Fundamentals of condenser bushings

Bushing is a device that enables one or several conductors to pass through a partition such as a wall or a tank, insulating the conductor from it

ABSTRACT

This article focuses on the concept of capacitance-graded, i.e. condenser bushings – both oil-impregnated and resin-impregnated paper bushings – for extra-high voltage transformers. After a description of the dielectric loss, the article goes on to describe the selection, testing, transportation, storage and installation of these bushings, so as to avoid a bushing failure which may lead to a catastrophic failure of transformers.

KEYWORDS

oil-impregnated paper bushings, resin-impregnated paper bushings, dielectric loss

1. Introduction

The bushing is a device enabling one or several conductors to pass through a partition such as a wall or a tank, insulating the conductor from it. In this case the tank refers to the tank of the EHV transformer [1].

Various type of bushings for different applications are defined in IEC-60137 [1] and IS: 2099 [9]. However, for extra-high voltage (EHV) power transformer applications (66 kV and above), different types of external media matter are used with the lower end dipped in oil inside the transformer main tank.

There are three types of bushings generally used in EHV transformer applications:

- Oil-to-air type – used for installations in outdoor substations, i.e. air-insulated substations (AIS),
- Oil-to-SF6 gas type – used in gas-insulated indoor substations (GIS) and in hybrid substations[1],
- Oil-to-oil type – used for oil-filled cable boxes to receive cables.

The condenser-type bushings include oil-impregnated paper (OIP) bushings and resin-impregnated paper (RIP) bushings. They have proved their superiority over the synthetic resin-bonded paper (SRBP

[1] A hybrid substation is a substation having both an indoor portion containing EHV equipment in SF6 gas enclosures, and an outdoor portion. This type of substation is constructed where space is a constraint for further expansion of the substation.

or RBP) bushings by meeting stringent partial discharge (PD) requirement as stipulated in IEC-60137 for the bushings for EHV transformers [1].

There are three types of bushings generally used in EHV transformer applications: oil-to-air, oil-to-SF6, and oil-to-oil type

2. Conceptualizing capacitance-graded (condenser) bushings

Equipotential gradient is illustrated by considering an example of five capacitors C_1, C_2, C_3, C_4, and C_5, each of 20 nF, connected in series to a 250 V supply with reference to the earth, Fig. 1, and by applying the equation (1):

$$\frac{1}{C_t}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\frac{1}{C_4}+\frac{1}{C_5} \qquad (1)$$

$$\text{Therefore, } C_t=\frac{20}{5}=4\ \text{nF}. \qquad (2)$$

In turn, the voltage developed against each capacitor is as follows:

$$\frac{250}{5}=50\ \text{V} \qquad (3)$$

The equipotential of 50 volts is maintained in the descending order from 250 volts to 0 volts (earth potential).

2.1 The concept of condenser bushings

The condenser bushing is conceptualized applying the principle of a uniform potential gradient/grading of the electric field from the live EHV conductor to the fixing flange of the transformer which is at the earth potential, through series capacitors.

The OIP/RIP bushings are manufactured with great precision maintaining equal capacitances between each cylindrical condenser, formed between two co-axial aluminium-foil cylinders encircling the bushing central pipe/rod over the layers of cellulose paper (superior grade kraft paper) wrappings. The kraft paper is dried by heated cylinders until the water content is reduced to a maximum of 1 %. The condensers thus formed are in series. The number of series condensers of equal capacitances is decided using computer-aided design, maintaining an equal potential gradient from the central tube/rod at high voltage to the bushing flange at the earth potential. The condenser core is built by wrapping the superior grade kraft paper between aluminium foils, and this is performed in a dust-free chamber subjected to a high degree of vacuum (0.005 mm) and then impregnated with degassed transformer oil in case of OIP bushings, or with epoxy resin in case of RIP bushings. They are finally assembled by being encapsulated under pressure in hollow cylindrical glazed porcelain bushings having appropriate creepage distance through the rain sheds/petty-coats and other necessary fittings and accessories.

The concept of the equipotential gradient from the live conductor to flange at the earth potential through cylindrical condensers formed as condensers in series, as explained above, is shown in Figure 2(a) [3], along with the formula expressing the calculation of the potential gradient E_x at any distance x from the centre of the central tube, shown in Figure 2(b) [4].

