21, rue d'Artois, F-75008 PARIS
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2016 CIGRE-IEC Colloquium
May 9-11, 2016
Montréal, QC, Canada

Development of dry-insulated 800 kV transformer bushings

LARS JONSSON
ROGER HEDLUND
ABB
Sweden

SUMMARY

High voltage condenser bushings are critical components in all electrical networks and failures can have serious consequences. Because of the high electrical stress levels in bushings, failure mechanisms tend to result in sudden and catastrophic failures 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 electric utilities now specify dry insulation technology with outer insulation made of non-brittle materials. This also includes several operators of 800 kV systems. However, switching to higher voltages involves several technical challenges for manufacturers.

The product specification was developed based on the requirements set by the power utility industry and includes several aspects beyond what is set by the international IEC standard. Examples of such requirements are direct replacement of existing bushings, temperature cycling and seismic requirements.

Many of the technical challenges when switching to 800 kV are non-linear, and consequently, it is often not just a matter of upscaling existing technology.

- *One example of the challenges is the draw rod system. The draw rod system makes installation and retrofitting transformer bushings much easier compared to other systems and provides good current-carrying capabilities under all operating conditions. However, it represents a major challenge and requires new approaches because of the much higher levels of thermal expansion between the different materials.*
- *Another example is temperature cycling and the combination of stresses it imposes on the different parts of the primary insulation and the composite insulators.*
- *The fact that several of the key dimensions were already set by the retrofit requirement also resulted in major challenges in the optimization process.*

Long service life for the outer insulation is ensured by using erosion-resistant, high quality HTV rubber with a high content of ATH filler and an optimized shed profile geometry.

lars.y.jonsson@se.abb.com

There are also many challenges in the manufacturing process due to the sizes of the required void-free products. These are considerably larger than those previously used and the entire production process must therefore be analyzed –from winding, drying and mold filling; curing and post-curing; to cooling and final assembly.
The final product has been fully verified and the first units were delivered in mid-2015.

KEYWORDS

Bushings, 800kV, RIP, Composite insulators

INTRODUCTION

High voltage bushings for transformers of the condenser type consist of three primary components: an outer insulation for minimizing creepage currents and preventing external flashover; an inner insulation (condenser core) for distributing the electrical field; 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. See Figure 1.

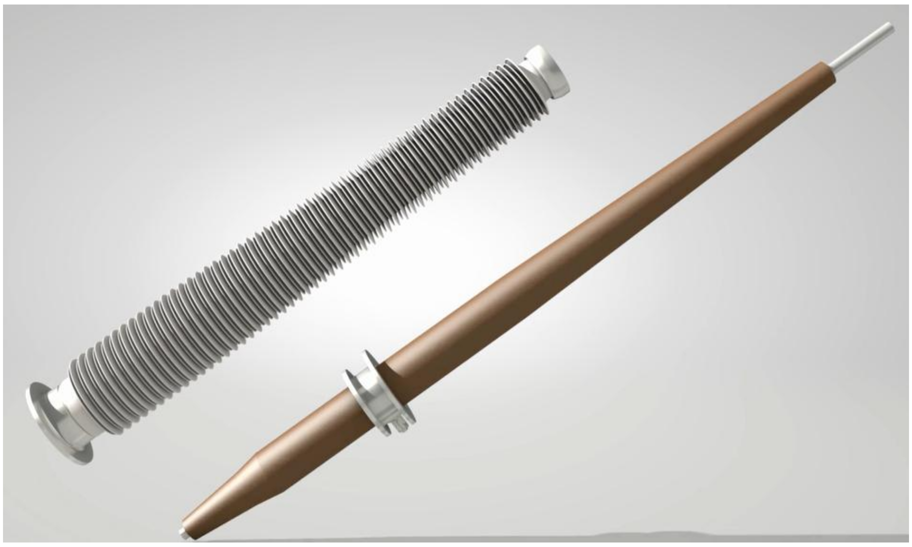

Figure 1. Primary bushing components: The outer insulation at the left and the inner insulation with the mounting flange and the conductor tube in the center.

To increase the dielectric strength of the inner insulation, it is impregnated either with transformer oil or a curable epoxy resin. The concepts are called Oil Impregnated Paper (OIP) and Resin Impregnated Paper (RIP). Use of OIP bushings began in the 1950s and is presently the dominating concept for the highest voltage levels, i.e. ≥ 735 kV. RIP bushings have been gradually developed for higher voltages as well, and are becoming increasingly common. The step up to the highest voltage levels however, has taken time. This is due both to the technical challenges as well as the general conservatism in the power industry.

