [7] and IEC 60507 [8] are based primarily on the experience of overhead line insulators and limited testing of bushings and hollow porcelains. The performance of vertical insulators can be restricted due to flashover caused by water cascading over the shed; IEC 60815 therefore recommends a shed spacing of 30 mm and a creepage to clearance

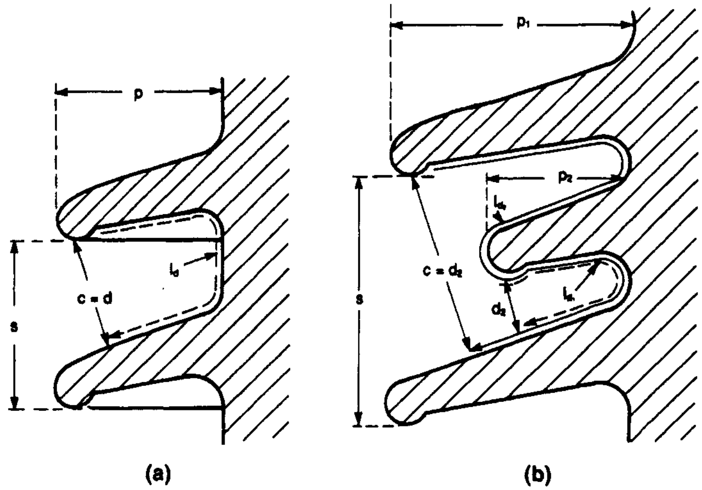

Fig 12.9 Typical porcelain insulator shed profiles
(a) *Normal sheds;* **(b)** *alternate long/short (ALS) sheds*

ratio (l_d/d) of less than 5. Insulators are normally designed for use in the vertical position; both specifications suggest that use horizontally would improve performance. Recent experience has shown this not to be the case [9] and it is now considered that an increase in creepage of 50% is necessary for horizontal use.

The application of composite insulators is limited at present due to concerns over durability. They have advantages over porcelain being lighter, explosion proof and having a greater hydrophobicity due to the nature of the silicone rubber moulded shed profile.

Having determined the height of the air side insulator (dimension *a*), the length of air side grading (dimension *b*) can be determined. It is not necessary to grade 100% of the air side insulator length; in practice 60% internal grading or less gives adequate surface grading for large bushings.

12.3.2 Oil end clearance

The oil side insulator (Figure 12.7, part 3) is usually a conical porcelain or cast resin shell. The internal axial grading over the condenser is dependent on the power frequency test voltage at a stress of approximately 12 kV/cm; this determines dimension *c*. It is normal that the oil side of a transformer bushing be conservatively stressed due to the consequences of a flashover within the transformer. Dimensions *b* and *c* together with the physical requirements of the mounting flange and current transformer determine the lengths l_l and l_n of the condenser.

12.3.3 Radial gradients

Whilst it is possible to design a bushing with a constant radial gradient, this can only be achieved at the expense of a variable axial gradient. In most cases a constant axial gradient is desirable and the radial gradient may be allowed to vary and will be a maximum at either the conductor or the earth layer.

The values are given as follows:

$$E_o = \frac{V(a+1)}{2\, a\, r_o \log b}$$

Earth layer stress

$$E_n = \frac{V(a+1)}{2\, a\, r_{n-1} \log b}$$

where $a = l_l/l_n$ and $b = r_n/r_0$.

E_0 is maximum when $a < b$ and E_n is maximum when $a > b$. A minimum insulation thickness is achieved when radial gradients at the HT layer and the earth layer are approximately equal, i.e. when $a = b$; however, this cannot always be achieved.

The radius r_0 is dependent on the current rating, the method of connection between the bushing and the transformer winding and on the bushing construction. An optimum value for r_n can then be calculated.

Having determined the limiting dimensions, the positions of the intermediate layers can be calculated. The detailed calculation method may vary but the object is to achieve acceptable radial stress on each partial capacitor and uniform axial stress, with the minimum number of layers.

Since, as stated, the axial gradient varies throughout the insulation thickness, the layer spacing for constant voltage per partial capacitor will also vary. In this way, a 420 kV bushing may contain about 70 layers.

12.4 Bushing applications

12.4.1 Transformer bushings

Transformers require terminal bushings for both primary and secondary windings. Depending on the system configuration the outer part may operate in air, oil or gas.

At distribution voltages up to 52 kV, noncondenser type bushings are generally used. In the case of dry-type transformers, the bushings form an integral part of the cast resin winding. With liquid insulated transformers, porcelain insulated bushings are commonly used for outdoor applications and cast resin for connections inside cable boxes or with separable connectors. These types of bushing are covered by the European standard HD506 [10].

Condenser-type bushings have been developed for rated voltages up to 1600 kV [11]. Transformer bushings are not exclusively of the OIP type. RIP and some RBP are used, particularly at ratings up to 245 kV. RIP has some advantages over OIP for certain applications.

In many cases, the flexible cables from the transformer winding are drawn through the bushing and terminated at the head of the bushing within the bushing tube. This 'draw lead' type of connection is limited to approximately 1250 A rating due to the dimensions of the flexible cable required. In cases of higher current ratings, connections may be made at the lower end of the bushing and the bushing tube itself used as the conductor as shown in Figure 12.10.

