NANOTECHNOLOGY IN HIGH VOLTAGE INSULATION SYSTEMS FOR TURBINE GENERATORS – FIRST RESULTS

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Abstract: In the electrical power industry one of the first applications of nanotechnology led to a new corona resistance enamel wire for inverter fed motors. In 2006 a research program had been started to improve the electrical properties of high voltage insulation systems for turbine and hydro generators. The erosion and treeing behaviour of hv generator insulation systems loaded with inorganic particles with the scale of some ten to fifty nano-meters had been studied. The outcome of this fundamental research work is a new, more efficient nano particle based ground wall insulation for large generators with a combination of improvements in electrical, mechanical and thermal characteristics.

This paper shows that with the application of specially treated spherical SiO_2 nano particles as part of a well approved epoxy-mica ground wall insulation, the properties of the insulation systems can be improved significantly. Resistivity to partial discharge erosion and electrical treeing is greatly increased and results in longer lifetime until electrical breakdown. Also, the mechanical and thermal properties, which are important for stator windings of large generators, show increased values due to the influence of nanocomposites.

As a first step, basic investigations on epoxy-mica nanocomposites were carried out on plate shaped specimens with standardized electrode configuration for screening tests on material properties. In the second step of development, the new nanocomposite insulation system was tested at small stator winding bars prepared by the same manufacturing process as the original stator winding coils. In the third step, the electrical and thermal tests are transferred to full-size generator stator bars. Compared to the established reference system, the new nano particle based high voltage insulation system shows a tremendous improvement in the electrical lifetime.

1 INTRODUCTION

High voltage rotating machines play a significant role in generating electrical energy as they are the key component in converting mechanical energy (wind propeller, gas, steam or water turbines) into electric power. The demand for new power stations, or for upgrading and refurbishment of existing units, continues to increase due to the global growth in electric power consumption. On the other hand, the deregulated and liberalized energy market leads to cost pressure and high operation reliability on the power plant assets of the utilities. This forces the manufacturer to develop new generator designs with higher efficiency, longer maintenance intervals and much lower lifetime operation costs.

The changed market situation creates a challenge to improve and optimise the winding insulation system of high voltage rotating machines. The generator manufacturers are requesting winding insulations that can withstand a higher electrical field strength than 2 – 3 kV/mm, which is common today, while keeping low production costs, high performance and long lifetime. A fundamental research program has been started to improve the electrical properties of high voltage insulation by using nano particle.

In combination with the different thermal, mechanical and ambient ageing stresses during operation, the electrical treeing mechanism is the main propagation process that finally leads to a breakdown of high voltage winding insulation [1].

Due to a significantly enhanced electrical field at the copper strands of the inner conductor or at the outer ground wall coating, the time interval for first tree initiation in the bars is not very long. After electrical treeing inception at unavoidable local field enhancements or at small delamination/voids, the electrical tree propagates through the epoxy-mica insulation system along the resin path at mica tapes as drawn in Figure 1.

Electrical breakdown tests at stator bars with vacuum impregnated epoxy-mica insulation system showed that the dielectric strength increases with mica content up to an optimum [2]. These old results demonstrated that the treeing path at the resin to mica interface should be as long and narrow as possible to get high electrical strength. Therefore, to slow down tree propagation, the mica content and the number of tape layers of the main wall insulation has be as high as the resin impregnation and curing process can allow [1, 3].

In addition to these well-understood measures, a significant delay and lengthening of electrical tree propagation through the main wall insulation could be reached by using specially treated inorganic SiO_2 nano particles within the resin matrix as shown in Figure 1. The promising results of the influence of nano particles on the performance of improved high voltage (hv) generator stator insulation are presented.

