HIGH VOLTAGE BUSHING: DESIGN, APPLICATION AND DIAGNOSIS FOR TRANSFORMER RELIABILITY

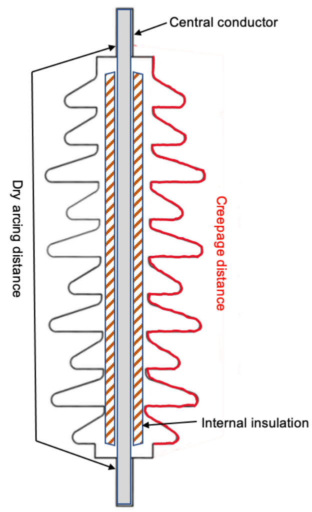
Bushing is the component in transformer that facilitates the passage of energised current carrying conductor through the grounded tank. Failure of this critical component is catastrophic due to exploding of the porcelain insulator can harm people working in the substation and possible damage to adjacent components. This article will look at recent development in transformer bushing design, failure mechanism and monitoring parameters that can be used to prevent the failure of transformer bushing.

INTRODUCTION

Bushing is designed to provide main connection from the winding lead out of the transformer tank. IEEE C57.190 define bushing as "an insulating structure, including a through conductor or providing a central passage for such a conductor, with provision for mounting a barrier, conducting or otherwise, for the purpose of insulating the conductor from the barrier and conducting current from one side of the barrier to the other". The bushing must be capable of withstand the voltage at which it is applied and able carrying the rated current without overheated the insulation. However, multiple stresses during transformer operation can cause insulation deterioration and lead to bushing failure.

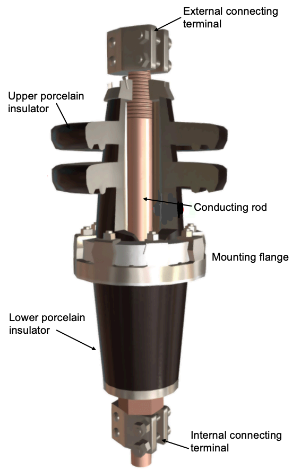
BUSHING DESIGN AND CONSTRUCTION

The design of any electrical bushing should take into consideration of several important aspects such as central conductor, bushing internal insulation and external insulation. The conductor should be able to carry the anticipated currents without overheating the surrounding insulation. At the same time, the inner bushing insulation should be able to withstand the nominal operating stresses and occasional transient electric field as well as limit the progression of insulation deterioration caused by partial discharge activities. Meanwhile, the external insulation should provide sufficient dry arcing distance to withstand lightning strikes and adequate creepage distance to prevent excessive flow of leakage current.



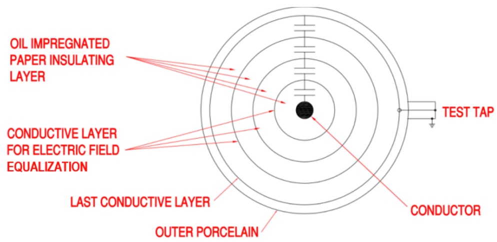
Main aspect of bushing design

Depending on how bushing was built and assembled, it can be broadly divided into two major categories; solid bushing and condenser type bushing. Solid bushings are typically constructed with a central conductor and porcelain or epoxy insulators at either end and connected directly to the transformer winding. The space between the conductor and the insulator may consist of only air or may be filled with mineral oil or some other special compound. The oil may be self-contained within the bushing, or it may be oil from the transformer in which the bushing is installed. At the middle of the porcelain insulator, the mounding flange and ground plane used for mounting the bushing to the transformer.

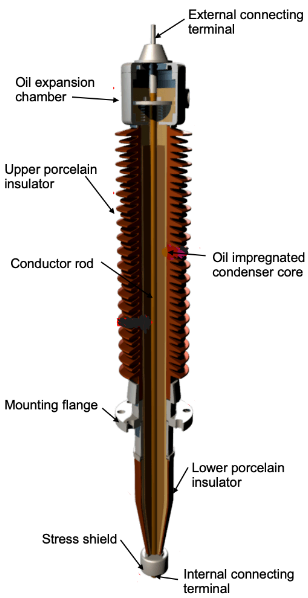


Solid porcelain bushing

Condenser bushings are relatively has complex design and normally used at higher system voltage. It is designed in the form of inner capacitance graded insulated core which is sandwiched between the central current carrying tube and external insulator to distribute and stabilised the electric field stress. As a results, this will reduce the diameter of the bushing, unlike that of the ungraded bushing, which needs larger diameter. To further increase a bushing's dielectric strength, the condenser insulation is saturated with mineral oil or other material. The conventional bushing design utilised plain kraft paper combined with grade mineral oil known as Oil Impregnated Paper (OIP) bushing and Resin Bonded Paper (RBP). A new state of the art bushing design comprise of wound core made of untreated crepe paper, which is then impregnated with a curable epoxy resin known as Resin Impregnated Paper (RIP). In recent years, other new technologies have become available on the market which are similar to RIP-technology, but offer advantages as the hygroscopic paper is being replaced by a non-hygroscopic synthetic material. Resin Impregnated Synthetics (RIS) technology is one of the available technologies.