With RIP insulation the layers are embedded in a solid material of sufficient strength that there is no need for a supporting tube. In the case of draw lead connection using paper insulated cables, a transformer end stress shield is unnecessary, which allows a reduction in the transformer turret diameter.

The oil end of the bushing may take two forms: conventional or re-entrant type. The conventional type is considered above. From a comparison of the two forms shown in Figure 12.11, it can be seen that the re-entrant type is shorter and, as no stress shield is required, the transformer turret diameter can be reduced. The re-entrant form has been used extensively in the UK on power transformers but has been replaced by the conventional type. Re-entrant bushings cause difficulties with their installation. The transformer lead must be insulated with paper to approximately 30% of the service voltage and it is possible for gases to become trapped on the inner surface.

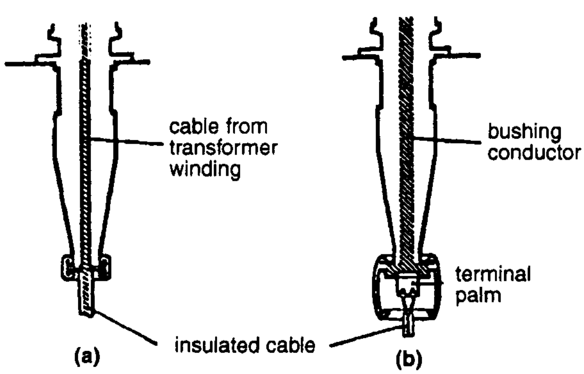

Figure 12.10 Transformer bushing connections
(a) *Draw lead type;* **(b)** *bottom connection type*

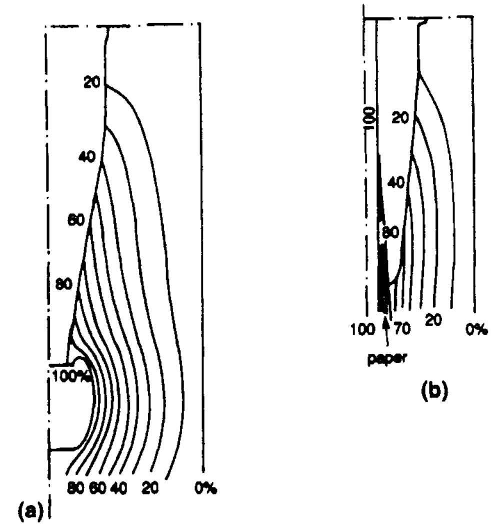

Figure 12.11 *Field plots of the transformer side of HV bushing connections* **(a)** *Conventional type;* **(b)** *re-entrant type*

At the mounting flange of the bushing a connection to the last layer of the condenser is brought through a test tapping. This tapping is used during partial discharge and capacitance measurement of the bushing and the transformer. As the capacitance of the tapping is low it is essential that it is connected directly to earth when in service to prevent generation of high voltage and sparking at the tapping terminal. In certain cases, particularly in North America, a potential tapping may be required. In this case, extra layers are included in the winding to provide a capacitance voltage divider. This type of tapping has high capacitance compared to the main bushing and can be used in service, connected to a bushing potential device, to provide a voltage source of up to 5 kV and an output power, typically 100 VA. This power may be used to supply relays and measuring equipment.

12.4.2 High current bushings

Bushings used on the low voltage side of generator transformers require special consideration due to their operating condition. Bushings of this type are often required to operate with their outdoor side enclosed in a phase isolated bus duct. This arrangement can produce ambient air temperatures as high as 90 °C around the bushing, differing greatly from the standard conditions. It is essential that the bushing and the connections are designed to reduce conductor losses and dissipate heat efficiently. At service currents of up to 40 kA, local heating due to poor connections can cause serious damage. To facilitate cooling, a multi-palm configuration is often used at the end terminals. Figure 12.12 shows an RIP condenser type bushing having an aluminium conductor. However, copper conductors and noncondenser types are also widely used.

Where low voltage, high current bushings are mounted in close proximity, consideration should be made of distortion of the current path in the bushing due to magnetic effects.

12.4.3 Direct connection to switchgear

Owing to advantages of space saving given by gas insulated switchgear (GIS) operating with gas (usually sulphur hexafluoride SF_6) at a pressure

