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# Study of new ecological magnet wires performances during thermal aging tests

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**Abstract-** The principal purpose of this work is to investigate the performance of new technologies of electrical insulation (Sol-gel material top coated with an extrusion layer) intended for winding machines wires. New configurations of coating wire produced by an eco-friendly process, with less environmental impact than conventional ones, are tested and compared. The working method is based on measurements of samples that are produced in accordance with international standards to characterize the electrical and thermal properties of the insulated wires. The performance analysis of insulations is composed of a sequence of dielectric tests and thermal aging tests. This latter test is realized after validation of the basic electrical and mechanical tests. During thermal aging, the parallel capacitance, tangent delta, and Partial Discharge Inception Voltage (PDIV) are measured to investigate the evolution of those dielectric parameters and to compare dielectric behaviour between different configurations of insulating materials. The results of the tests show that an extrusion resin with fillers had a longer lifetime compared with non-filled resins. The concentration of sol-gel influenced the lifetime of insulated wire. This study shows some indicators of thermal improvement, but the percentage of sol-gel used is yet very low and therefore, far from the main objective of using fully sustainable products. The sol-gel formulation tested in higher concentrations had a lower performance of basic mechanical properties required for winding wires. However, the extrusion process for magnet wire insulation is possible and gives good results with pure stable thermoplastic polymer and mineral fillers on extrusion resins.

## I. INTRODUCTION

Sustainable mobility is widely developed, electrification of cars, planes, and all means of transport as well as reducing the consumption of polluting products in manufacturing sectors are current issues. On the other hand, the electrical industrial sector is seeking to increase efficiency by reducing the mass of electrical machines and devices [1]. In the environmental footprint of electrical motors[2], the manufacturing process of magnet wire requires high levels of energy consumption and pollution particles liberated on the environment [3]. With the increase of electrification, the wires manufacturers use tend to be increased. Research and development of new technology or new products are necessary to find a compromise between increasing performance and reducing pollutant processes.

A magnet wire requires a compromise of several properties, such as physical, mechanical, thermal, and electrical. For developing a process and choosing materials, the physical, mechanical, and thermal properties are all essential for the machine winding application. Several standards define the specifications of magnet wires for windings taking into

account these properties [4]. This study is focused on thermal and dielectric properties for different configurations of insulation.

Beyond the development of magnet wire using less enamelling pollutant process, this study consists of analysis between experimental dielectric results and its interpretation based on literature.

## II. LITERATURE BASIS

The dielectrics properties behaviour of Electrical Insulation Systems (EIS) changes under temperature constraints. Several works have explained these phenomena [5-13].

### A. Relative Permittivity and Parallel Capacitance

The impact of temperature on the capacitance of insulators is still under investigation. However, several studies show that the capacitance of insulators increases with temperature [7-10]. The parallel capacitance is commonly used to represent the inter-turn insulation and depends on the relative permittivity. Its evolution at low frequency is related to a phenomenon of conduction DC which increases with the temperature [6]. The phenomenon of augmentation of parallel capacitance can be principally explained by the variation of the dielectric constant caused by temperature [12].

### B. Partial Discharge Inception Voltage

Past works show us a decreasing behavior of Partial Discharge Inception Voltage (PDIV) as a function of temperature [1],[7-8]. Recent work using twisted pairs as samples obtained a PDIV decreasing with temperature, justified by the increased field strength between the air wedge gaps due to the increase in the complex relative permittivity of the insulation layer at high temperature [6].

### C. Dissipation Factor

Thermal aging is one of the deterioration processes which causes an increase in dielectric losses [11]. Two causes explain the behavior of the dissipation factor with the temperature, the molecular conditions inside the material, and the conductivity influence in high temperature.

- The dipole relaxation is a phenomenon that contributes to the dielectric loss factor ( $\tan \delta$ ) in polar dielectrics. The dipoles orient themselves to a greater or lesser extent in response to the electric field. In the solid, the dipoles suffer friction with the polymer matrix, so this is an obstacle to the reorientation of the dipoles in response to the applied field. The

reorientation process has a time constant or several time constants. If the dipole oscillates  $45^\circ$  to the phase of the electric field, the loss induced by the dipole is maximized, resulting in a peak in the dielectric loss called the "dispersion peak". As the temperature increases, the viscosity of the polymer tends to decrease, resulting in a reduction in the reorientation time constant and an increase in the frequency of the dispersion peak [13].

- At high temperatures, conduction can contribute to dielectric losses in a non-negligible way. The loss tangent includes a term  $\sigma(E, T)/\epsilon\omega$ , where the function  $\sigma(E, T)$  corresponds to the electric field and temperature-dependent conductivity [6].