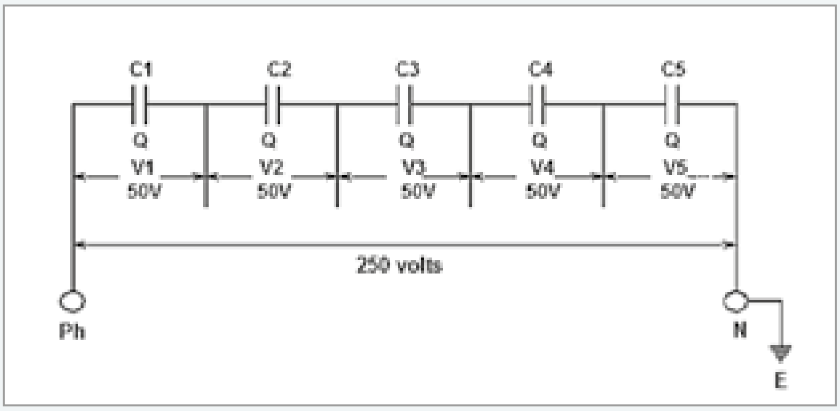

Figure 1. A specimen circuit of capacitors, each of 20 nF, connected in series

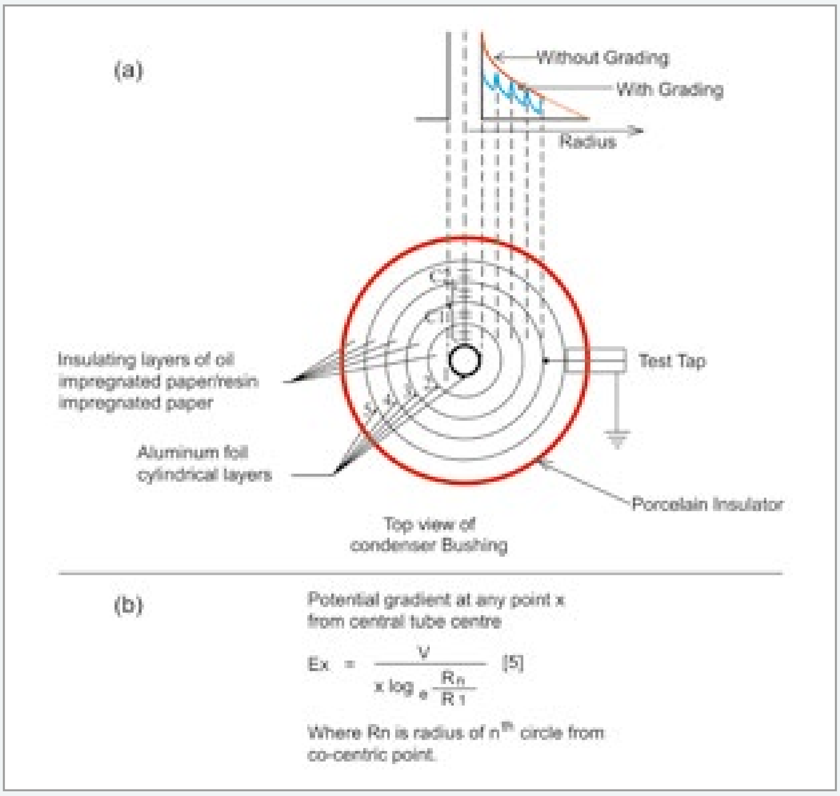

Figure 2. (a) The concept of potential graded condenser bushings [3]; (b) calculation of the potential gradient E_x at a distance x from the centre of the cylindrical tube/rod of the bushing [4]

The graded bushing has a more uniform distribution of potential as compared to that of the ungraded bushing

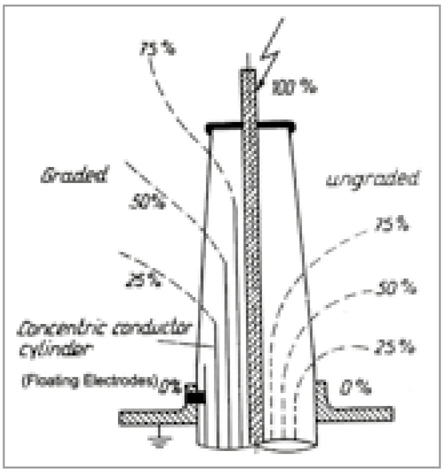

Figure 3. Comparison of potential distribution in graded and ungraded bushings [5]

The voltage distribution of graded and ungraded bushings is illustrated in Figure 3. The distribution of potential in the graded bushing from 100 % voltage to 0 % voltage is uniform as compared to that of the ungraded bushing. The graded bushings control the field longitudinally (axially), resulting in ultimate reduction in diameter of the bushing, unlike that of the ungraded bushing, which needs larger diameter (i.e. increase in volume to accommodate more insulating material) and becomes bulky for the same voltage class.

2.2 Definitions and significance of C_1, C_2 and tan δ

Locations of C_1 and C_2 in a condenser bushing are illustrated in Figure 4. The significance of measurements of tan δ and capacitances is mentioned hereunder:

- C_1 is the total capacitance of all the capacitors formed from the central conductor to the test tap
- tan δ (the dissipation factor) is the measure from the central tube/conductor of the condenser bushing to the test tap
- C_2 is the capacitance between the test tap and the flange of the bushing (at earth potential)

The abovementioned two measures of C_1 and tan δ are benchmark measurements for assessing the quality of insulation of the condenser bushing.

When the test tap cover is closed, C_2 is connected in series with C_1 to form the total capacitance of the bushing from the central conductor to the fixing flange on the turret. The flange, in turn, is earthed on the top cover of the transformer which is kept at the earth potential.