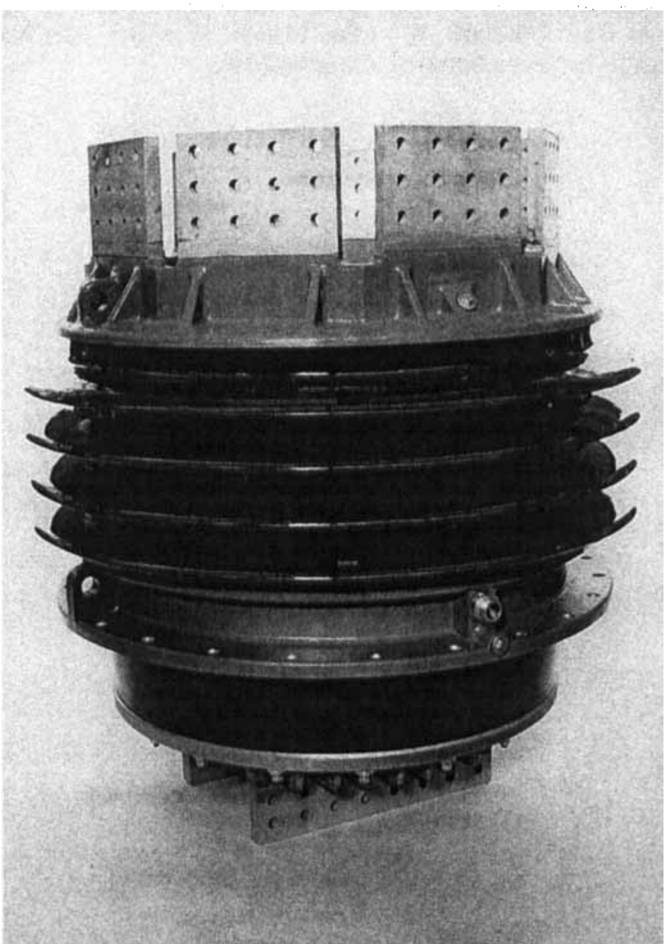

Figure 12.12 36 kV 31500 A resin impregnated paper transformer/air bushing

of about 4 bar(g), it is increasingly common for transformers and switchgear to be directly connected. Direct connection also reduces pollution problems in coastal and industrial areas, giving increased system reliability. Oil to gas bushings, used to provide the interconnection, generally have a double flange arrangement for connection to the transformer turret and the GIS duct. The bushing design therefore needs to be flexible to cater for the requirements of different equipment manufacturers. To reduce problems of interchangeability, IEC 61639 [12] gives dimensions for the gas side of the bushing, in particular the flange fixing and gas end terminal dimensions.

It is important that escape of gas from the GIS is minimised. Precautions must be taken with the bushing design to effectively seal the conductor and flange interfaces to prevent leakage of gas into the transformer. Figure 12.13 shows typical arrangements where double seals are provided at each position, the effectiveness of which can be tested by applying high pressure between the seals [13].

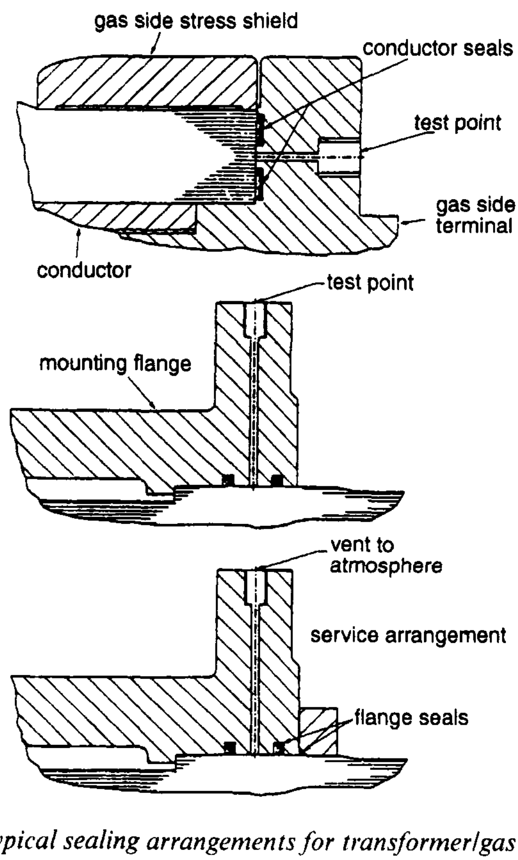

Figure 12.13 Typical sealing arrangements for transformer/gas bushings

RIP bushings provide an ideal solution (Figure 12.14), and are available up to 525 kV. Because of the gas-tight nature of the insulation an additional porcelain shell is unnecessary. The dry insulation can be mounted at any angle without any need for oil expansion devices as would be required with OIP. The high electric strength of the resin also allows reduced axial dimensions, particularly of the gas part.

Electrical tests for oil to gas bushings require special arrangements. The gas side is tested in gas instead of oil to prevent contamination of the bushing seals and the gas duct in service. Draw lead type bushings are generally not used as the risk of leakage of gas through this site-made joint would be undesirable.

12.4.4 Switchgear bushings

Entrance bushings for high voltage gas insulated switchgear often utilise pressurised porcelain. The gas within the bushing is common with the duct. Stress control is achieved by profiled electrode screens between the flange and the conductor. The porcelain must be dimensioned to withstand the full pressure of the system and presents an obvious danger if damaged in service. An improvement of this technique is the so-called 'double pressure' bushing where a glass reinforced plastic tube is used as a liner and the gap between the tube and porcelain is at reduced gas pressure.

