High Voltage Insulation Failure Mechanisms

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Abstract- There are many statistics dealing with failure causes of high voltage rotating machines. While these statistics prove the relevance of the insulation as failure cause, they give little information on the real failure mechanism. This paper gives results of a research project which was launched to investigate degradation and final breakdown of the mica insulation in rotating machines. The project was performed by the Swiss Federal Institute of Technology in Zurich in collaboration with several industrial partners and electric power companies.

Final failure of the insulation is usually caused by electric breakdown through a tree channel. Formation and propagation of trees in the mica insulation therefore reflect the ageing process of the insulation. Dominating ageing factors of the mica insulation are thermal and mechanical stress. Manufacturing defects of the mica insulation - such as delaminations, cracks, voids and wrinkled or damaged mica layers - accelerate the formation and propagation of trees. We conclude that good workmanship and proper application of the insulation materials are important factors for the lifetime of high voltage rotating machines.

I. INTRODUCTION

Several statistics are dealing with failure causes of high voltage rotating machines in [1 - 7]. Some of these statistics only specify the part of the machine which failed without giving any deeper insight in the failure mechanism. Other publications distinguish between the damage which caused the machine to fail and the root cause which effected the damage. All statistics agree that breakdown of the winding insulation plays a major role in the failure of high voltage rotating machines.

Several authors investigated failure mechanisms of the mica insulation under laboratory conditions using sample bars or other test specimen [8, 9]. Their main findings are:
1) Although electric breakdown is causing the final failure of the electrical insulation, electrical stress is not the dominating ageing factor. It is rather believed that the ageing mechanism is dominated by thermal degradation of the binder resin, mechanical stress caused by vibration and switching pulses and stress caused by the different thermal expansion coefficients of the materials involved.
2) Ageing under thermal, mechanical and electrical stress shows an increase in lifetime at moderate temperatures up to approximately 130°C and a rapid decrease if the ageing temperature is increased up to 180°C. These findings are explained on one hand by an increasing thermal degradation of organic matter and on the other hand by a decrease of internal stress and crack formation in the binder resin at higher temperatures.

Based on these facts, the goal of this study was to develop a failure model of the high voltage insulation in rotating machines dependent on the operating conditions.

II. INVESTIGATIONS AND RESULTS

A. Electrical treeing in the needle-plane arrangement

The needle-plane arrangement in epoxy cubes allows direct observation of the phenomenon of electrical treeing. Test samples as shown in fig. 1 with an edge length of the epoxy cubes of about 4 cm were prepared. Electrical tree propagation was monitored with a video camera.

Treeing and the formation of branches started immediately after voltage application. Propagation of the trees towards the grounded electrode was detained by the embedded mica tape, trees spread on its surface instead. When the tape edge was reached treeing continued towards the grounded electrode (Fig. 2). Measured average breakdown times were around 100 hours. In all experiments trees could only penetrate the mica tape if it was damaged, e.g. by bending or folding.

Treeing in the needle-plane arrangement was also investigated by partial discharge measurements. Fig. 3 shows the typical evolution of PD peaks during an experiment which

4,5) T. Weiers and R. Vogelsang worked at the project during their stay at the Swiss Federal Institute of Technology Zurich.
lasted about 60 hours or $1.1 \times 10^7$ 50Hz voltage cycles. PD activity in the tree channels started after 10 hours and then rapidly decayed for the next 30 hours. This effect is usually attributed to the formation of conductive degradation products of the binder resin. During the last third of the experiment the PD activity increased until breakdown.

Applying both methods it was found that treeing mostly started at the edge of the copper conductor stack which can easily be explained by the increased electric field strength at this point. While the tree was propagating it never went straight to the outer grounded electrode, but followed the edges of the mica tape, at least to some extent (Fig. 5).

We assume that the tree was able to "take shortcuts" at places where the mica insulation had imperfections or defects such as voids, cracks, delaminations, resin accumulations at tape overlaps and wrinkled or damaged mica layers. Such defects abet the formation and propagation of trees in the mica insulation and thus reduce its lifetime. These assumptions could be confirmed by micrographs of the mica insulation of bars with short life time showing many wrinkles and voids (Fig. 6). These findings are in good agreement with the results of the needle-plane experiments, where we observed that the electrical tree is not able to penetrate the mica tape if it is undamaged, but can easily break through if the tape had been bent or kinked before embedding in the needle-plane test specimen.

