

A New Insulation System for Inverter Driven Motors

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1. Introduction

Sales of inverter driven motors have increased rapidly in the past and a future growth of the order of 10 % per year is a realistic prediction. Reasons for this development are the demand for flexible motors in automated production processes and the need for energy saving. Modern variable speed drives using pulse width modulation (PWM) of the electrical supply fed to AC motors result in improved constant flux control which permits optimisation of the developed torque / speed characteristic across the operating speed range.

There are however some effects of the PWM waveform that need to be considered when using a motor in a variable speed drive application: The fast rate of voltage changes results in high voltage stresses that have a detrimental effect on the conductor insulation of the motor windings. These surge voltages can be 2 to 3 times higher than the nominal voltage of the motor which may cause partial discharge and dielectric breakdown. To avoid winding failure of inverter driven low voltage motors the insulation has to be designed to withstand these high voltage stresses.

Several solutions have been proposed for the insulation of the winding wire. This paper presents a new mica based insulation for inverter driven motors. Results of ageing tests are given and compared with other materials.

2. Low voltage inverter drives and the problem of surge voltages

There has always been a large demand for drives with adjustable speed. During the 50's this segment was dominated by DC motors because it was easier to adjust DC voltages since only one voltage had to be controlled instead of three in AC motors. Nevertheless these machines had a relatively bad efficiency, they were quite large and not very robust. During the following years the three-phase AC motor became

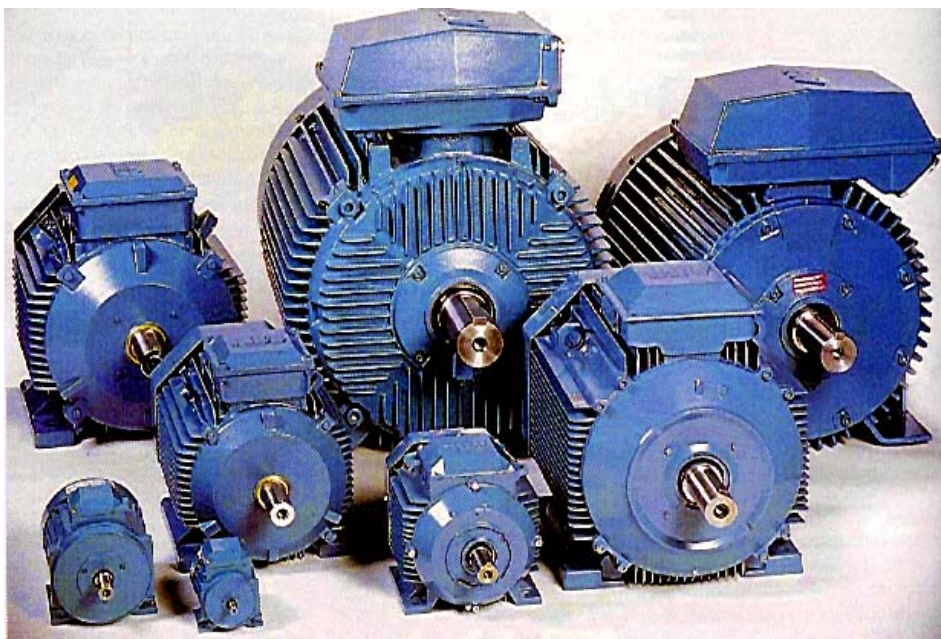


Figure 1: Inverter driven motors

more and more popular due to its robust construction, simplicity and little need for maintenance. But the vast majority of AC motors had fixed speed and a change became only possible in the mid 80's when technical solutions for frequency inverters became less expensive and more compact. This was the breakthrough of inverter driven motors which are now available in the range of 100 W to 1000 kW (Figure 1).

The introduction of the inverter driven motor caused a problem which was underestimated for a long time: 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 drive and transmission effects in the cable. They are dependent on the pulse frequency and rise time of the inverter, the motor cable length and the design of the stator winding of the motor. The pulse rise-times are so short (0.25 μ s – 1 μ s) that their propagation along the motor cable to the motor can change the pulse shape and may produce a voltage overshoot. Due to this effect the terminal voltage of the motor may reach peak values of two times the pulsed output voltage of the inverter.

In addition to this there is an uneven voltage distribution in the motor windings depending on motor and winding parameters. This has little effect on the main motor insulation systems between phases and from phase to earth – which are generally designed to withstand large over voltages - but it causes high stresses of the insulation between turns. The voltage potential between turns, especially between randomly touching conductors within a coil or – in the worst case - between coil ends may reach peak values of 40 to 70 % of the incident terminal voltage.

There is a constant search for faster power switching devices with higher pulse frequencies, shorter rise-times and steeper wavefronts. Higher pulse frequencies have several benefits: The speed control of the drive is smoother and harmonic losses and the audible noise from the motor are lower. The problem of surge voltages in low voltage inverter drives will therefore remain an important issue.