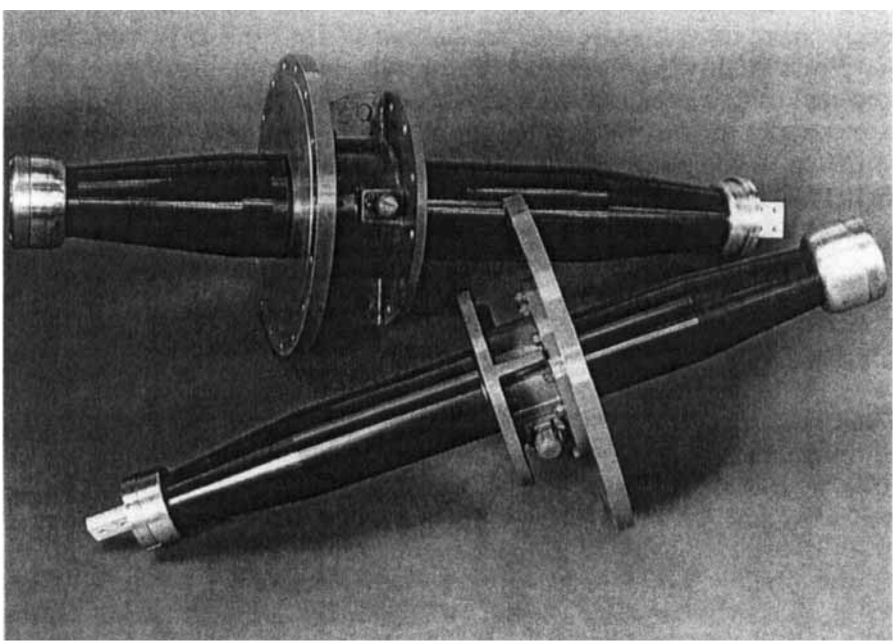

Figure 12.14 Resin impregnated paper transformer/gas bushings

RIP gas to air bushings have been manufactured up to 525 kV. The RIP condenser seals the GIS and the porcelain may be filled with a compound material or gas at low pressure. This enables a lightweight porcelain to be used and operation at any angle without modification. Developments of this type of bushing are being made to replace the porcelain by a composite insulator or to mould silicone rubber sheds directly onto the RIP surface. As the gas side may be used directly into, or close to, a circuit-breaker, the components of the bushing must exhibit resistance to the decomposition products of SF_6, particularly hydrogen fluoride (HF). This can be achieved by coating the RIP with a special alumina-rich varnish.

Gas insulated bushings with composite weathershell have also been developed. The gas filling of this type of bushing is generally common with the GIS (Figure 12.15). Stress control is achieved by internal profiled electrodes which screen the mounting flange and improve stress distribution over the insulator. The selection of the type of rubber and the shed form is important to achieve good performance under polluted and heavy wetting conditions. Different methods are used in the manufacture of the composite insulator which use room temperature or high temperature vulcanised silicone rubbers applied by moulding or continuous extrusion techniques. The performance of each is different and must be carefully assessed in relation to the site condition.

In GIS, very fast transients (VFTs) generated by disconnecter switching are recognised to present a problem to the internal connection bushings. Owing to the speed of propagation of the VFT, it is possible to develop a high voltage between the conductor and the first layer of the condenser. At present, no test exists within IEC 60137 [1] to demonstrate acceptability of the bushing design. However, tests have been proposed which apply lightning impulse chopped within the gas duct at approximately 70% of the rated BIL.

12.4.5 Direct current bushings

Direct current bushings require special consideration. HVDC schemes are becoming increasingly popular for the transmission of power over long distances and also for the connection of separate AC networks. These so-called back-to-back schemes may be used on systems of different frequency and asynchronous operation or to increase operational stability. Such systems operate at typically ± 80 kV DC while long distance transmission occurs at up to ± 600 kV DC.

The design of a DC bushing is influenced by the resistivities of the various materials used as opposed to their permitivity in the AC case. While permittivities of paper, oil, porcelain, etc. are of a similar order, their resistivities vary by up to 10 000: 1. It is therefore important to study the voltage distribution in the core and the surrounding area [14].

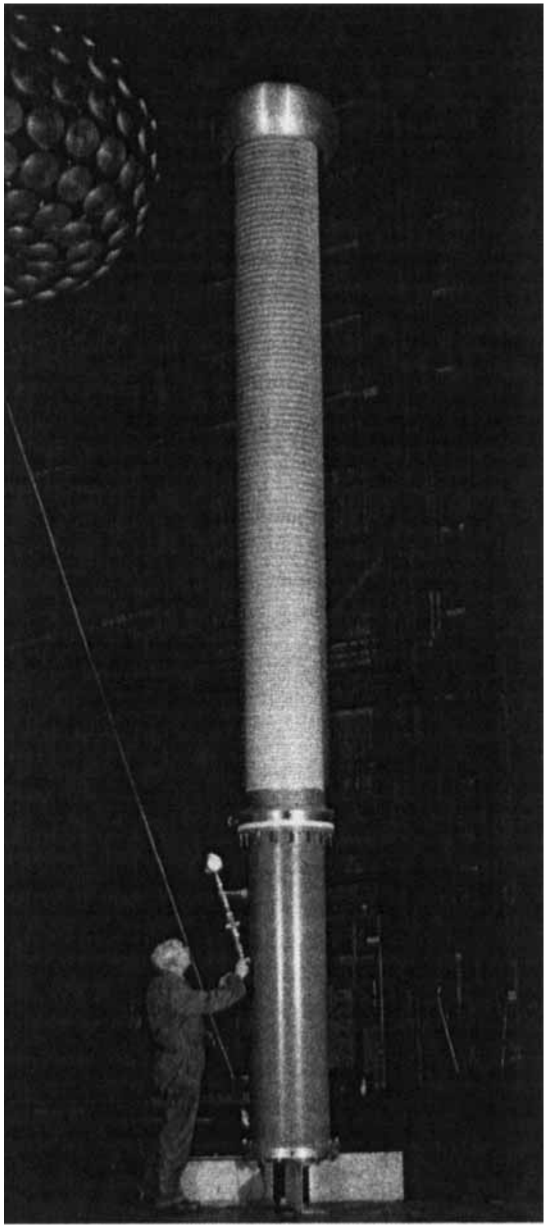

Figure 12.15 Composite gas insulated GIS/air bushing

The effect on field distribution is shown in Figure 12.16. The upper plot shows the AC field in a typical oil-impregnated paper transformer bushing. A concentric field is produced in the oil between the paper insulated stress shield and the transformer turret wall. In the centre plot, the DC

