Insulation Failure Mechanisms of Power Generators

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Introduction

Several statistics have been published dealing with failure causes of high voltage rotating machines in general and power generators in particular [1 - 4]. 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. The survey of 1199 hydrogenerators carried out by the CIGRE study committee SC11, EG11.02 provides an example of such an investigation [5]. It gives detailed results of 69 incidents. 56% of the failed machines showed an insulation damage, other major types being mechanical, thermal and bearing damages (Figure 1a). Root causes which led to these damages are subdivided into 7 different groups (Figure 1b).

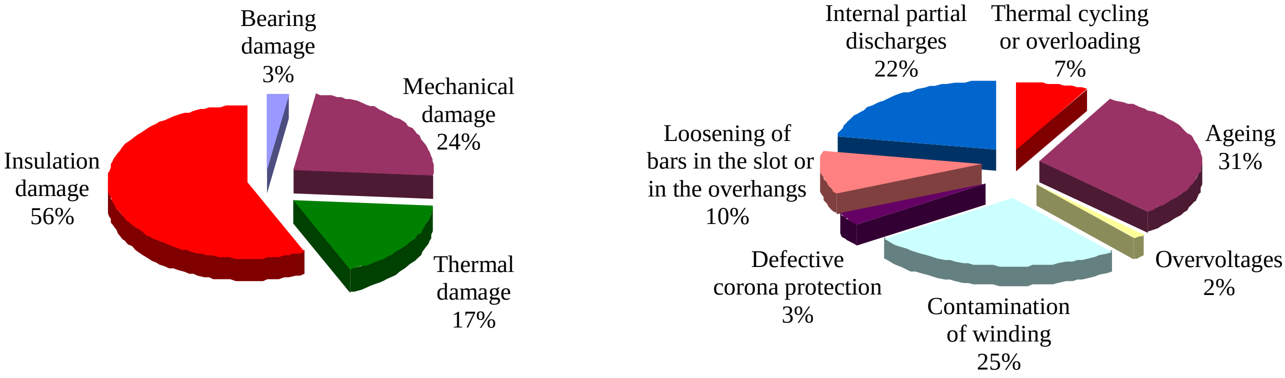


Figure 1a and 1b. Damages of hydrogenerators (left) and root causes of insulation damages (right) [5]

It may therefore be deduced that insulation failure is a significant root cause for the breakdown of high voltage rotating machines.

Several authors investigated failure mechanisms of the mica insulation in the laboratory using sample bars or other test specimen [6, 7]. 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 (Figure 2).

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, a joint research project was launched which included several industrial partners, electric power companies and the Swiss Federal Institute of Technology in Zurich. The goal of this study was to develop a failure model of the power generator insulation dependent on the operating conditions of the power generator. The investigation covered electrical, thermal and mechanical ageing of specially developed specimens, standard sample bars and original generator bars.

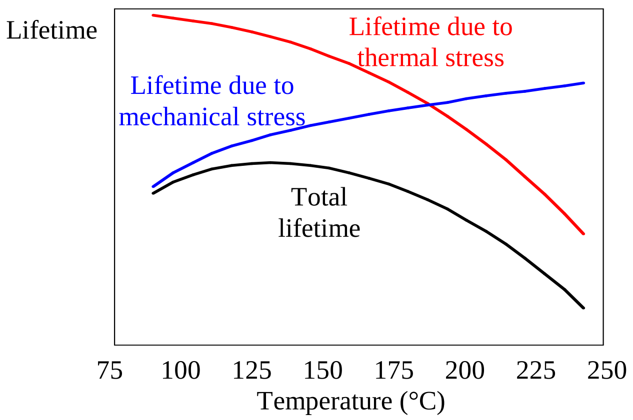


Figure 2. Schematic graph showing the lifetime of mica insulation as a function of thermal stress (red curve), mechanical stress (blue curve) and their interaction (black curve).

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 figure 3 with an edge length of the epoxy cubes of about 4 cm were prepared. The size of the mica tape was 2 x 4 cm. Electrical tree propagation was monitored with a video camera.

