NEW PAPER-FREE INSULATION TECHNOLOGY FOR DRY HIGH-VOLTAGE CONDENSER BUSHINGS

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ABSTRACT

A new Resin-Impregnated Synthetics (RIS) paper-free technology of high-voltage, dry, fine-graded condenser bushings is presented. In RIS technology, paper is replaced by polymeric fiber fabric which does not attract nor absorb humidity. The core is directly coated by a silicone insulator. A family of oil-air bushings based on the new RIS technology for voltages from 24kV to 170kV, has been developed and tested. The design tests have proven that the dielectric, thermal and lifetime properties of the RIS bushings surpass or are at least as good as those of the RIP cores. Climatic chamber test has shown that the RIS material absorbs almost no water and that its dielectric loss is not dependent on long exposure to extremely high humidity. This allows for easy transportation, uncritical storage in the period of installation and reliable performance in service. Type tests for the RIS bushings according to IEC and IEEE standards have been passed (however, bushings are not manufactured to the IEEE dimension standards) and first pilot installations have been agreed with electrical utilities for which the bushings have been commissioned in 2011. The developed family of RIS bushings covers oil-air bushings but the technology can be used for other fields of applications also.

INTRODUCTION

A high voltage bushing is a device used to carry current at high potential through a grounded barrier. Condenser bushings, also called fine-graded or capacitance-graded bushings, are mostly used in high-voltage domain.

In the traditional technologies of condenser bushings, the main electrical insulation consists of a band of paper, coiled-up around the conductor or supporting tube, which is subsequently impregnated by oil or epoxy resin. During winding, sheets of electrically conductive material are inserted between the layers of wound paper band to form field-grading layers. More detailed description of the technology can be found e.g. in [1].

One of the first technologies used for around 100 years was the Resin Bonded Paper - RBP technology. The RBP bushings are produced from resin coated paper and wound in an ambient atmosphere of the workshop. RBP bushings are subsequently not free from voids and hence partial discharges, have regularly high dissipation factor and the RBP core is not gas tight and therefore not applicable for SF6 apparatuses. Nowadays most utilities do not accept RBP bushings any more. Most major bushing suppliers have discontinued their manufacturing.

The second well know technology and today still predominant, covering more than 70% of worldwide demand, is the Oil Impregnated Paper – OIP technology. The condenser core is dried and impregnated under vacuum with transformer grade mineral oil and placed inside an insulating envelope built up from porcelain or composite, which keeps the bushing tight. OIP bushings can be manufactured with low capacitive loss and free of partial discharges. The condenser core remains in a liquid phase throughout its entire life, what could cause leakage problems. The bushing is not pressure-free and not explosion-proof. Transportation, handling and installation must be done according to strict rules. The loss factor has to be checked periodically to keep the cellulose and oil aging process under control.

The state-of-the art technology is the Resin Impregnated Paper – RIP technology. RIP bushings have a curable resin impregnated condenser core that is in direct contact with the transformer oil or any other clean medium. For outdoor application either the porcelain or composite insulator is used. RIP bushings provide a list of significant advantages, such as being fully dry and pressure-free, high temperature class, partial discharge free, low dielectric losses, fire resistance, outstanding mechanical properties. Because of those characteristics, the RIP bushings provide major benefits, like: transportation, storage and installation at any angle, possibility of energizing immediately after installation, long life and long inspection-free periods and an excellent seismic withstand capability.

NEW TECHNOLOGY FOR DRY FINE-GRADED BUSHINGS - RESIN IMPREGNATED SYNTHETICS (RIS)

In the new technology described in [7] and in this paper, referred to as Resin Impregnated Synthetics or RIS, the dense paper of OIP or RIP bushings is substituted by a fabric made of synthetic polymer fibers. Such fabric can be impregnated by liquids of much higher viscosity, including particle-filled resins. In particular, alumina- or silica-powder filled epoxy resin can be used, a robust insulating material proven for decades in other high- and medium-voltage applications. Application of filled epoxy resins opens way to outstanding technical improvements of the bushing technology, such as better thermal properties of the material and shorter, less energy intensive manufacturing processes. One of the early prototypes of a condenser core of a RIS bushing is shown in Figure 1. The wound structure, prior to impregnation, is also shown compared to the traditional one made of paper.

Figure 1: An early prototype of RIS condenser core manufactured at ABB Corporate Research in 2004 (left) and its wound fabric structure compared to the one made of paper (right).

Using the filled epoxy resin, the condenser core can be molded and hardened in a short-time process. The drying of the core prior to impregnation can be entirely eliminated due to no humidity absorption by the fibers. For the air exposed parts of the bushing, the condenser core can then be directly overmolded by silicone elastomer material, forming the external insulator with its shape and properties providing the creepage length and electrical insulation characteristics required for outdoor conditions. The above features result in an uncommonly short manufacturing time for a high-voltage bushing.

Figure 2: Family of oil-air RIS bushings for voltages from 24kV to 170kV.