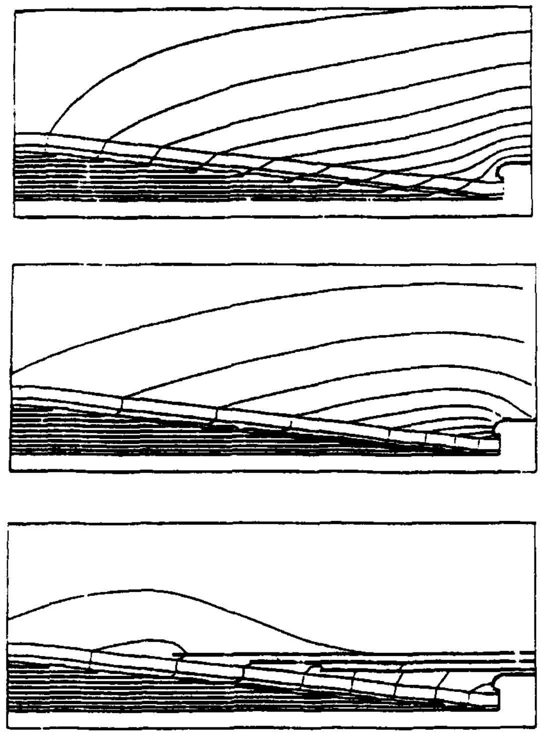

Figure 12.16 Field plots of HVDC bushings

field of the same arrangement is illustrated, where the high resistivity of the paper, compared to that of oil, concentrates the stress in the shield insulation. To reduce this stress concentration and the stress of the surface of the porcelain, concentric cylinders of pressboard are placed around the bushing. This technique is illustrated in the lower plot. In the practical case a greater number of cylinders and conical barriers may be required to achieve suitable stress control. As the resistivity ratios vary with temperature, studies of the field are made across the operating range of the transformer. It is important therefore that the transformer and bushing manufacturers co-operate in this detail of the design.

In a DC scheme, pollution and fire risks are a major concern. To reduce both, bushings have been developed to operate horizontally to project directly into the convertor building. Alternative solutions are contrasted in Figure 12.17, which are comparable to the situations at EdF Les Mandarin and at NGC Sellindge, respectively, at either end of the 280 kV DC Cross-Channel Link. In France, more conventional OIP bushings are used in the transformer connected to the convertor equipment by dry type RIP wall bushings.

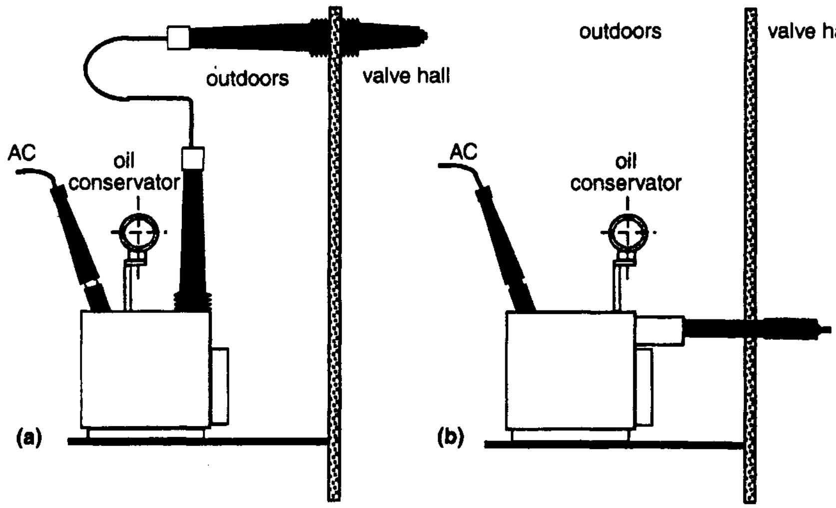

Figure 12.17 *Alternative arrangements for convertor transformers*
(a) *Outdoor bushings;* **(b)** *through-wall transformer bushings*

At Sellindge, due mainly to space restrictions, horizontally mounted through-wall bushings were used on the convertor transformer. These are dry type RIP bushings and, being indoors, require no porcelain weather shell and admit no oil to the building. Figure 12.18 shows a 215 kV convertor transformer manufactured by Alstom Transformers, Stafford, UK for the Chandrapur back-to-back scheme in India. The bushings shown are RIP type, mounted in service as Figure 12.17*b*. The through-wall bushing is designed to plug into the transformer insulation system which houses a special spring loaded current contact which also caters for tolerances within the transformer construction.

