11th INSUCON International Electrical Insulation Conference, Birmingham, UK, 26-28 May 2009

INSULATING SYSTEMS FOR HIGH VOLTAGE MOTORS

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ABSTRACT

High voltage motors cover nominal voltages of 3.3 – 15 kV with power outputs between 0.1 and 50 MW. They are widely used in industry sectors where high power is required; typical examples are mining, pulp and paper, oil and gas, chemical, automotive, cement and other industries. The range of applications covers pumps, refiners, mills, compressors, blowers, fans, conveyor systems etc. High voltage motors have to run in harsh industrial environments; efficiency, reliabilty and low-maintenance operation are therefore key elements. Design and manufacture of the machines have to deal with these criteria. The insulating system of a high voltage motor has a substantial influence on all these factors. It is therefore important that it is carefully selected and applied.

Materials generally used for the main wall insulation of high voltage coils are glass- or film-backed mica tapes with an epoxy, polyester or polyesterimide binder resin. Other components of the insulating system are corona protection materials and a variety of complementary materials for mechanical consolidation and protection of the motor against environmental impacts. Application technologies are the resin-rich process and global vacuum pressure impregnation. These insulating materials and application technologies have been developed and optimised over a long period and can be regarded as mature systems. Nevertheless innovations are being made in this field. They enable motor manufacturers to improve the performance of their machines and reduce costs.

INTRODUCTION

Design and manufacturing of high voltage motors undergo a permanent development and improvement process. Main trends are:

- Increasing power/weight ratio
- Lower manufacturing cost
- Higher reliability / less maintenace cost
- Increasing percentage of inverter high voltage driven motors

Insulating systems of high voltage motors are exposed to different stress factors:

- Thermal: up to class temperature (mostly 155 or 180°C), hot spots can achieve higher temperatures
- Electrical: 3.3 - 15 kV
- Mechanical: Stress due to changes of load, vibrations and different thermal expansion of the materials involved
- Environmental: Exposure to different kinds of ”dirt” like dust, abrasion particles, humidity, water, lubricants and other chemicals, etc.

Insulating systems for high voltage motors have to be designed to resist all these stress factors and to ensure reliable operation. Components of an insulating system are:

- Conductor insulation
- Main wall insulation
- Resins and varnishes
- Corona protection materials
- Complementary materials like banding and sealing tapes; ropes, cords and sleeves; composite materials for slot wedging.

COMPONENTS OF INSULATING SYSTEMS FOR HIGH VOLTAGE MOTORS

Conductor insulation and stack consolidation

The conductor insulation in rotating machines has to fulfil mainly two tasks:

- To provide insulation between turns
- To provide good adhesion between the copper conductor and the main wall insulation.

Materials used for high voltage conductor insulation are summarised in table 1. They cover glass fibers applied by single or double lapping or by braiding. Usually the fibre layer is impregnated with a varnish for further improvement of its mechanical and electrical properties. The Daglas insulation consists of a fused glass/polyester fibre blend which can also be applied without impregnation. Daglas is typically used for Roebel bars because it is more resistant to the bending operation used for Roebel transposition. Polyesterfilm/mica-tapes are used to achieve highest corona resistance and dielectric strength. All these conductor insulations are also available with an additional adhesive B-stage coating which enables rapid consolidation of the conductor stack before applying the main wall tape. Without the adhesive, the application of traditional stack consolidation materials like B-stage glass fabric or polyester fleece tapes is recommended.

Litz wire conductors are used to replace solid rectangular wires in order to allow smaller coil overhangs, larger conductor profiles and a higher efficiency due to lower proximity and skin losses.

