Dry transformer bushings with composite insulators – the obvious combination for increased reliability

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1. Introduction
The high voltage (HV) condenser bushing is a critical component found in all electrical networks and whose failure can have serious economic consequences.

Because of the high electrical stress levels in bushings, failure mechanisms tend to result in sudden and catastrophic failures of an explosive nature. A lot is gained if the consequences of a failure can be reduced, and this is probably why a growing part of the utility industry now specifies dry insulation technology with outer insulation made of non-brittle materials.

This article is aimed at reviewing certain key aspects related to design, verification and service experience of dry high voltage bushings fitted with composite insulators.

2. High voltage condenser bushings
Condenser bushings facilitate electric stress control through the insertion of floating equalizer screens made of aluminum or other conducting materials. The condenser core in which the screens are located decreases the field gradient and distributes the field along the length of the insulator. The screens are located coaxially resulting in an optimal balance between external and internal puncture strength; see Figure 1.

Condenser cores are generally impregnated with transformer grade mineral oil and placed inside an insulating envelope of oil and porcelain, which prevents the bushing oil from mixing with the transformer oil. The system is called Oil Impregnated Paper (OIP) and accounts for more than 80% of all installed bushings.

The outer insulation is made from an insulating material and is of the anti-fog type with alternating long and short sheds to produce a long creepage distance with good self-cleaning properties.

Figure 1 – Schematic view of a condenser core with coaxially located aluminum foils in a web of insulating material.

2.1 Trends
Many utilities have now arrived to the conclusion that the dry Resin Impregnated Paper (RIP) technology is a valuable contribution in reaching better overall performance figures. The somewhat differently designed condenser core is heated, dried and vacuum impregnated by a curable epoxy resin to form a solid unit, free from oil.

The latest addition to the dry concept is Resin Impregnated Synthetics (RIS), where the paper web is replaced by a polymeric fiber to obtain a dry insulated solution that does not absorb moisture during handling and storage.
The outer insulation can be of two types, ceramic or polymeric. Ceramic insulators have a long history and will be used for many years to come, it is likely however, that their role will diminish in the foreseeable future as the industry seeks improved insulator performance in order to reduce overall costs, and to improve safety, seismic withstand and pollution performance along with lower insulator weights.

Besides the migration towards dry technology with composite insulators and the use of new materials in the main insulation outlined above, striving towards higher transmission voltages continues to put extraordinary challenges on the development of bushings. Standard solutions of up to 1200 kV AC and 800 kV DC presently exist and another big step was taken in 2012 when a bushing for 1100 kV DC was successfully type tested; see Figure 2.

![Figure 2 – In 2012, ABB finished type testing of the world’s very first bushing for 1100 kV DC.](image)

3. Verifying tests

Bushings, as with other electrical equipment, are subject to industry standards. The international IEC standard has broad global acceptance and describes in detail, among other things, testing. Manufacturers have to comply with certain tests to verify the design as such, as well as routine testing to verify the quality of the individual bushings. Some examples are;

- Electrical
- Mechanical
- Thermal
- Tracking and erosion
- 1000-hr salt fog test
- Hardness

Additional tests may also be carried out to verify long-term performance, or performance under extreme conditions. Some examples are;

- Various cyclic tests, e.g. temperature and bending
- Arcing tests
- Fire testing
- Seismic tests
- Hydrophobicity test
- Ageing tests

Two examples of additional testing of particular interest for dry bushings with composite insulators are detailed below. Further discussion is in Section 4, which deals with the outer insulation more specifically.

3.1 Fire testing

The purpose of the test was to quantify the difference between OIP and RIP bushings in regard to fire resistance. Two important factors for how severely a fire develops are time to ignition and peak heat release.

- Time to ignition, among other things, determines the likelihood of multiple seats of fire occurring simultaneously.
- A material can burn slowly or quickly and the peak heat release is one of the parameters that describe the effect of a fire, as well as the capability to extinguish the fire.
3.1.1 Cone calorimeter testing

Test samples were taken from the insulation system in a 500-kV OIP bushing and from a 500-kV RIP bushing; see Figure 3. The specimen surface is heated and an external spark-igniter ignites the pyrolysis gases. Time to ignition is determined for the different materials. The heat release rate is then determined by measurements of the oxygen consumption derived from the oxygen concentration and the flow rate in the exhaust duct of the test chamber.