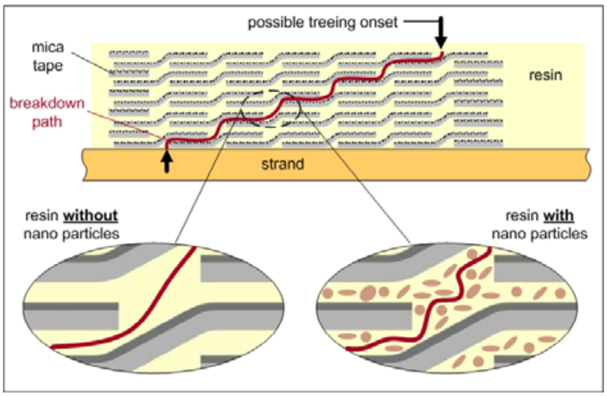


Figure 1: Delay of tree propagation through main wall insulation by using specially treated inorganic SiO_2 nano particles within the resin

2 INVESTIGATION ON MATERIAL PROPERTIES (SCREENING TESTS)

To achieve a more efficient nano particle based hv ground wall insulation system, as a first step fundamental research work on different epoxy resin systems filled with a variety of special treated SiO_2 components was carried out [4, 5]. For these screening tests a standardized type of sample was used, which is easy to produce and to handle, and which generates reliable and comparable results.

Depending on type, amount and preparation process of the nanocomposites the characteristic properties of the nano resin system, such as partial discharge resistivity, electrical treeing behaviour, and also mechanical or thermal strength are strongly influenced.

2.1 Partial Discharge Resistivity

To investigate the partial discharge (PD) erosion behaviour of specially treated inorganic SiO_2 components in comparison to pure epoxy resin, a cylindrical electrode alignment according to International Standard IEC 60343 [6] has been used. The IEC (b) electrode arrangement is given in Figure 2. At the gore between the well defined radius R1 of the hv rod electrode and the sample surface, the electric field enhancement generates partial discharges which stress the surface of the insulation material. By applying a constant voltage level the amount and depth of material erosion is a measure for surface PD resistivity of the material. To minimise the influence of uncontrolled ventilation of air, humidity and by-products, and to prevent electrical flashover, the active test region is encapsulated by a casing with a PMMA ring.

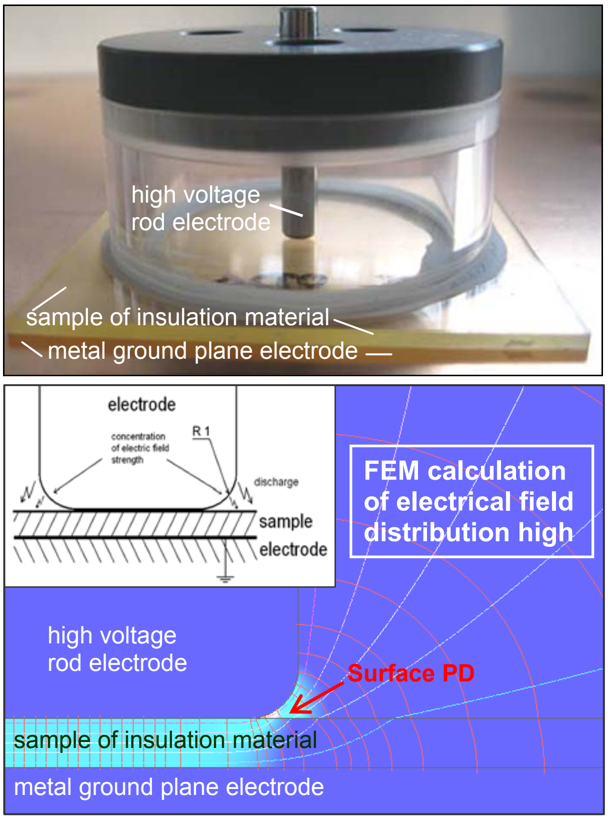


Figure 2: Test set-up acc. IEC 60343 [6] with rod-plane electrode configuration to investigate material resistivity to surface partial discharges

All tests were carried out with thin plane-type samples of 70 mm x 70 mm and the same thickness of 2 mm. To generate a defined PD surface stress a constant AC voltage of 13 kV was used. Samples of pure epoxy resin were compared to samples with different degrees of nano silica filler content, which is distributed uniformly in the epoxy matrix [5]. For all tested specimens the same type of epoxy resin was used independent of the mixture of the compound. All samples were prepared in the same way with a standard surface roughness of 2...3 µm.