TABLE 1 Conductor insulation for high voltage motors

Conductor insulation	Temperature index	Application, remarks
Glass fibre (Silix®) (E-glass fibre, single or double lapped or braided)	155 - 180	Can be applied on bare or enamelled wire and with or without B-stage overcoat
Daglas (glass/polyester fibre blend, single or double lapped and fused)	155 - 220	
PET/mica tape (Samicafilm®)	155 - 180	With or without adhesive for stack consolidation

Main wall insulation

The main wall insulation separates the high voltage conductor from the grounded stator core. It is exposed to a high electrical stress, especially on the corners of the conductor stack where the field strength is 2 to 3 times higher compared to the side faces. For more than a century mica has proven to be a reliable and persistent insulating material for the main wall insulation although its application requires some elaborateness. Several application technologies are used for the main wall insulation:

- Soft cell: The mica tape is applied without any further impregnation and curing process. This technology is only used for small motors (≤ 6.6kV) and for repair if the RR- or VPI-process are not applicable.
- Resin-rich (RR): Mica tapes (Samicatherm®) with a high resin content are taped and cured in a coil press.
- Vacuum pressure impregnation (VPI): Mica tapes (Samicapor®) with a low resin content are taped. The resin is added in the VPI process and the insulation is cured in the oven. Global VPI is mostly used for high voltage motors, the stator is impregnated as a whole.

In both cases - RR and VPI - the final resin content of the cured main wall insulation should be 25 - 30%. Mica tapes used for the main wall insulation are summarised in table 2.

Usually calcined mica paper is used for or RR mica tapes and uncalcined for VPI tapes. Calcination of mica is a thermal process to reduce the particle size of the mica resulting in a paper with very samll mica platelets, and therefore a higher density and lower porosity compared to uncalcined mica paper. The higher porosity of the uncalcined mica paper facilitates impregnation of the mica insulation in the VPI process.

TABLE 2 Main wall insulation tapes for high voltage motors

Mica tape	Construction	Thickness (mm)	Application
Filosam®	Mica paper, PET film, glass threads	0.13 - 0.15	Soft cell ≤ 6.6 kV
Samicatherm®	Mica paper, glass fabric	0.19 - 0.26	Resin-rich
Samicatherm P®	Mica paper, PET film	0.16	Resin-rich ≤ 6.6 kV
Samicapor®	Mica paper, glass fabric	0.15 - 0.18	VPI
Samicapor P®	Mica paper, PET film	0.18	VPI ≤ 6.6 kV

Often the question is asked whether RR- or VPI-insulations show a higher lifetime. Calcined mica paper gives indeed higher electric breakdown values. But the difference in lifetime between RR/calcined mica and VPI/uncalcined mica insulations vanishes with increasing complexity of the test specimen, see figure 1.

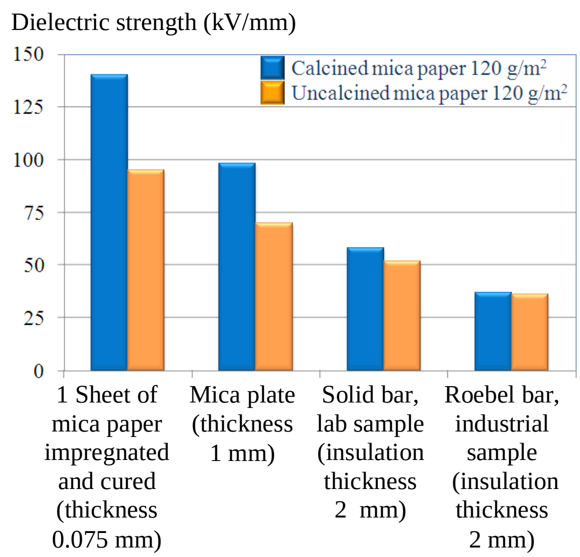

Figure 1 Dielectric strength of different test specimen made with RR/calcined mica and VPI/uncalcined mica insulations and application technologies respectively

Mica tapes with polyester film backing are often used for smaller motors with a rated voltage ≤ 6.6kV, primarily due to their lower price. But it was also found that the polyester film gives a higher dielectric strength compared to a glass fabric backing, even after ageing [1]. Limits to the use of film backed mica tapes are set by the reduced impregnatability in the VPI process and the lower mechanical strength of the main wall which both make them unfavourable for larger coils with rated voltages > 6.6 kV.