3. Insulation requirements for inverter drives

Table 1 gives a compilation of the surge voltages appearing in inverter driven motors:

Table 1: Surge Voltages in Inverter Driven Motors				
Insulation	Surge Voltage Factor	Surge Voltages		
		U_N = 400 V U_d = 565 V	U_N = 575 V U_d = 815 V	U_N = 690 V U_d = 975 V
Phase – Earth	2.0 · U _d	1130 V	1630 V	1950 V
Phase – Phase	2.3 · U _d	1300 V	1870 V	2240 V
Conductor – Conductor	(0.4 ... 0.7) · 2.0 · U _d	450 ... 790 V	650 ... 1140 V	780 ... 1365 V

U_N = Nominal Voltage

U_d = Intermediate Circuit Voltage = $\sqrt{2} \cdot U_N$

The table shows that surge voltages in inverter driven motors reach peak values up to 3 times higher than the nominal voltage of the motor. The standard insulation systems used for the main motor insulation between phases and from phase to earth are generally able to withstand these surge voltages. Much more critical is the conductor insulation which has to endure high electrical stresses and which may be destroyed if partial discharge occurs and if conventional enamelled wires for low voltage applications are used.

IEC 60034-17 (1998) has revised the respective standard giving withstand characteristics for motor insulation. IEC 2/1085A/Committee Draft (1999) – which is an amendment to IEC 60034-17 (1998) – gives a guide for the design of inverter fed drives. It contains a graph shown in figure 2 with two profiles A and B as limit curves for motors up to 500 V AC and from 500 V to 690 V AC respectively. The figure indicates the peak voltage / rise-time profile that is required for reliable operation of an inverter drive.

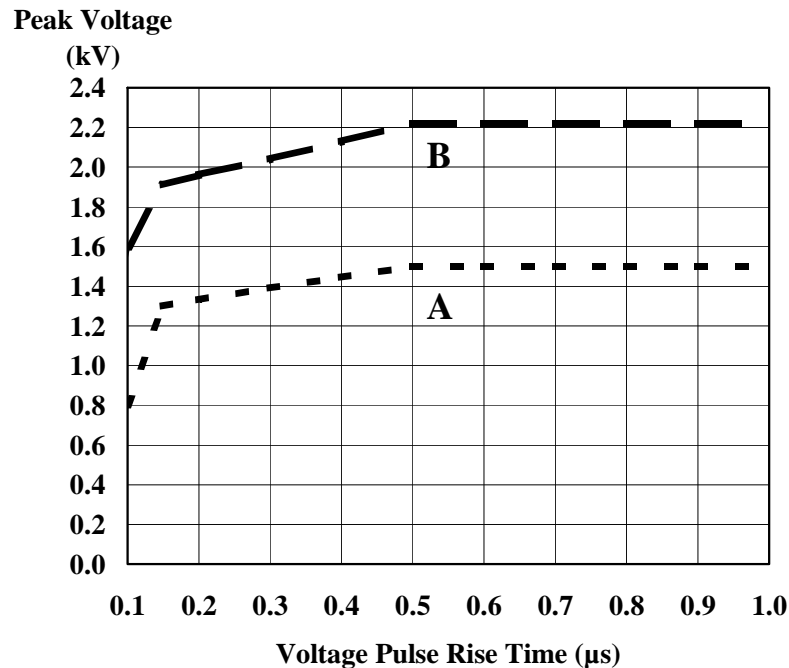


Figure 2: Limit curves of admissible motor terminal peak voltages for AC motors up to 500 V AC (curve A) and from 500 V to 690 V AC (curve B)

4. Ageing mechanism of insulation systems in inverter drives and test results

The detrimental effect of surge voltages in inverter drives is caused by partial discharges in air gaps between conductors which destroy any insulating material based on organic polymers such as wire enamels. The partial discharge inception voltage (PDIV) is a function of the distance between two conductors, the permittivity of the insulating material in between and ambient factors such as temperature and humidity. PDIV was measured for different wires in a twisted pair test performed at room temperature with 50 Hz AC. Measured values are:

Wire:	PDIV:
Enamelled wire grade 2	830 V
Filled enamelled wires	790 ... 940 V
SamicaShield® wire	1270 V
SamicaShield® wire impregnated *	1890 V
(* with polyesterimide resin 3340)	

The results show that PDIV of enamelled round wire in a low voltage motor is about 800 V at room temperature; it will be reduced by 10 to 15 % if the temperature of the motor increases to 155 °C. If partial discharge occurs in a motor winding it will rapidly destroy the enamel insulation of the conductor followed by an inter-turn short circuit and finally by total failure of the motor. As can be derived from table 1, inverter drives with at a rated voltage ≤ 400 V usually show no partial discharge between conductors since surge voltages are lower than the PDIV of the coil winding.

The situation is different for inverter drives with a nominal voltage between 400 and 690 V. Surge voltages are mostly above PDIV and partial discharge will occur. Filled wire enamels are available on the market which should prevent motors from premature failure due to partial discharge. The problem is that PDIV of enamelled wires with fillers is the same or only slightly higher compared to standard wires and the effect of the filler is not the elimination of partial discharge but a slower rate of erosion under corona conditions. The other disadvantage of filled enamelled wires is their limited mechanical strength and the brittleness of the coating.