The depth of material erosion was scanned with a high resolution of 20 µm in both surface directions with a laser triangulation instrument. In Figure 3 the different amounts of material erosion at pure resin and at resin with 26 wt.% nano particles after the influence of PD activity is shown. The longer the sample of pure epoxy is affected by PD the more volume of resin is eroded near the rod electrode. Also a rougher surface appears and at distinctive locations deep craters are developing. The craters with conductive erosion by-products form pits of higher electrical field strength and the PD activity concentrates on those spots. This results in constituting treeing channels which finally lead to electrical breakdown.

The profile of erosion depth in Figure 3 demonstrates that after PD stress of about 720 h, critical eroded channels with more than 300 µm can be identified at pure epoxy resin samples.

Even 240 hrs of stress are enough to achieve craters of about 200 µm at non-filled epoxy resin, whereas the nano filled system consisting of the same epoxy resin matrix shows a uniform erosion of 50 µm, reaching 100 µm only after 720 h stress.

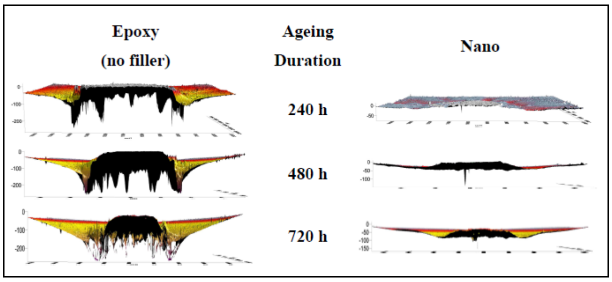


Figure 3: Depth of material erosion due to surface PD - Comparison of pure epoxy resin (non-filled) and nano sized silica filled epoxy resin shows better PD resistance of the filled system [4]

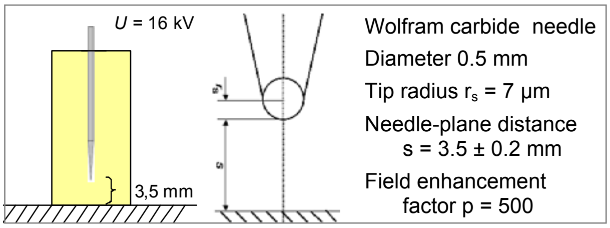
The most important advantage of the new nano composite system appears in the smooth erosion profile compared to the non-filled epoxy. Deep pits with high local field strength that would be the starting point of electrical treeing degradation are well suppressed by the nano particles within the resin matrix.

Further investigation on different parameters of erosion degradation such as, *Surface Roughness, Depth of Erosion, Eroded Volume, PD Energy* and also a description of the observed process of degradation are described in [5, 9]. In coincidence with other research [7, 8] it can be concluded that due to the nano sized particles mixed into the resin matrix, the erosion process is inhibited efficiently with strong dependence on the amount and type of nano sized filler material.

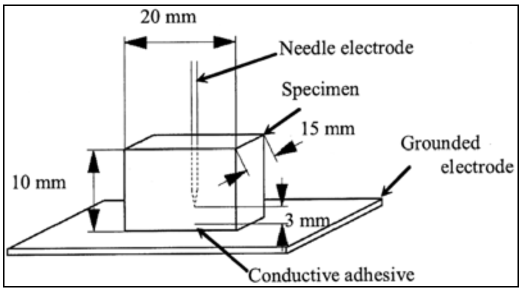
2.2 Treeing Process

The treeing behaviour of epoxy resin specimens with specially treated nano scaled SiO_2 components were investigated by several researchers [10 - 12]. Typical needle-plane test configurations which are used to obtain an extreme electrical high field enhancement to start the treeing process are given in Figure 4. The metal needle electrode with a small tip radius r_s is moulded in a cured resin block, which is fixed on a grounded metal plate. For the distance s between the needle and plane electrodes s = 3.5 mm resp. 3.0 mm are used. Together with the needle radius this results in an electrical field enhancement factor $p = (s + r_s)/ r_s$ of 500 resp. 600 at the needle tip.

