

A High Voltage Insulating System with Increased Thermal Conductivity for Turbo Generators

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1. Introduction

The concept of mica based insulation and its application in high voltage rotating machines has been developed and optimized within the last 50 years and it has reached a level where further improvements seem difficult to achieve. The components of the main wall insulation are mica paper (about 65 % by weight), resin (25 %) and glass fabric or other support materials (10 %) [1]. Unfortunately all these materials – which have excellent electrical insulating properties – have a relatively low thermal conductivity.

In turbo generators with direct cooling systems – where the stator bars have hollow conductors cooled by hydrogen gas or water – the heat generated in the conductor is transmitted directly to the coolant and the thermal conductivity of the main wall insulation has little influence on the efficiency of the cooling system.

The situation is different in turbo generators with indirect cooling systems, where the steel core of the stator is cooled by hydrogen gas or air and the electrical losses generated in the conductors produce heat which has to pass through the main wall insulation to the coolant. Indirectly cooled turbo generators are increasingly used because they do not require auxiliary equipment as used in direct cooling systems. The generator construction can be kept simpler and the operational reliability and maintainability can be improved. However, the mica insulation acts as a thermal barrier restricting the efficiency of the cooling system and thus limiting the power density and capacity of the generator. The range of thermal conductivity of mica insulation is between 0.25 and 0.30 W/mK whereas values for copper or steel are 1500 or 300 times higher respectively (Figure 1).

If the thermal conductivity of the insulation is higher, the thermal gradient in the insulation will be reduced resulting in less thermal stress.

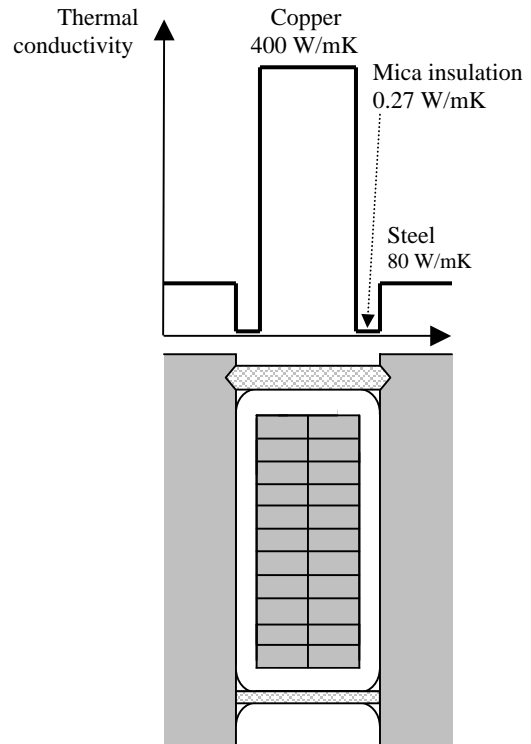


Figure1: The mica insulation as a thermal barrier in a generator stator

There are several principal ways to improve the transfer of heat from the conductor to the coolant:

- Reduced main wall thickness
- Increased thermal conductivity of the mica insulation
- Higher operating temperature with higher heat resistant insulation

The first solution requires a main wall insulation with higher dielectric strength which is not available for turbo generators for the time being. The second approach – the application of an insulation system with high thermal conductivity (HTC) – is much more realistic [2]. In this way the generator performance can be improved without any modification of the well established coil design and insulation wall thickness and the long term reliability of the generator is maintained. Figure 2 shows the impact of the application of an HTC insulation system with doubled thermal

conductivity on the design of an indirectly hydrogen cooled turbo generator. The HTC insulation system can be used to reduce the stator coil temperature by $\geq 10\text{ }^{\circ}\text{C}$ or to increase the power density (= power per weight) by $\geq 10\%$ without changing the frame size whilst maintaining the operating temperature. A total increase in power density of 20% can be realized in combination with optimizing the ventilation system.

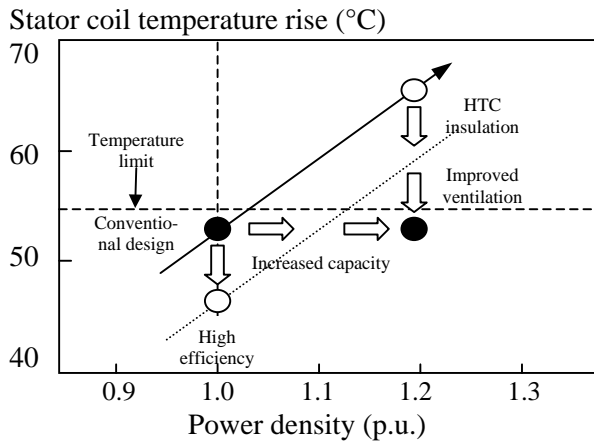


Figure 2: Impact of an insulation system with high thermal conductivity on the design of turbo generators

Therefore it is possible to expand considerably the output range of indirectly cooled turbo generator capacity. The HTC technology will have a remarkable impact not only for new generators but also for rewound machines.