Ceramic outer insulators 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 been developed as a perfectly good alternative to ceramic material. Silicone rubber attains maximum energy absorption at wave lengths lower than sunlight, and consequently provides significantly better service life than other polymeric materials.

The bushings are standardized under IEC 60137 with regard to testing of electrical, thermal and mechanical properties. Type testing is performed to verify the various design solutions for each product concept, and the critical steps in the production process for each manufactured unit are verified in routine testing. In the present project, a wide range of additional tests have also been performed to verify important long-term properties as well as performance under extreme conditions.

CONCEPT SELECTION

The biggest advantage of the RIP concept for utilities is the dramatically decreased consequences in the event of bushing failure. Although phase-to-ground flashover can have many causes – due both to failure of the bushing itself and electrical, mechanical and thermal stresses from the grid system – flashover in an OIP bushing nearly always produces an explosion with shattered insulators and oil spills as a result. 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 lessening the consequences of failures [2], [3].

Besides not shattering in the event of failures, composite insulators consisting of silicone 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, entailing that water forms droplets on the surface instead of a water path. This reduces creepage currents and consequently erosion, as well as reducing flashover risks under 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 with minimal risk of moisture penetration. There are no parting lines either, where salt and pollutants could collect. See Figure 2.
- 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 HTV rubber – a high temperature, vulcanized silicone rubber with 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 the optimized amount also speeds recovery of the hydrophobic properties after heavy rain, for example. Experience from the field has also shown that HTV rubber is highly resistant to erosion and retains its hydrophobicity for extended periods [4].
- 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.

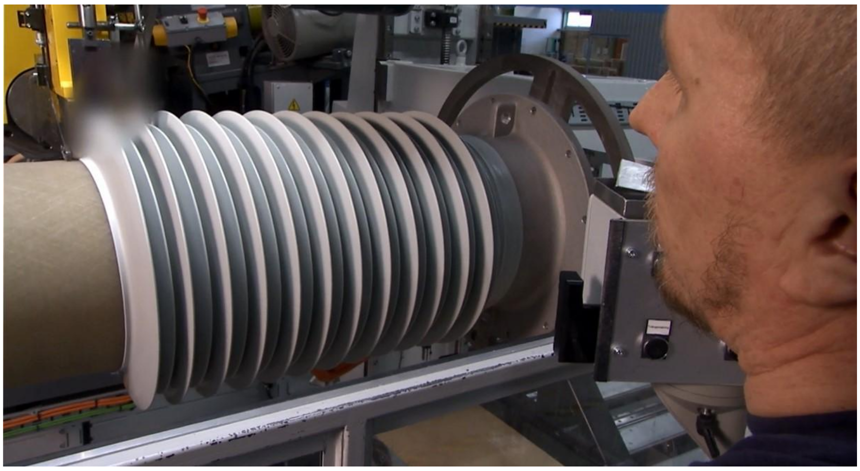

Figure 2. Manufacture of outer insulation.

EXAMPLES OF IMPORTANT PRODUCT CONSIDERATIONS

Primary data for bushings for voltages between 735 and 800 kV has been specified in the IEC 60137 standard for quite some time. This however, is insufficient for specifying the product's optimal performance. ABB/ASEA has delivered products for the relevant voltage levels since 1965, and consequently, extensive delivery statistics are available. The company also benefits from close collaboration with various utilities, which is especially advantageous when new products are developed. A few examples of important product considerations are as follows:

- Reactors and transformers are very rarely standardized with regard to rated power. Bushings are stringently standardized products and an extensive analysis of various utilities' requirements must therefore be performed before one of the major cost drivers can be established, namely maximum operating current.
- Another major cost driver is the required wet switching impulse withstand since this to a large extent determines the bushing's length. This is especially of major significance for RIP bushings since the length is closely related to the complex casting and hardening process, the dimensions for process vessels, equipment for machining, etc. Data for wet switching impulse withstand is specified by the various utilities and generally complies with IEC standards, but in certain cases it must be compensated for elevation above sea level, for example, for the relevant installations in order to achieve the requisite product performance.
- Seismic requirements apply in some parts of the world. Although there are internationally applicable standards, there are also local variants. During the engineering process, extensive dialog is necessary between transformer manufacturers and utilities in order to assess, for example, installation angles and structural reinforcement factors where the bushing will be installed.
- In certain other cases, there are also specific other requirements that reflect local conditions. One such case that will be addressed below is temperature cycling.
- Experience has also shown that bushings will likely be replaced during the service life of a transformer/reactor. The bushing's design must consequently be flexible and permit dimensional adaptation to previously installed equipment, regardless of manufacturer. Bushing replacement in the field without lowering the oil level requires special focus on detailed design solutions. An example of this is the draw rod system, which will be addressed below.

