Properties of a New Ecoefficient Coating for Magnet Wire

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Abstract—Classical magnet wires used for manufacturing electrical machine and transformer windings are made with polluting processes involving carcinogen solvents and CO₂ emissions. Their production also requires significant electric energy. An innovative varnish produced with a more ecological process, without any solvent and no CO₂ or NOx emission, has been proposed. The insulation of this copper wire is composed of an UV-polymerized polyester acrylate layer covered by an extruded thermostable resin (polyphenylene sulfide). The present work aims to explore the properties of this new efficient coating for magnet wire application. Calorimetric, thermogravimetric and dielectric analyses were performed to study the new coating. Accelerated tests were conducted to highlight the structural and dielectric changes occurring during thermal ageing.

Keywords—magnet wire; eco-friendly dielectric; free-solvent

I. INTRODUCTION

Conventional enamelled wire requires the use of polymeric insulation coating. This latter is often based on polyester-imide and polyamide-imide substrates, which are deposited in successive layers, following passages in trays varnish, containing solvents. Some of these volatile organic compounds (VOC) evaporate but can be treated and eliminated by direct burning. However, their combustion generates a lot of CO₂, with known harmful ecological impact. Besides, an undesirable residual quantity is released directly into the atmosphere and escape to any treatment process.

Moreover, the process described hereabove is energetically expensive. Indeed, the polymerization of the insulating layers is obtained after 20 passes that combine the evaporation of solvents initially present in the original varnish and heating needed for trans-esterification and condensation of the varnishes.

Face to these drawbacks, an new generation of environmentally friendly magnet wire has been developed [1,2]. The wire manufacturing involves a non-polluting, solvent-free process without CO₂ or NOx emissions. The insulation is obtained by coating the copper wire with a photocurable polyester acrylate (PEA) that can be polymerized using UV light. This substrate is subsequently covered by an extruded thermoplastic heat-resistant resin (polyphenylene sulfide-PPS). Therefore, the insulation can be easily modified to fulfill new electrical requirements by adding micro-particles or organic compounds to the initial resin.

The present work aims to study the dielectric and thermal proprieties of this new insulation, in view of its application to electrical machine windings. Differential scanning calorimetry, thermogravimetric and dielectric tests were performed to analyze the structure and behavior of the layers. Accelerated thermal aging tests were also conducted to exhibit the change of the molecular structure and the dielectric properties of the insulation compared to its initial state. Physico-chemical analyses allowed the construction of reliable relationships between the materials structure and their macroscopic properties. They also brought interesting insights as regards the substrates thermal degradation and their adaptation to the intended use. The behavior of the materials has been studied at high temperatures via dielectric measurements. Thermal aging tests also allowed determining changes in the dielectric spectra of the PPS.

In electrical machines, short-circuit stator usually begin with a short circuit located between several turns of the same winding, following the deterioration of their insulating material. This phenomenon often begins by the appearance of partial discharge (PD), which gradually creates weaknesses in the local turn-to-turn insulation. Consequently, focus was made on turn-to-turn insulation behavior of the studied wire by partial discharge inception voltage and turn-to-turn capacitance measurements, during the same accelerated thermal aging of dielectric spectra analysis. The results are cross-correlated in order to assess the behavior of the new wires.

II. EXPERIMENTAL ASPECT

A method for polymerization by ultraviolet (UV) using resins without solvent is developed in order to have non-aggressive for the environment and improve product quality, while eliminating emissions of VOC. Polymerization process
using UV radiation is developed since the 1970s. It is used to convert a fluid to a solid film under the effect of radiation by using UV lamps. This polymerization may be radical, if the system is based on acrylic monomers, whereas it may be cationic, if the monomers are of epoxy or vinyl ether. This type of polymerization is advantageous to its speed, efficiency, and offers good quality material and high strength without the emission of VOC. The temperature must be monitored for homogeneous polymerization. The studied wire insulation is composed of two layers. A polyester acrylate (PEA) layer is polymerized by UV light and is subsequently covered by an extruded thermoplastic heat-resistant resin (polyphenylene sulfide-PPS).

Fistly thermal properties are highlighted through calorimetry and thermogravimetric analyzes. Thereafter, the influences of temperature and frequency on dielectrical and electrical properties of the polymers are investigated from the measurement of their capacitance, loss factor and partial discharge inception voltage under short and strong thermal cycles.

A. Materials

In order to perform the study of the new ecoefficient coating for magnet wire, different substrate combinations were produced for study. All specimens were copper wires of 0.95 mm diameter but covered by specific insulating layers with the following characteristics:

- Extruded crystalline PPS;
- UV-polymerized polyester acrylate + extruded amorphous PPS (named "amorphous wire");
- UV-polymerized polyester acrylate + extruded crystalline PPS (named "crystalline wire");
- UV-polymerized polyester acrylate + extruded crystalline PPS+ aliphatic bonding layer (named "new magnet wire").

As it is important to compare the performance of this new magnet wire with the one usually used in low voltage electrical machine, samples with polyester-imide+polyamide-imide+aromatic bonding layer (named "classical magnet wire") were also used.