2. Design of an insulating system with high thermal conductivity

The basic concept of the HTC insulation system involves the addition of filler materials with high thermal conductivity. Its application for high voltage rotating machines was disclosed earlier [3]. However it is not so simple to select the appropriate filler material and to incorporate it into the mica insulation. Requirements for a filler material to be used in high voltage insulation are:

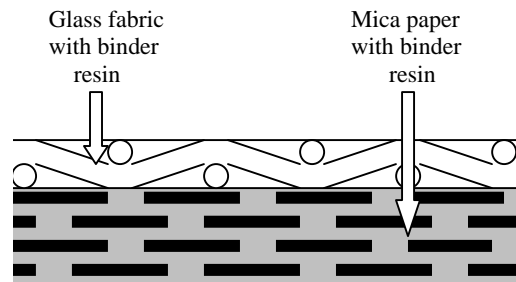
- High thermal conductivity
- High electrical insulating capability
- High partial discharge resistance
- Compatibility with the binder and impregnating resin
- Chemical stability and low toxicity
- Availability in consistent quality
- Practical cost

A selection of inorganic solids with insulating properties and high thermal conductivity is given in the following table:

Diamond	2000 W/mK
BN (cubic)	1300 W/mK
BeO	370 W/mK
AlN	150 W/mK
BN (hexagonal)	40 – 120 W/mK
SiC	25 – 100 W/mK
Si ₃ N ₄	50 W/mK
MgO	25 – 50 W/mK
Al ₂ O ₃	25 – 40 W/mK

If the requirements stated above are applied to this list of inorganic solids, two types of filler material are suitable to be used in high voltage insulation: BN (hexagonal) and Al₂O₃.

The usual mica insulation used in high voltage rotating machines consists of mica paper, resin and glass fabric (Figure 3). Where should the filler be placed?



Mica	0.3 – 0.6 W/mK
Glass	0.8 – 1.2 W/mK
Binder resin (epoxy)	0.2 W/mK

Figure 3: Thermal conductivity of materials used in mica insulation

It is possible to add the filler to the mica paper, but tests have shown that any incorporation of a filler material into the mica paper disturbs the orientation and cohesion of the mica platelets. The result is a decrease in mechanical and electrical properties of the mica paper, whereas the thermal conductivity shows a little increase. Since the binder resin is the component with the lowest thermal conductivity compared to mica and glass, it is preferable to add the filler to the binder resin *between* the layers of mica paper, i.e. in the meshes of the glass fabric.

The VPI technology offers two principal ways to introduce a resin loaded with filler material into the mica insulation: The filler material can either be in

the tape or it can be part of the impregnating resin in the VPI process. The idea of adding a solid filler to the VPI resin was rejected for several reasons:

- The filler might settle in the VPI tank during storage
- The filler might be filtered by the tape during the impregnating process
- The filler may affect the long term stability of the VPI resin
- The VPI resin could also be needed for “non HTC“ applications

Therefore the filler has to be added to the binder resin in the glass fabric during the process of mica tape production.

The thermal conductivity of the main wall insulation is a function of the type and amount of filler added. It is shown in figure 4 for BN (hexagonal) and Al₂O₃ as function of the volume fraction of filler material.

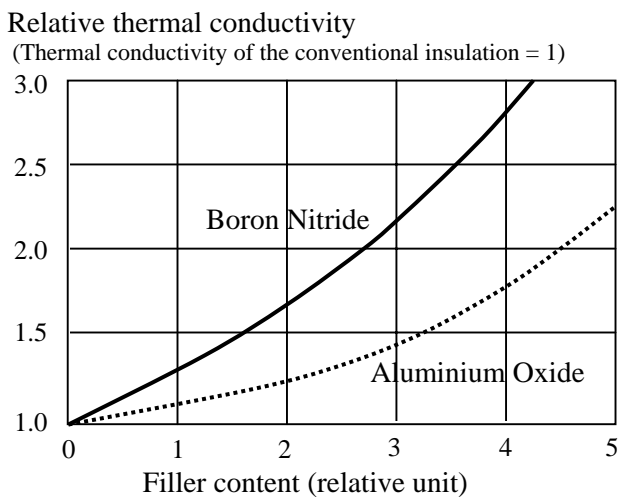


Figure 4: Thermal conductivity of mica insulation as a function of filler type and content

The amount of filler that can be incorporated into a mica tape is of course limited. Limiting factors are:

