
 PROTECTION AND SAFETY

Dry insulation for condenser bushings

High-voltage (HV) condenser bushings are critical components of all electrical networks. Because they are subject to high levels of electrical stress, failures in HV condenser bushings tend to be catastrophic. Producing bushings for use at 800 kV and above requires careful design and manufacture.



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High-voltage (HV) condenser bushings are critical components found in all electrical networks. Because they are subject to high levels of electrical stress, failures in HV condenser bushings tend to result in sudden and catastrophic events of an explosive nature. There is much to gain if the consequences of failures can be reduced, and this is probably why a growing number of utilities now specify dry insulation technology with an outer insulation made of non-brittle materials. However, producing bushings for use at 800 kV and above requires careful design and manufacture, and is not just a matter of upgrading existing, lower-voltage technology as the technical steps that need to be taken to ensure trouble-free operation are often nonlinear →1.

Condenser bushings are a familiar sight to anyone working in the world of HV. Though presenting an outward impression of simplicity, these essential components of the power grid have emerged from a design and manufacture process that is highly sophisticated.

Condenser bushings consist of three primary components: an outer insulation for minimizing creepage currents and preventing external flashover; an inner capacitance-graded insulation “condenser” for distributing and stabilizing the electrical field (thus “condenser”); and a conductor system for carrying the current.

In the inner insulation there are a number of very precisely positioned, coaxial layers of conducting material in a paper web →2. To increase the dielec-

Since the 1980s, silicone rubber has gradually been developed as a perfectly good alternative to ceramic material.

tric strength of this insulation, it is impregnated with either transformer oil or a curable epoxy resin. These approaches are called oil-impregnated paper (OIP) and resin-impregnated paper (RIP), respectively. Use of OIP bushings began in the 1950s and is still the dominant concept for the highest voltage levels, ie, those from 735 kV. RIP bushings have been gradually developed for higher voltages too and are becoming increasingly common, but the step up to the highest voltage levels has taken time due to the technical challenges involved as well as general conservatism in the power industry.

For the outer insulator, ceramics have dominated for quite some time. Various forms of polymeric materials have been tested over the years, but the effects of sunlight have limited service life. Since the 1980s however, silicone rubber has gradually

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01 Producing condenser bushings with dry insulation for voltage levels of 800 kV and above requires much skill and care in design and manufacture. Shown is routine electrical testing of the first commercial delivery.

been developed as a perfectly good alternative to ceramic material. Silicone rubber attains maximum energy absorption at wavelengths lower than those present in sunlight and consequently provides significantly better service life than other polymeric materials.

Advantages of RIP

The biggest advantage of the RIP concept for utilities is the dramatically decreased consequences in the event of bushing failure. Although phase-

The mechanical engineering effort for the dry-insulated 800kV bushing has been extensive, especially concerning seismic requirements.

to-ground flashover can have many causes – for example, failure of the bushing itself or electrical, mechanical or thermal stresses from the grid system – flashover in an OIP bushing nearly always produces an explosion that results in shattered insulators and oil spills. The consequences are especially serious when transformers catch fire [1]. Because RIP bushings do not contain highly flammable and energy-rich oil, the risk of fire is largely eliminated. There are a number of other factors that also support the benefits of RIP technology when it comes to reducing the consequences of failures [2], [3]. Besides not shattering in the event of failures, composite insulators consisting of sili-

cone rubber that is extruded on a filament-wound tube have a multitude of other positive properties as outer insulation:

- Thanks to the chemical structure of the silicone, the insulator's surface is hydrophobic, so water forms droplets – instead of a water path – on the surface. This reduces creepage currents (and, consequently, erosion), and flashover risks in extreme weather conditions.
- The continuous nature of the manufacturing process produces a chemical bond between the tube and insulator. Because both the silicone rubber and filament-wound tube are entirely free of joints, the electrical field distribution is smooth and continuous, and there is minimal risk of moisture penetration. There are also no parting lines where salt and pollutants could collect →3.
- Extrusion also provides the opportunity to optimize the insulator's shed profile for different applications. This results in a further reduced electrical field, which in turn lessens the risk for tracking and erosion [2].
- The chosen polymeric insulation material is a high-temperature vulcanized (HTV) rubber that has a carefully balanced mixture of pure silicone and an aluminum trihydrate (ATH) filler as the basic material. Besides mechanical strength, the ATH filler is also temperature- and fire-resistant, and recovery of hydrophobic properties after heavy rain, for example, is rapid if the amount of ATH used is optimized. Experience from the field has also shown that HTV rubber is highly resistant to erosion and that it retains its hydrophobicity for extended periods [4].

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02 Primary bushing components: Outer insulation (left); inner insulation with mounting flange and conductor (right).

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03 Manufacture of outer insulation.

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04 Details from the FEM analysis for the mounting flange.

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05 FEM calculation of silicone sheds.

- This type of insulator is significantly lighter and mechanically stronger than corresponding ceramic insulators. This is very important in withstanding the effects of earthquakes and short circuits, as well as in limiting damage during handling.

Important considerations when developing bushings for 800kV

A few examples of important considerations to be kept in mind when developing dry-insulated bushings for 800kV are:

- A major cost driver is the required wet switching impulse withstand since this, to a large extent, determines the bushing's length. This is of special significance for RIP bushings since length is closely related to the complex casting and hardening process, process vessel dimensions, machining equipment specifications, etc.
- Seismic requirements apply in some parts of the world. During the engineering process, extensive dialog is necessary between transformer manufacturers and utilities to assess, for example, installation angles and structural reinforcement factors where the bushing will be installed.
- Regard for requirements that reflect local conditions, such as ambient temperatures.
- A flexible design that permits dimensional adaptation to previously installed equipment, regardless of manufacturer.