Resins and varnishes

Resins are used in high voltage insulation mainly as binder resin for mica tapes or as impregnating resin in the VPI process. These resins have to perform several tasks:

- laminate the mica tapes
- fill the voids
- provide good adhesion to the conductors
- provide mechanical strength
- protect from chemicals, dirt and humidity

Furthermore they must have excellent electrical, thermal and mechanical properties to meet the requirements during the whole lifetime of the motor.

Binder resins for RR mica tapes are usually based on novolac-epoxy with an accelerator.

The majority of high voltage motor manufacturers is using the global VPI process due to its lower cost. Basically five different types of VPI resins are used worldwide:

- Epoxy
- Epoxy/anhydride
- Epoxy hybrid (mixture of epoxy and polyester or polyesterimide)
- Polyester
- Polyesterimide

Requirements for VPI resins do not only depend on the type and size of the machine to be manufactured but also on the manufacturing process and equipment and the other materials used for electrical insulation. Last but not least they may vary according to health, safety and environmental regulations being valid for the site.

In general a low resin viscosity is favourable for high voltage application to ease impregnation of the mica insulation and to reduce the VPI cycle time. Furthermore storage and impregnation temperature of the resin should be the same and preferably be room temperature to avoid any heating and cooling processes and to save energy and time. The shelf life of the resin is usually defined by the time during which the viscosity increase at storage temperature does not exceed a certain value. The tolerated maximum viscosity increase depends on the application but - as a guide line - it should be ≤ 50 % of the initial value. The duration of use depends also on the consumption rate or the amount of fresh resin added periodically. Ideally the duration of use is ∞ which means that the amount of fresh resin added to replace the liquid used is sufficient to keep the viscosity below the tolerated limit.

Other preferable handling properties of the resin are little or no sensitivity to moisture, small environmental and health hazards and a low toxicity. The gel time of a VPI resin should be reasonably short to avoid losses of resin during the curing cycle. On the other hand too short gel times will reduce the shelf life of the resin. Also a short cure time is desirable to reduce the VPI cycle time. Table 3 gives an overview on the desirable features of VPI resins.

TABLE 3 Desired properties of VPI resins

	Requirements
Liquid resin	
Viscosity (for high voltage)	≤ 300 mPas at RT
Storage Temp.	15 - 25°C
Shelf life at storage temp.	6 – 12 months
Duration of use (see text)	∞
Sensitivity to moisture	Low or none
Flash point	> 30°C
Gel time 120°C	2 - 6 min.
Cure time 150°C	2 – 8 h
Cured resin	
Thermal class	F - H
Tan δ (measured on mica laminates)	$\tan \delta_{RT} \leq 2$ % $\tan \delta_{155°C} \leq 8$ % $\tan \delta_{180°C} \leq 16$ %

Most of the VPI resins used today are epoxy resins based on bisphenol-A/F-epoxy. With the trend to high voltage motors for higher temperature classes (class F → H), polyesterimide resins become more popular. They offer excellent thermal and electrical properties for a favourable price. Table 4 gives an overview on some VPI resins, their properties and application range.

TABLE 4 VPI resins for high voltage motors

	Thermal class	**Viscosity (mPa·s) at 23°C**	**Appli-cation**
Epoxy			
Permafil® 74041	H	4000 -8000	≤ 6.6 kV
Permafil® 74038	H	1200	≤ 15 kV
Epoxy/anhydride			
Damisol® 3407	F	400	≤ 15 kV
Epoxy hybrid			
Damisol® 3415	F	90	≤ 15 kV
Damisol® 3313	H	100	≤ 15 kV
Polyesterimide			
Damisol® 3340	H	200-500	≤ 6.6 kV
Damisol® 3032	H	200-300	≤ 6.6 kV
Damisol® 3308	H	150	≤ 15 kV
Damisol® 3309	H	170	≤ 15 kV

Varnishes are not suitable for impregnation of the main wall insulation of high voltage motors, the evaporating solvent would leave voids. These liquids are applied as finishing and overcoat varnishes for the motor body. There are air-drying and oven-curing solutions.