- Handling properties such as tape stiffness and robustness of the tape at high taping speeds
- Permeability of the insulation in the VPI process [4]
- Mechanical and electrical properties of the insulation wall (flexural strength, dissipation factor, dielectric strength and voltage endurance)

Figure 4 shows that – compared to Al₂O₃ - a lower fraction of BN (hexagonal) is required to achieve

the target thermal conductivity of the insulation. In fact the target of 100 % increase in conductivity can be achieved with a lower volume fraction of BN (hexagonal) compared to Al₂O₃. Another advantage of BN (hexagonal) is its form; crystalline BN has the shape of platelets not unlike mica, whereas Al₂O₃ particles are spherical. Therefore BN (hexagonal) is a more suitable filler in a mica tape, it is less abrasive and easier to apply.

The only disadvantage of BN (hexagonal) is its cost; the price of the BN filler material is higher than Al₂O₃. This was the reason that Al₂O₃ was selected as the filler material for the first mica tapes with higher thermal conductivity [5]. But since the increase in conductivity was only about 50 % there was no widespread application for this product.

Application and impregnation tests performed with VPI mica tapes containing BN filler proved the suitability of this filler material. Some mica tape properties relevant for handling are:

		Samicapor Standard	Samicapor HTC
Thickness	mm	0.15	0.20
Stiffness	N/m	39	54
Porosity	s/100ml	840	960
Impregnation*	h	1.0	2.0

* Time measured till full penetration of a 6 mm insulation was obtained. Resin viscosity was 30 – 50 mPa·s and pressure applied was 4 bar [6].

Application tests of the HTC mica tape performed on full size Roebel bars under manufacturing conditions proved the handling quality of the tape, see figure 5.



Figure 5: Application test of HTC mica tape on full size Roebel bars

3. Evaluation tests of the HTC insulation system on Roebel bars

In the HTC insulation system the relative volume ratio of mica will be decreased due to the addition of filler. It is therefore possible that the dielectric characteristics of the insulation may be affected depending on the amount and the quality of filler added. In particular, the effect on the voltage endurance has to be considered. Figure 6 shows voltage endurance test results of Roebel bars manufactured with the HTC insulation system compared to conventional bars. Both types of Roebel bars were manufactured in the same production process and they both show similar characteristics over the whole electrical stress range. No effect of filler addition can be found, and these results successfully confirm the development concept.

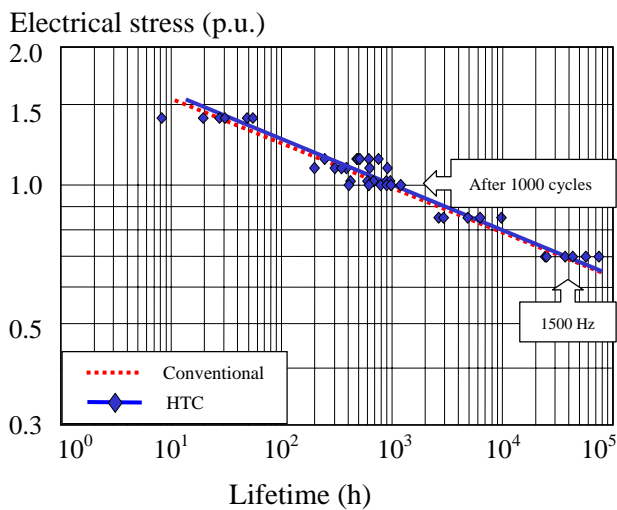


Figure 6: Voltage endurance characteristics of HTC and conventional insulating systems measured on Roebel bars

Bending rupture tests showed that the measured strain at fracture of the HTC insulation system is never inferior to that of the conventional insulation over the normal operating temperature range of turbo generators. Poor mechanical brittleness and less ductility of the insulation could be avoided by carefully selecting the type and content of filler.

Figure 7 shows the $\tan \delta$ voltage characteristics of factory made Roebel bars with the HTC insulation system. The figure indicates that the HTC insulation has the same $\tan \delta$ characteristics as the conventional one over the whole voltage range.

Figure 8 shows the breakdown voltage versus thermal ageing at 155 °C measured on a large

number of Roebel bars. No difference is observed comparing the HTC with the conventional insulation.

