Significance of Defects Inside In-Service Aged Winding Insulations

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***Abstract*—This study aims to gain insight into the consequences of local defects in stator winding insulation; therefore, optical (microscopic) inspections and voltage-endurance tests have been carried out on in-service aged generator bars. In this context, generator bars with mica–bitumen insulations and generator bars with mica–epoxy insulations were investigated. The mica–bitumen insulations had been in service for 43 years in a 12 kV hydro-generator. The generator bars with mica–epoxy insulation had been dismantled from two identically constructed 10.5-kV generators after 35 and 36 years of service. The time to breakdown values obtained from the voltage-endurance tests were evaluated using a Weibull distribution. Apart from the scale parameter, Weibull exponent of this distribution allowed for the identification of early failures. The voltage-endurance tests carried out on replacement bars for these generators did not yield any early failures; such failures, however, were detected on both types of the in-service aged insulations. In particular, these occurred at high levels of electric stress and at delaminations between the copper conductor and the groundwall insulation. It is concluded that the interpretation of the measured time to breakdown values and their scatter depends on the level of electric stress.**

***Index Terms*—Dielectric breakdown, electrical insulation, insulation life, machine windings, mica insulation.**

I. Introduction

SINCE the introduction of thermoset resins for micaceous insulations for high-voltage rotating machines, the resistance of these insulations to thermal cyclic aging has improved considerably [1]–[3]. At the same time, the electric stress in these insulations has increased from 1.1 kV/mm to more than 3 kV/mm [4]. Apart from the increase in electric stress, other aspects such as the slot packing and the temperatures these insulations are exposed to have changed [5], [6]. Fig. 1 illustrates the components of a winding insulation system of the type that is discussed in this paper. In addition to groundwall insulation, the winding includes conductive corona protection and stress-grading. The latter two are supposed to suppress discharges between the stator and the groundwall insulation, and surface discharges in the endwinding region outside the stator.

Formerly, asphaltic insulations for high-voltage rotating machines, often, suffered from girth-cracking problems [7], [8]. These were caused [9] by different thermal expansion coefficients of copper conductor and mica–bitumen groundwall insulations. The mechanical stresses that occurred between copper conductor and the groundwall insulations during thermal cycles yielded fatigue cracks in the interface between copper conductor and the groundwall insulation [10]. Another problem of those (asphaltic) insulations was tape separation (delamination) at elevated temperatures. With the introduction of insulation systems impregnated with epoxy resins, these became less prone to tape separation [11]. Moreover, the voltage stress applied to these insulations also increased, and so, the question of whether a longer service life can be expected for these insulations remains open.

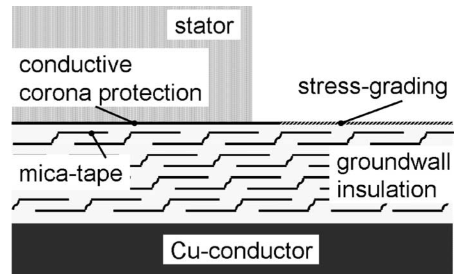

Fig. 1. Components of a winding insulation.

New insulation systems can be evaluated by comparing their electric, thermal, and mechanical characteristics to the corresponding values obtained from the reference systems [12]. Due to financial and time limitations, the tests on new insulation systems are mostly limited to 10 000 h or less. At the same time, it is known that the extrapolation of thermal, mechanical, and electrical aging laws to service stress levels would overestimate the insulation life [13]. Investigations on in-service aged insulations circumvent the (experimental) time constraints during testing. Moreover, they are carried out on specimens that have been exposed to realistic combinations of aging stresses.

Several researchers have, already, addressed the problems found in in-service aged insulations [6], [14]–[16]. For instance, cracks between copper conductor and the groundwall insulation were also found inside (dissected) in-service aged resin-rich winding insulations; these cracks, however, did not lead to unacceptable $\tan\delta$ tip-up values and a reduction of insulation life could not be conclusively demonstrated [6]. Another study on generator bar insulations from turbo-generators yielded a noticeable decrease in voltage endurance after 77 400h ($\hat{=}$ 9 years) of service-aging [14]; however, the time to breakdown values obtained in this study were still in the acceptable range for new insulations. So, no hints on possible premature failures due to insulation aging could be given in these studies.