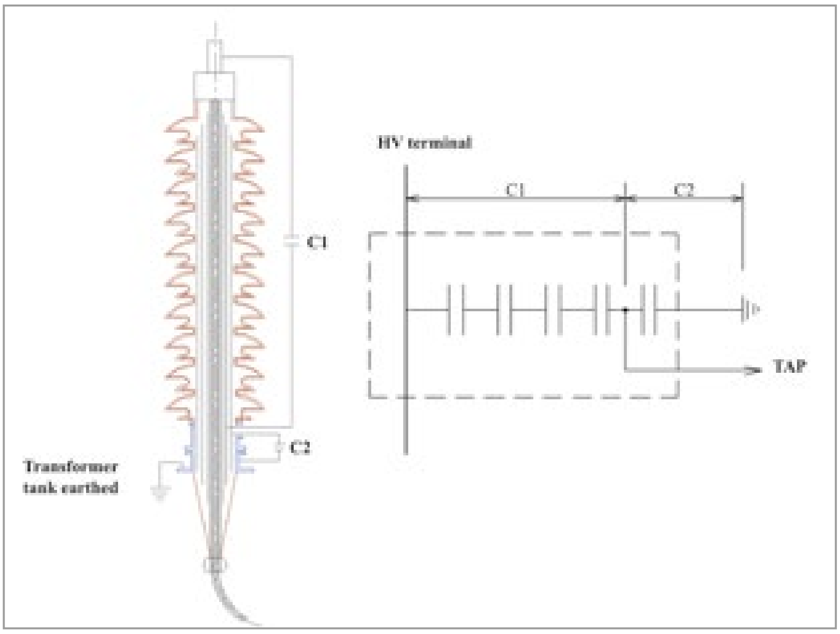

Figure 4. C_1 is the total value of the capacitors in series from the central rod/tube to test tap and C_2 is the total value of capacitors from test tap to the bushing flange

2.3 Effects of a series capacitor failure

If assumed that C_1, C_2, C_3, C_4 have capacitances of 100 pF each, as shown in Figure 5, by applying the equation (1) the following is obtained:

$$\frac{1}{C_t} = \frac{1}{100} + \frac{1}{100} + \frac{1}{100} + \frac{1}{100} = \frac{4}{100} \qquad (4)$$

Therefore, the total capacitance is:

$$C_t = \frac{100}{4} = 25\ \mu\text{F} \qquad (5)$$

If one of the capacitors is shorted, for example C_3, based on the equation (4) the following can be obtained:

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{x} + \frac{1}{C_4} = \frac{3}{100} \qquad (6)$$

Therefore: $$C_t = \frac{100}{3} = 33.33\ \text{pF} \qquad (7)$$

So, it can be established that total capacitance will increase if one or more of the capacitors in series get shorted.

3. Dissipation factor tan δ

The measurement of the dissipation factor signifies the quality of the insulating material. It is defined as the ratio of the current through the impurity seen as the resistance to the current through the original capacitance of the condenser bushing. In other words, any increase in the dissipation factor tan δ is an indication of deterioration of its original insulating quality. The significance and the phasor representation of tan δ in reference to the construction of condenser bushings, see section 2.1 and Figures 2(a) and 4, is explained as follows.

The angle δ is the loss angle and the tan δ is the loss factor (dissipation factor).

In an AC voltage circuit, when a sinusoidal voltage is applied across an ideal capacitor, the capacitive current leads the applied voltage by 90° (i.e. $I_C = \omega CV$). Impurities, if any, developed in the capacitor act as a resistor in parallel. The current I gets divided into two parallel paths, one through the capacitor and the other through the resistor (impurity). They are indicated as I_C and I_R, respectively, Fig. 6.

As per the phasor diagram, the current

> **C_1 and tan δ are benchmark measurements for assessing the quality of insulation of the condenser bushing**