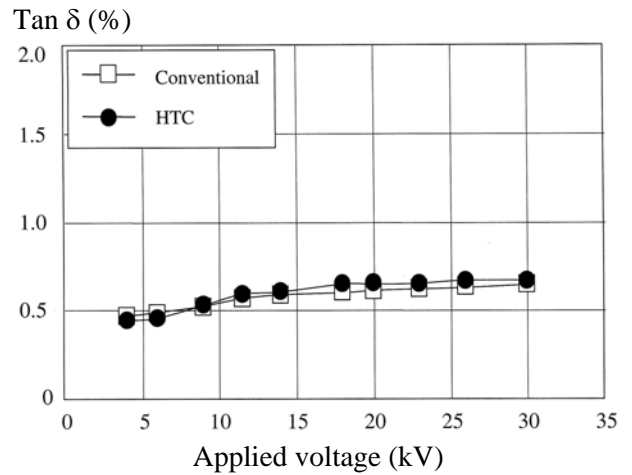


Figure 7: $\tan \delta$ vs voltage characteristics measured on factory made Roebel bars

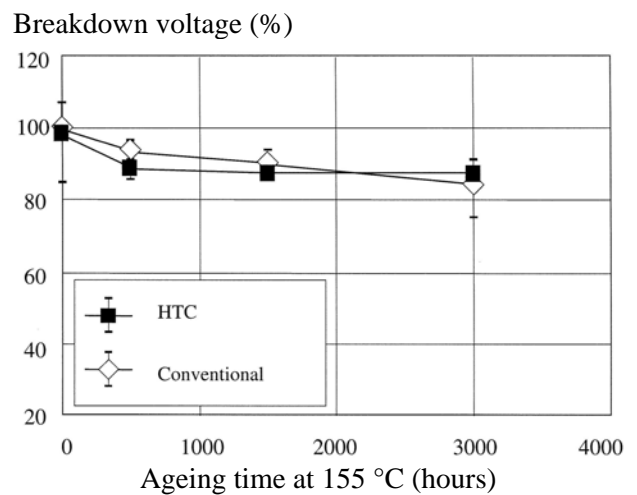


Figure 8: Breakdown voltage as function of ageing at 155 °C measured on Roebel bars

Finally the thermal conductivity of the HTC insulation was measured on a specimen taken from each of 36 factory made bars. The result was a mean value more than two times higher than the thermal conductivity of conventional bars. Temperature measurements performed on a 250 MVA hydrogen cooled turbo generator with the HTC insulation showed an operating temperature reduction of the stator coils of 10 °C compared to an identical machine with conventional insulation. The stator with the HTC insulation is shown in figure 9.

A three-phase sudden short circuit test was performed on the same 250 MVA generator to



Figure 9: Stator of a 250 MVA turbo generator equipped with the HTC insulating system

verify the mechanical strength of the HTC coils against electromagnetic force. No deformation or cracks were found on the endwinding insulation in the detailed inspection after testing.

4. Discussion of results and outlook

We have established a technology of applying an insulation system with high thermal conductivity (HTC) without changing the main wall thickness or the slot design. The new technology offers a significant reduction of the operating temperature of the stator coil and a higher efficiency of the machine without any basic generator design changes. This means that the long term reliability of the generator operation is ensured.

Using the HTC insulation system and thereby reducing the stator coil temperature by improving the efficiency of the cooling system is an essential step to extend the range of indirectly hydrogen gas and air cooled generators. The different ranges of turbo generators given by their cooling systems are now transferred to new design categories as shown in figure 10. This means that the upper limit of air or hydrogen indirectly cooled generators can be extended up to 400 MVA for air and 600 MVA for hydrogen respectively.

The big advantage of indirectly cooled generators is their shorter manufacturing lead time and the elimination of the rather complex stator water cooling system and auxiliary equipment. They offer a high degree of reliability in combination with low maintenance cost. If the HTC insulation system is applied also to existing units for rewinding, an increase in efficiency or capacity is to be expected without changing the original design (Figure 2).

Thus we believe that the HTC insulation system meets the needs of original equipment manufacturers as well as those of repair shops and can bring real benefits to the electrical generation industry.

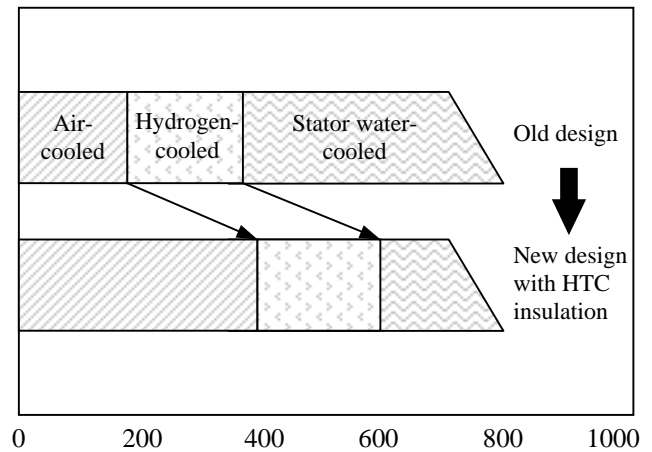


Figure 10: Extended range of capacity for indirectly cooled turbo generators

5. References

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