Corona protection materials

Corona or partial discharge in rotating machines is a phenomenon caused by the ionisation of gas molcules (usually air) in a strong electric field. Corona usually refers to visible luminous discharges, whereas the term partial discharge is rather used for hidden discharges in voids. The term partial discharge (PD) indicates that the insulation between conductors is partially bridged and an exchange of electric charges is taking place. However named, the physical cause and the effect on insulating materials are the same. PD can result from breakdown of gas in a void, in an electric tree channel or along an interface. Usually PD does not cause immediate failure of a rotating machine. But enduring PD is detrimental to insulating materials. Although mica, the main insulating component in rotating high voltage machines, is corona resistant, precautions must be taken to prevent the onset of PD. PD induces several mechanisms which destroy the insulation:

- Local overheating of the insulation
- Generation of free radicals and ions
- Formation of nitric acid by decomposition of air
- Onset of UV radiation

Organic insulating materials such as binder resins, films and fleeces are especially vulnerable when exposed to PD. PD can develop anywhere in the rotating high voltage machine where a gas-filled volume is exposed to the electric field (see figure 2).

Voids and delaminations *inside the finished mica insulation* cannot be repaired. An accurate application of the mica tape and a correct implementation of the resin-rich or VPI process are the prerequisites for a void-free main wall insulation.

To avoid *PD between the conductor and the main wall insulation internal corona protection materials* are applied on the consolidated conductor stack. This can be a suitable conductive tape or - to fill the gaps on the top and bottom sides of Roebel bars - a conductive mastic.

External PD, also known as *slot discharge*, occurs in the slot portion between the outside of the main wall insulation and the laminated stator core if the voltage exceeds a certain level. External PD can be prevented by applying *external corona protection materials* such as a conductive coating on the main wall insulation; usually a conductive tape or a varnish is used. It is essential that the conductivity of the coating be correct, that it not change with impregnation or curing, and that

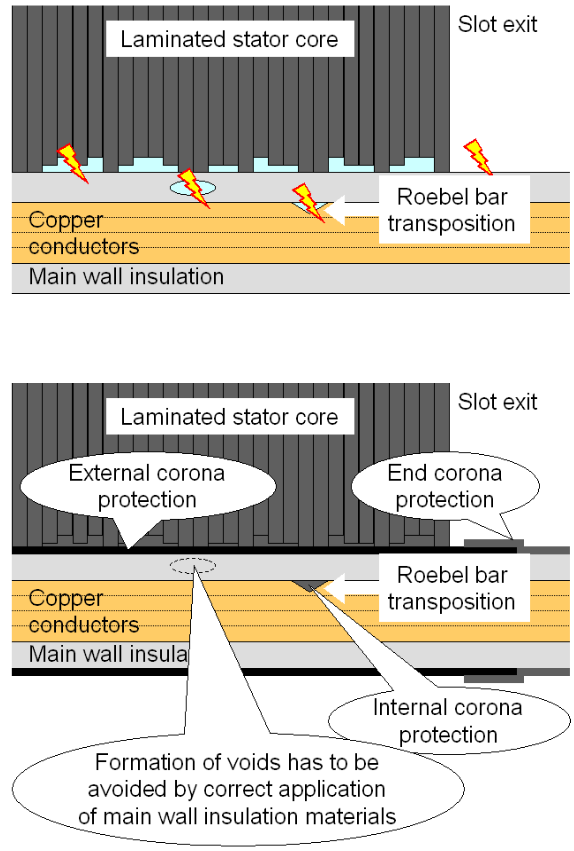

Figure 2: The figure on top shows the places in the stator core and at the slot exit where partial discharge (PD) or flashovers can occur. The figure below shows the application of corona protection materials to prevent PD.