Using a treeing test setup with an electrode configuration according to Figure 4 (a) non-filled (oEP) and nano sized 26 wt.% silica filled (n26) epoxy resin samples were exposed to an AC voltage of U = 16 kV until breakdown. Because the maximum electrical field strength at the needle tip was in the high range of E_{max} ≈ 800 kV/mm first electrical trees started after a short inception delay time only.



(a) Electrode configuration with p = 500, see [10]



(b) Electrode configuration with p = 600, see [11]

Figure 4: Test setup of two typical needle-plane arrangements used for treeing process research with nanocomposites

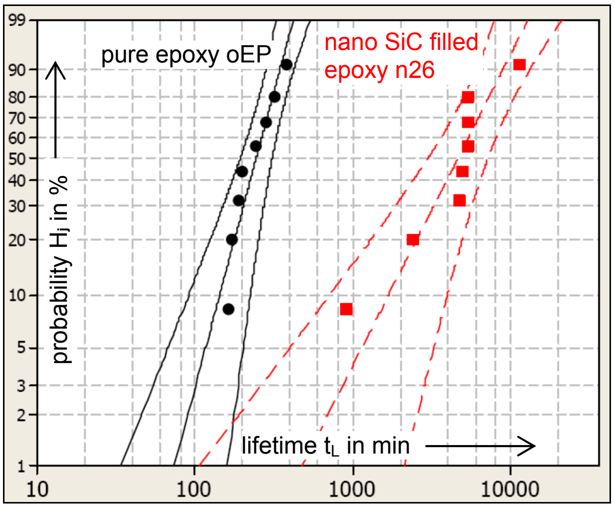


Figure 5: Lifetime t_L of non-filled (oEP) and nano sized silica 26 wt.% filled (n26) epoxy resin stressed with 16 kV AC in config. (a) of Fig. 4

The lifetime t_L of all samples until electrical breakdown was measured and plotted in a Weibull distribution probability diagram (Figure 5). It can be seen that the lifetime t_L of the set of specimens with nano particles (n26) is more than one decade longer than for the set of specimens with pure epoxy resin (oEP). The mean value (Weibull 63%) for the collective of pure epoxy resin (oEP) reaches 272 min while the mean of the collective with nano particles (n26) has a value of 5663 min, which is a more than 20 times longer lifetime for the insulation system with spherical SiO_2 nanocomposites.

The comparison of the treeing structure of samples with pure epoxy resin and samples with 26 wt.% nano sized silica filled epoxy show an increase of a number of tiny tree channels at samples with nano particles, but a significant decrease of tree size and long direct path to ground electrode. More details of investigation and interpretation of the treeing phenomena are given in [10] and [11].

Both the electrical lifetime tests as well as the treeing structure investigations came to the result that nano particles, when properly mixed and dispersed in the resin matrix, increase breakdown strength and retard the growth of treeing. The nano sized particles act as a kind of barrier to the treeing process and hold up the propagation of tiny erosion channels at the particle-matrix interface. Obstructing the tree growth results in significant longer lifetime until breakdown and higher electrical strength of the insulation system.

As treeing and breakdown is efficiently inhibited by mixing nano particles into epoxy resin it might be possible to design a thinner and more powerful insulation system for generator stator windings.