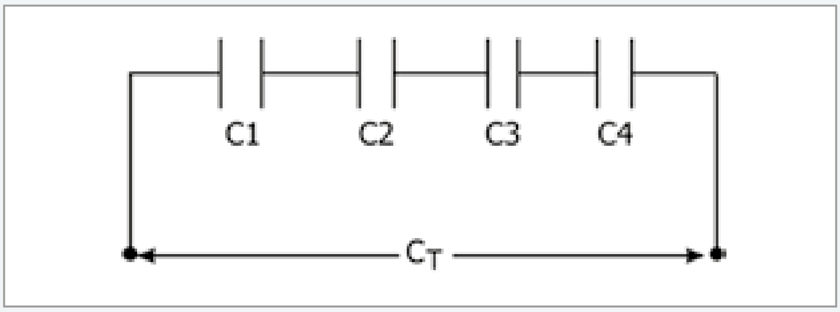

Figure 5. Equal capacitors in series

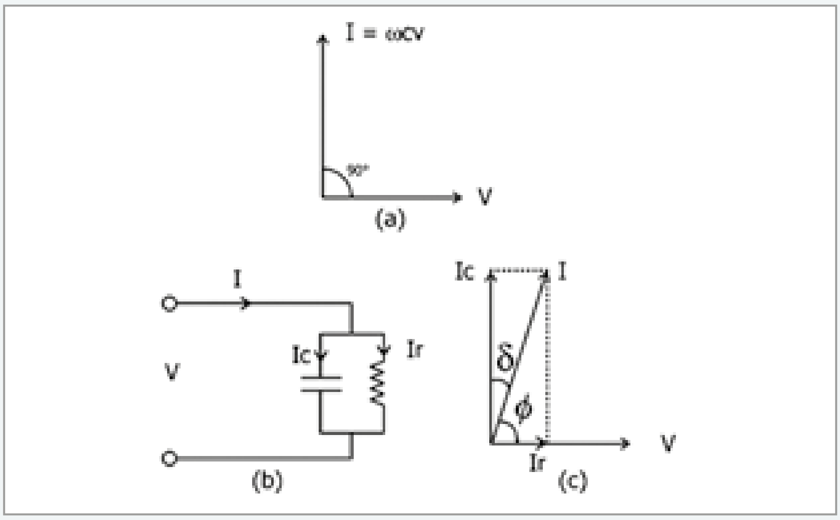

Figure 6. The loss angle δ = 90 - ϕ is the angle between the phasors I_C and I

phasor I no longer leads the voltage phasor V by 90°, but rather by $\phi°= 90° - \delta$.

Therefore: $I_C = I{\cdot}\cos\delta$, $\omega CV = I{\cdot}\cos\delta$ (as $I_C = \omega CV$)

$$\text{Thus, } I = \frac{\omega CV}{\cos\delta} \quad (8)$$

$$\text{Dielectric loss} = V{\cdot}I{\cdot}\cos\phi = V{\cdot}I{\cdot}\sin\delta = V{\cdot}\frac{\omega CV}{\cos\delta}\sin\delta \quad (9)$$

$$\text{Dielectric loss} = \omega CV^2 \cdot \tan\delta \quad (10)$$

where,

$$\tan\delta = \frac{I_R}{I_C}$$

In view of (8), (9) and (10), the following can be inferred:

- Increase in tan δ value is an indication of deterioration of the insulation.
- Increase in C takes place when either moisture ingresses into the insulation or some of the condensers get shorted.
- Dielectric loss is directly proportional to tan δ, C and square of the voltage as $\omega = 2\pi f$, where f (frequency of a power system) normally does not vary sharply; therefore, ω is considered to be constant.

4. Dissipation factor vs. power factor

Dissipation factor tan δ is used in European and Asian countries, including India, whereas in the U.S., Canada and some other countries power factor cos ϕ is used to specify the power losses in the insulation [6].

$$\tan\delta = \frac{\text{PF}}{\sqrt{1+\text{PF}^2}} \text{ and PF} = \frac{\tan\delta}{\sqrt{1+\tan^2\delta}} \quad (11)$$

A sample comparative calculation using the formula $\tan\delta = \frac{\text{PF}}{\sqrt{1+\text{PF}^2}}$ is:

a) for PF = 0.4; tan δ = 0.371
b) for PF = 0.5; tan δ = 0.447

In other words, tan δ is directly proportional to the power factor, and if PF increases, tan δ shall also increase. It can be observed that there is a very minor difference between the values of tan δ and the power factor.

5. Selection of bushings

5.1 Main parts of an OIP bushing

The main parts of an OIP bushing are illustrated in Figure 7a.

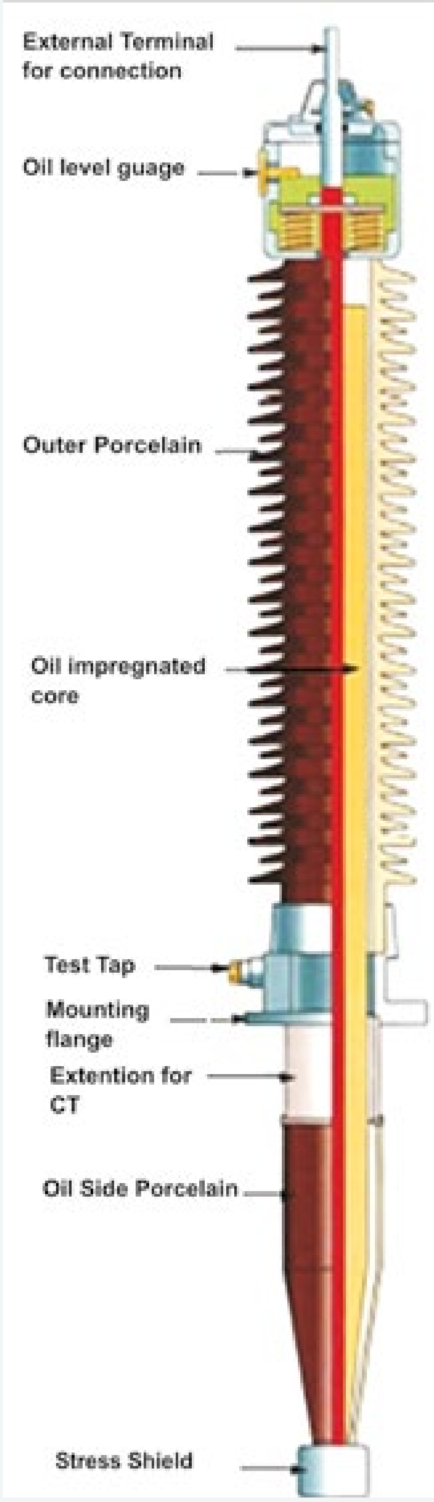

Figure 7a. Components of a condenser bushing [7]