In order to gain an overview on the prevalent failure causes of winding insulations, the surveys carried out by the IEEE working group [5] and the CIGRÉ committee SC11 [17] provide valuable information. One-third of the insulation failures

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reported in the CIGRÉ survey on hydro-generator failures are ascribed to insulation aging. This is in variance with the laws of electrical, mechanical, and thermal insulation aging, which are described in [18]–[21]. The conclusion that one-third of the failures within the first 40 years of service are attributed to aging is not supported by these laws.

To improve insight into the possible causes of insulation failures, stator bars with both asphaltic and thermoset insulation systems have been investigated in this study. The results obtained from the investigation on the two types of generator bars are compared and related to the characteristics of the corresponding materials. It will be shown that insulation breakdown in thermoset winding insulations is still governed by the weakest site and not by the average dielectric strength. So, tests that are sensitive to local defects such as partial discharge measurements and dielectric withstand tests on whole generators seem to be promising in estimating the reliability of high-voltage rotating machines.

II. Specimens

Two different types of in-service aged winding insulations were investigated in this study. The first set of specimens comprised six generator stator bars, which had been in service for 43 years in a 12 kV (rated voltage) hydro-generator. Class B insulation [22] of these bars was of mica–bitumen type. The maximum temperatures measured in the slots of this machine were close to 85 °C. The insulation thickness in the straight section was 4.1 mm. This corresponds to an electric field stress of 1.7 kV/mm.

The second set of specimens comprised 63 generator bars. These were dismantled from two identically constructed hydro-generators after 35 and 36 years of service. The generators were part of a pump storage power station with corresponding high electrical and thermal loads. Mica–epoxy insulation systems of these generator bars were manufactured using the resin-rich technology with inner and outer corona grading tapes. The rated voltage was 10.5 kV. This corresponds to an electric field strength of 1.9 kV/mm in service. In turbine operation mode, the temperatures measured in the slots reached maximum values of 90 °C. In pump operation mode, these temperatures were lower by 10 °C.

III. Visual Inspection and Micrograph Analysis of In-Service Aged Insulation

None of the mica–bitumen insulated generator bars showed an abrasion of the groundwall insulation due to loose bars in the slot. No damage of the (conductive) outer corona protection due to slot discharges (as described in [15]) was visible. Apart from the slot section, no "white powder" due to partial discharge activity in the endwinding region was detected. The appearance of "white powder" has previously been reported as a symptom of partial discharge activity in this region [23].

Along the slot sections, the insulations exhibited humps at cooling slots (Fig. 2) of the stator. As there were sites at which insulation had expanded into these cooling slots, the degradation of the insulation was expected to vary locally.

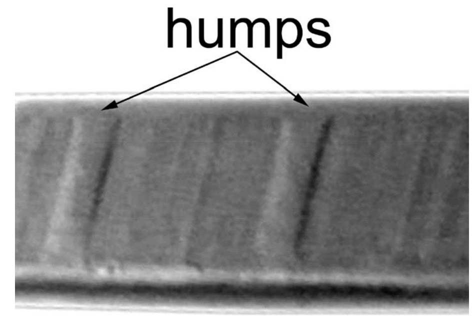

Fig. 2. Humps on the surface of mica–bitumen insulations at cooling slots of the stator.

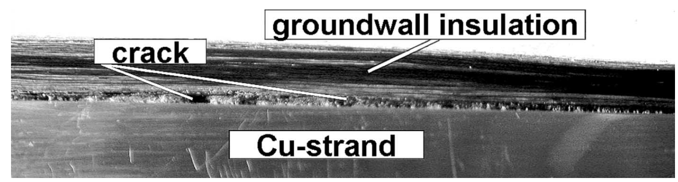

Fig. 3. Full-length delamination between copper conductors and mica–bitumen groundwall insulation.

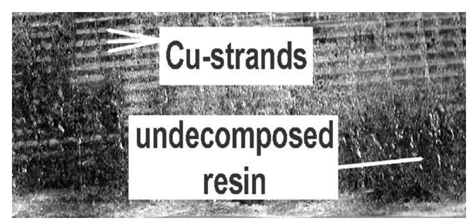

Fig. 4. Undecomposed resin on the surface of copper strands, which are delaminated from the mica–epoxy groundwall insulation.