TECHNICAL CHALLENGES

Introduction

For the relevant voltage levels, dielectric heating of inner insulation is of major significance during engineering. Oil-insulated bushings have effective convective cooling for handling dielectric and resistive losses, which is not the case for RIP bushings. All in all, this requires an extensive theoretical analysis to ensure thermal stability under all testing and operational conditions, as well as to comply with overload requirements in accordance with applicable standards. These calculations, which are naturally verified through testing, have also constituted the basis for modified requirements for certain parameters in the insulation material.

Because high voltage bushings generally require very low levels of partial discharge, one of the greatest challenges in manufacturing RIP bushings is impregnation and hardening of the inner insulation. The capability to manage complex manufacturing processes with minimal process deviations is thus entirely decisive for successful manufacture of high voltage, dry-insulated bushings.

With such complex technical processes in manufacture, it has also been difficult to directly utilize experiences from existing products for lower voltages because many decisive parameters are not linearly scalable, but instead can be 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 800 kV bushing is, for example, more than twice that of a corresponding product for 500 kV systems, and the length of the air side is over 40 percent longer.

Mechanical engineering

The guiding principle in mechanical engineering has been to minimize material consumption with retained compliance with strength requirements. To achieve this optimization, the bushing is considered as a single system in which all parts together provide the product's strength. This entails that the respective sub-components must be in strict compliance with the set requirements, which places stringent demands on the technical expertise of the sub-contractors in testing and analyzing the sub-components they deliver. Development of the outer insulation and the mounting flange is worthy of special mention. They were subjected to very extensive calculations as well as material and mechanical tests to ensure that the requirements were actually fulfilled.
Mechanical engineering has been extensive, especially in regard to the seismic requirements. A solid base of experience from previous seismically tested bushings from the GSB series has been of great benefit, particularly in regard to modelling and analysis of dampening and natural frequency. Nonetheless, several finite element analyses (FEM) have been conducted – linear as well as non-linear – 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 Hydro-Québec's separate specification. See Figures 3 and 4.