PDIV in coil windings can be increased by impregnating the motor with a suitable resin. To obtain a void free filling of the coils the VPI technique has to be applied. Furthermore resin characteristics and impregnation process parameters have to be adjusted carefully to avoid resin run-off during the impregnating and curing cycle. If these requirements are met we can expect an increase of PDIV by 300 to 600 V. But we also have to consider that during thermal, mechanical and electrical ageing of the resin cracks will appear and PDIV will decrease again.

For more than a century mica is the preferred material in high voltage insulation due to its superior resistance to corona. It seemed obvious to use mica as conductor insulation for low voltage inverter drives also, but the conventional mica insulation available was too thick for this application. Von Roll Isola therefore developed SamicaShield[®], a winding wire with a new type of mica insulation which is very thin. The thickness of the insulation of SamicaShield[®] wires varies between 0.09 and 0.18 mm depending on type and application. Measured PDIV of SamicaShield[®] wires is 1270 V which is above all surge voltages between conductors as given in table 1.

Ageing test results

Round wires with different insulations for low voltage motors were stressed in a pulse endurance test with a pulse width modulated voltage of 2 kV at 20 kHz and a rise-time of 0.025 μ s using an impulse generator. The round wire had a diameter of 1.18 mm (bare copper) and was applied in a twisted pair arrangement. Time was measured till electric breakdown. Results are:

Wire:	Endurance:
Enamelled wire grade 2	≤ 0.5 h
Filled enamelled wire	≤ 50 h
SamicaShield [®] wire	≥ 1100 h

In a field test the lifetime of five inverter driven motors with different enamel coated wires and with SamicaShield[®] wire was compared under accelerated ageing conditions. The motors with enamelled wire and filled enamelled wire showed partial discharge in the coil windings, whereas the motor with SamicaShield[®] wire was free of partial discharge. Lifetimes till motor failure were approx. 100 h with standard enamelled wire and approx. 200 h with filled enamelled wire. The ageing test of the motor equipped with SamicaShield[®] wire was finished after 4000 h without motor failure.

The Korean Electrotechnology Research Institute (KERI) tested 26 inverter driven low voltage induction motors for elevator application. Six different types of insulating materials were used including SamicaShield[®] and PDIV, maximum PD magnitude Q_m , ΔI , $\Delta \tan \delta$ and breakdown voltage were measured of each motor. The motors with SamicaShield[®] gave the best results in all measurements. The results were published at the IEEE 2000 conference in Los Angeles.

5. Summary

Today adjustable speed power units with frequency converters and 3-phase current induction motors are a standard. However the coil windings of these motors are exposed to surge voltages caused by the fast rate of voltage changes which may – in motors with nominal voltages between 400 V and 690 V - lead to partial discharge, inter-turn short circuit and finally total failure of the motor. To prevent these motors from failure several solutions are proposed:

- The use of filters or other units which are placed between inverter and motor. These solutions need correct matching to the application, they also need extra space and cost and they reduce the efficiency of the power unit.
- The use of filled enamelled wire. The problem of this solution is that it has no or little effect on the partial discharge inception voltage, but it will slow down the rate of erosion under corona conditions. Furthermore filled enamelled wires have limited mechanical strength due to the brittleness of the coating.
- Von Roll Isola developed SamicaShield[®], a winding wire with a new type of very thin mica insulation. Mica is the preferred insulating material in high voltage machines and is known to have superior electrical and thermal properties. Partial discharge inception voltage of SamicaShield[®] wire is 1270 V which is above all surge voltages between conductors to be expected in inverter driven motors with nominal voltages between 400 V and 690 V. Pulse endurance tests simulating the stress generated in inverter drives resulted in lifetimes of SamicaShield[®] wire at least 20 times higher than filled enamelled wire and about 2000 times higher compared to standard grade 2 enamelled wire. These results were confirmed by field tests with inverter driven motors.

Von Roll Isola offers a complete family of insulating materials especially developed for inverter drives with rated voltages of 400 to 690 V. The product range includes:

- SamicaShield[®] wire in diameters of 0.70 – 2.00 mm and with an increase in insulation of 0.18 to 0.36 mm.
- Slot insulation Myosam, which is a 160 g/m² Samica[®] mica paper coated on both sides with PETP–film or –film plus –fleece. The mica paper ensures the long term corona resistance of the slot insulation.
- Phase insulation Myoflex PF, which is a PETP–film coated on both sides with PETP–fleece. The fleece absorbs the impregnating resin and reduces the risk of resin run-off.
- Impregnating resins 3032 and 3340 (both rigid) or 3037 (flexible) which are all UL approved class H polyesterimide resins. These resins combine good tank stability with a fast gel time (1.5 – 2.0 min. at 120 °C) to be used in high throughput production.

6. References

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