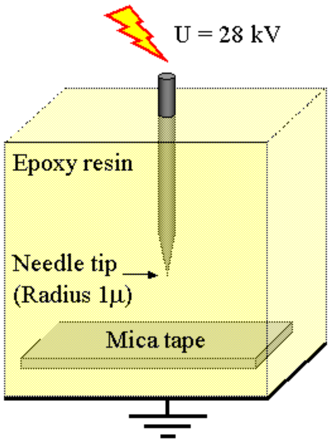


Figure 3. Needle-plane test sample

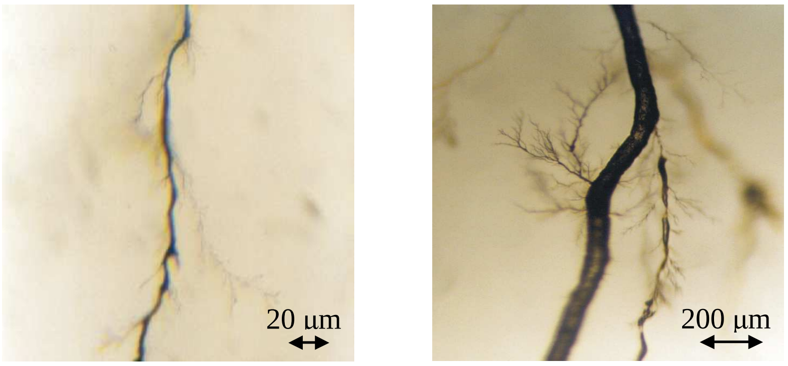


Figure 4. A small tree (left) and a broader tree channel (right) which is sufficiently conductive for breakdown

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 continued to propagate on the surface of the mica tape instead which required most of the total breakdown time. When the tape edge was reached treeing continued rapidly heading for the grounded electrode. Breakdown did not occur immediately after the first branches reached the ground. More branches were generated and the diameter of the tree channels increased up to 50-200 µm. At this stage conductivity and continuity of the tree channels were sufficient to cause breakdown (Figure 4). Measured average breakdown times were around 50 - 100 hours. In all experiments trees could only penetrate the mica tape if it was damaged, e.g. by bending or folding.

B. Electrical treeing in the mica insulation of bars

1 m long model bars with an insulation thickness of 2 mm prepared with VPI and resin-rich technology were used for $3U_n$ voltage endurance tests (Figure 5). The voltage applied was 32 kV AC. To verify if electrical trees can be found in the mica insulation sections of the bars were examined by X-ray methods. Figure 6 shows an example of a bar section; the tree is accented graphically. The tree path could also be traced by burning off the binder resin of the mica insulation in an oven and carefully removing layer by layer of the mica tape. Applying both methods it was found that the tree 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.

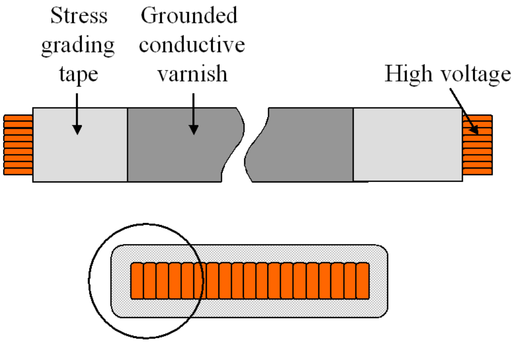


Figure 5. $3U_n$ model bar used for voltage endurance tests. Treeing was investigated in the encircled section.

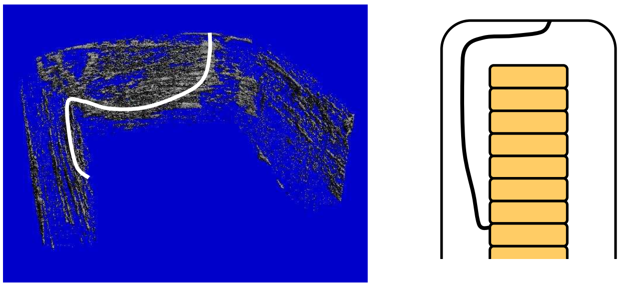


Figure 6. Tree path in a $3U_n$ model bar uncovered by X-ray methods (left) and traced by burning off the binder resin and removing the layers of mica tape (right).

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 showing many defects (Figure 7). 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.

