CONDUCTOR INSULATION FOR ROTATING MACHINES

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INTRODUCTION

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

- To provide insulation between turns
- To provide good adhesion to the copper conductor and the main wall insulation and the impregnating resin respectively

The conductor insulation is positioned in a critical place of the coil or bar:

- It is subject to a high electric field, especially on the edges of rectangular wires used for high voltage machines (see figure 1).
- It is at the interface of materials with different thermal expansion coefficients: Copper / mica insulation in high voltage machines and copper / impregnating resin in low voltage machines respectively. In both cases the conductor insulation is exposed to severe shear forces (see figure 2).
- It is in close contact to the copper which usually sees the highest temperature in rotating machines.
- It has to sustain severe flexural stress during coil manufacturing (loop winding and coil forming), especially if small bending radii are applied.

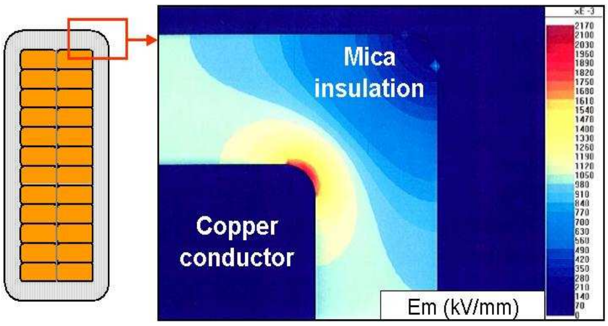

Figure 1 Calculation of the electric field strength at the edge of a rectangular copper wire. The field strength at the edge is 2 to 3 times higher than on the side face.

Materials for conductor insulation have to be selected to meet these requirements during the lifetime of a machine. Many different factors determine the choice of the appropriate material:

- Type of the machine
- Nominal voltage
- Thermal rating
- Cost
- Delivery period

In practice a wide variety of materials is used for conductor insulation – as single materials or as combinations thereof.

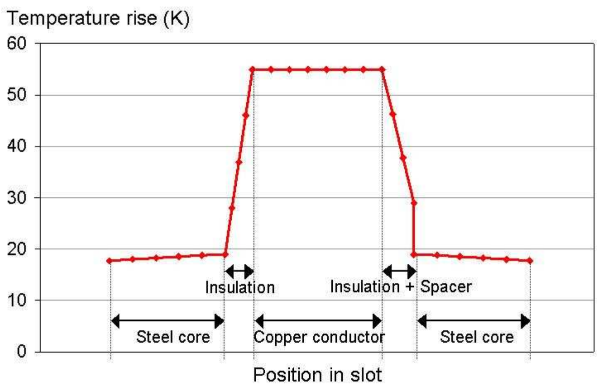

Figure 2 Temperature distribution calculated for the cross section of an air-cooled turbo generator Roebel bar. The temperature difference between copper conductor and steel core is approx. 35 K causing shear forces in the intermediate conductor and main wall insulation [1].

STANDARD TYPES OF INSULATED WINDING WIRES AND THEIR APPLICATION

Enamelled winding wires

Enamelled winding wires are mostly used for low voltage motors and generators and - in combination with a fibre- or tape-covering - for high voltage rotating machines. An overview on the different enamel coatings for these applications is given in table 1. Winding wires with a bond coat allow to replace the impregnation of the coil with a varnish or resin by a simple baking process which is more economical.

Fibre-insulated winding wires

The fibre insulation improves the mechanical properties of the conductor insulation considerably. Fibres are applied on the winding wire by single or

TABLE 1 Types and properties of enamelled winding wires for rotating machines

Type of enamel	Tempera-ture index	Application, remarks
Modified Polyurethane + thermoplastic bond coat	130 - 155	Low voltage, bondable
Modified Polyurethane	155 - 180	Low voltage, solderable
Modified Polyesterimide	180	Low voltage, solderable
Modified Polyesterimide + Polyamide-imide + thermosetting bond coat	200	Low voltage, bondable
Modified Polyesterimide + Polyamide-imide	200	Low voltage, high voltage in combina-tion with fibre or tape insulation
Polyamide-imide	220	
Polyimide	240	

TABLE 2 Types and properties of fibre-insulated winding wires for rotating machines