It is therefore obvious that the manufacturing quality of the mica insulation has an influence on the lifetime of high voltage coils or bars. Voltage endurance tests were done to verify this. The Weibull plots in fig. 7 show a significant difference in the lifetime of sample bars with and without wrinkles in the mica insulation.

**C. Thermal and mechanical ageing of bars**

It was stated in the introduction that thermal and mechanical stress are the dominating ageing factors of the insulation in high voltage rotating machines. Therefore a large number of
Voltage endurance tests were performed to investigate the two stress factors. Fig. 8 shows the influence of the ageing temperature on voltage endurance investigated in a combined thermal/ electrical ageing test. Results show that the lifetime of the insulation is higher at 160°C than at 20°C which is in accord with the statements cited above [8, 9]. This can be explained by a higher flexibility of the binder resin at elevated temperature which minimises the risk of crack formation, but also by a reduction of internal stresses coming from the curing reaction which usually takes place at temperatures around 160°C. However, at 180°C thermal degradation of the binder resin was the dominating ageing factor and lifetime of the model bars was considerably reduced. According to T. Weiers [10] the optimal ageing temperature for maximum lifetime of epoxy based mica insulations is about 90°C.

Mechanical stress is exerted on the insulation of high voltage rotating machines due to vibration, different thermal expansion coefficients of the materials involved as well as transient and centrifugal forces. Vibration experiments were conducted on sample bars using a newly developed vibration equipment which allowed 100 Hz vibrations with an amplitude of ± 0.5 mm. Insulation life was measured applying vibrational and electrical stress simultaneously and compared to bars exposed to electrical stress only. Two different insulating materials were used for this test: Insulation A, a combination of a glass-backed mica tape and an epoxy based VPI resin and insulation B, a combination of a polyesterfilm/-fleece backed mica tape and a polyester based VPI resin. Results show that the lifetime of insulation B was reduced through vibration by a factor around 10, whereas the lifetime of insulation A was not altered (Fig. 9).
The vibration experiments did not include mechanical abrasion of the slot corona protection as the sample bars were not placed in a slot model. Abrasion of the conductive layer in the slot by the sharp edges of the laminated stator core is an additional factor damaging the insulation and reducing its lifetime, especially if the wedging of the bar in the slot becomes loose. As a consequence partial discharge occurs, adding chemical degradation of organic insulation materials to the mechanical erosion caused by vibration. In the literature, this vicious circle is considered one of the main causes of premature failure of high voltage rotating machines [2]. Fig. 11 shows the impact of vibration: the slot corona protection is worn except for the positions of the air ducts.

All experimental work of this study was conducted at the high voltage laboratory of the Swiss Federal Institute of Technology Zurich. A more detailed description of the test equipment and the specimens is given by T. Weiers [10] and R. Vogelsang [11].

III. CONCLUSIONS

Breakdown of the winding insulation plays a major role in the failure of high voltage rotating machines. The final failure of the insulation is usually caused by electric breakdown through a tree channel. Formation and propagation of trees in the mica insulation therefore reflect the ageing process of the insulation. We found that treeing is accelerated by defects in the mica insulation such as delaminations, cracks, voids and wrinkled or damaged mica layers. Such defects are either manufacturing failures or they result from ageing.

Ageing is not dominated by electrical stress but rather by the combination of different stress factors, of which thermal and mechanical wear are the most important. Thermal stress of epoxy based insulation systems is relevant if it exceeds the optimal temperature range substantially, i.e. above 135-140°C. Mechanical stress of the insulation is due to vibration, different thermal expansion coefficients of the materials involved as well as transient and centrifugal forces. We found that vibration alone had no negative effect on the voltage endurance of insulation systems composed of glass backed mica tapes and epoxy based binder resins, whereas other insulation systems sustain a considerable reduction of lifetime due to the formation of cracks parallel to the mica layers. In the long run mechanical stress and thermal degradation of the binder resin can provoke a loosening of the bar or coil in the slot. The resulting vibrations will cause abrasion of the slot corona protection by the sharp edges of the laminated stator core and partial discharge will occur irrespective of the insulation system used.

Insulating systems used for rotating high voltage machines are mature products and will last for decades if they are applied properly. We found that early breakdown of the insulation can very often be attributed to manufacturing defects and therefore we conclude that good workmanship and correct application of the insulating materials are important factors for the lifetime of power generators. We also think that the experimental study of individual deterioration factors is essential for future establishment of residual life estimation of the generator insulation and further work in this field is necessary.

REFERENCES

[1] North American Electric Reliability Council (NERC)

Fig. 11. Abrasion of the slot corona protection due to vibration