3.1.1.1 Time to ignition

![Graph showing time to ignition for different materials](image)

Figure 4 – Time to ignition (in seconds) for the different materials.

3.1.1.2 Peak heat release

![Graph showing peak heat release for different materials](image)

Figure 5 – Peak heat release (in kW/m²) for the different materials.

3.1.1.3 Energy release

The energy release was also analyzed from the different materials. When taking into consideration the total energy based on actual mass of the different materials in the two bushing concepts, the energy release does not show any major differences. It is however worth noting that the free oil represents more than 60% of the total energy in an OIP bushing.

3.1.2 Ignitability

If a bushing with a composite insulator is exposed to open fire from an external source, it is relevant to know whether the insulator possesses self-extinguishing properties, or keep contributing to the fire. The analysis was performed on a small scale vertical flame test according to a standardized procedure, UL 94. The silicone rubber self-extinguished immediately once the flame was removed and thus fulfilled the highest rating, V0.
3.1.3 Remarks

The relevance of small-scale fire testing can always be questioned since factors such as shape, orientation and the environment surrounding the specimen and the conditions of ignition are all different from field conditions. The small-scale testing detailed here is likely an underestimation of the difference between OIP and RIP from a fire resistance point of view. In reality, when an oil impregnated system fails catastrophically it often exposes a bursting surface that is easily ignited compared to the standardized test procedure used here. RIP on the other hand, usually cracks with a relatively clean surface structure similar to what was tested.

3.2 Internal arcing test

There are a number of root causes for bushing failures, both internal and external. The end-result is not untypically followed by a catastrophic event. The purpose of this test was to simulate the breakdown of a dry 400-kV bushing with a composite insulator. Set-up and execution were carried out in cooperation with a major European power utility.

3.2.1 Test set-up

The test object, an ABB type GSB 420 dry bushing, had a hole drilled to the conductor, and a copper wire was connected to the flange. This was done to create a short circuit between the conductor and flange in order to simulate a flashover in the bushing's most stressed section on the air-side.

Simulating an air-side flashover, rather than an inside transformer flashover, is of more interest since it relates to a safe working environment for the staff.

The test object was then placed in upright position and connected to the test circuit. Finally, the bushing was exposed to a short-circuit current of 63,000 amperes for 0.5 seconds, which in this context is a very long time. The peak current reached 145,000 ampere at the test start; see Figure 6.

3.2.2 Results

The outside of the test object was intact after the test. The only visual indication was a discoloration of the lower section of the air-side.

To ascertain what had happened internally, the bushing was cut along its length. One crack had occurred in the condenser core; see Figure 7.

4. Outer insulation

The outer insulation on polymer HV bushings is generally silicone rubber, either HTV (High Temperature Vulcanizing) silicone rubber or LSR (Liquid Silicone Rubber). The two most common production processes are injection molding and helical extrusion.

Extrusion, which only uses HTV silicone, has several distinct advantages for production of HV bushings. The complete housing for the bushing, independent of shape and length, is continuously extruded in one step and joints and mold lines are thereby avoided. Moreover, the shape of the shed, which is determined by the nozzle of the extruder, can be easily changed, which enables realization of product-specific geometries that reduce the electrical field and increase pollution performance.

Figure 6 - Testing.

Figure 7 – Inside of the bushing.
4.1 Design

The design of the silicone rubber housing involves design of the shed profile geometry and material selection subject to performance requirements and constraints given by the selected manufacturing process and costs.