A family of oil-air bushings with silicone external insulators for voltages from 24kV to 170kV has been developed based on that new technology and is shown in Figure 2. The RIS bushings of the family fulfill all specifications required by the standard IEC 60137 (2008) [2]. The electrical, thermal and mechanical properties are specified also according to the relevant IEEE standards [3].

The new RIS bushings are characterized by a low electrical loss factor, typically below 0.35% while the electrical design of the bushings and the void-free impregnation process allow for partial discharge (PD) free operation up to twice maximal phase-ground operating voltage, specified at the PD measurement background noise of 2pC. This performance, equivalent to that of to the state-of-the-art RIP bushings, is significantly higher than the minimum required by IEC standards which specifies a loss factor <0.7% and PD levels of 10pC at 1.5 and 5pC at 1.05 times maximal phase-ground operating voltage, respectively.

The creepage distance of the silicone insulators of the developed RIS bushings allow for operation of the bushings in environment of pollution severity class e (very heavy) according to IEC 60815-1 (2008) [4]. The angle of mounting is allowed from vertical to horizontal (0° - 90°) due to the dry structure of the bushings.

DESIGN- AND TYPE TESTS OF RIS BUSHINGS

The new family of the RIS bushings has passed all the dielectric type tests required by the relevant IEC and IEEE standards, including power-frequency withstand, full-wave and chopped wave lightning impulse withstand, capacitance and loss factor measurements and partial discharges. As discussed in the previous section, with the latter two points much higher requirements are posed in the test than those required by the standard.

Temperature rise type tests have also been done for the RIS bushing family and confirmed the specified current ratings. The RIS technology benefits from the thermal properties of the inorganic powder filled epoxy resin material. The measured thermal conductivity of the RIS insulation material, in the radial direction of the bushing, is more than twice higher than that of the RIP material. Measurements for both materials have been done at 95°C. The higher thermal conductivity of the RIS material gives more freedom in the thermal design of the bushings.

The limits of the mechanical performance of the material have been tested in a multiple-bending test, in which the cantilever force required to be withstood during 1 minute by the IEC standard [2] was applied up to 700 times to the bushing. After each of the cycles of bending of 100, 300 and 700 cycles in total, a full dielectric test including impulse testing has been applied to check the condition of the bushing. The test has been passed after each cycle without changes of the electrical properties of the bushing.

The structure of the RIS bushing, without parallel application of materials strongly differing in the coefficient of thermal expansion, together with the low-temperature performance characteristics of the materials themselves, results in good performance of the bushings even at extremely low temperatures. The RIS bushings have been tested down to -60°C.

In the example test, three temperature cycles from -60°C to +100°C have been applied to 36kV RIS bushings. The temperature drop from +100°C down to -60°C was conducted within the time of 16h while the holding time at each temperature level was 38h. The 3 units have passed the full dielectric test, including lightning impulse, after the temperature cycling, demonstrating not changed performance of the samples.

To test the interface between the condenser core and the silicone insulator, a water immersion test (boiling water test) was performed on three 24 kV RIS bushings. One bushing was thermo-mechanical pre-stressed acc. IEC 60099-4 [5]. The sample was bent to the specified long-term load. The direction of the load changed every 24 h. The temperature cycles have been performed in parallel to the long-term load. Two cycles from -40 °C to +60 °C have been applied with a cycle duration of 48h.

After pre-stressing, all three bushings were kept in a vessel with boiling deionized water with 1 kg/m^3 of NaCl for 42 hours. The samples were fully immersed in water during the test.

Thereafter, all three bushings passed the full dielectric test acc. IEC 60137 type test specifications [2], including lightning impulse, capacitance and tanδ measurement. Afterwards the adhesion of the silicone insulator on the condenser core was tested. The testing procedure showed unchanged cohesive bond of the silicone.

Figure 3: Adhesion of silicone after water immersion test to epoxy (left) and to aluminum (right)

HUMIDITY ABSORPTION

The main challenge to master the RIP technology is to optimally dry and process the paper during the production, as well as to protect its dry condition during transportation, storage, installation and service. Insufficient measures in any of the mentioned stages can result in an increased dielectric loss factor and reduce the lifetime of the bushing.

In the new RIS bushing technology the paper, and thus cellulose, is eliminated from the insulating material. This drastically reduces its ability to absorb humidity. Thus, even though the condenser core is not protected in the bushing by any humidity barrier such as external porcelain insulator or glass-fiber-epoxy tube, the loss factor is not dependent on the environmental conditions or on the storage time prior to operation.

The performance of the RIS bushing in high humidity has been tested in a controlled environment of a climatic chamber at 40°C and the relative humidity of 95%. This extremely high humidity conditions correspond to almost 50g/m^3 absolute water content in air and is higher than the highest extreme value of 40g/m^3, to be encountered anywhere on earth and only for a short time. The average values in the most humid climates are at least twice lower [6].