PEA and PPS thicknesses were 15 µm and 80 µm, respectively.

Polyphenylene sulfide PPS is a semi-crystalline thermoplastic with high performance, good thermomechanical stability and chemical resistance versus various fluids. It also presents a good electrical resistivity. Its polymerization is carried out by a heterogeneous reaction of one or more polyharmonic with sulphide (S) and sodium carbonate (Na₂CO₃), which leads to a partially branched structure. The polymerization can also be performed using polycondensation of metal alkali to have a linear structure. This type of polymer is specified by a high heat resistance, high thermal insulation and low electrical loss factor (0.0013 at room temperature for a frequency of 1 MHz). It can also maintain a high crystallinity even in hot and humid conditions.

Polyester acrylate (PEA) is a thermosetting amorphous polymer obtained by curing the polyester-based UV acrylate monomers that are characterized by a high chemical reactivity and low volatility. This used varnish layer is solvent-free and polymerized by a radical reaction under UV. With very good film-forming properties, PEA can be used on a wide range of enameled wires, from 0.1 mm to flat ones, while maintaining its flexibility properties, adhesion and chemical resistance.

B. Thermal analysis

Differential scanning calorimetry (DSC) was employed to evaluate the characteristic temperatures of each polymeric substrate (glass transition, crystallization and melting temperatures). The analyses were performed with a Mettler Toledo Star 1 device. These calorimetric experiments were carried out in air from ambient temperature to 350 °C, with a heating rate of 10 °C/min. During the measurements, each sample was set in an aluminum pan that was consecutively placed in the measurement heating cell. An empty pan was used as reference.

Thermal gravimetric analyses (TGA) were performed on Q50 from TA Instruments under air flow (25 ml/min). The experiment consisted of recording the weight change of the samples as a function of temperature. In order to register the complete degradation of the polymer, tests were performed from ambient temperature to 800 °C, with a heating rate of 10 °C/min.

C. Dielectric spectra analysis

The spectra were measured at room temperature with a Solartron 1260 frequency analyzer coupled to a 1294 dielectric interface. The measurements were done at room temperature, at frequencies comprised between 1 Hz and 1 MHz.

The samples presented circular sections insulated with polymer layers. A cell measurement has been performed to have a structure equivalent to a cylindrical capacitor. It consists of the polymer layer (dielectric) between the conduction wire (inner electrode) and another conductive plate (outer electrode). The insulation has been covered with conducting graphite paint to eliminate the empty space located between the insulation and the copper plate, which may disturb the measurements. The capacitance and the loss factor measurements were achieved by connecting the conductor and the graphite layer to the frequency analyzer.

D. Turn-to-turn insulation analysis

Twisted pair specimens insulated by PEA and PPS layers have been prepared according to EIC 60851-5 [3]. The samples are fixed in a rigid support and placed in an oven controlled in temperature. Accelerated aging tests at 250 °C were conducted according to IEC 60172 [4].

The turn-to-turn capacitance is measured with the impedance analyzer Agilent E4980A and a connecting cables system based on a 4-point method, in order to eliminate their influences on measurements [5]. Before and between each thermal cycle the PDIV and the turn-to-turn capacitance were measured. During the tests the twisted pair specimens have been subjected to 50 Hz sinusoidal waveform by using a test circuit based on IEC 60270 [6], in order to detect partial discharges apparent charge above 2 pC [2,5]. This system includes an ac high voltage supply, a coupling capacitor, the
twisted pair and a measuring impedance $Z_m$ connected in parallel to the sample, an ICM PD detector and a fast oscilloscope.

### III. RESULTS AND DISCUSSION

Thermal analyzes were achieved by DSC and TGA measurements. The thermograms are respectively presented on Fig. 1 and 2. In previous paper, UV-polymerized polyester acrylate (PEA) and PPS layers thermal characteristics have been studied [2].

![DSC thermogram of PEA+crystalline PPS and PEA+amorphous PPS](image1)

**Fig. 1.** DSC thermogram of PEA+crystalline PPS and PEA+amorphous PPS

![TGA thermogram PEA+crystalline and PEA+amorphous PPS layers](image2)

**Fig. 2.** TGA thermogram PEA+crystalline and PEA+amorphous PPS layers

The calorimetric behavior of PPS-PEA wire is very similar to that observed with pure PPS. Indeed, the thickness of PEA layer is quite small and the only transitions that are observed in PPS-PEA thermogram are characteristic of the only PPS. The more crystalline PPS doesn’t show any signal characteristic of the amorphous domains (Tg and recrystallization). This grade is expected to be more interesting as it contains less heterogeneities and smaller intermolecular space compared to “amorphous” PPS. The crystalline layer can also create a stronger cohesive energy with a high velocity, compared to the amorphous one. TGA curve shows the degradation of both insulations from 430 °C that is significantly higher than the degradation inception of PEA (230°C [2]). This means that the PPS acts as a protective layer against PEA layer oxidation. This protection should be more efficient with crystalline PPS, as the amorphous one has a disordered macromolecular morphology, leading to greater oxygen permeability.