The total capacitance will increase if one or more of the capacitors in series get shorted

5.2 Voltage ratings

Bushings are manufactured with voltage ratings equivalent to the highest system voltages. For example, HV bushings of 420 kV are used on the HV side and the bushings of 245 kV on the 220 kV side of 400/220/33 kV transformers. The other voltage ratings of bushings used include 145 kV for 132 kV systems, 36 kV for 33 kV systems, etc. When selecting HV bushings, it is also important that they have a higher basic insulation level (BIL) than that of the transformer winding. BIL is the highest lightning impulse voltage expressed in kVp (kilovolts peak) which power equipment can withstand without any damage. For example, 400/220 kV class transformers are equipped with HV bushings rated for 420 kV with the BIL of 1,425 kVp, while the BIL rating of the transformer winding is 1,300 kVp [8]. This is essentially required for maintaining insulation coordination between the insulation of the windings and that of the bushings against the ill-effects of peak lightning impulse voltages.

As per the phenomenon of the lightning impulse voltage wave, it rises from zero value to its peak value (in kVp) in 1.2 µs and then falls to 50 % of the peak value in 50 µs. This is denoted as 1.2/50 µs, Fig. 8 [1, 9].

5.3 Minimum nominal creepage distance

Minimum nominal creepage distance is the shortest distance along the surface of an insulator between two conductive parts. In the case of bushings, this is the distance between the bushing top metallic dome/terminal and the flange, which is referred to in terms of mm/kV, Fig. 9 [1, 9].

The requirement for the creepage distance may be specified by the customer based on the pollution level of the location where the power transformers are to be installed, as shown below [1, 9]:

- Heavily polluted – 25 mm/kV
- Very heavily polluted – 31 mm/kV

The manufacturers generally install bushings suitable for heavily-polluted atmosphere with a creepage distance of 25 mm/kV, unless a different specific pollution level is specified by the customer.

5.4 Arcing distance

Arcing distance is the shortest distance in the air external to the insulator between metallic parts which normally have the operating voltage between them, Fig. 9.

The arcing distance depends on the altitude. If the altitude where the transformer is to be installed exceeds 1,000 m, then the arcing distance needs to be increased. Considering that air density at high altitudes is lower than that at the sea level, the dielectric strength of the atmospheric air at high altitudes will also be lower. The arcing distance needs to be increased by 1 % for each 100 meters exceeding 1,000 m [1, 9].

5.5 Type of sheds of the bushings for AIS applications

The shapes of porcelain sheds are also important while selecting the porcelain bushings for AIS applications, which depend on ambient conditions such as snow, fog, etc. There are two types of sheds of such bushings for use in an EHV transformer, as illustrated in Figure 10a and 10b.

It is essential that the customers (OEMs) indicate the type of the sheds required for the bushings for EHV transformers they propose to manufacture.

5.6 Ambient temperature

Transformer manufacturer should also be informed about the minimum and maximum ranges of the ambient temperature where the transformer will be located. According to the standards, these temperature ranges are as follows:

- – 40 °C to + 40 °C for cold countries, as per IEC 60137 [1]
- – 5 °C to + 50 °C for tropical countries like India, as per IS: 2099 [9]

5.7 Angle of inclination for mounting

The types of bushings are also designated as per angle of inclination [1, 9]:

- Vertical bushings are designed and constructed to be installed up to and including 30° from the vertical.
- Horizontal bushings are designed and constructed to be installed at an angle equal to or greater than 70° from the vertical.

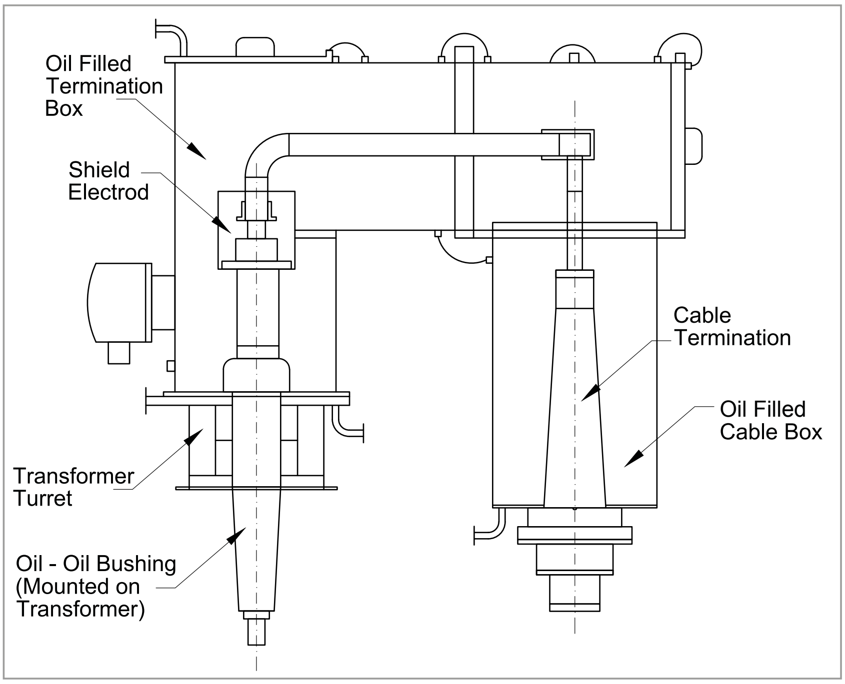

Figure 7b. Oil-to-oil type bushing used for cable connection through an oil-filled cable box

