INTRODUCTION

The history of high voltage electrical machines starts with the disclosure of the electromagnetic induction by M. Faraday in 1832 and the dynamo electric principle by W. Siemens in 1866. Already from the beginning the engineers recognise the importance of the insulating material for electrical machines due to the electrical, thermal and mechanical stress. The first insulation materials were wood, caoutchouc, glass, gutta-percha and textiles, but already in 1858 the first impregnated materials using bitumen or asphalt together with cotton came into service (1). The lack of temperature resistant materials accompanies the development of electrical machines up to now. At 1900 the introduction of the three phase AC system and the demand for larger machines with higher rated voltage led to the insulation design of high voltage electrical machines, which, at least in Europe, is more or less unchanged up to now. The disclosure of mica as an excellent insulation material for electrical machines in 1892 shows again the long history of materials used until today.

The demand on increasing power for large rotating machines leads to higher rated voltages and, as consequence, to higher electrical stress. Furthermore, the increasing rated voltage causes a higher risk of partial discharges within the insulation material as well as on the surface, in particular at the end of the coils. Fig. 1 shows as an example the relation between generator rating and rated voltage for large turbine generators (2), which can be approximated by a straight line.

The first two parts were important also at lower voltages, the last one becomes important with increasing rated voltages.

MATERIAL STRESSES

The insulation material stress can be divided into three groups
- electrical stress,
- thermal stress,
- mechanical stress.

It is important to know, that these three stresses have a mutual influence, but they are not always increasing the effect of a single stress.

Electrical stress

The electrical stress in high voltage electrical machines is given by the electrical field strength, which is related to the electrode geometry. The conductor edge radius plays an important role. Table 1 shows the uniform field strength and the maximum field strength at the edge of the conductor as function of the insulation thickness and the conductor edge radius (2).

Table 1 Electric field strength for various insulation thickness and edge radii

<table>
<thead>
<tr>
<th>Rated Voltage (kV)</th>
<th>Insulation Thickness (mm)</th>
<th>Electric Field Strength (Uniform, kV/mm)</th>
<th>Electric Field Strength (Edges, kV/mm)</th>
<th>Emax/E</th>
<th>Conductor Edge Radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.0</td>
<td>2.0</td>
<td>15</td>
<td>10.5</td>
<td>0.6</td>
</tr>
<tr>
<td>21</td>
<td>6.0</td>
<td>2.0</td>
<td>8.4</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
<td>27</td>
<td>7.3</td>
<td>2.1</td>
<td>10.7</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
<td>30</td>
<td>8.0</td>
<td>2.2</td>
<td>10.8</td>
<td>5.0</td>
<td>0.6</td>
</tr>
<tr>
<td>30</td>
<td>7.2</td>
<td>2.4</td>
<td>4.7</td>
<td>0.6</td>
<td>3.0</td>
</tr>
<tr>
<td>40</td>
<td>9.5</td>
<td>2.2</td>
<td>5.8</td>
<td>2.2</td>
<td>3.0</td>
</tr>
<tr>
<td>40</td>
<td>8.0</td>
<td>2.0</td>
<td>4.8</td>
<td>1.6</td>
<td>5.0</td>
</tr>
</tbody>
</table>

It can be clearly seen, that the ratio Emax/E decreases strongly with increasing edge radius, and this is more pronounced for larger insulation thickness.
Another contribution to the electrical stress is the occurrence of partial discharges. Within a solid or liquid insulation material the field strength in a minute void depends on the relation of the permittivity of the two materials involved. Assuming a permittivity of about 4 for the solid material and about 1 for the gas filled void, the electrical field strength within the void is four times larger than the mean field strength depending on the angle of the field lines, and this may lead to a breakdown in this small void and to a deterioration of the electrical strength (3).

Also important for the evaluation of an insulating material for high voltage electrical machines is the long time behaviour of the insulating material under operating conditions. The endurance strength of an insulating material depends on

- the partial discharge behaviour,
- the leakage or creepage current,
- the treeing behaviour,
- the field strength,
- the dielectric behaviour.

In IEC 60505 (4) an empirical equation concerning the life time and the electrical stress is given as

\[
L = K \cdot V^{-n}
\]

with life time \(L\), voltage \(V\), constant \(K\) and exponent of life time \(n\).

Fig. 2 shows an example for the Equ. (1), measured on experimental stator bars for 21 kV (2).

Furthermore, the increasing use of pulse controlled converters has changed the wave shape of the applied voltage and increased the stress of the winding insulation (5). Fig. 3 shows the voltage shape and amplitude and the relative stress of insulation material used in converter fed machines. Besides the amplitude also the steepness of the applied voltage is much higher compared to sinusoidal voltage, and therefore the voltage distribution within the windings and the coils will be non-linear due to the material and stray capacitance (5).