2.3 Thermal Conductivity

The thermal conductivity of the nanocomposite was measured dependant of the filler content with the stationary thermal flow method according to ISO 8301. Figure 6 shows that with the increase of the filler content, the thermal conductivity also increases. With an amount of 26 wt.-% nano particles in the resin the thermal conductivity increases by 15% in comparison to pure resin.

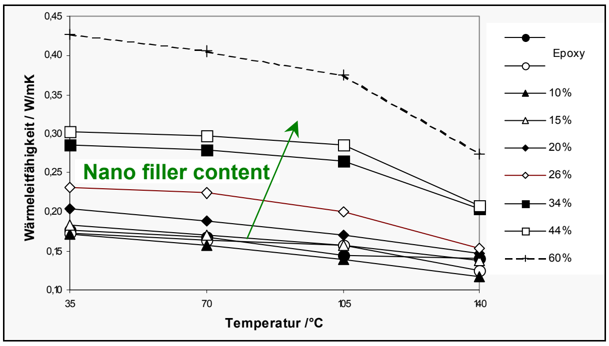


Figure 6: Influence of silica nano filler content (0 – 60 wt.%) in epoxy resin specimen on thermal conductivity in relation to temperature.

3 EPOXY-MICA GROUND WALL INSULATION WITH NANO PARTICLES

The fundamental investigation on nanocomposites performed in several laboratories worldwide came to the result that important insulation system characteristics like partial discharge resistivity, electrical erosion structure, treeing process and the mechanical and thermal properties could be improved significantly by using specially treated inorganic nano sized components like spherical SiO_2 particles [13].

To check whether these insulation system improvements by using nanocomposites could also upgrade the performance of the well approved epoxy-mica ground wall insulation of stator winding coils, further research work is needed which has to be focused on the original generator insulation system. Therefore different stator winding bars with the new inorganic SiO_2 nanocomposite as part of the established taped epoxy-mica system were fabricated and tested.

3.1 Investigation on small stator winding bars

3.1.1 Test Specimen

All small stator winding bars were taped with the same standard mica tape which is also used for original stator coils of U_r = 6.6 kV rated voltage. They were vacuum impregnated with epoxy resin and cured according to the original manufacturing process. Table 1 summarizes the design features of the small test bars with pure epoxy and with SiO_2 nano particle loaded epoxy resin.

Table 1: Design features of small stator winding bars as test samples

Coil length	360 mm
Layer mica tape	4 (HLL)
Mica tape	Standard (glass baked)
Thickness on insulation	1.25 mm
Design	Standard (Large Drive)
Rated Voltage	6.6 kV
Resin (Reference)	Epoxy
Resin (new development)	Epoxy with nano particle
Number of Sample	7 (of each kind of resin)

Figure 7: Seven small stator winding bars with grading system prepared for electrical testing

After impregnation and curing of the bars they were fixed at the outer corona protection (OCP) section with metal plates to ground the insulation system as in the stator core slots (Figure 7).

3.1.2 Dissipation factor measurement

The voltage dependent measurement of dielectric dissipation factor tanδ = f(U) is an approved and sensitive measure to control full impregnation and well curing of all taped layers of the high voltage main insulation. The low tip-up of tanδ = f(U) curve Figure 8 confirms the good impregnation quality of all stator bars with standard MICALASTIC insulation system and with new nanocomposite insulation.

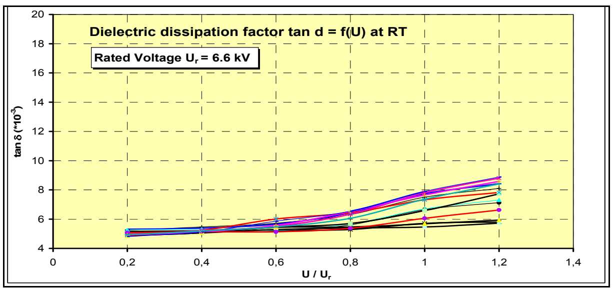


Figure 8: Dielectric dissipation factor tanδ = f(U/U_r) of small stator bars with nanocomposite insulation

The probability plot in Figure 9 demonstrates that the dissipation factor tip-up of the bars with the new nanocomposite insulation achieved an even slightly better impregnation quality (lower tip-up) than the standard MICALASTIC insulation system.