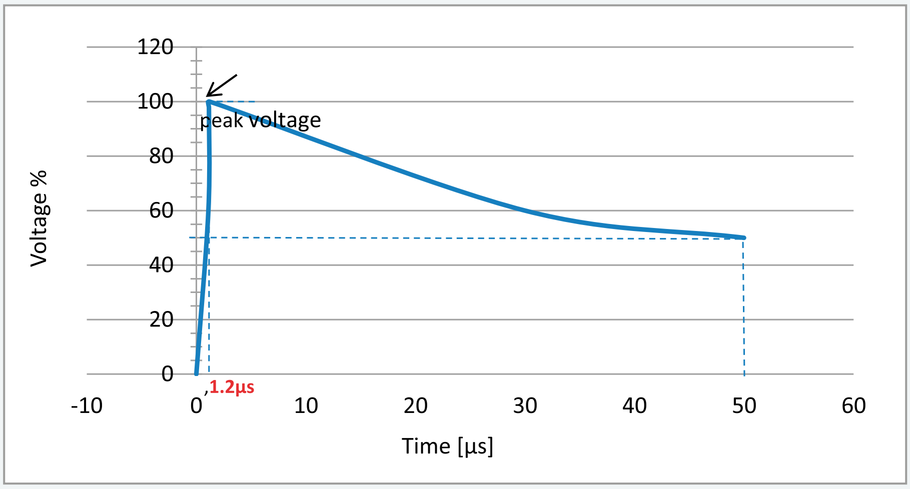

Figure 8. Lightning impulse voltage profile

The requirement for the creepage distance is specified based on the pollution level of the location where the power transformers are to be installed

6. Factory tests

As stipulated in IEC 60137 [1] and IS: 2099 [9], the bushings are subjected to the following tests:

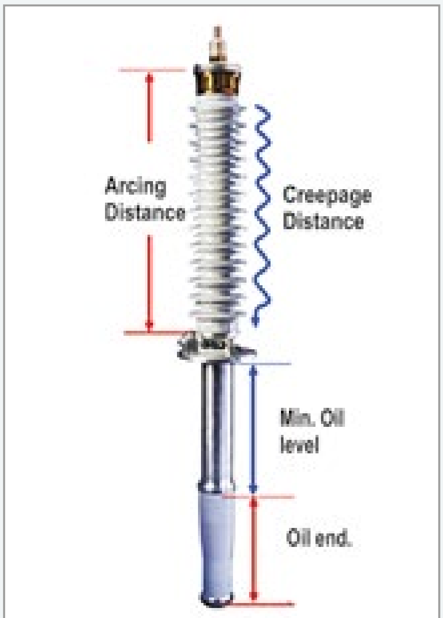

Figure 9. Arcing distance and creepage distance of the bushing

- **Type tests.** Type tests are performed on a few selected bushings out of the lot to prove that the design adopted by the manufacturers satisfies the specification and GTP of the customer. These tests are invariably witnessed by the customer's representative.
- **Routine tests.** Routine tests are performed on each and every unit of the bushing. This is mandatory on the part of the manufacturer.
- **Acceptance tests.** Acceptance tests are performed on a few randomly selected bushings, and they are generally witnessed by the representative of the customer. These tests are also called FAT (Factory Acceptance Tests).

6.1 Routine tests

1. Measurement of dielectric dissipation factor tan δ and capacitance at ambient temperature
2. Dry power frequency voltage withstand test
3. Dry lightning impulse voltage withstand test (for U_m >72.5 kV)
4. Measurement of partial discharge quantity*
5. Tests on tap insulation
6. Pressure test on liquid-filled and liquid-insulated bushings

** The maximum discharge quantity at U_m should be <10 pC in case of OIP & RIP bushings, as prescribed by IEC: 60137*

6.2 Acceptance tests

Acceptance tests are the same set of tests as routine tests.

6.3 Type tests

1. Wet power frequency voltage withstand test
2. Dry lightning impulse voltage withstand test
3. Dry or wet switching impulse voltage withstand test
4. Thermal stability test
5. Temperature rise test
6. Thermal short time current withstand test