4.1.1 Shed geometry.

IEC 60815-3 specifies permissible ranges for the following parameters (AC applications):

- Spacing/overhang ≥ 0.65
- Minimum shed distance ≥ 40 mm (for alternating sheds)
- Creepage distance versus clearance ≤ 4.5
- Difference between overhang of the larger and smaller sheds ≥ 15 mm
- The sheds' upper inclination angle 5–25°

No requirement is put on the shed's lower inclination angle but it is mentioned that protected creepage distance is beneficial in areas with type B pollution [2]. In direct coastal and liquid industrial environments, the protected creepage distance is of great importance in preventing the entire surface from being covered with liquid electrolytes. In published studies on the ageing performance of line insulators in fog conditions, it has been observed that insulators with protected creepage distance maintain their initial surface hydrophobicity for a much longer time [3, 4]. In a study on ageing performance in rain conditions [5], it was observed that insulators with a small inter-shed spacing and a small shed inclination are particularly susceptible to degradation of their properties under rain conditions. Water drops collecting on the sheds of such insulators are the cause of corona discharges and lead to the formation of water channels, the collection of water on the sheds edges and the bridging of inter-shed spaces by cascades of water drops. Highly detrimental was the wetting of the undersides of the sheds by water bouncing off the surface of the sheds below.

For DC conditions, no standard is yet agreed upon but based on experience with HVDC systems with voltage up to 600 kV, recommendations have been formulated for UHVDC shed profiles for vertically installed silicone rubber insulators with an alternating profile [6, 7]:

- Spacing/overhang ≥ 0.9
- Spacing ≥ 65 mm (for vertical position)
- Difference between overhang of the larger and smaller sheds ≥ 20 mm
- The sheds' upper inclination angle > 10°
- The sheds' lower inclination angle > 3°

For bushings installed in a near horizontal position and bushings with smaller diameter, the sheds can be different from the requirement.

Another important feature is the design of the shed tip. A large shed tip radius increases the tear strength of the shed and reduces the electrical field at the shed tip. Figure 8 shows an example of a bushing where the difference in electrical field between a shed tip radius of 1 mm and 2.3 mm is 12% in clean conditions. With a drip edge geometry of the shed tip, a large tip radius can be realized without significant increase of material consumption. This feature has been utilized to compact the design of the recently developed 1100-kV DC bushings mentioned in Section 2.

![Figure 8 – Electrical field around shed tips with different radius. Left R=1.0 mm, right R = 2.3 mm.](image-url)
4.1.2 Materials
High quality HTV silicone with a high ATH filler content is a proven outdoor insulation material for HV applications and the dominant material for HV bushings. A good balance between tracking/erosion and hydrophobicity can be obtained with high quality raw materials. The optimum ATH level is still not defined but it is suggested that more than 40% by weight is required to achieve a significant improvement of the tracking/erosion performance in the inclined plane test [8]. According to [9] optimum outdoor performance is obtained with an ATH filler content of 55% to 60% by weight.

4.2 Verifying tests

4.2.1 Laboratory test
IEC 62217 describes mandatory tests for polymer housings. No test is prescribed for the important property hydrophobicity however, even though a test method for hydrophobicity transfer recently was proposed by CIGRE WG D1-14 [1]. Testing shows that a good quality HTV silicone with 50% ATH content, recovers a hydrophobic surface within 24 hours from pollution.

Further verification of the tracking/erosion resistance and hydrophobicity has been made through a 5000-hour multiple stress test followed by determination of the wettability class directly after the test. No flashovers occurred during the test and no tracking or erosion was observed. The hydrophobicity after the aging test was very good with typical values of WC1-3 (WC1 = hydrophobic surface, WC7 = hydrophilic surface). After removal of the pollution layer with isopropyl alcohol, the surface became fully hydrophobic, i.e. WC1.

4.2.2 Field testing
The pollution performance of complete insulators has also been verified in several field tests. A recent test of a production line hollow-core insulator was performed in 2009–2010 at the Koeberg Insulator Pollution Test Station (KIPTS), managed by ESKOM in South Africa. KIPTS is generally accepted as a severe coastal test station for pollution and ageing of outdoor insulators. The winter cycle is considered as a light to medium pollution test and the summer cycle as a heavy to very heavy pollution test. The acceptance criteria for the test are similar to the IEC 62217 1000-hour salt fog test and allow for some material degradation without failing the test. The insulator passed the full-year test however, without any signs of tracking, erosion, puncture or cracks in the material. The tested insulator had a helically extruded housing of ATH-filled HTV silicone rubber and a relatively open alternating shed profile with a 8º lower inclination angle. The specific creepage distance was 32 kV/mm.