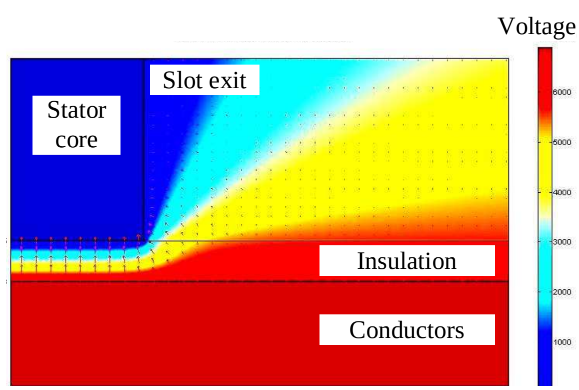

Figure 3: Calculated electric field at the slot exit of a stator. The arrows show the strength and direction of the electric field. The electric potential is represented by colours and shows a steep rise on the insulation surface at the slot exit.

the coating keep its function for the lifetime of the machine. The conductivity has to be sufficient to eliminate PD in the slot but not so high as to short-circuit the stator lamination stack and to give rise to eddy currents.

There is an increase of electric field strength at the *slot exit* of the stator, as seen in figure 3, which can cause surface discharges on the surface of the coil or bar endwindings. This can be prevented by applying *end corona protection materials* such as tapes or varnishes. Usually they contain silicon carbide, which is a semiconductive material showing a nonlinear voltage-current characteristic. This material produces a stress-grading effect on the insulation surface outside the core.

Standard corona protection materials are summarised in table 5.

TABLE 5 Conductive and semi-conductive tapes for corona protection

	Thick-ness (mm)	**Resis-tivity Ohm sq**	**Application**
Conductive mastic 8004 in tape form	2-3	≥ 5000	Internal corona protection for Roebel bars.
CoronaShield® 215.51	0.1	200-400	Impregnated poly-ester fleece tapes for slot corona protection.
CoronaShield® 215.55	0.085	200-400	
CoronaShield® 217.01/21, 217.02/22, B-stage	0.22	Variable	Impregnated poly-ester fabric tapes for end corona protection. B-stage for RR, fully cured for VPI technology.
CoronaShield® 217.31, fully cured	0.25	Variable	

PD can also occur *outside of the stator*, e.g. in the end-winding section or between high voltage connections or unshielded lead cables and grounded parts, e.g. the stator frame. Causes may be dirt, high humidity, sharp points or insufficient distance between adjacent coils.

For more than a decade the trend to inverter driven motors also includes the field of high voltage motors. However, problems appear due to surge voltages, high repetition frequencies and steep wavefronts of the of the inverter pulses. The last of these is especially severe for the stress grading materials used in the coil endwindings to avoid surface arcing. This problem is widely discussed in the literature and solutions are shown using conventional stress grading materials [2-4].

Complementary materials

Complementary materials are used in high voltage motors mainly for mechanical consolidation and for protection against environmental stress. These materials are:

Finishing tapes. They protect the main wall insulation in the overhang area against environmental stress and mechanical damage. Finishing tapes give a hermetic sealing of the main wall insulation. Their use is highly recommended if the RR technology is applied.

Ropes, cords and sleeves. Ropes and cords consist of a braided glass or polyester yarn sleeve with a core of glass yarn or staple glass fibers, sleeves are hollow. These materials are used for intercoil lacing and tying in the endwinding area to reduce vibration. They are unimpregnated for use with VPI or B-stage impregnated for RR application.

Composite materials. U- and L-profiles, strips, sheets or machined parts are used in different areas of high voltage motors. They are composite materials with a polyester or epoxy matrix and glass or polyester fabric, fibers or mica paper as reinforcement. Most important is the slot wedging of the coil or bar in the stator and rotor slot to avoid vibration in the slot. Figure 4 shows the application of condcutive and non-conductive slot-packing materials.