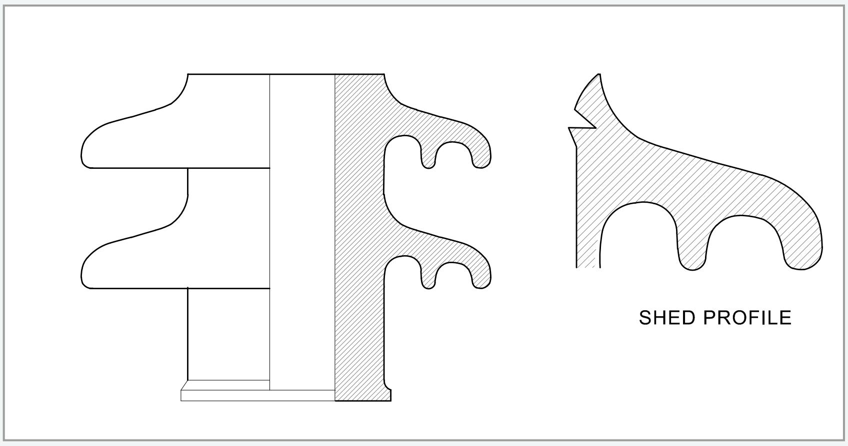

Figure 10a. Anti-fog shapes of porcelain sheds

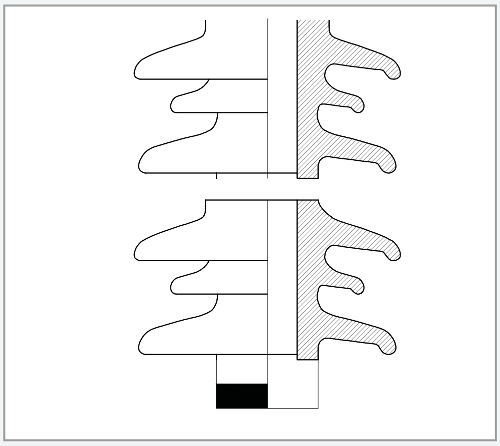

Figure 10b. Alternate shapes of porcelain sheds

The shapes of porcelain sheds are also important while selecting the porcelain bushings for AIS applications

7. Dynamic current withstand test
8. Cantilever load withstand test
9. Tightness test on liquid-filled and liquid-insulated bushings

Before and after the thermal and dielectric tests, measurements of tan δ, capacitance and partial discharge are carried out to check and verify whether a puncture or any other significant damage has occurred during the course of the above listed tests.

7. Transportation, storage and installation of the bushing

The following points need to be strictly followed during the transportation, storage, unpacking, handling and erection of the EHV bushings [10].

7.1 Transportation

Bushings can be transported in a wooden crate maintaining an angle of 6 to 8 degrees to the horizontal plane, so that the oil end is at the lower level. The transportation should be jerk-free.

7.2 Storage

Bushings can be stored outdoors with tarpaulin covering, maintaining the 6 to 8 degree inclination to the horizontal plane and keeping the oil end at the lower level.

7.3 Unpacking and handling

- While unpacking the bushings, care should be taken such that the bushings do not experience any kind of jerks.
- Steel rope and chain pulley block should not be used for lifting, instead, manila or nylon ropes should be used for lifting the bushing from the crate, ensuring that the ropes hold the bushing at its top and bottom ends, for lifting it horizontally or in some angle of inclination.
- Never rest the bottom stress shield on the ground (in the case of non-detachable stress shields).

7.4 Erection

- The bushing should be carefully checked physically for any damages, cracks, etc.
- The insulation resistance (IR) should also be measured. Workmen should not be allowed to climb over the bushings for any work such as connecting the leads and overhead jumpers, etc. Instead, a proper bucket truck/bucket crane should be used for the workmen to stand and pull the lead in order to make lead connections in the draw-lead type bushings as well as the draw-rod connection type bushings. Similarly, the jumpers from the overhead gantry to the bushing terminals should also be connected through this arrangement.
- Before it is energised, the bushing must be kept in an upright position or mounted on the transformer for a period of minimum 24 hours [10].
- For lifting and installing the bushings, non-metallic ropes, preferably nylon ropes should be used, Figure 11 [10].

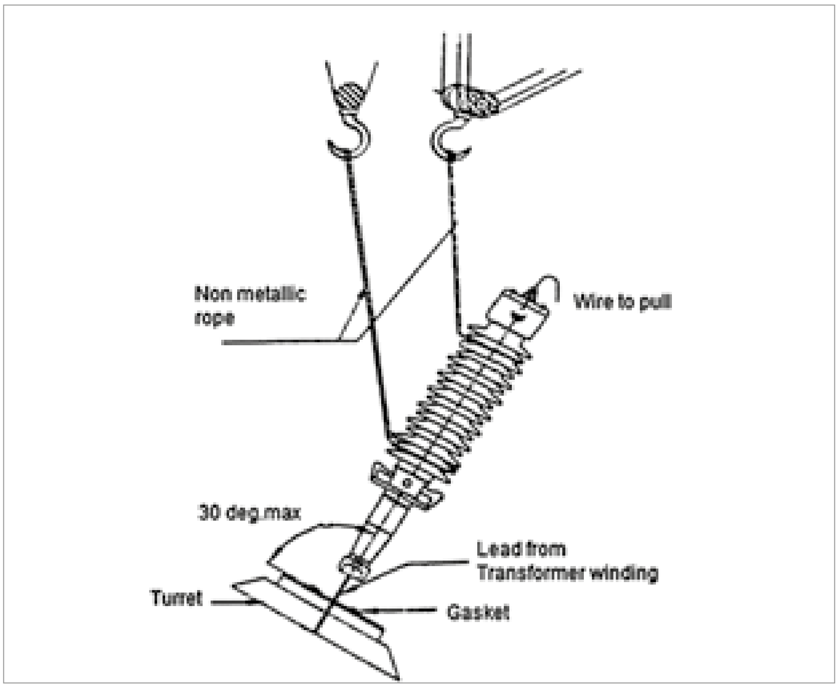

Figure 11. Installation/erection of a bushing (draw-lead type) [10]