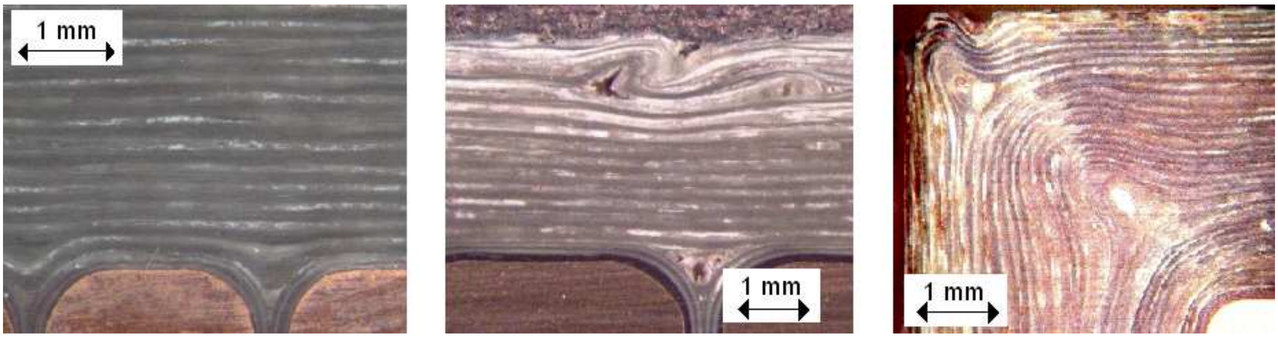


Figure 7. Perfect mica insulation (left) and mica insulation showing various defects (two micrographs on the right) such as voids, wrinkled and folded mica tapes

It is therefore obvious that the manufacturing quality of the mica insulation has an influence on the lifetime of the coil or bar. Several voltage endurance tests were done to demonstrate this using different bar types as shown in figure 8. The resulting Weibull plots are given in figures 9 - 11. Figure 9 compares the lifetimes of bars manufactured under industrial conditions and bars made in the laboratory. Applying the mica insulation carefully on model bars in the laboratory results in a slight increase of the characteristic lifetime. Figure 10 shows the lifetime of bars which were manufactured applying a poor and a correct VPI impregnation process. Poor impregnation gave a mica insulation with lots of voids, the characteristic lifetime of the sample bars investigated was reduced by a factor 10. Figure 11 gives the difference between bars with and without wrinkles in the mica insulation. Again, the difference in lifetime is significant. Manufacturing defects and treeing paths in the mica insulation of the different bars were analysed as described above. We conclude that these defects enhance the formation and propagation of electrical trees and thus reduce the lifetime of the insulation.

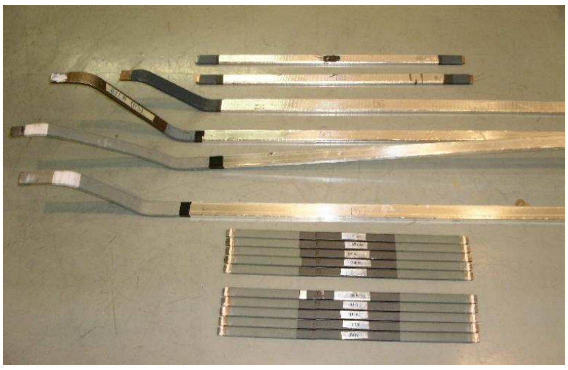


Figure 8. *Different types of model bars used for voltage endurance measurements*

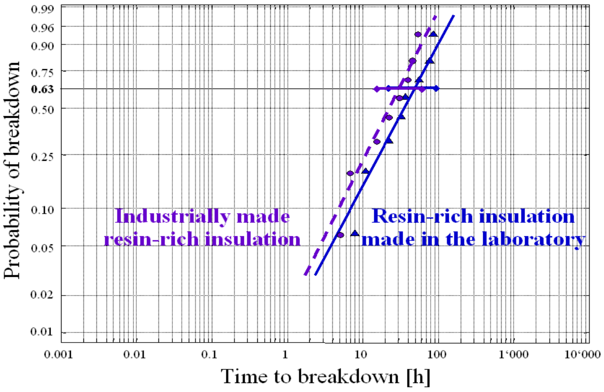


Figure 9. *Voltage endurance of industrially made bars and model bars made in the laboratory*