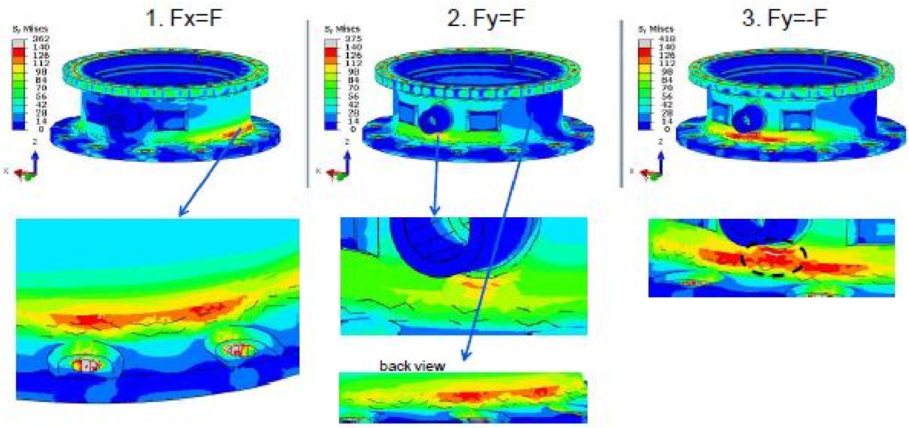

Figure 3. Details from the FEM analysis for the mounting flange

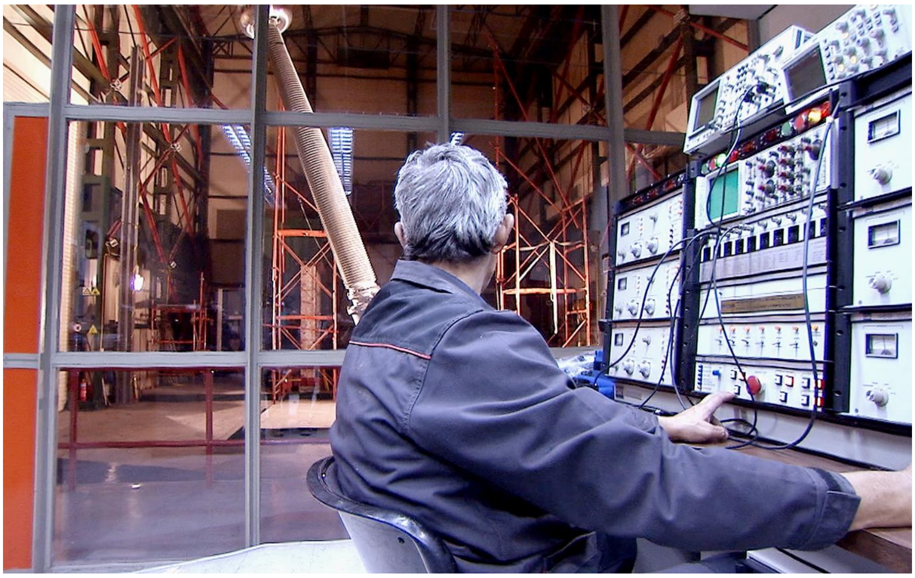

Figure 4. Full-scale testing on shake table

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 re-design. 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. The fact that movement of the materials is considerably greater, relatively speaking, also affects the design of the shielding arrangement in the transformer when it is not mounted on the bushing.

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

Thermal engineering

The previously mentioned temperature cycling test consists of four cycles in which the ambient temperature varies between -50°C and +40°C with carefully specified up and down ramping times. No visible defects and subsequent routine electrical testing in accordance with IEC 60137 are mandatory for compliance with customer requirements. The main challenge is in coping with the substantial temperature gradients. This is obviously due to the large mass that takes considerable time to reach the specified ambient temperature. The combination of the condenser core's mass that cools the insulator and increased ambient temperature creates stress in the material, which is a technical challenge.

In-depth analyses using, for example, Differential Scanning Calorimetry (DSC) and Dynamic Mechanical 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 manufacture of the outer insulation. See Figures 5

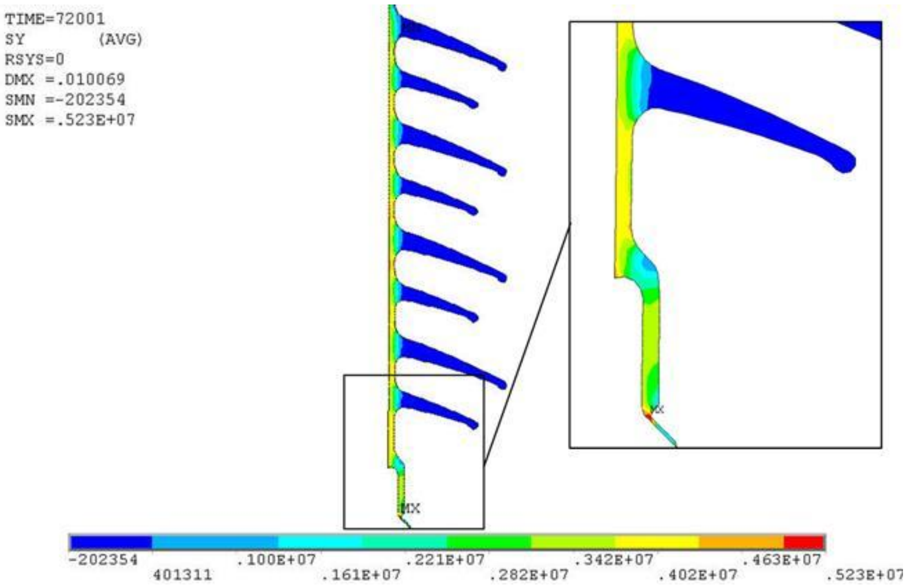

Figure 5. FEM calculation of silicone sheds

Manufacturing

The challenges involved in winding condenser cores for these voltage levels are largely related to control of placement of the condenser core's conducting layers. The dimensional change that occurs when drying alters the layers' axial dimensions more than the radial. Temperature effects have also entailed that process tools must be dimensioned to handle substantial changes in length during casting.
The requirements for low dielectric losses in comparison with bushings with lower voltages obviously entail an additional challenge during drying, and this places stringent demands on achieving minimal deviations during manufacture.
During the actual casting process, nearly 2000 kg of epoxy must be injected into the cellulose core and hardened without 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.

After the casting process, the condenser core must be machined to its final dimensions. Here as well, the temperature is of the greatest importance in achieving the requisite tolerances for the finished product.

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

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