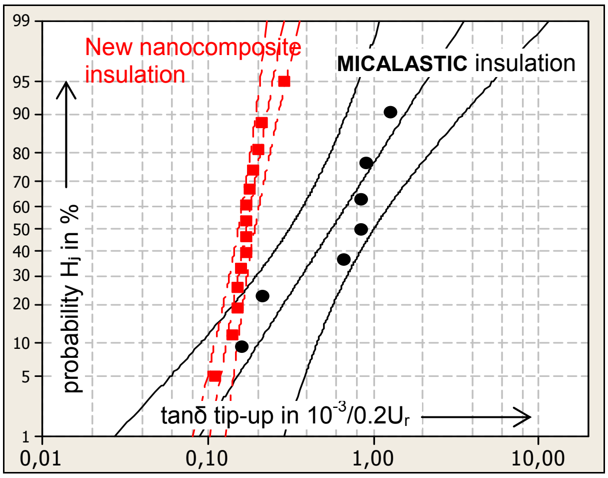


Figure 9: Distribution of tanδ tip-up of MICALASTIC insulation and new nanocomposite insulation

3.1.3 *Voltage endurance test*

As the lifetime of a generator stator winding is in most cases limited by the electrical breakdown of the high voltage (hv) main insulation, the voltage endurance curve of a new insulation system in comparison to the experienced reference system is one of the most important measures to qualify the new insulation system.

To accelerate the voltage endurance tests, a constant test voltage in the range of 3 – 5 times of normal operating voltage is applied to the stator bars. In Figure 10 the mean values (Weibull 63%) of the different breakdown test collectives, each of them has 7 or more samples, are plotted in a diagram of field strength E_D versus lifetime t_L.

The lifetime curves clearly demonstrate that the improved erosion stability of new insulation with SiO_2 nano particles leads to significantly increased lifetime up to a factor of 5 – 10. As these results were achieved at small stator bars only, the next step to qualify new nanocomposite insulation has to be an investigation on original generator bars.

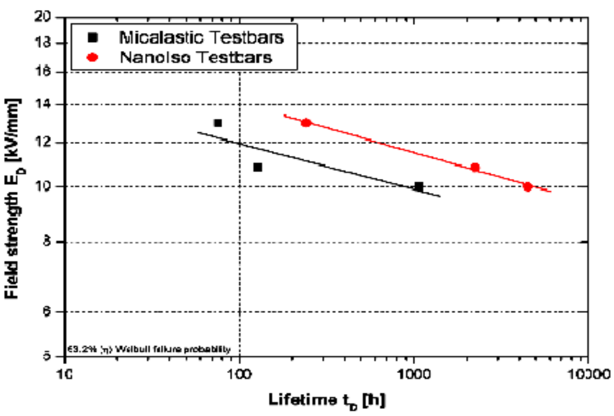


Figure 10: Comparison of electrical lifetime curve of MICALASTIC insulation and new nano insulation

3.2 Investigation on original generator stator winding bars

3.2.1 *Test Specimen*

Forty stator winding bars with the original cross section of an indirect cooled hydro generator of 13.8 kV and 1.6 m length were manufactured with standard mica tapes and original VPI impregnation and curing process. For comparison tests different sets of 8 bars with pure epoxy resin and with nano particle loaded epoxy resin were produced. Figure 11 shows these bars in an hv test cell connected to a voltage endurance test of 2.5 times rated voltage.