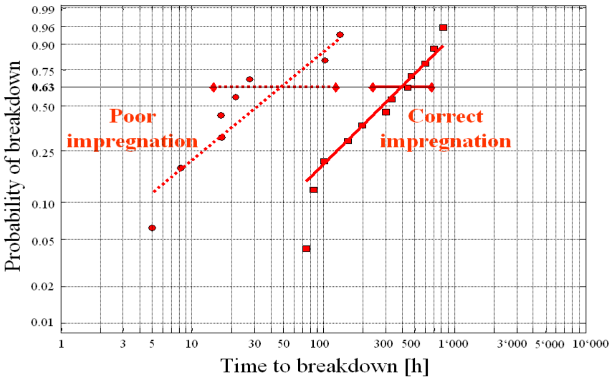


Figure 10. *Influence of the VPI impregnation quality on voltage endurance*

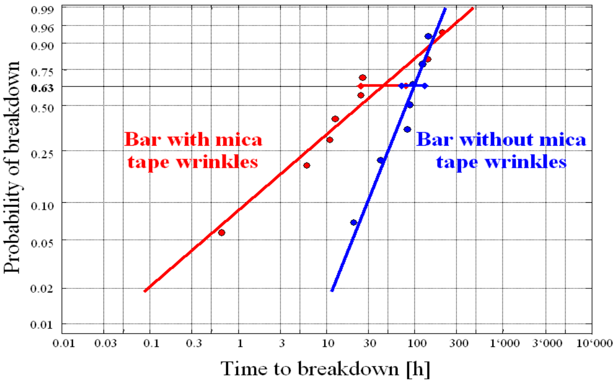


Figure 11. *Voltage endurance of generator bars with and without wrinkled mica tape layers*

C. Thermal and mechanical ageing

In the introduction it was stated 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 was performed to investigate the two stress factors. Figure 12 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 [6, 7]. 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 the reduction of internal stresses coming from the curing reaction which usually takes places at temperatures around 160°C. It may also be that the longer life at 160°C is due in part to a post curing effect that occurs at the higher temperature. However, at 180°C thermal degradation of the binder resin is the dominating ageing factor and lifetime of the model bars was considerably reduced. According to T. Weiers [8] the optimal ageing temperature for maximum lifetime of epoxy based mica insulations is about 90°C, which is within the usual operating range of large power generators.

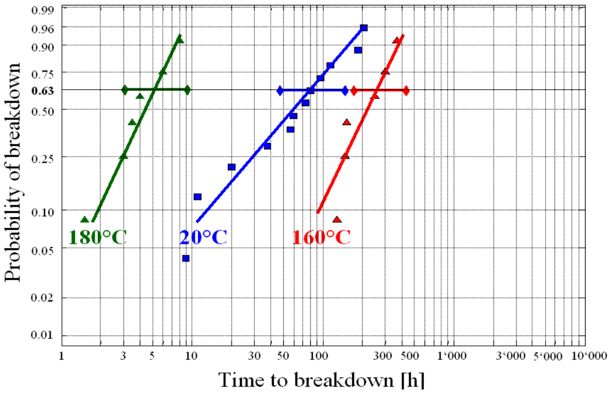


Figure 12. *Influence of the ageing temperature on voltage endurance*

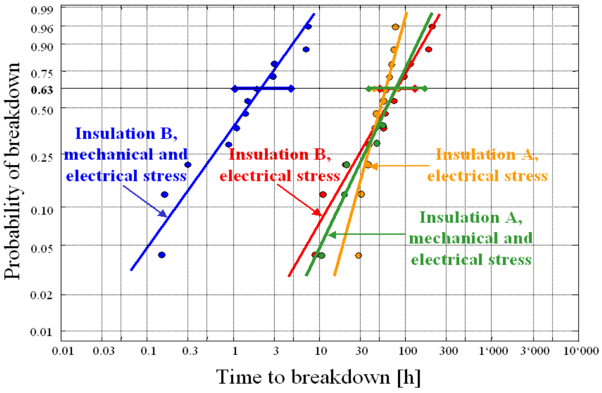
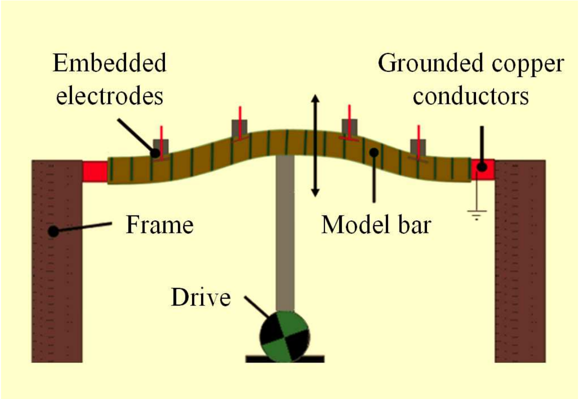


Figure 13. *Influence of mechanical stress (vibration) and type of insulation on voltage endurance*