As the PEA layer is much thinner than the PPS one, the effect of temperature on the variation of the equivalent capacitance of the insulation is very close to the one of a single PPS layer.

Fig. 3 shows the dielectric spectrum of the PPS for different temperatures. The loss factors values are relatively high, but within an interval usually observed in applications for low voltage electrical machine. For temperatures below 80 °C, the capacitance variation is relatively low. Indeed, the PPS structure where both phenyl rings are bonded to sulfur through a bond angle of 110 ° C, that gives to the phenyl structure a relatively large dipole moment (1.46 Debye) [7]. However, as the molecular chain has a zigzag structure, the total dipole moment of the PPS is very low. The dipoles of the main chain are also difficult to orient. Beyond 80 °C, the glass transition is initiated and increases the molecular mobility in the amorphous phase that allows the orientation of polar bonds C-S and chain segment. Therefore, there is a significant increase of the PPS permittivity, observable via the capacitance increase over the entire frequency range. Beyond 120° C, the glass transition occurs, PPS also undergoes cold crystallization (see Fig. 1). The larger increase in the capacitance and loss factor with temperature in the low frequency area, compared to the rest of the spectrum, is likely due to the increase in chain mobility beyond the Tg, and also to the increase of the material conductivity with temperature.

Fig. 4 shows the spectra obtained on PPS insulation in the initial state and after a thermal aging of 3 days at 250 °C. A significant increase of the sample capacitance after thermal aging is observed, on the entire studied spectrum. An additional relaxation peak appears around 50 Hz. It is accompanied by a shift of the high frequencies peak towards higher frequencies and a disappearance of the peak, at low frequencies. These reflect a significant change in the material. In fact, the thermal aging induces scission of the chemical bond in the material, leading to structural changes, oxidation and possible copper penetration in the insulating layer, near the conductor, which result in the formation of cuprous oxide [8, 9]. The growth of the latter may be at the origin of a decrease in the thickness of the insulation and, thus to the capacitance increase observed across the entire spectrum.

![Dielectric spectra of PPS-insulated magnet wires at different temperatures](image3)

**Fig. 3.** Dielectric spectra of PPS-insulated magnet wires at different temperatures

![Thermal aging effect on the dielectric spectrum of PPS-insulated magnet wires](image4)

**Fig. 4.** Thermal aging effect on the dielectric spectrum of PPS-insulated magnet wires (T=250 °C, 3 days).
Nowadays, polyimides, polesterimides and polyamide-imides are widely used in electrical machines winding insulation wire. The windings are impregnated with a varnish that keeps the winding in the slots. The ideal impregnation into the winding heart is difficult, which led to cover the wire with a bonding layer with solvent (aromatic). We propose to use the new enameled wire, with a bonding layer, replacing the impregnation, by plastic-based biopolymers (aliphatic).

Therefore, the behavior of the turn-to-turn insulation made with this new magnet wire must be assessed and compared to the one of classical wires.

Fig. 5 illustrates the temperature dependence of the loss factor measured at 10 kHz for a turn-to-turn insulation of the new magnet wire. It is possible to observe 3 dielectric relaxation phenomena which can be related to the DSC thermogram (Fig. 1). The first relaxation appears at low temperature at 80 °C. It corresponds to molecular (or dipolar) orientation. Two last relaxations are finally observed at high temperature starting from 200 °C. They may correspond to the relaxation of separated free charges near the electrodes for the first one (electrode polarization), and to the PPS fusion for the second one.

According to IEC 60172 [4], ten thermal cycles of one day duration are applied to the samples. In order to carry out a strong constraint, 250 °C has been chosen as the exposure temperature (just below the PPS fusion). The measurements of turn-to-turn capacitance and Partial Discharge Inception Voltage (PDIV), are achieved before and after each cycle.

Results are given in Fig 6. It must be pointed out firstly, that the turn-to-turn capacitance increases, during thermal aging, and confirms the results observed on fig. 4. The new magnet wire also performs better in terms of Partial Discharges Inception Voltage. These values decrease during the aging test, but remain higher than those of classical wire. Indeed, in the case of classical wire, the insulation are deposited by several separately layers after passes, but the new magnet wire is manufacturing with only two layers, limiting the occurrence of air void, which weaken the insulation.

It is to note that the thermal aging produces the same effects on the turn-to-turn capacitance and the PDIV as for classical wires [8]: indeed, the turn-to-turn capacitance increases while PDIV decreases.

IV. CONCLUSION

The present study focuses on a new magnet wire insulation free of organic volatile compound, composed of a UV-polymerized PolyEster Acrylate layer covered by an extruded PolyPhenylene Sulfide layer. The thermal and dielectric characteristics of the insulation and its behavior during thermal aging were studied to assess the proposed wires for electrical machine windings. The results confirm the correlation between the PDIV and the turn-to-turn capacitance, and the possibility to use this latter as an aging indicator as it is the case with classical enamelled wires. The good behavior under certain conditions, relative to partial discharges inception, suggests the use of PEA-PPS as insulating layers for enamelled wires. However, additional measurements are needed to evaluate and improve their behavior for stronger thermal stress and obtain wires with a higher thermal class.

REFERENCES