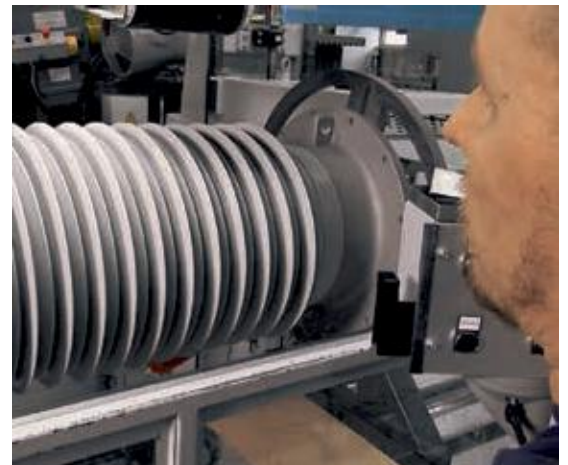
Mechanical engineering aspects

The mechanical engineering effort for the dry-insulated 800kV bushing has been extensive, especially concerning seismic requirements.

A solid base of experience from previous seismically tested bushings from the GSB series has been of great benefit, particularly with regard to modelling and analysis of dampening and natural frequency. Nonetheless, several finite element (FEM) analyses have been conducted – linear as well as nonlinear – with subsequent verification tests of critical components. The dynamic analyses have been performed both with required response spectra (RRS) and test response spectra (TRS). The calculated results have been verified with full-scale shake table testing and are in compliance with the seismic requirements as stipulated in IEEE 693-2005 and other, even more demanding local specifications →4.

The draw-rod solution, used by ABB since the 1970s to simplify installation and replacement of bushings in the field presented mechanical challenges that resulted in a partially new technical solution. Compared to oil-insulated bushings with ceramic insulators for corresponding voltages, the higher temperature expansion in RIP bushings made it impossible to retain the contact force between different current-conducting components without a major redesign. In-depth mechanical analyses, such as for buckling cases, short-circuit force, contact forces, etc., have been performed with the support of FEM analyses and associated testing.

Due to the dry bushings' general difficulty in dissipating heat, new low-resistive material combinations have sometimes been necessary to reduce losses. This has led to challenges when it comes to corrosion protection in harsh industrial and coastal environments. New materials have also entailed the introduction of newly developed sealing systems. All design solutions, including those related to corrosion, have been verified by testing.



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— This article is based on the following CIGRE paper: L. Jonsson, R. Hedlund, "Development of dry-insulated 800kV transformer bushings," 2016 CIGRE-IEC Colloquium, © 2016 IEEE, Montreal, Canada.

References

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Thermal engineering aspects

Dielectric heating of inner insulation can be of major significance. Oil-insulated bushings have effective convective cooling for handling dielectric and resistive losses; RIP bushings do not. This necessitates an extensive theoretical analysis of designs to ensure thermal stability under all testing and operational conditions, as well as to comply with overload requirements.

During the temperature cycling tests, the ambient temperature was varied between -50 and +40°C, with carefully specified up and down ramp times. The main challenge is to cope with the substantial temperature gradients and associated mechanical stress set up by the condenser core's cool mass and elevated ambient temperatures.

In-depth analyses using, for example, differential scanning calorimetry (DSC) and dynamic mechan-

An entirely new production facility was necessary to make the new bushing series.

ical thermal analysis (DMTA) have been necessary to gain a detailed understanding of crystallization at various cooling temperatures and of how stresses in the materials occur. Extensive FEM analyses of the cooling and crystallization process in different sections of the insulation, followed by verifying component testing, were conducted prior to the final, full-scale tests that were performed on a complete bushing. These analyses led to, among other things, optimization of certain steps in the manufacture of the outer insulation →5.

Manufacturing

Because high-voltage bushings generally require very low levels of partial discharge, one of the greatest challenges in RIP bushing manufacture is the impregnation and hardening of the inner insulation. The ability to manage sophisticated manufacturing processes with minimal process deviation is thus entirely decisive. With such complex manufacture processes, it has also been difficult to directly utilize experience from existing products for lower voltages because many critical parameters are not linearly scalable, but are quadric or even cubic in nature. This can place requirements on production equipment many times greater than what may be initially perceived: The weight of a dry 800kV bushing is, for example, more than twice that of a corresponding product for 500kV systems, and the length of the air side is over 40 percent longer.

The challenges involved in winding condenser cores for these voltage levels are largely related to placement control of the condenser core's conducting layers. The dimensional change that occurs when drying alters the layers' axial dimensions more than the radial dimensions. Temperature effects have also entailed that process tools must be dimensioned to handle substantial changes in length during casting.

During the actual casting process, nearly 2,000kg of epoxy must be injected into the cellulose core and hardened without the formation of air cavities. Air cavities would otherwise cause electrical discharges during the final routine test and necessitate scrapping of the bushing. To avoid this, hardening of the epoxy must be closely monitored throughout the process.

An entirely new production facility – with a winding machine, process equipment and updated control equipment, as well as entirely new equipment for machining – was necessary to make the new bushing series. The first commercial deliveries were made during 2015. ●

