A New Test Method for Assessing the Impact of Thermal Cycling on Hydrogenerator Stator Insulation

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Abstract- A fast growing amount of renewable energy from wind or solar plants with their inherent production fluctuations requires conventional backup and storage capacity in order to keep grids stable. Hence, hydropower plants in Switzerland are increasingly selling peak energy in a liberalized European electricity market. This development leads to higher start/stop-cycle frequencies of their hydrogenerators and some older machines are also subjected to more starts per year than they were originally designed for. In consequence the high voltage insulation system in the stator conductor bars is stressed by a higher number of thermal cycles which might shorten machine lifetimes significantly. In this paper a new test for assessing the impact of thermal cycling in modern mica/epoxy insulation systems is presented. The new method isolates insulation aging exclusively caused by thermal cycling by the use of cycles with short heating intervals and a maximum temperature close to the glass transition point of the insulation system's binder (epoxy) resin. The insulation aging condition is monitored with non-destructive measurements of the Dissipation Factor and Partial Discharges during, and a destructive voltage endurance test after completion of the thermal cycling. A first implementation of the new test method with 1,500 cycles resulted in no severely greater deterioration of the cycled group compared to an uncycled group but shows the necessity of further investigation.

I. INTRODUCTION

Cyclic thermo-mechanical stress in the high voltage insulation system of generator stator bars is a consequence of temperature changes at startup and load changes during operation. The greatest stresses occur when a generator is rapidly brought to full output after a complete cool down. The increasing current produces heat in the stator copper conductors according to the law of Ohm. The heating of the copper causes an expansion proportional to its coefficient of thermal expansion ($\alpha_{Cu} = 1.7 \times 10^{-5}\ K^{-1}$ [1]). The different thermal expansion of the mica/epoxy groundwall insulation ($\alpha_{tox} = 10...100 \times 10^{-6}\ K^{-1}$ [1]) causes shear stresses at the copper-insulation interface and tensile stresses inside the insulation volume. The shear and tensile stresses are determined by the spatial temperature gradient in the bar during heat up and the difference between the temperature in the stress-free state at the beginning of the epoxy curing process during the manufacturing of the bars and the operation temperature. The mechanical stresses also increase with the bar length because of relatively higher thermal expansion in axial direction [2].

The cyclic shear stresses weaken the bond between the conductor strands and the groundwall insulation and can eventually result in delaminations at the conductor insulation interface and between the laminated mica tape layers in the groundwall [3, 4]. Once the voids caused by delaminations and fatigue cracks have grown large enough, partial discharge (PD) sets in and erodes the epoxy resin through oxidation of the polymer chains. Eventually the PD will bore a hole through the organic parts of the insulation and cause failure [5].

The goal of the new thermal cycling test method presented in this paper is to maximize the stress which is solely related to thermal cycling and minimize all other aging factors. In this way the insulation aging caused by thermal cycling can be isolated and more precise conclusions about its aging impact can be drawn.

II. EXISTING THERMAL CYCLING TESTS

Thermal cycling tests have been standardized both by IEEE and IEC. The test according to IEEE 1310 [6] uses full-size bars which are subjected to 500 thermal cycles between 40°C and the thermal class temperature for the insulation (e.g. 155°C for Class F systems). The copper temperature is raised to the upper limit in about 45 minutes by an appropriate current. When the upper temperature limit is reached, the current is shut off and the bar is cooled down by ventilation with air in about 45 minutes. After completion of the cycling the remaining insulation strength is determined by a destructive voltage endurance test. Additional diagnostic measurements (PD, tan$\delta$) may be performed at predefined cycle numbers. IEC stipulates a test method which, in contrast to IEEE 1310, tests the bars inserted in slots, equipped with realistic fixation elements and end-winding bracing [7].

III. THE NEW THERMAL CYCLING TEST METHOD

It has been shown that insulation lifetimes under thermal, mechanical and electrical stress actually increase at moderate temperatures up to approximately 130°C (see Fig. 1). The lifetime maximum at this temperature can be explained by the softening of the epoxy binder resin above its glass transition point of about a 100°C. The transition of the mechanical properties from a hard, glass-like state to rubber-like state leads to a decrease of internal stress and crack formation in the epoxy which reduces the aging speed. Above the maximum lifetime temperature thermal aging through oxidative degradation outweighs the positive effect of an elevated temperature and the insulation lifetime rapidly decreases [8].
Therefore a maximum temperature of a 100°C for a thermal test cycle is ideal for two reasons: firstly, the mechanical stresses in the insulation are most severe below the glass transition point of the epoxy and secondly, the margin of 55°C to the temperature class limit (based on a Class F insulation) also minimizes aging by thermal degradation. In addition, the maximum test temperature of a 100°C is a good reproduction of actual maximum operating temperatures of hydrogenerators. The minimum test temperature is 30°C which, in the case of air cooling, gives the same cooling duration as in the conventional cycling tests (for a bar of the same dimensions).

An important feature of the new test method are its heating periods which are an order of magnitude shorter compared to the tests mentioned in the previous chapter (in the implementation of the test a heating period of 3 minutes is used, see chapter IV). Because of the limited heat conductivity of the conductor/insulation interface and in the insulation itself, a quicker heating (and thermal expansion) of the copper yields a higher spatial temperature gradient across the interface and the groundwall insulation and therefore maximizes shear and tensile stresses. An additional benefit of the short heating periods is a considerable reduction of the duration of a complete cycle.