Type of fibre	Tempera-ture index	Application, remarks
Daglas® (Glass/Polyester fibre blend, single or double lapped and fused)	155 - 180	High voltage, Roebel bars
Glass (E-glass fibre, single or double lapped or braided)	155 - 220	High voltage, Roebel bars, Traction motors
Type of varnish used for impregnation of the fibre covering		
Epoxy	155	High voltage
Polyesterimide	180	
Polyamide-imide	200	
Silicone	220	
Polyimide	220	Traction motors

TABLE 3 Types and properties of tape- and film-insulated winding wires for rotating machines

Type of film or tape	Tempera-ture index	Application, remarks
Polyester film (PET)	130	Low voltage
Polyester film (PEN)	155	
PET/Mica (Samicafilm®)	155 - 180	High voltage
Aramide paper (Nomex®)	180	Pole coils
Polyimide film (e.g. Kapton®)	220	Traction and high tempe-rature motors

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. Fibre-insulated wires are typically used for Roebel bars because the fibre insulation is more resistant to the bending operation used for Roebel transposition. Standard fibre-insulated winding wires and impregnating varnishes are summarized in table 2.

Tape- and film-insulated winding wires

Tape- and film-insulated winding wires are less commonly used in rotating machines compared to fibre-insulated winding wires. Exceptions are PET/Mica and Polyimide film taped wires used for high voltage, traction and high temperature motors. Standard winding wires are summarized in table 3.

TESTING OF CONDUCTOR INSULATION

IEC 60851 specifies a variety of test methods to define the properties of round and rectangular winding wires. Test methods relevant for testing the quality of the conductor insulation are summarized in table 4. The multitude of test methods reflects the importance of the conductor insulation for winding wires.

NEW DEVELOPMENTS

Although winding wires are mature products there are still new developments in this field. The following compilation gives descriptions of some recent developments.

Corona-resistant conductor insulation for inverter driven motors

The demand for inverter driven motors has increased rapidly since the mid 80's when technical solutions for frequency inverters became less expensive and more reliable. But the new technology also caused a new problem: The increased stress on the motor winding insulation generated by surge voltages resulted in motor winding insulation failures, mostly in systems using AC supply voltages above 400 V. These stresses are caused by the interaction of the fast rising voltage pulses of the inverter and transmission effects in the cable. Due to this effect the terminal voltage of the motor may reach peak values of 2-3 times the pulsed output voltage of the inverter. Most critical are surge voltages between turns whereas the phase and ground insulations are generally designed to withstand large overvoltages.

Von Roll has developed two winding wires for inverter driven motors: Thermex® 200 CR, a round wire with a corona-resistant enamelling and SamicaShield®, a round wire with a mica insulation. Mica is the preferred material for high voltage insulation due to its superior resistance to corona and it is therefore obvious to use it also as conductor insulation in inverter driven motors. The problem to be solved was to get a reasonably thin mica insulation for this application. The resulting winding wire - SamicaShield® - has an increase due to insulation of 0.18 – 0.30 mm depending on type and application.

Ageing tests of Thermex® 200 CR and SamicaShield® are shown in figure 3. The figure shows results of a pulse endurance test performed at voltages of 2 and 3 kV with 20 kHz and a pulse rise-time of 0.025 µs. Thermex® 200 CR and SamicaShield® gave the longest lifetimes. The superior properties of SamicaShield® were also proven in a field test with 26 inverter driven motors for elevator application performed by the Korean Electrotechnology Research Institute (KERI) [2].

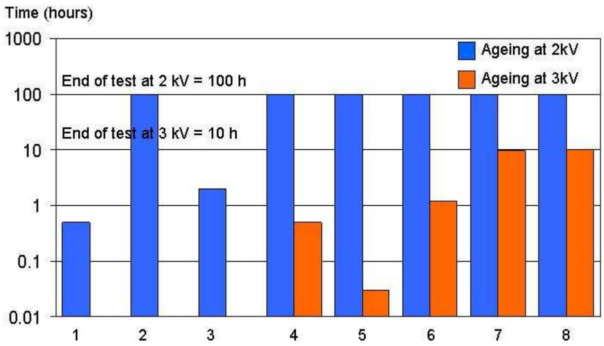

Figure 3 Pulse endurance test of round wires with different insulations:
1: Enamelled grade 2
2: Corona-resistant enamelled (Thermex® 200 CR)
3: Glass lapped
4: Enamelled + Polyester film taped
5: Polyimide film taped
6: Corona-resistant Polyimide film taped
7: SamicaShield®
8: SamicaShield® impregnated (Resin Damisol 3340)