In DC schemes pollution induced flashovers [15] have occurred and, where mounted close to a building, nonuniform wetting of bushing insulator has caused problems. Where a polluted insulator is partially protected from rainfall by the building, the difference in surface resistivity in the dry and wet parts reduces the flashover voltage. Various methods of improvement using booster sheds [16] and improving hydrophobicity of the insulator [17] surface have been examined.

12.5 Testing

Adequate testing is essential to ensure reliable operation over the required service life. Routine and type tests are performed in accordance with IEC 60137 [1] and IEC 60060 [18]. Figure 12.19 shows a transformer bushing installed in an oil-filled tank being prepared for test.

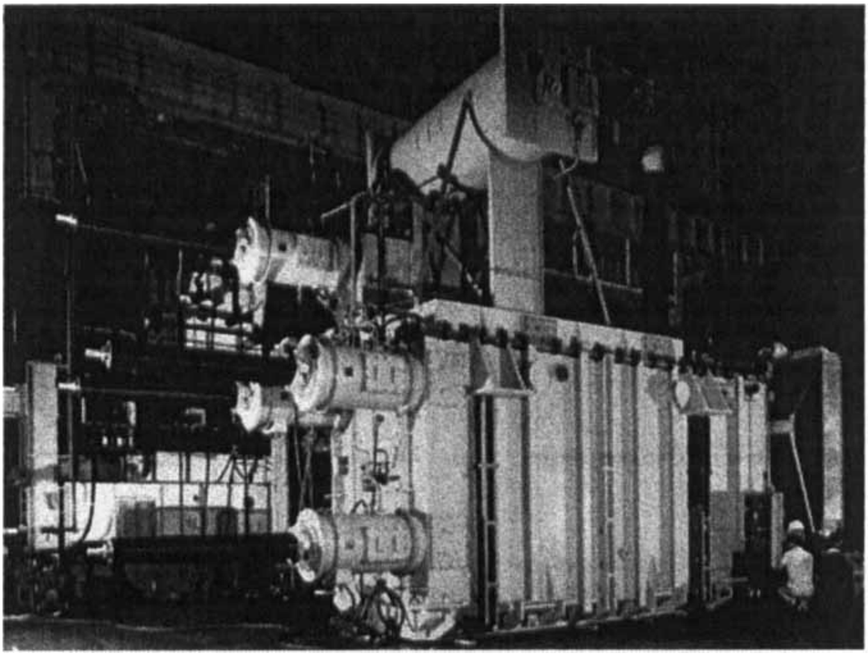

Figure 12.18 210 kV DC 2500 A resin impregnated paper bushings

12.5.1 Capacitance and dielectric dissipation factor measurement

This test is probably the most universally applied of all tests on high voltage bushings and insulation systems. Measurements are made by Schering Bridge, or similar equipment, and give an indication of the quality of the bushing processing. Dissipation factor, or tangent delta, is identical in value to power factor in the range of values obtained. Tangent delta is a measure of the losses in the insulation and can indicate the degree of cure of resinous materials or the moisture content of RBP and OIP. The typical tangent delta/voltage curve for a correctly processed bushing is flat up to at least rated voltage. An increase in tangent delta, particularly below working voltage, would almost certainly cause deterioration in service, due to increased dielectric losses or internal partial discharge.

12.5.2 Power frequency withstand and partial discharge measurement

Although classed as separate tests, power frequency withstand and partial discharge are often combined. Partial discharge is a major cause of failure in bushings and, as discussed earlier, may occur in voids, cavities