After the voltage-endurance tests, which will be discussed in Sections IV and V, the bars were dissected and micrographs were taken. These show cracks in the interface between copper strands and groundwall insulation (Fig. 3). These cracks are known to occur as a consequence of mechanical strain due to different thermal expansion coefficients of the insulation and metal parts [9]. Such cracks, which are a symptom of thermal cyclic degradation, were found over the full length of insulation. The widths of these cracks increased outside the slot section.

The microscopic analysis of the groundwall insulation showed that the mica tapes had separated from each other during several decades of service. This delamination was very well visible outside the slot sections of the bars and below the humps shown in Fig. 2. This finding further contributed to the expectation for the residual voltage endurance to vary locally.

Delaminations between copper strands and the groundwall insulation were also found in the generator bars with resin-rich mica–epoxy insulation systems. These delaminations were associated with resin decomposition zones that were caused by the partial discharge activity in these delaminations (Figs. 4 and 5). The appearance of the decomposed resin can be described as white or gray powder. In particular, the resin was, often, found to be totally decomposed at the edges.

Fig. 5. Decomposed epoxy resin on the surface of copper strands.

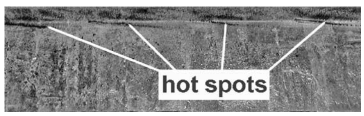

Fig. 6. Degradation of insulation due to hot spots at Roebel transpositions.

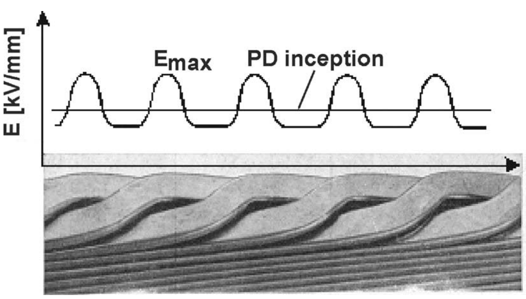

Fig. 7. Elevated electric field that leads to PD inception at Roebel transpositions.

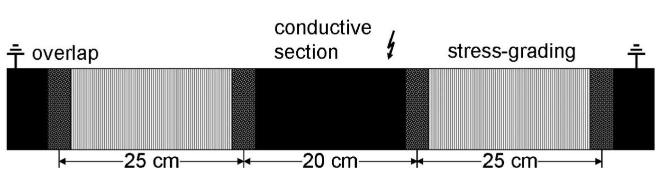

Fig. 8. Preparation of the alternating conductive and stress-grading sections along the insulation.

Under the microscope, black colored spots could be observed all over the insulation. These spots (indicated in Fig. 6) are caused by the partial discharge activity at high electric field sites. Due to Roebel transposition of copper strands (Fig. 7), such high electric field sites occur at the edges of copper wires. The black colored spots closely followed the pattern of Roebel transposition.

IV. Voltage-Endurance Tests

After visual inspection, the residual dielectric strength of the mica–bitumen insulation was anticipated to depend on locally different degradation of the groundwall insulation. The investigation of the local residual voltage endurance was facilitated by manipulating the straight sections of the tested mica–bitumen bars. The outer surface of the bars was divided into alternating conductive and stress-grading sections (Fig. 8).

The conductive sections consisted of the original conductive corona protection varnish and were 20-cm long. The stress-grading sections were 25 cm in length, to which a new stress-grading tape was applied. A voltage of 36 kV rms, 50 Hz was applied to all individual sections that were covered with the original conductive corona protection varnish.

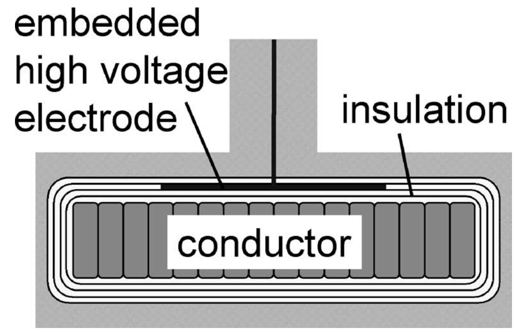

Fig. 9. Embedded electrode for investigations on locally confined defects.