8. Bushings dos and don'ts

Dos:

1. Check and verify if the bushing has been transported in a crate so that the oil end is at the lower level and the bushing is inclined making an angle of 6-8° with the horizon.
2. Check and verify if there is any damage to the crate externally before unpacking the bushing.
3. Unpack the bushing with care so as to avoid any kind of damage to the bushing or the porcelain of the bushing.
4. Verify the name plate details.
5. Handle the bushings with non-metallic nylon ropes while removing from the crate, hoisting and assembling onto the transformer.
6. While storing the bushing in a crate, make sure that the bushing is inclined making an angle of 6-8° with the horizontal plane, with its oil end at the bottom.
7. The bushing should be covered with tarpaulin and stored in a shed to safeguard it against rain and atmospheric moisture.
8. Clean the bushing insulator thoroughly before testing it for tan δ and capacitance.
9. Check for oil level and oil leakages in a bushing.
10. If spare bushing is to be tested, it should be fitted in the upright position in an oil chamber filled with transformer oil and then tested.
11. Before installation of the bushing, the unit should be kept in the upright position for more than 24 hours.

Tan δ, capacitance and partial discharge are measurements before and after the thermal and dielectric tests to verify whether any significant damages have occurred

12. Verify that the terminal clamps are Cu-Al bimetallic clamps.
13. Verify that the terminal clamps are suitable for particular ACSR (Aluminum Conductor Steel Reinforced) or AAA (All Aluminum Alloy) conductor used for jumpering.
14. Verify that the test tap cover is electrically connected to the bushing flange.
15. Verify that the test tap cover is properly fixed on to the test tap.
16. Proper safety measures are to be taken so as to safeguard the life of men, material and instruments from high voltage induction.
17. Proper record of the bushings should be maintained for routine maintenance, such as IR value, tan δ and capacitance measurements and thermovision survey reports.
18. Care should be taken while testing for tan δ and capacitance of C_2 that is test tap to flange, the test voltage range should be 500 V to 2 kV only.
19. Immediately replace the bushing whose tan δ and capacitance values are deteriorating from the standard values.

Don'ts:

1. Do not accept the bushings without test certificates of the tests witnessed by the authorized representative of the customer.
2. Do not unpack the bushing from the crate unless required for erection/assembling.
3. Do not at any case or circumstances use any metallic rope for lifting, hoisting and mounting the unit on the transformer.
4. Do not test the bushing if the weather is very moist and rainy.
5. Care should be taken not to test the tan δ and capacitance of C_2 that is test tap to flange with any voltage beyond 2 kV
6. Do not try to dismantle the bushing at the site without approval of the competent authorities/manufacturers.
7. Do not climb on the bushing for cleaning, making connecting terminal clamps, etc.

Conclusion

There are three types of bushings generally used in EHV transformer applications: oil-to-air, oil-to-SF6, and oil-to-oil type.

The graded bushing has a more uniform distribution of potential as compared to that of the ungraded bushing.

C_1 and tan δ are benchmark measurements for assessing the quality of insulation of the condenser bushing.

The requirement for the creepage distance is specified based on the pollution level of the location where the power transformers are to be installed.

References

[1] IEC – 60137, Edition 7.0 2017- 06, *International Electro-technical Commission Standard for Insulated bushings for Alternating Voltages Above 1000 V*

[2] S.Tenbohlen,J Jagers et al. *Development and results of a worldwide transformer reliability survey*, CIGRE A2 Colloquium 2015,China, 20-25 Sept 2015, on behalf of CIGRE WG A2.37, CIGRE, Formation of WG A2-37 Document DTD, 14.01.2008

[3] Marcos E.G Alves, J. C. da Silva, S.A. Cemig, *Online Capacitance & Tangent Delta Monitoring for Condensive Bushings*, CIGRE Conference, Brasil, 20-24 Dec 2007

[4] E. W. Golding, *Electrical measurements and measuring instruments*, 4th edition, 1955 (reprinted in 1962)

[5] NPTEL lecture notes, retrieved from http://nptel.ac.in/courses/108104048/lecture3/slide3.htm

[6] HAEFLEY TEST AG's Midas 228x, operating instructions

[7] THVS OIP Condenser Bushing for High-voltage Transformers, Type OTA72.5 kV to 1200 kV up to 5000 A, Trench High Voltage Products Ltd, Shenyang, China

[8] Central Board of Irrigation and Power, *Manual on Transformers*, No. 317, April 2013

[9] IS: 2099 - 1986 (Reaffirmed 2003), *Indian Standard Specification for Bushings for Alternating Voltage Above 1000 Volts*

[10] Alstom T&D, *Instruction manual for installation and O&M of OIP condenser bushings (Oil to Air) (24kV...420kV)***:**

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