4.3 Service experience
The more than 14 years of service experience with the outer housing realized through a seamless helical extrusion of high quality HTV silicone with a high ATH filler content is excellent. More than 100,000 ABB composite hollow-core insulators are in service in over 70 countries worldwide, representing all types of climates without a single failure due to flashover or ageing. Applications include both AC and DC voltage, including UHV and UHVD. Chemical analysis of shed samples retrieved from insulators service aged for 10 years shows no detectable ageing. The analysis included solvent swelling, FTIR spectroscopy, thermo gravimetric analysis, hardness tests and determination of the silicone oil content.

Further information has been gained by inspection of service of aged insulators at sites considered to be representative for different types of climate and pollution.

4.3.1 Examples from Argentina
A detailed survey regarding long-term service experience of ABB composite apparatus insulators made of HTV silicone rubber with helical profile has been made [10]. The main target for the survey was insulators installed preferably in rather severe polluted service conditions. Argentina was chosen together with Australia, China, Iceland, Denmark, Oman and Sweden. The inspected insulators represented voltage classes 145-420 kV at AC and 400-500 kV at DC. The operational time of inspected insulators was in the range 2-17 years. In total, 58 insulators at 11 sites were closely inspected.
The most contaminated place in this survey was a substation in Mendoza, Argentina, located just in a middle of a 4-lane intensive traffic road from each side of the substation. At the Guaymallen and PIP substation in Mendoza were four 145 kV AC live tank breakers with composite insulators inspected after 5 years of service; see Figure 10. The substation has a cold desert climate (Koeppens climate classification) with high UV. The pollution type is inland and industrial with severity d – Heavy (E6 according to IEC 60815-1). The SCD (Specific Creepage Distance) of the insulators is 27.9 mm/kV.

The insulators in Mendoza are in very good condition. The utility do not clean the polymer insulators at the site. The present state of the insulators proves that this is not necessary, even though the insulators are covered with a thick pollution layer. Measurements showed that the surfaces exhibit good hydrophobicity (Wettability Class WC 2). There were no signs of ageing of the silicone rubber due to direct sunshine, even though the region is known for high levels of UV radiation.

5. Summary and conclusions

A large amount of the energy in an OIP bushing is contained in the oil, which in the event of an explosive failure may be sprayed over the equipment and thereby causing multiple seats of fire and expose a very large surface to possible ignition.

- Time to ignition is, with the exception of gel, ten times longer for the components in a RIP bushing compared to an OIP bushing. This is likely to prevent ignition.
- The release of energy is very high for oil. RIP (as well as OIP) also has relatively high release of energy. The other components, including the gel, burn very slowly.

Using only non-brittle materials is advantageous in bushings since the consequences for the transformer and the rest of the substation will be small in the event of a major failure, such as the one simulated.

Outer insulation based on silicone rubber provides excellent pollution performance and minimizes the risk for flashovers. A long service life is ensured by using erosion-resistant, high quality HTV rubber with a high content of ATH filler and proper shed profile geometry.

Figure 10 – Substation 145 kV, Mendoza, Argentina, EDEMSA

From the complete survey are the following conclusions derived regarding ABB composite apparatus insulators made of HTV silicone rubber:
- Long term performance is good - no ageing or deteriorations of any significance was observed
- Good performance with respect to pollution and ageing
- UV resistance is good - no signs of ageing of silicone rubber in areas known with high levels of UV radiation
- Hydrophobicity was very good - Wettability Class within 1-3
Biography

Lars Jonsson works as Senior Technical Specialist at ABB, Sweden. He has worked with transformer components and their applications for twenty-five years. His experience includes design, product development and field investigation of bushings.

Mr. Jonsson is the convenor of IEC SC 36/JMT5, responsible for the bushing standards IEC 60137 and IEC 62199.

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He joined ABB in 1998 and has since then held various positions in Sweden, Switzerland and Australia in the field of R&D, product development, project management, product management as well as marketing and sales.

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