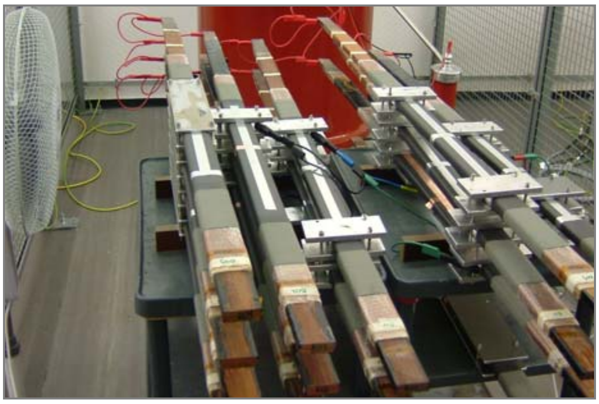


Figure 11: Voltage endurance test at stator bars with the original cross section of an indirect cooled hydro generator of 13.8 kV

The dissipation factor measurement resulted in the same low tip-up values for the bars with standard MICALASTIC insulation and with new nano particle loaded insulation system, which demonstrates the good impregnation of the thicker insulation of original 13.8 kV stator bars also. All tested bars had a maximum tip-up well below $1{\cdot}10^{-3}/0.2U_N$.

3.2.2 *Voltage endurance test*

The results of the first voltage endurance test at 2.5 times rated voltage are given in Figure 12. The standard MICALASTIC insulation achieves a 63% mean value of 648 h while the nano particle loaded bars reach 8,537 h. Tested on original bar sections, the new SiO_2 nanocomposite insulation improves the lifetime of the hv stator main insulation by a factor of 13.

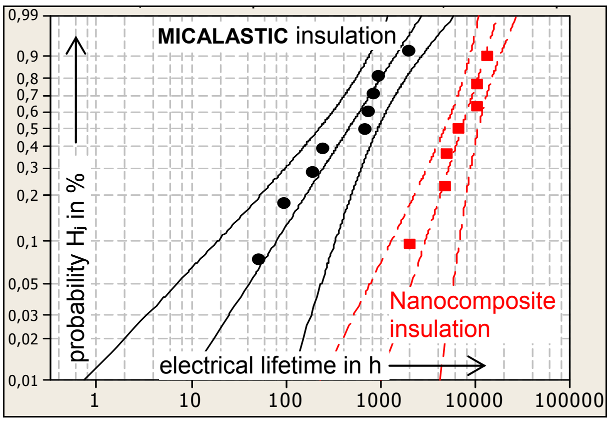


Figure 12: Voltage endurance of original stator bars at 2.5 times rated voltage

4 NEXT STEPS

In the next development step the electrical, thermal and mechanical qualification tests are being transferred to full-size generator bars with a main insulation of 22 kV rated voltage and length of 6 m. The functional qualification procedure of the new candidate insulation system compared to the well proved and established high voltage insulation system is performed according to international standard IEC 60034-18 series [14] dealing with functional evaluation of insulation systems for rotating electrical machines. This qualification program includes the following tests:

1. Thermal aging and classification tests at three different temperatures
2. Electrical aging – voltage endurance tests at three different levels resulting in lifetime curves
3. Multifactor aging by applying thermal cycle and electrical stress in parallel to the main insulation
4. Thermo-mechanical bending endurance in parallel with electrical stress as a multifactor aging test.

If the new candidate insulation system with nanocomposite shows better performance than the established reference system, the final step of the R&D project will be started. An indirect cooled generator will be equipped with a complete stator winding with the new and much thinner high performance insulation with SiO_2 nano particle.

5 CONCLUSIONS

Based on the very promising results of material investigations and insulation testing at generator stator bars the following conclusions can be drawn:

(1) Plate shaped samples consisting of epoxy resin containing different degrees of nano sized silica filler verified that the erosion is inhibited efficiently with strong dependence to the amount of filler.

(2) The nano sized SiO_2 particles act like a barrier to the treeing process and hold up the propagation. Obstructing the tree growth results in a significant longer lifetime until breakdown, and much higher electrical strength of the insulation system.