**Figure 3 Terminal voltages for line feeding and pulse controlled converter supply**

Finally the end of each coil represents a geometric arrangement similar to bushing or cable termination, where a potential grading is necessary to control the electrical field strength parallel to the surface, the tangential component of the field strength. The stress grading is usually done by conductive tapes, but it should be taken into account the influence of the loss factor measurement and the changes of the tapes after the impregnation (5, 6).

The requirements on the insulation material concerning electrical stress are,

- high breakdown voltage resp. high electrical breakdown field,
- good long-time performance,
- no or low partial discharges resp. no voids within the insulation or on the interfaces between the insulation systems,
- very small leakage or creepage currents.

**Thermal stress**

The thermal stress of the insulation material is determined by the losses within the conductors. The dissipated heat shall be transferred from the conductor to the iron core through the insulating material, and usually materials with good electrical performance have less good thermal performance. The evaluation of thermal behaviour is defined in IEC 60085 (7) and the insulation materials are grouped according to the thermal classes, which gives the operating temperature of 135°C for class B, 155°C for class F or 180°C for class H.
It is also well known, that the temperature very often plays the dominant role in the ageing behaviour of insulation materials. The relation between the life time and the temperature is given by Equ. 2 according to (4):

\[ L = A \exp \left( -\frac{E}{kT} \right) \]  

with life time \( L \), constant \( A \), activation energy \( E \), Boltzmann constant \( k \) and absolute temperature \( T \).

This thermal behaviour is true for polymer insulating materials like cross linked polyethylene, but insulation systems with a combination of different materials may show another behaviour. Fig. 4 gives the results on electrical breakdown field strength of model stator bars as function of stress time with the temperature as parameter (8).

The life time increases with increasing temperature for these test samples. The reason for this behaviour is the reduction of internal mechanical stress with increasing temperature. A further increase of the temperature above the glass temperature \( T_G \) of the insulating material is combined with a change of the loss factor, a change of the permittivity and the electrical field distribution in the laminated insulating material and therefore the life time will be reduced as shown in Fig. 5 for model stator bars, tested at a field strength of about 17.5 KV/mm.

The thermal stress has also an influence on the interface between metallic and insulating parts. The expansion and contraction of the two types of material as function of the temperature will be different due to thermal expansion coefficients and therefore gaps or voids between the insulation material may occur. Also the spatial temperature differences can lead to high mechanical stress and generate delaminations or voids.

Fig. 6 shows as an example voids within the impregnated part of the insulating material and at the interface between insulating material and conducting material as corona shield.

The requirements on the insulating material concerning thermal stress are

- high long time performance,
- small changes after many temperature cycles,
- no delamination within the insulating material and at the interfaces,
- no reduction of PD inception voltage within the specified temperature range (9).

**Mechanical stress**

Besides the electrical and thermal stress the insulating material is also loaded with high mechanical stress. This stress is caused by the combined thermal-mechanical stress due to expansion or contraction of the material as function of the temperature, by the dynamic forces of the rotating parts of the electrical machine, the mechanical stress by clamping forces and the continuous alternating mechanical stress. Therefore the insulating material may creep due to the high mechanical stress and reduce the mechanical and electrical performance. The mechanical stress will also contribute to the ageing performance of the insulating material, and a failure of the mechanical performance due to fatigue of the material leads to an electrical failure within a breakdown. Also a simple break of a mechanically
stressed insulated part of the machine may cause an electrical breakdown of the insulation.

The requirements on the insulating material concerning mechanical stress are

- high mechanical strength,
- good long time performance,
- no reduction of mechanical strength within the specified operating temperature and operating voltage.

**Combined electrical, thermal and mechanical stress**

The insulating material in electrical machines is loaded with a combination of all three stresses in different ways. The weighting of the single stress and influence on the ageing of the insulating material changes depending on the load condition, the applied voltage or the environment conditions. Generally, the electrical performance decreases with the life time and the parameter temperature and tension accelerate or delay this behaviour to a certain extent, assuming that the temperature will be within the specified limits of the relevant temperature class and the material will not be mechanically overstressed. Fig. 7 shows measuring results on model stator bars with alternating mechanical load at two different temperatures and an electrical field stress of 7 kV/mm.

![Figure 7 Life time as function of mechanical stress](image)

It can be evaluated from Fig. 7 that the increase of temperature leads to a decrease of life time, determined by the electrical breakdown of the test samples, below a mechanical load of 75 N/mm. In Fig. 4 was shown, that the increase of the temperature has led to an increase of the life time, which means that a combination of stresses may also lead to a compensation of the different ageing effects.