TABLE 4 Test methods for characterisation of the conductor insulation as specified by IEC 60851

IEC 60851	Test no. and method	Applicable to	Property tested
Part 3: Mechanical properties	8: Flexibility and adherence (Mandrel winding test, stretching test, jerk test, peel test, adherence test)	Enamelled, fibre- and tape-insulated round and rectangular wires	Resistance to stretching, winding, bending or twisting without showing cracks or loss of adhesion of the insulation
	11: Resistance to abrasion	Enamelled round wires	Resistance to scraping with a needle without giving electrical contact
	18: Heat and solvent bonding tests (Helical coil, twisted coil)	Enamelled round wires	Bond strength of a coil under load
Part 4: Chemical properties	12: Solvent test	Enamelled and fibre-insulated round wires	Hardness of the insulation after immersion into solvents
	16: Tests for wires for use in refrigerants (Extraction test, solvent test, blister test)	Enamelled round wires	Change of mass and formation of blisters after immersion into solvents and refrigerants
Part 5: Electrical properties	13: Breakdown voltage	Enamelled, fibre- and tape-insulated round and rectangular wires	Dielectric strength at room and elevated temperature
	14: Continuity of insulation (low and high voltage)	Enamelled round wires	Integrity of the wire insulation
	19: Dielectric dissipation factor (tan δ)	Enamelled and bunched wires	Dielectric losses
Part 6: Thermal properties	9: Heat shock test	Enamelled or tape-insulated and bonded round and rectangular wires	Resistance to heat shocks without appearance of cracks
	10: Cut-through test	Enamelled round wires	Hardness of the insulation under load at elevated temperature
	15: Temperature index	Enamelled round and rectangular wires	Thermal endurance according to IEC 60172
	21: Loss of mass	Enamelled round wires	Loss of mass at elevated temperature
	22: High temperature failure test	Enamelled round wires	Insulating performance of the conductor insulation up to 450°C

New conductor insulations for traction motors

Insulating materials in traction motors have to withstand high temperatures and frequent changes of load and temperature. Standard materials applied for conductor insulation are glass fibres and polyimide film. Von Roll has enlarged the range of products by developing two new winding wires: VS 240 and VS 240 VF. The conductor insulation of both products consists of a polyimide enamelling and a glass/polyester fibre covering impregnated with a polyimide varnish, the temperature index being 240 (Figure 4). The difference between the two products is the increase due to insulation: It is 0.20 – 0.25 mm (VS 240) and 0.15 – 0.19 mm (VS 240 VF) respectively. They offer a true alternative to polyimide film taped wires and have excellent dielectric and mechanical properties.

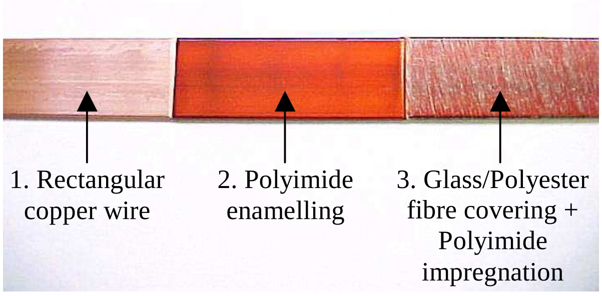

Figure 4 Construction of winding wires VS 240 and VS 240 VF

Newly developed Daglas insulated winding wires for Roebel bars in power generators

The use of Daglas insulated winding wires for Roebel bars is state of the art. Although the Daglas insulation is quite resistant to the bending operation used for Roebel transposition an insulating chip is usually placed at the conductor crossover to prevent any inter-turn failure at this position. This operation is handmade and therefore time-consuming and uneconomical. A new Daglas insulation with increased mechanical strength was developed to eliminate the extra insulation at the Roebel transposition (Figure 5):

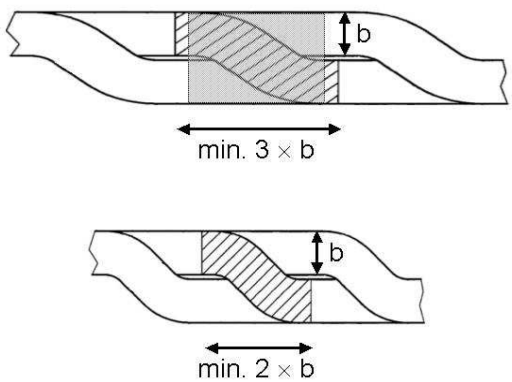

Figure 5 Roebel transposition: Old process with insulating chip at the conductor crossover (top figure), new process with new Daglas insulation without insulating chip and a narrower crossover (bottom figure)