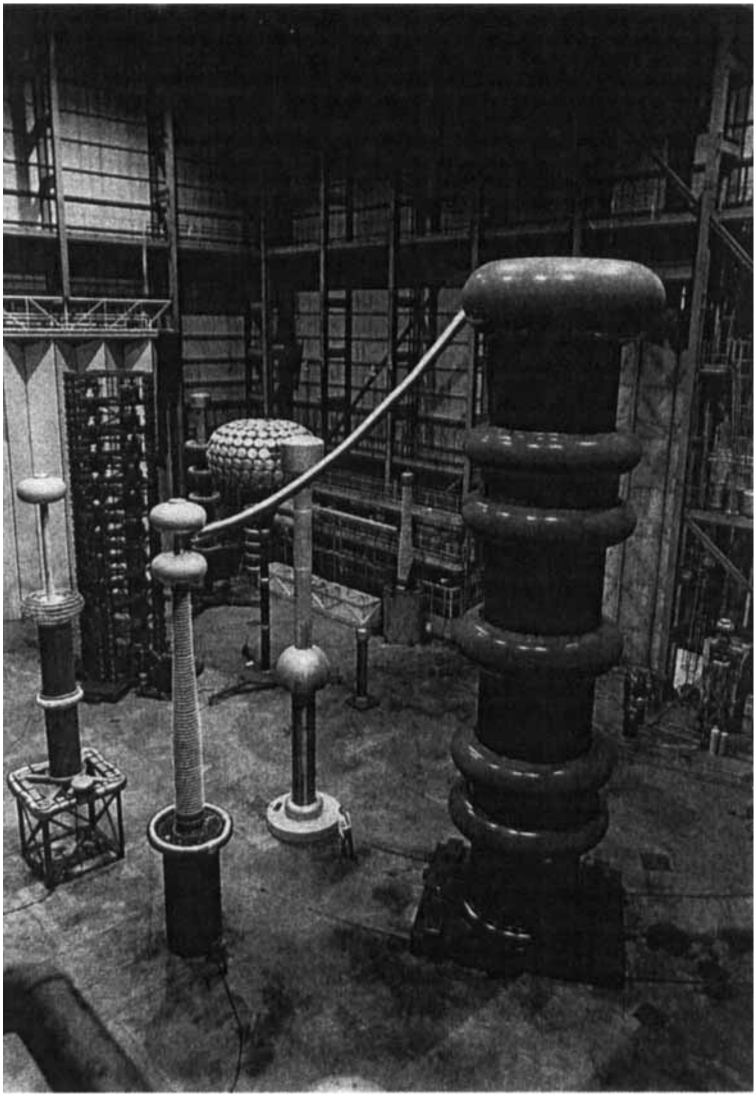

Figure 12.19 Bushing tests at BSTS Clothier Laboratory

or inclusions in solid or liquid impregnated insulation and surface discharges at material boundaries.

In earlier times, an audible 'hissing' test was used to assess the quality of RBP insulation. A trained ear could detect discharge of about 100 pC. RBP bushings with this limit of discharge at 1.05 $U_r/\sqrt{3}$ have given years of satisfactory service and this limit has been retained in recent specifications.

Discharges have a more damaging effect on OIP and a limit of 10 pC at 1.5 $U_r/\sqrt{3}$ is agreed. In general, well processed OIP and RIP insulation are free from detectable discharge at this level. Modern discharge detection equipment has been developed to improve the sensitivity of the measurement. Most systems monitor current from the bushing test tapping and display on an oscilloscope in the form of an ellipse. Partial discharges appear as pulses, the magnitude of which can be compared to a calibrated pulse. Much work has been published on partial discharge interpretation [19, 20]. From the position of the discharge pulse on the ellipse, it is possible to recognise certain types of fault. When combined with the routine power frequency withstand test, normally applied for 1 min, the stress dependence of any discharge can provide further information on the discharge site. Researchers have shown that potentially damaging voids in a GIS spacer insulator may be undetected by conventional discharge measuring techniques. A system has been developed [21] that uses X-ray scanning to reduce the discharge inception voltage, increase sensitivity and locate the discharge source. This technique, known as X-ray induced partial discharge (XIPD) detection, may find use in the testing of RIP bushings where void location is important; however, safety in the industrial environment is essential.

For transformer bushings, changes have been made in the latest revision of IEC 60137 [1] so that bushing withstand tests should be carried out at 10% above that of the transformer for which they are destined. In some cases, transformer manufacturers specify bushings co-ordinated one level above the transformer to avoid the possibility of internal fault during transformer test and the ensuing cost of rebuild.

12.5.3 Impulse voltage tests

Lightning and switching impulses represent transients occurring naturally in a high voltage system under operation. Tests with impulse voltage are designed to demonstrate the response of equipment to transients over a wide frequency range. Dry lightning impulses are applied to all types of bushing as a type test and wet switching impulse tests on bushings above 300 kV rating. Fifteen impulses of positive polarity and 15 impulses of negative polarity are applied to the bushing during type test. As the internal insulation is considered non-self-restoring, a maximum of two flashovers are allowed in air external to the bushing insulator with no internal fault permitted. To ensure that transformers, complete with bushings, can be safely subjected to impulse test, it is increasingly common for dry switching and chopped lightning impulses to be applied to bushings as a routine test. Negative lightning impulse tests have been carried out routinely by some bushing manufacturers for a number of years, and this has now been incorporated in IEC 60137 for bushings rated 300 kV and above. During impulse testing it is common to measure the current flowing through the bushing by a low resistance shunt in the tapping earth connection; this gives greater sensitivity in the detection of partial breakdown of the insulation.

12.5.4 Thermal stability test

This test is particularly applicable to bushings for transformers of rated voltage above 300 kV and is intended to demonstrate that the dielectric losses do not become unstable at the operating temperature. The test is carried out with the bushing immersed in oil heated to 90 °C. A voltage is applied equal to the maximum temporary overvoltage (usually $0.8U_r$) seen by the bushing in service. By continuously measuring the capacitance and tangent delta of the bushing, the dielectric losses are calculated. Should the bushing be incapable of dissipating these losses, the tangent delta would increase and thermal runaway would occur, resulting in breakdown of the insulation.

Because of the inherently low value of tangent delta of OIP and RIP bushings, thermal stability is not normally a problem. In certain applications, such as oil to gas bushings where the cooling is restricted, special attention should be paid to thermal stability.

It is the intention of the specification IEC 60137 that dielectric and conductor losses be applied to the bushing simultaneously. This is not always possible due to design restrictions of the bushing, and conductor losses are considered separately during the temperature rise test.

12.5.5 Temperature rise test

This test is intended to demonstrate the ability of the bushing to carry rated current without exceeding the thermal limitations of the insulation. OIP and RIP are restricted to a maximum temperature of 105 °C and 120 °C, respectively. The higher thermal rating of the RIP material does not necessarily mean that smaller conductors can be used. RIP is a good thermal insulant and the design of OIP bushings more readily allows cooling of the conductor by convection within the oil of the bushing. The service condition of different types of bushing, particularly high current bushings used in phase isolated bus ducts, must be carefully considered. In a typical test, a bushing achieved a rating of 10 kA under the standard test conditions laid out by the specification, while with an increased ambient air temperature, equivalent to the duct, the maximum current was reduced to 7 kA. This causes obvious difficulty in the specification and use of this type of bushing.