For the test the oil side of the bushing was installed in a metal cylinder to simulate the humidity penetration into the body only at the air side, as in real operation at a transformer. The value of the loss factor was measured at regular time intervals. For the measurement, the bushing was taken out of the climatic chamber, the metal cylinder was removed and the tanδ values were measured with an Omicron testing bridge without cooling down the bushing. The test was running for 205 days.

The results are shown in Figure 4. Those results correspond to the RIS condenser core coated by the silicone insulator. Anyway, as the humidity barrier properties of the silicone elastomer are very limited and taking the extremely long time of the measurement, it can be considered valid also for a naked RIS condenser core body. As shown in Figure 4, the loss factor has been very stable during the whole test period. The initial room temperature value of tanδ is very low, less than a half of the maximum allowed by the IEC standard [2]. The value of tanδ measured later on, during the test, is even lower as the loss factor of the applied RIS material decreases with increasing temperature towards its minimum occurring at around 40°C – 60°C.

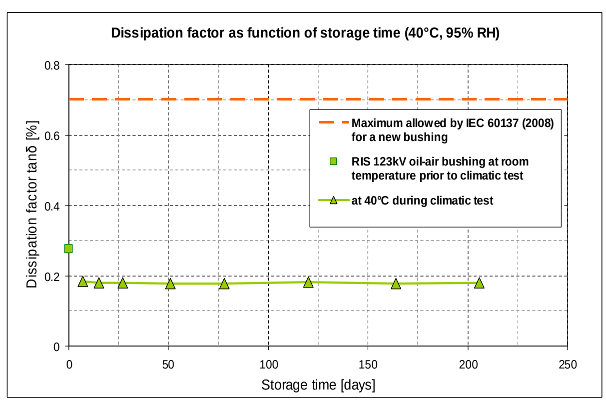

Figure 4: Time dependence of loss factor of a 123kV oil-air RIS bushing in extremely high humidity.

EXPERIENCE WITH PILOT INSTALLATIONS

Field experience with RIS bushings has been gathered at the Koeberg Insulator Pollution Test Station (KIPTS) in South Africa and with reference installations on transformers under operation in substations.

The test installation at the Koeberg Insulator Pollution Test Station (KIPTS) in South Africa consisted of two 123kV RIS bushings which were energized from April 2009 for one year. The KIPTS station, situated some 20km north from Cape Town, at the coast of the Atlantic Ocean, is often considered as the most severe outdoor pollution test station. It's characterized by very large daily temperature changes frequently exceeding 20°C and very high humidity. The pollution includes saline fog, industrial pollution and dust from agricultural areas. No failure of the electrical insulation was noted in any of the RIS bushings during or after the test.

The first reference installation on a transformer, including three 72.5 kV RIS bushings, was energized in June in 2011 in Grynau substation operated by Axpo in Switzerland. Axpo is the second largest Swiss utility. The climatic conditions at the station can be regarded as moderate. The temperature varies between -15°C in winter to maximally 30°C in summer. The altitude is app. 400 meters above sea level. An on-line monitoring system has been installed to be able to measure and record the characteristics of the bushings. The pictures in Figure 5 show the installation at KIPTs and in Grynau.

The second reference installation has been installed in South Africa in a substation operated by ESKOM. It includes three 123 kV RIS bushings. The climatic conditions are sub-tropical with intense UV radiation and maximal ambient temperatures above 35°C.

The third reference installation is installed on two parallel transformers installed by BKW in Switzerland. They include two times three 145 kV RIS bushings and one 72.5 kV RIS bushing for neutral point. The climate is moderate with cold and humid conditions in early winter time.

Figure 5: Two 123kV oil-air RIS bushings at KIPTS test station (SA) (left); a 72.5kV RIS bushings operating at Axpo's substation Grynau in Switzerland (middle) and its connection to the monitoring system (right).

CONCLUSIONS AND OUTLOOK

The new resin-impregnated synthetics (RIS) paper-free technology of dry fine-graded condenser bushings has been developed and tested. In the RIS bushings the paper is replaced by polymeric fiber fabric which, unlike cellulose, does not attract nor absorb humidity. Climatic chamber test have shown that the RIS material absorbs almost no water and thus its dielectric loss is not dependent on long exposure to extremely high humidity. This allows for easy transportation, uncritical storage in the period of installation and reliable performance in service.

The performed design tests have proven that the dielectric, thermal and lifetime properties of the RIS bushings surpass or are at least as good as those of the RIP cores. Thus a new product family of oil-air bushings based on the RIS technology for voltages from 24kV to 170kV has been developed and successfully tested. The developed family of RIS bushings covers oil-air bushings only but the technology can be used for higher voltages and other bushing types as well. Further research and development will be needed to fully explore the prospects and potential of this new technology.

Pilot installations of the RIS bushings have been commissioned in 2011 to gain field experience. Market introduction has started in February 2012.

We can expect that the world-wide trend to shift from OIP to dry type bushings will be accelerated due to the new features of the RIS technology.

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