Cross section of condenser bushing

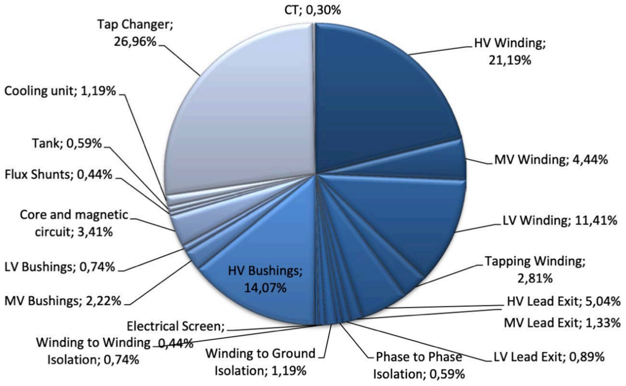


Oil Impregnated Paper (OIP) bushing

The external insulator of bushing is invariably porcelain for OIP condensers and silicon rubber for RIP condensers, both serving the same purpose of limiting the flow of leakage current and preventing external flashovers. In addition, OIP condenser bushings are also fitted with a spring-loaded expansion chamber to allow for oil volume fluctuations due to varying temperature. In order to limit high potential stresses inside the transformer enclosure, the stress shield are fitted at internal bushing terminals.

BUSHING FAILURES

A failure of transformer bushing sometimes resulting in transformer failure which can incur additional costs, much higher than the cost of the failed bushing and lead to downtime of the transformer. A statistical reliability survey published by CIGRE indicates that 17% of power transformer breakdown caused by bushing failure. Moreover,



Reliability survey of transformer component failure. 17% caused by bushing failure. (Source: CIGRE TB642:2015 - Transformer Reliability Survey)

bushing failures are the most common cause of transformer fire and explosion. This demonstrated that it is important for utilities to have a comprehensive management programme to reduce bushing failure and possible risk of transformer fire or explosion.

FAILURE MECHANISM

Defects in a bushing may originate from one or more main parts of the bushing construction: core, core surface, oil, porcelain inner surface and so on. Several mechanism of bushing failure is described in this article.

Moisture

Moisture is one of the main factors that can cause transformer failure as well as to high voltage bushing. Leaking gasket due to mechanical stress and ageing will be the most common causes of moisture ingress particularly for OIP and RIP bushing. Since RIS bushing use a synthetic mesh and the resin filled epoxy system, no moisture can migrate into RIS bushing core. Presence of moisture will forms various polar compounds including acids that attack and break the paper. At some point two or more conductive layers will break down and short together. When this happens, the remaining concentric capacitors will have a larger voltage stress across each capacitor, which eventually cause catastrophic failure of transformer bushing.

Switching and Lightning Transients

Transformer installed closed to high voltage breakers or disconnecting switches, which are frequently being operated are subjected to electrical switching transients. Depending on the distance and how the transformers are connected to the breakers/disconnect switches, the impact can be significant. The energy introduced by Very Fast Transients (VFT), Lightning Transients and Switching Transients in the network will results in short term overvoltage and risk into bushing operation. Nevertheless, long overhead line and cable connection will provide high impedance and high capacitance, which will attenuate the wave and minimize the impact. Further, the maximum amplitude of transients can be effectively controlled by using surge arrestors.

Installation of lightning arrester at transformer bushing

Mechanical Stress

Mechanical forces can destroy transformer bushing

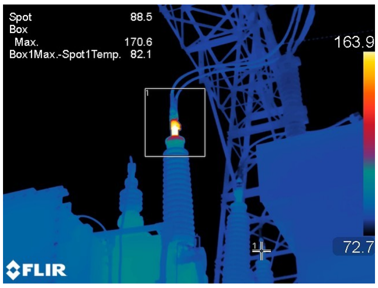
The overhead line and cable connection connected to air part of the bushing introduced vertical and horizontal forces. The changing load current of an overhead line will result in different temperatures of the wire conductor itself and result in a different quasi-static mechanical force. Transient mechanical forces can also be introduced by wind and through-faults. This excessive mechanical forces can mechanically destroy a bushing. The quasi-static forces and the transient force do have the potential to weaken the sealing system of bushings and would lead to moisture ingress.