(3) With the application of SiO_2 nano particle as part of well approved epoxy-mica ground wall insulation, mechanical and thermal properties of the insulation can also be improved significantly. A 15% to 30% higher thermal conductivity has been achieved compared to the reference system.

(4) The voltage endurance tests carried out on original generator stator bars show a tremendous improvement in the electrical lifetime of the new nano particle based high voltage insulation system. In comparison with the approved reference system an increase of a factor of 10 seems to be realistic.

The new insulation system allows a more efficient generator stator winding design and sustainable power plants in the near future.

(5) The newly developed nanocomposite insulation system offers a more effective design of stator windings. It results in less thickness of insulation, but more copper material instead and better heat transfer, due to reduced thickness and filler in particular. It opens new design variations for generators in power increase and retrofit projects.

6 REFERENCES

[1] Vogelsang, R.; Time to breakdown of high voltage winding insulation with respect to microscopic properties and manufacturing qualities. PhD Thesis, ETH Zurich, Hartung-Gorre Verlag Konstanz, 2004

[2] Wichmann, A.: Reliability and Testing of High-Voltage Stator Insulation for Large Rotating Machines, IEEE Winter Meeting 1972, New York

[3] Baumann, Th.; Hillmer Th.; Klee, P.; Stoll, D.: Optimized, Emission free Production Process for Main Wall Insulation with Enhanced Lifetime Properties, EIC 2011, Annapolis, USA

[4] Brockschmidt, M.; Groeppel, P.: Das Erosionsverhalten nanopartikulär gefüllter Dielektrika unter elektr. Teilentladungen; RCC-Fachtagung, Berlin 2009

[5] M. Brockschmidt, F. Pohlmann, S. Kempen, P. Groeppel: Testing of Nano-Insulation Materials, EIC 2011, Annapolis

[6] IEC 60343: Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges

[7] Anglhuber, M.; Rätzke, S. Kindersberger, J.: Koronabeständigkeit und Füllstoffverteilung von Epoxidharzformstoffen mit nanoskaligem SiO_2-Füllstoff, ETG-Fachtagung „Grenzflächen in elektrischen Isoliersystemen“, Würzburg 2008, pp. 21 - 26

[8] Preetha, P.; Thomas, M. J.: Partial Discharge Resistant Characteristics of Epoxy Nanocomposites, IEEE Trans DEI Vol.18, No.1, Feb. 2011, pp.264 - 274

[9] Hoffmann, C.; Brockschmidt, M.; Peier, D.; Untersuchungen zur TE-Resistenz von EP-Harzen mit nanoskaligen SiO_2-Füllstoffen, ETG-Fachtagung “Grenzflächen in Isoliersystemen”, Würzburg 2008,

[10] Hoffmann, C.; Jenau, F.; Das teilentladungsbedingte Alterungsverhalten von SiO_2-Nanopartikeln in Modell-anordnungen bei Wechselspannung, TAE-Seminar, Esslingen, 2011

[11] Tanaka, T.; Matsunawa, A.; Ohki, Y.; Kozako, M.; Kohtoh, M.; Okabe, S.: Treeing Phenomena in Epoxy/Alumina Nano-composites and Interpretation by a Multi-core Model, IEEJ Trans. FM, Vol.126, No.11, 2006, pp. 1128 - 1135

[12] Danikas, M. G.; Tanaka, T.: Nanocomposites – A Review of Electrical Treeing and Breakdown, IEEE Electr. Insul. Magazine Vol.25, No.4 July/Aug. 2009, pp. 19 - 25

[13] Tanaka, T.; et al.: Polymer Nanocomposites – Fundamentals and Possible Applications to Power Sectors, Technical Brochure 451, Cigre WG D1.24, February 2011, Cigre Paris

[14] IEC 60034-18: Rotating electrical machines - Functional evaluation of insulation systems