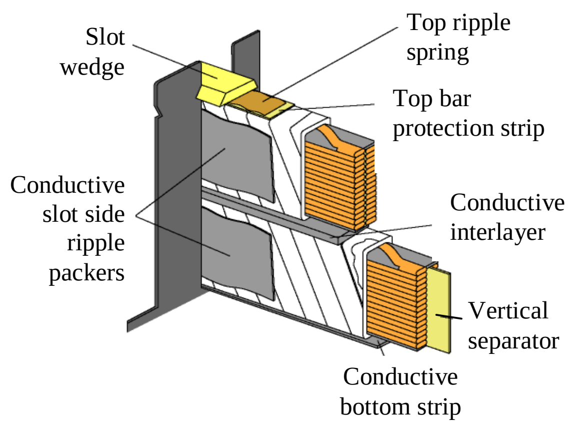

Figure 4: Conductive and non-conductive slot-packing materials are necessary for wedging the coil or bar in the slot. Conductive materials additionally bridge the conductive surface of the coil or bar to the stator core.

NEW DEVELOPMENTS

Insulating materials for high voltage motors have been developed and optimised over a long period and can be regarded as mature systems. Nevertheless innovations are being made in this field. They enable motor manufacturers to improve the performance of their machines and reduce costs. Examples are:

Slot corona protection tapes with increased thermal resistivity

CoronaShield® 2500 NB 70 based on Nomex® technology is a newly developed conductive tape. The tape contains no binder resin, rather conductive particles are fixed in the non woven structure of the Nomex® paper. The main advantage of the tape is its high thermal resistance, which makes it suitable for class H machines and above. Figure 5 shows model bars before and after an ageing test. The conductive coating of the conventional tapes A and B has almost completely degraded, whereas CoronaShield® 2500 NB 70 remains intact.

Before ageing:

After ageing:

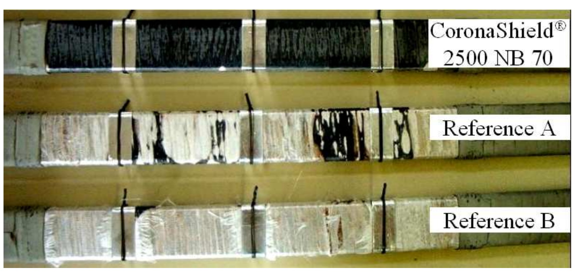

Figure 5: Ageing of model bars with conventional conductive tapes (A and B) and CoronaShield® 2500 NB 70. Ageing conditions were 800 hours at 200°C and 17 kV with an insulation thickness of 2 mm. The conductive coating of the conventional tapes has almost completely degraded.

Fast curing coil consolidation materials

A new range of fast curing products for the consolidation of (Roebel-) bars and double layer coils was developed. The product range covers:

- Different grades of separator materials for stack consolidation (rigid for the slot part and flexible for the end windings)
- Mica based mastic and conductive mastic for interstice, Roebel crossover and gap filling. The conductive grade serves as internal corona protection.

The main feature of the new products is a curing cycle of 15 minutes at 120 °C compared to 1 hour at 160°C with conventional materials. After this cycle a glass transition temperature of ≥ 120 °C is reached which is sufficient to provide mechanical and dimensional stability of the bar or coil for further handling. After the full curing cycle of the main wall the glass transition temperature will be above 150 °C and all fast curing products then meet class F requirements. The shelf life of the products is ≥ 4 months at room temperature. The reduction of processing time and saving of oven capacity and energy is substantial.

Flat coil technology

For motors up to 13.8 kV the flat coil technology offers a considerable cost saving potential. In this technology the main wall insulation is applied directly on the loop and the resulting flat coil is subsequently formed to a 3-dimensional coil. Applying the mica tape on the loop allows the use of simpler taping machines and higher taping speeds. Moreover the complete coil including the coilends can be insulated in one process. However, the overlap of the mica tape has to be increased at coil sections being bent in the subsequent forming process. The forming of the coil is not a simple spreading but has to make use of more sophisticated machines which are able to form the final diamond coil in a step-by step process. Nevertheless the flat coil technology enables important cost reductions of the motor manufacturing process and - using modern and highly automated processing equipment - allows a higher and more consistent quality of the final product.

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