12.5.6 Other tests

In addition to the major electrical tests discussed, tests or calculations are usually required to demonstrate the suitability of the bushing. These include the following:

1. leakage tests, resistance to leakage by internal or external pressure of oil or gas
2. cantilever test, demonstration of the ability of the bushing to withstand forces imposed by connections, short-circuit, self-loads, etc.
3. seismic withstand, usually demonstrated by static calculations, the effect of the stiffness of the equipment to which the bushing is mounted is also important. Guidance on the seismic qualification of bushings is given in IEC 61463 [22]. This report proposes methods of calculation and test. In parts of the USA utilities have prohibited or restricted the use of porcelain insulators due to potentially hazardous seismic damage and have imposed the use of composite insulation with strict testing. Figure 12.20 shows such a bushing on a shaker table.

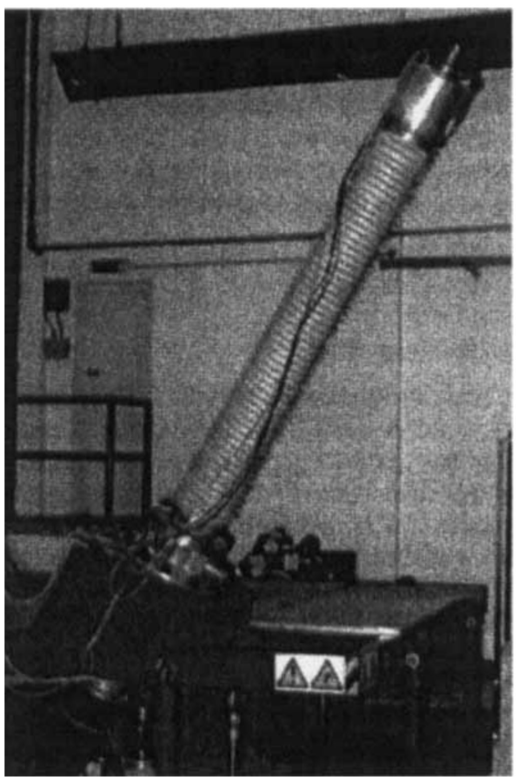

Figure 12.20 Seismic withstand test on 245 kV OIP composite bushing

4. short-circuit, again usually demonstrated by calculations, given in IEC 60137, to prove adequate thermal capacity to prevent overheating and insulation damage during short-circuit events.

12.6 Maintenance and diagnosis

Bushings are hermetically scaled devices generally operating in service under low electrical and mechanical stress. Ingress of moisture, however, due to gasket defects, is a major cause of insulation deterioration. Internal partial discharge can result from moisture ingress, system overvoltages or inadequate stress control. External contamination build-up and the risk of pollution flashover can be reduced by periodic washing or the use of silicone rubber or grease coatings.

Dielectric diagnosis techniques can be applied to installed bushings [23]. On-line infra-red scanning and radio influence voltage (RIV) measurement can detect thermal problems and corona. Off-line measurement of capacitance and tangent delta can be made on bushings and compared with factory results and other similar equipment. Information on bushing insulation should include ageing, moisture content and condenser breakdown.

A continuous tangent delta monitor for on-line transformer bushings has been developed [24, 25]. Signals derived from test tappings on all bushings within a substation are compared and abnormal changes activate an alarm. The system is claimed to be cost-effective in high-risk situations. Transformer manufacturers now offer integrated packages for on-line monitoring of power transformers; these use the bushing tapping as a voltage source and partial discharge sensor [26].

With OIP insulation, dissolved gas analysis (DGA) offers an established technique for the assessment of insulation condition. Most published work refers to transformer insulation [27, 28] comparing the relative concentrations of fault gases. DGA information specific to OIP type bushings is given in IEC 61464 [29]. This report was compiled by bushing experts based on information from bushings in service. Guidance is given on the significant level of fault gases, interpretation of typical faults and recommendations for action (see Tables 12.3 and 12.4).

Today the trend is for the development of on-line diagnosis techniques to minimise the need for periodic line diagnosis in assessing insulation condition and thereby predicting fault development and extending equipment life.

Table 12.3 Typical faults occurring in bushings

Case no.	Key gases generated	Typical examples	Characteristic faults
1	H_2, CH_4	Discharge in gas filled cavities resulting from incomplete impregnation or high humidity	Partial discharge
2	C_2H_4, C_2H_2	Continuous sparking in oil between bad connections of different potentials	Discharge of high energy
3	H_2, C_2H_2	Intermittent sparking due to floating potentials or transient discharges	Discharge of low energy
4	C_2H_4, C_2H_6	Conductor overheating in oil	Thermal fault in oil
5	CO, CO_2	Overheating of conductor in contact with paper: overheating due to dielectric losses	Thermal fault in paper

Table 12.4 Normal gas concentrations

Type of gas	Concentration, μl gas/l oil
Hydrogen (H_2)	140
Methane (CH_4)	40
Ethylene (C_2H_4)	30
Ethane (C_2H_6)	70
Acetylene (C_2H_2)	2
Carbon monoxide (CO)	1000
Carbon dioxide (CO_2)	3400

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