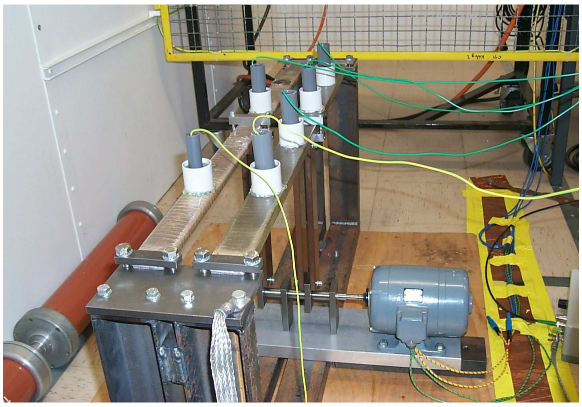


Figure 14. Vibration test equipment. Voltage was applied to the model bars by embedded electrodes.

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 1 m long sample bars using a vibration equipment which allowed 100 Hz vibrations with an amplitude of ± 0.5 mm (Figure 14). Insulation life was measured applying vibrational and electrical stress simultaneously and compared to bars exposed to electrical stress only. Voltage was applied to the bars by embedded electrodes. They were set directly into the insulation in order to avoid any surface discharges. The sharp edges of the electrodes initiated tree inception immediately after voltage application. Insulation thickness and voltage applied were the same as for the 3Un model bars (2 mm, 32 kV AC). The advantage of this test method is that up to four breakdown measurements can be performed with one bar. R. Vogelsang [9] proved that voltage endurance results obtained with the method of embedded electrodes agree with lifetimes measured according to IEEE 1043.

Two different insulating materials were used for the vibration tests: Insulation A, a combination of a glass-backed mica tape and an epoxy based VPI resin which is mostly used for large power generators, 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 (Figure 13). Micrographs of insulation B show delaminations parallel to the mica layers which are supposed to trigger and accelerate treeing; but the formation of cracks perpendicular to the mica layers could not be observed. Polyester resins are known to give a lower adhesion and a higher shrink during curing compared to epoxies. This effect is enhanced by the mica tape used for insulation B; polyesterfilm as a carrier material results in a lower mechanical strength of the insulation than glass fabric.

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 literature, this vicious circle is considered one of the main causes of premature failure of high voltage rotating machines [2]. Figure 15 shows the impact of vibration, the slot corona protection is worn except for the positions of the air ducts.

Figure 15. Abrasion of the slot corona protection due to vibration

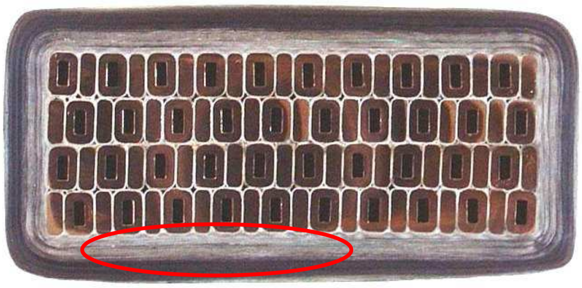


Figure 16. Discoloration of the mica insulation due to leakage of cooling water [10]

D. Investigation of original generator bars

Used and new original hydro generator bars of different origin were available for investigation. Voltage endurance tests, visual and microscopic inspection were carried out to compare results with the findings of the laboratory test samples. Figure 17 gives micrographs of bar sections in different phases of ageing showing delaminations and voids.

Examining bars originating from hydro generators with a vertical shaft alignment we detected bars with deteriorated or detached slot corona protection. The reason for this defect was found to be the lubricant of the bearings penetrating into the stator slots if the sealing had become leaky. The leaked lubricant had a detrimental impact on the slot corona protection.

Leakage of cooling water in directly cooled generators is also known to deteriorate the main wall insulation [10]. This type of damage could be detected in cross sections of the affected mica insulation by a distinctive discoloration (Figure 16).