CONDITION ASSESSMENT OF TRANSFORMER BUSHING

Early detection of certain ageing parameters can prevent catastrophic failure of transformer bushing. Therefore a regular diagnostic measurement is essential for a safe operation of bushings as well as transformers. The value of the diagnostic analysis is in an ability to point to a failure mode.

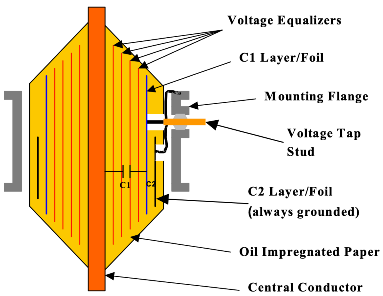
Thermal Monitoring

Infrared camera is often used for thermal monitoring annually to detect a loose connection of transformer bushing. Even the thermal monitoring does not indicated internal problem in bushing, poor contact condition can generate hot spot and eventually cause bushing failure.



Hotspot at transformer bushing

Power Factor and Capacitance



C1 and C2 bushing insulation

The measurement of power factor or dielectric dissipation factor and capacitance is the most common technique for condition assessment of transformer bushing. It was performed at normal frequency of 50 Hz or 60 Hz to determine the internal insulation condition. Increasing of power factor value indicated high moisture level or high amount of contaminants in insulation system. There are two sections of insulation measured on transformer bushing; main insulation (C1) between the centre conductor and potential point or voltage test tap, and tap insulation (C2) which is insulation between potential point and ground mounting flange. The power factor should be compared to the value stated at bushing nameplate or can refer to the limits according to IEC 60137 and IEEE C57.19.01.

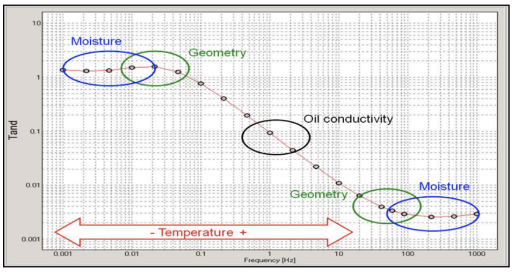
Standard	Bushing Type		
	RIP	OIP	RBP
Typical new value	0.3% - 0.4%	0.2% - 0.4%	0.5% - 0.6%
IEC 60317	< 0.7%	< 0.7%	< 1.5%
IEEE C57.9.01	< 0.85%	< 0.5%	< 2.0%

Typical limits of bushing power factor

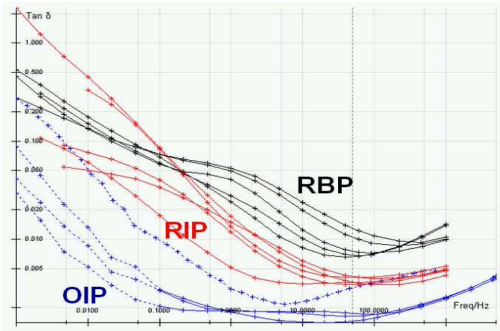
Similarly, the measured capacitance C1 should be compared with the value given on the rating plate of the bushing or with the 10 kV routine test report. If an increase of more than 3% compared to the factory measured value or an extremely low value, this could indicate a partial puncture on insulation layer and the bushing must not be taken into service.

Dielectric Response Measurement

The new diagnostic technique may involves measurement of power factor and capacitance at different frequencies from 0.1mHz until 1kHz. The measurement principle and set-up is similar to traditional 50/60Hz power factor testing but lower measurement voltage is often used (140V to 1400V). The dissipation factor plotted against frequency shows a typical inverted S-shaped curve. With increasing temperature, the curve shifts towards higher frequencies. Moisture influences mainly the low and high frequency areas. The middle section of the curve, with the steep gradient, reflects oil conductivity.



Parameter affecting dissipation factor at various frequency



Dielectric response of for OIP, RBP and RIP bushing

Dissolved Gases Analysis

The Dissolved Gas Analysis (DGA) is the most widely used method in the diagnosis of power transformers. In the case of bushing with oil impregnated paper (OIP), DGA could be used as a supporting tool for typically used diagnostic methods based on capacitance and power factor measurements. A limitation of the use of the DGA method lies in the need to respect the special procedures of taking the oil sample from the bushing, which, without a special commitment, may cause the bushings damage and the necessity of the transformer to be switched off. The general rules concerning the detection and characterisation of faults in bushings are the same as in the case of power transformers. This means that in the first step of the condition assessment of bushings it is necessary to check whether the measured gas concentrations exceed the typical values, and if this takes place, the nature of the defect can be determined in the next step. IEC 60599 has proposed typical concentration value of gases in transformer bushing.

H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
140	1000	3400	40	70	30	2

The 95% typical concentration values (ppm) in bushings proposed in IEC 60599 Standard.

Next Issue

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