- A Daglas wire based on Thermex® 200 or 220 with a single Daglas covering and a polyamide-imide overcoat. The insulation increase is 0.19 – 0.22 mm.
- A Daglas wire based on Thermex® 220 with a double covering of Daglas and glass and an thermosetting epoxy overcoat. The insulation increase is 0.25 – 0.28 mm.

Both wires are designed for use in automatic Roebeling machines for the production of hydro- or turbo-generator bars.

A rectangular wire with a self-bonding overcoat for pole coils

The use of self-bonding round winding wires with a thermoplastic or thermosetting bond coat is well known for the application in small low voltage motors. This technology can now also be used for the production of large field coils, e.g. for wind turbine generators.

Thermibond® M is an enamelled rectangular winding wire with a thermosetting bond coat. The epoxy based bond coat allows bonding temperatures of 140 – 200°C and bonding pressures between 0.04 and 2 N/mm^2. Typical pressure times are around 1 hour. The adhesion between adjacent conductors is strong enough for handling the pole coils during assembly of the generator but it also allows to pull the bonded wires from the compressed coil without any wire enamel detachments. Thermibond® M is suitable for class 220 machines (Figure 6). Advantages for the manufacturer of pole coils are:

- No use of bonding varnish, no solvent emissions
- Cost reduction, shorter manufacturing cycle
- Homogeneous coating of the winding wire, no influence of solvents or impregnating agents

Figure 6 Pole coils produced with Thermibond® M

A new range of mica based conductor insulations for high voltage motors

Von Roll has developed a new range of mica based conductor insulations for rotating high voltage machines. The new range of Samicafilm® is composed of six grades with different constructions and thicknesses (0.06 – 0.09 mm). The main features are:

- New grades of very fine mica paper with grammages of 30, 50, 65 and 75 g/m^2.
- One or two polyester films as carrier material.
- An epoxy based adhesive coating on one or both sides of the tape which acts as hot melt bond coat during the consolidation of the conductor stack. The bond coat is thermoplastic when pressing and thermosetting during the cure cycle of the main wall insulation.

Common to all grades of Samicafilm® is the economical consolidation process of the coil: 5 min. in the coil press at 150°C is enough to consolidate the slot portion of the coil and to provide sufficient mechanical strength for further handling of the coil (Figure 7).

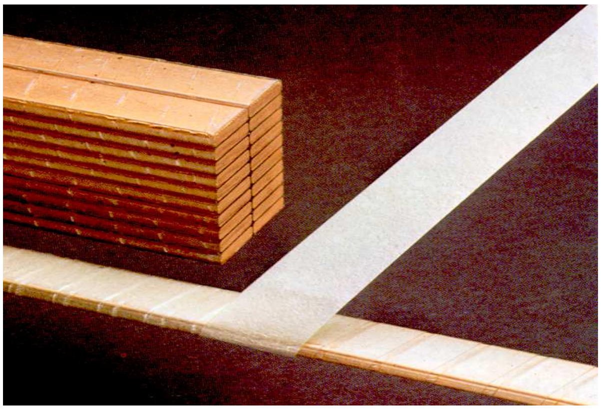

Figure 7 Application of Samicafilm® for high voltage coil consolidation

Samicafilm offers an additional advantage in the repair business where down times of machines often are crucial. The delivery time for a small lot of enamelled winding wire with defined dimensions may sometimes be too long. In such cases it is often easier to produce the bare copper wire and to apply Samicafilm®.

CONCLUSIONS

The conductor insulation in rotating machines does not only act as interturn insulation but also as an interface between the copper conductor and the main wall insulation and the impregnating resin respectively. In this dual function it has to meet a multitude of different requirements which are reflected in IEC 60851. This standard lists a large number of different test methods to specify the quality of the winding wire and its insulation.

Although winding wires are mature products there are a number of new developments in this field. The principal advantages of the new products presented in this paper are:

- Higher performance
- Cost reduction in manufacturing of rotating machines

References

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