Thermal cycling without the simultaneous application of high voltage doesn’t lead to insulation failure by itself. Therefore diagnostic measurements are needed to detect potential insulation deterioration caused by the thermal cycling. Before completion of the full number of cycles these measurements must obviously be non-destructive. The measurements should also be sensitive to thermal degradation because if it can be shown that there is little or no thermal degradation after the cycling, any remaining significant deterioration must exclusively originate from the cycling because no other stresses are applied. In addition, a test for partial discharges is needed because an increase of PD activity is a typical symptom of delaminations and voids which can be caused by thermal cycling [Stone]. Previous investigations have shown that Dissipation Factor (tanδ) measurements below partial discharge inception voltage are a robust indicator of aging caused by oxidative degradation [9]. The increase (tip-up, Δtanδ) of tanδ between a voltage below PD inception (usually 0.1-0.2 Un) and the rated voltage (Un) is used as mean to assess the total amount of PD in the insulation as the additional losses at Un are caused by PD. As the tanδ tip-up test only gives information about the total amount of PD, it is completed by a phase resolved PD pattern test which detects PD pulses from individual faults.

After completion of the thermal cycling the insulation strength of the cycled bars is tested with a destructive voltage endurance test and the measured breakdown times are compared with a control group of uncycled bars.

IV. EXPERIMENTS ON STATOR BARS

For the first implementation of the test, 16 service-aged hydrogenerator stator bars were used, divided into two equal groups of 8 cycled bars and 8 uncycled bars. The bars were removed from a 23-year old stator of a Swiss hydropower plant rated 11.5 MVA, 0.80 PF, 10 kV, 50 Hz with a Class F VPI stator insulation. Through the experiment with service aged bars a deeper insight on the behavior of pre-aged mica/epoxy insulation under cyclic stress can be gained. This is needed to assess the risk of subjecting older hydrogenerators to increased thermal cycling stress.

Fig. 2 shows the temperature profile and timing of the cycling experiment. The copper conductors are heated to a maximum temperature of 100°C by the I^2R losses of a circulating current. When the copper temperature reaches 100°C the current is shut off and ambient air is ventilated over the bars until they reach 30°C. The bar surface reaches its temperature peak of 69°C with a delay of 90 seconds. With a heating time of 200 seconds and a cooling time of 1250 seconds, a full cycle takes 1450 seconds and the complete test of 1500 cycles approximately 600 hours.
Fig. 3 shows the results of the tanδ measurements before, in the middle and after the 1500 thermal cycles. The tanδ was measured at 0.1 $U_n$ with guard rings to prevent influences from the semi-conductive field grading tapes at the bar’s ends. The values in the range of 0.6 to 0.7% before the cycling are typical for a healthy, epoxy impregnated insulation. After 750 cycles the values of both measured bars have slightly increased but after completion of the test at 1500 cycles the values are virtually identical as before the cycling. The higher tanδ measured after 750 cycles are most probably due to a higher bar temperature during the measurement [10]. Thus the thermal degradation during the test is obviously minimal.

Fig. 4 shows the tanδ tip-up values calculated between 0.1$U_n$ and $U_n$. The values are relatively low for both test bars and there is no clearly increasing tendency (Farahani measured tip-up factors above 3 after 1,500 cycles in a thermal cycling experiment with comparable test bars [11]). Therefore the increase of PD activity after the 1500 test cycles seems to be rather small. This finding is also confirmed by the phase resolved PD patterns (see Fig. 5 and Fig. 6) which show patterns with almost identical distributions of the apparent charges after 750 and 1500 cycles. Hence, insulation deterioration through formation of new delaminations and/or voids is negligible. After completion of the thermal cycling a destructive voltage endurance test with 3.5$U_n$ was performed on the 8 cycled bars and the 8 uncycled bars of the control group. Fig. 7 shows the Weibull plot for the measured breakdown times [Stone]. The 90% confidence intervals of the characteristic life (time with 63% breakdown probability) overlap only
slightly [12]. However, based on a sample size of 8 specimens in each group and the rather large uncertainty of the Weibull scale parameter for the uncycled group, a conclusive statement about the significance of the difference is not yet possible.

V. CONCLUSIONS

A new test method for assessing the impact of thermal cycling to hydrogenerator stator insulation has been presented with the theoretical background and the results from a first implementation with test stator bars.

The new test was designed with the aim of maximizing aging stresses originating from thermal cycling while at the same time minimizing aging solely related to thermal stress. This is achieved by thermal cycles with short heating intervals and a maximum temperature close to the glass transition point of the insulation system’s binder (epoxy) resin. By doing so, it is now possible to isolate insulation aging exclusively caused by thermal cycling and assess aging properties of specific insulation systems.

The new test method was first implemented in an experiment with service-aged hydrogenerator stator bars. The test with 1,500 cycles resulted in no severely greater deterioration of the cycled group compared to an uncycled group. However, the statistical analysis of the experiment also shows the necessity of further investigation in order to quantify the insulation aging caused by thermal cycling.

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REFERENCES