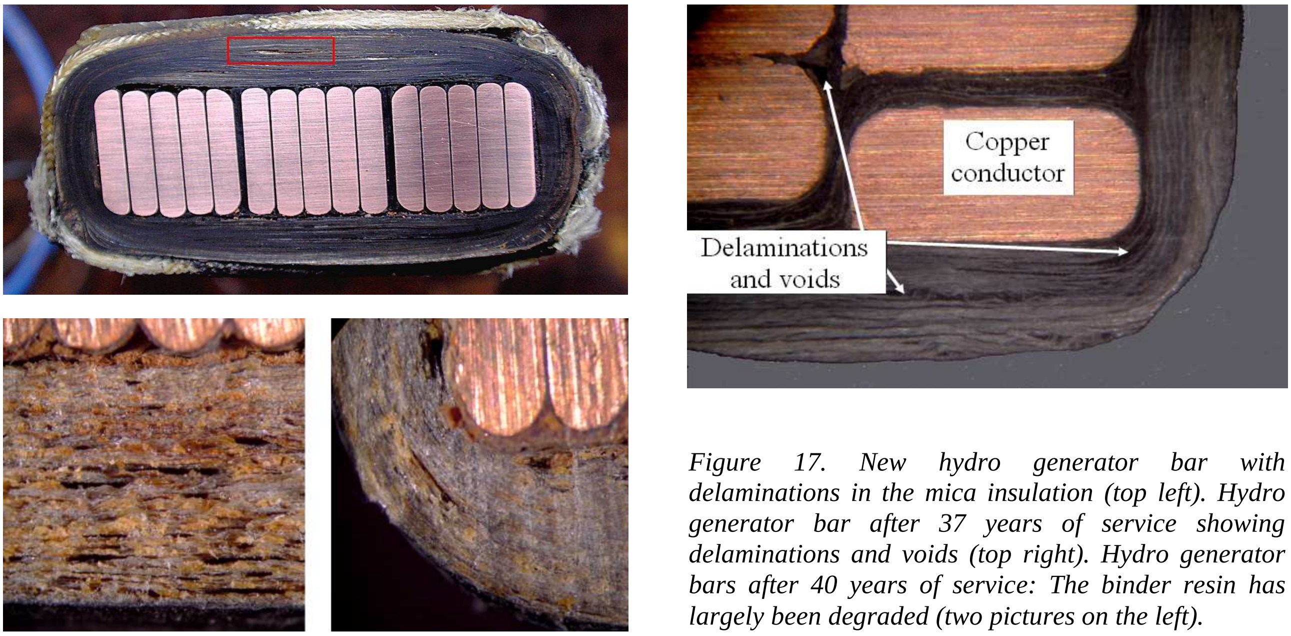


Figure 17. New hydro generator bar with delaminations in the mica insulation (top left). Hydro generator bar after 37 years of service showing delaminations and voids (top right). Hydro generator bars after 40 years of service: The binder resin has largely been degraded (two pictures on the left).

The depletion of lifetime through ageing is shown in figure 18 comparing the voltage endurance of used, but still functional generator bars with new ones. The remaining lifetime of the used bars is drastically reduced.

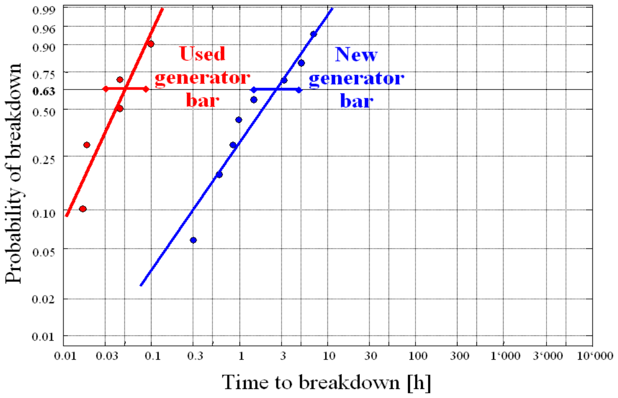


Figure 18. Comparison of new with used, but still functional generator bars

All experimental work was conducted at the high voltage laboratory of the Swiss Federal Institute of Technology Zuerich. A more detailed description of the test equipment and the specimens is given by T. Weiers [8] and R. Vogelsang [11].

Conclusions

If we exclude any abnormal or faulty operating conditions, premature power generator insulation failures can be classified as:

- Design failures
- Material failures
- Manufacturing failures
- Maintenance failures

The final failure of the insulation is usually caused by electric breakdown through a tree channel. Formation and propagation of trees in the 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, rapid changes in load as well as centrifugal forces. Insulation systems mostly used for large power generators are composed of glass backed mica tapes and epoxy based binder resins. Surprisingly we found that vibration alone had no negative effect on the voltage endurance of this type of insulation system, whereas other insulation systems showed a considerable reduction of lifetime. But if wedging of the bars becomes loose, vibration 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. Other insulation damages observed in used hydro generator bars were due to leakage of bearing lubricant or cooling water.

Insulating systems used for large power generators 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 failures and therefore we conclude that good workmanship and correct selection and 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.

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