At the same time, neighboring conductive sections and the inner copper conductors were grounded. The applied voltage was chosen equal to three times the rated voltage of the specimens.

To evaluate the insulation at locally confined defects, embedded high-voltage electrodes, as described in [1] and [24]–[26], were employed. This method allows the measurement of electrical tree propagation times in winding insulation [24]. Similar to a needle tip in needle-plane arrangements, the electrical tree inception occurs at the edges of the high-voltage electrode (Fig. 9). Measurements on the dependence of voltage life on electrode length [25] suggest to use electrodes 20 mm $\times$ 20 mm in lateral dimensions. In order to check the results for consistency with previous investigations [27], the electrodes were embedded 2 mm above the copper conductor. A voltage of 32 kV rms, 50 Hz was applied to the electrode. The procedure for embedding the electrode into the insulation was previously developed. This was done by comparing the time to breakdown values of electrodes embedded into the insulation during taping and electrodes embedded after taping [27].

It must be emphasized that only the groundwall insulation is investigated by the applied experimental procedure. Other parts of the insulation system such as corona protection are not assessed. This procedure was chosen because the local residual dielectric strength of the insulation was expected to vary locally. Its aim was to gather information on the significance of defects detected during the visual inspection.

For the availability of 63 generator bars with the resin-rich mica–epoxy insulation, a breakdown test was done on four bars. Two of them were phase end bars and two of them were removed near the neutral point. After applying the rated voltage of 10.5 kV for 1 min, a ramped ac voltage test with a rate of rise of 1 kV/s [28] was carried out. The breakdown occurred in the slot section. A withstand voltage of minimum five and maximum seven times the rated voltage was measured. Based upon this information, a voltage level of 37 kV for the first voltage-endurance tests was determined. Accounting for the duration of the first voltage-endurance test, two other test levels at 30 and 26 kV were chosen. The expected residual insulation life was expected to lie in the interval between 10 and 100 h for the highest, between 100 and 500 h for the medium, and between 500 and 1000 h for the lowest test level. Due to mechanical strains, which stem

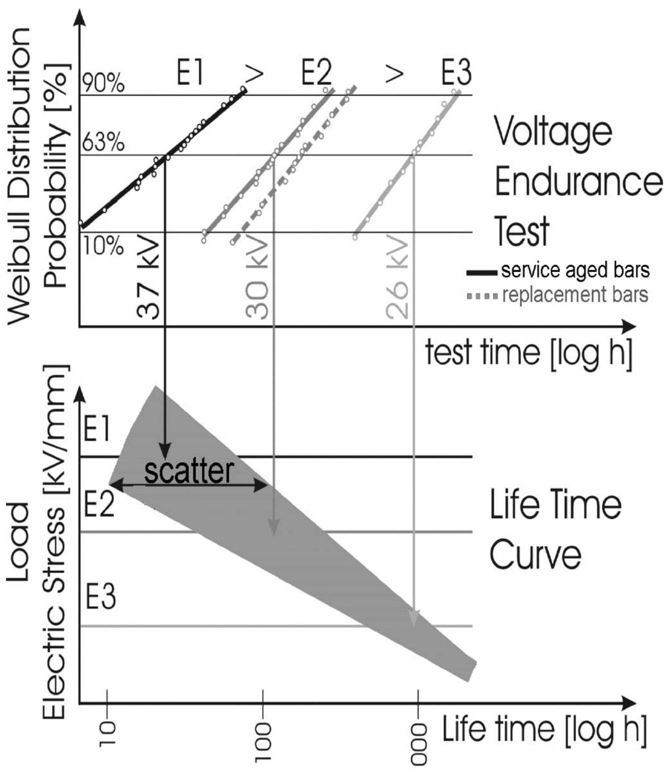

Fig. 10. (Scatter) of the time to breakdown values obtained from in-service aged mica–epoxy insulations depending on the electric stress (E1, E2, and E3).

from the production process, the electrical aging at elevated temperatures results in prolonged insulation life [14], [27]. For this reason, the investigated insulations were electrically aged at room temperature.