The change of the insulating material due to combined electrical and thermal stress can be seen in the change of the dissipation or loss factor tan δ. The following two figures should be used as examples for model measurement. Fig. 8 shows the dissipation factor as a function of the temperature and voltage (2). The dissipation factor increases extremely small with the applied voltage and increases considerably with the temperature, but this is not harmful, if after cool down the dissipation factor reveals no increase exceeding the allowable value.

![Figure 8 Dissipation factor as function of temperature or voltage](image)

Fig. 9 shows the dissipation factor before and after ageing (10). It can be seen that the increase of the dissipation factor is very low for new insulating material as function of the applied voltage, but considerable for aged material. The changes correspond to the residual life time, i.e. with the consumption of insulating performance, but not with the short time breakdown voltage. The strongest increase of the dissipation factor is combined with the shortest life time (2A), and the weakest increase with the longest life time (1A).

![Figure 9 Dissipation factor as function of voltage with (1A-3A) and without ageing (1-3)](image)

The evaluation of the performance of the insulating materials is therefore difficult and the determination of
the residual life time of insulation will be possible only by comparison measurements and the use of data bank.

INSULATING MATERIALS

Already at the beginning of high voltage electrical machines E. Haefely recognised the importance of the voids within the solid insulating material. In 1910 he developed a so called iron press procedure to avoid minute voids in the insulation. Furthermore, it was very early realised that mica has a very good performance against partial discharges and that a combination of shellac and mica on paper as supporting material leads to a good high voltage insulating system. The impregnating process was supported by pressure in order to fill up all the small voids within the insulating material.

The next step in the development of insulating material was the replacement of the natural product lie shellac or bitumen by synthetic resin like polyester and epoxy resin. Also the size of the used mica material changes from plates of natural mica to very small particles of mica used as mica paper. The main task of the impregnation material was to glue the mica in order to get a mechanical strength. The displacement of small voids and the increase of the thermal conductivity and electrical performance due to a more linear voltage distribution were additional and useful effects.

The use of paper is limited, due to some typical properties of paper. Paper has a strong hygroscopical behaviour which leads to a strong increase of the dissipation factor. Furthermore, paper will change its chemical structure at high temperature, in particular under the influence of oxygen. The temperature limit is about 105°C, which means temperature class A. Therefore, paper may be used in electrical machines, but the temperature is limited and the content of binder material like phenol resin should be high to impede the absorption of humidity.

The group of synthetic resins contain the phenol resins, the polyester resins and the epoxy resins. The phenol resins were used as cured and heat-resistant material for a long time, and the well known trade name is bakelite. The electrical performance of insulating systems with phenol resin is not very high, because the curing process is a kind of polymerisation with byproducts like water vapour and gaseous solvent which may generate small voids within the insulation system.

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OUTLOOK

The references Meyer (1), Wichman (2) and Clark et al (11) give an overview on the insulation systems for electrical machines in steps of about 20 years starting in 1960 and ending 2000. The conclusion out of these references is, that mica has such a good performance regarding partial discharge behaviour, that this component still exists in electrical machine insulation systems due to the high electrical, thermal and mechanical stress on the insulating material.

The manufacturing processes have been improved by using vacuum pressure impregnation (VPI), (2,8,13) by...
high quality of the applied material, by appropriate mixtures of resin and hardener as well as by heat-resistant additives to the resin. The improvement in the quality of electrical machines is also determined by the installation of the windings and the configuration of each winding region, in particular at high rated voltages.

The increasing performance of the insulating material and the manufacturing technology leads to a higher stress on the insulating material and higher requirements on the technology. The high sensitivity of the insulating material on details within the material components and the manufacturing processes makes the dedication to processing details more important. Improvements may be reached by small steps in developing new material, adjusted to the stress in electrical machines, and in developing improved manufacturing procedures. On the other side, a change in the stress like impulse shaped voltages superimposed on the sinusoidal voltage will also change the requirements on the insulating system and the improvements may be compensated by higher electrical stress.

The partial discharge resistance will remain one of the main problems which has been solved by mica or mica paper, but filled polymer material may obtain the same or better performance in future (11, 12).

The thermal management material used in the electronic industry may also be used in future for electrical machines to gain smaller and more efficient machines, compensating the initial increased material costs.

Good insulation systems for a long machine life can be assured by attention to the material stress and strength, by the manufacturing quality, to appropriate testing procedures and after-market inspections.

REFERENCES