V. Residual Voltage Endurances

The test for the local residual voltage endurances on sections of mica–bitumen insulations 20 cm in length (Fig. 8) yielded time to breakdown values between 1 min and 7.5 h. The time to breakdown values have been statistically evaluated using a cumulative Weibull distribution $F_{\eta,\beta}(t)$ with two paramters η and β:

$$F_{\eta,\beta}(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad \eta = 1.6\,\text{h},\ \beta = 0.45. \quad (1)$$

The scale parameter η specifies the time after which 63% of the specimens have failed. Weibull exponent β relates to the slope of the Weibull curve in the (cumulative) probability plot (Fig. 10). In case of early insulation failures ("infant mortality"), the slope will decrease and the value of β will be less than 1. A value of Weibull exponent $\beta < 1$ has previously been determined [29] on winding insulations with locally confined defects. This suggests that the in-service aged winding insulations, which have been investigated in this study, include locally confined defects, too.

In order to verify this assumption, copper electrodes as described in Section IV were embedded

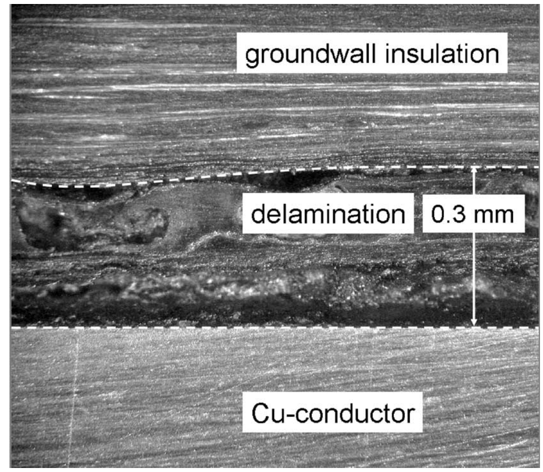

Fig. 11. Delamination found at an early failure site.

- within the slot section but outside the humps shown in Fig. 2,
- directly into the humps, and
- just outside the slot section where the delamination between copper strands and the insulation was comparably large in size.

The time to breakdown values obtained outside the humps were statistically analyzed using a two-parameter Weibull distribution (1), and a value of 1.2 h was found for the scale parameter η and a factor of 5.2 ($\beta = 1.7$) was determined for the scatter between the minimum and maximum time to breakdown value. This is consistent with the scatter measured on new winding insulations [30].

On the other side, time to breakdown values that were less than 1 min were found; these occurred when the electrodes were embedded within the humps (Fig. 2) or above a (large) delamination between copper strands and the groundwall insulation. Fig. 11 gives an example of a (large) delamination found at an early failure site. The delamination was found between a high-voltage electrode (Fig. 9) embedded outside the slot section of the tested bar and copper conductor. This confirms the assumption that the residual voltage endurance of mica–bitumen insulations is governed by local defects and that it varies locally.

Due to the availability of 63 generator bars and several replacement bars with mica–epoxy insulation systems, the voltage-endurance tests on these insulations could be carried out at three voltage levels: early breakdowns occurred particularly at the higher test levels (37 and 30 kV). Some of these happened very early, so that other factors, apart from electrical aging, must be crucial. The characteristic breakdown behavior of the replacement bars was unambiguous. No early failures occurred. Compared to the in-service aged specimens, the characteristic lifetime (scale parameter η) of the replacement bars was longer by a factor of 2.5. The test durations of all generator bars were statistically evaluated using two-parameter Weibull distributions (1). Fig. 10 shows the results of the statistical evaluation. For each of the three test levels, the corresponding Weibull curve is plotted. In addition, Fig. 10 includes a dashed line that is the reference curve obtained from the replacement bars. Furthermore, a common lifetime curve was derived from these Weibull distributions. This curve gives the relation between the applied electric field and insulation life. It is depicted below the Weibull probability plots in Fig. 10.

The slope of the Weibull curve corresponding to the higher test levels is smaller than the slope obtained from tests at 26 kV. At the lowest voltage level and during the tests on replacement bars, no early failures were detected. This results in a larger slope of the Weibull curve (Fig. 10). Weibull exponent β obtained from the statistical evaluation of time to breakdown values (1) confirms the assumption of early failures. Weibull exponents corresponding to the 37- and 30-kV test levels were less than 1. This means that these two probability functions were dominated by failures after short test duration. Weibull exponent corresponding to the lowest test voltage of 26 kV and to the tests on the replacement bars were very similar and greater than 1. This behavior is interpreted as pure (electrical) aging of the resin-rich insulation system.

VI. Discussion

The aging of insulation systems for high-voltage rotating machines can be described by ambient, electrical, thermal, and mechanical processes. Partial discharges, which occur in areas with an electric field above the PD inception voltage, can be both a symptom and a cause of the electrical aging of an insulation [24], [31]. In case of micaceous winding insulations, mainly the (epoxy) binding material is decomposed by partial discharge activity. This irreversible change of the (binding) material properties is a premise for the degradation of the material [32]. Traces of irreversibly decomposed epoxy resin, which were found in the investigated specimens, are shown in Fig. 5 and at the edges of Roebel transposition in Fig. 6. The resin was decomposed into white or gray powder. At high-electric-field sites, it turned to carbon black (Fig. 6).

Thermo-mechanical stresses cause cracks to occur between the groundwall insulation and copper strands (Fig. 3). These thermo-mechanical stresses are caused by the operating mode of the machines. In particular, pump storage machines are exposed to a large number of starts from zero to full load. As the machine has not warmed up yet, different thermal expansion coefficients of copper conductor ($\alpha_{\mathrm{Cu}} = 170 \times 10^{-7}/\mathrm{K}$ [9]) and the (resin rich) mica–epoxy groundwall insulation ($\alpha_{\mathrm{ins}} = 1.1 \times 10^{-7}/\mathrm{K}$ [33, p. 622]) result in mechanical strain. Based on these values, a temperature rise ΔT between 20 and 138 °C on $l = 1$-m long specimen yields difference in elongation Δl close to 2 mm:

$$\begin{aligned} \Delta l &= l(\alpha_{\mathrm{Cu}} - \alpha_{\mathrm{ins}})\Delta T \\ &= 1(170 \times 10^{-7} - 1.1 \times 10^{-7})118 \\ &\approx 2\ \mathrm{mm}. \end{aligned}$$

The resulting cracks were found in both the investigated insulation systems.

The evaluation of the voltage-endurance tests was carried out by employing a two-parameter Weibull distribution (1). For both the investigated insulation systems, early failures (Weibull exponent < 1) occurred only on the in-service aged bars, while none of the tested replacement bars failed early. The dissection of these bars with early failures revealed resin decomposition zones, as described earlier (Fig. 5). Bars that were tested at an elevated electric stress ($\hat{=} 3\,V_{\mathrm{pp}}$) were, especially, likely to show early failures. So, the choice of the test level in voltage-endurance tests on in-service aged insulations is crucial for estimating the reliability of insulation.

The results obtained from both the investigated insulation systems consistently show that the voltage endurances are governed by local defects; however, there is, nowadays, a variety of designs for insulation systems for high-voltage rotating machines [34]. Furthermore, the manufacturing quality is known to have a significant impact on the reliability of the insulation system [23], [35]. For these reasons, the results obtained in this study should not be generalized before further reports on investigations on in-service aged winding insulations become available.

VII. Conclusion

1) Since the residual voltage endurance was found to depend on the weakest site in both the in-service aged insulation systems, tests sensitive to locally confined defects such as partial discharge measurements and dielectric withstand tests gain significance; however, the risks associated with carrying out dielectric withstand tests remain.
2) The resistance to electrical tree growth and thermal cyclic degradation has improved with the advent of micaceous insulations impregnated with thermoset resins; nevertheless, the reliability even of these modern insulation systems is found to be governed by local defects.
3) Apart from manufacturing, weak sites in the insulation can also originate from service. To enhance the reliability of rotating high-voltage machines, periodic diagnostic tests such as offline partial discharge measurements should be applied.

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Christof Sumereder, photograph and biography not available at the time of publication.

Tilman Weiers, photograph and biography not available at the time of publication.