### III. ENAMELLING AND EXTRUSION PROCESS

The main steps of the process of insulation application around a copper conductor are:

- 1) Annealing oven: The process starts with the annealing furnace, where a copper conductor is cleaned in an atmosphere without oxygen and is softened, which is important to acquire the necessary flexibility to support the winding operations and warrants the best adhesion of the primer layer on copper with an etched surface.
- 2) Varnish application: an insulation layer in a solvent phase is applied around the conductor by enamelling dies.
- 3) Curing: Once the varnish is applied to the copper surface, the wire passes in an oven for the curing process. Around 70% of the solvents from the varnishes are extracted and the dry extract remains on the surface of the wire.
- 4) The evaporated solvents are passed through a catalyst where they are burnt off and the heat from the catalyst is reused by the curing oven temperature control.
- 5) Steps 2 and 3 are iterated to reach the targeted thickness.

This enamelling process is repeated several times until reaches the insulation thickness. In this study, an enamelling process is used for a small part of the insulation thickness (between 20% and 30% of the thickness). Most of the insulation thickness is made by only one pass by the extrusion machine, resulting in a resin coating. The final configuration obtained in this process is represented in Fig. 1, the copper conductor with a first coat composed of enamel thin layers and a final extruded layer.

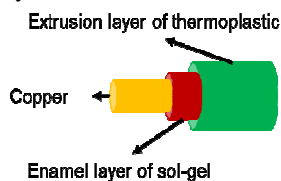


Fig. 1. Enamel-extruded wire

### IV. MATERIALS INSULATORS

To increase the thermal resistance of an insulator, it is important to choose the materials classed for higher temperature operation. The high-temperature resistant insulation supports a temperature operation above  $175^\circ\text{C}$  [14]. They are characterized by having high thermal stability, high dielectric strength, and good adhesion to the cooper [15].

The conventional materials used for wire insulation for high-temperature applications are Polyestherimide, Polyamide-imide, and polyimide [16]. Polyimide (PI) is known for its thermal resistance, its thermal class can reach  $240^\circ\text{C}$  for  $25\mu\text{m}$  thickness. Polyamide-imide (PAI) combines the good properties of PI and good processability, its thermal index is around  $220^\circ\text{C}$ . The PAI is frequently used on topcoats in electrical insulations of wires with a Polyestherimide (PEI) bottom coat. The PEI is a modified version of PI, with lower thermal stability due to its flexible ether linkage; its thermal class is  $200^\circ\text{C}$ .

Materials used on the bottom layer of the insulation were applied by the classic enamelling process. As an extrusion layer, a thermoplastic polymer is used for the topcoat. It's a crystalline resin that has high heat resistance [17]. Precedent works with mineral fillers have shown an improvement in mechanical properties [18-19]. The mineral fillers are also implemented in an extruded layer of some configurations tested.

Contents of silica-based sol-gel were implemented in the second layer of PAI varnish (enamel) before the extrusion layer. The sol-gel process contributes to improving the enamel wire properties, and better properties of breakdown voltage after thermal degradation [20]. Recent works using silica particles have shown improvement in glass transition temperature [21].

### V. RESULTS AND DISCUSSIONS

Different insulations configurations on a copper conductor of  $0,95\text{ mm}$  diameter are tested. The PEI and PAI polymers have been used as primer insulators of  $25\mu\text{m}$  of diameter increase.

Thermal aging tests are carried out accordingly to the specifications of the IEC 60172 standard [22]. The aging temperature is  $250^\circ\text{C}$  and the cycle duration is 72h. Eleven twisted pairs samples are prepared following the standard specifications [23]. The proof test voltage used is 1000V, due to the increase of diameter (insulation coat). The lifetimes obtained by this experimentation are presented in Table I.

TABLE I  
AGING TEST OF ENAMEL-EXTRUDED WIRES AT  $250^\circ\text{C}$

Wires insulation composition	Lifetime (h)
PEI + extruded layer of thermoplastic polymer	348
PAI + extruded layer of thermoplastic polymer	420
PEI + extruded layer of thermoplastic polymer with mineral micro fillers	492
PAI + extruded layer of thermoplastic polymer with mineral micro fillers	708

The lifetimes indicate that the extruded layer has a relevant influence on the thermal resistance of the insulation configuration during the aging test. The wire containing micro fillers on extruded layer has resisted longer than those that are not filled.

Following the first indications, new configurations have been exploited using the mineral micro fillers and adding sol-

gel to the primer enamel. We used the sol-gel products on the enamel layer to verify their influence on the improvement of thermal resistance during thermal aging.

Table II shows the results of an aging test at a higher temperature, 300°C. This test has a group of eleven samples of the most performant wire of the precedent aging, comparing it with a group of eleven samples of a new wire insulated with sol-gel contents on the enamel PAI layer and filled resin on extrusion. In this case, it's possible to observe the higher performance of the group of samples insulated with sol-gel contents, which failed the proof test voltage after 7 thermal cycles (the duration per cycle is 24h), and the samples insulated with PAI + thermoplastic filled insulation failed after 3 cycles at 300°C. This higher performance is also verified in a 250°C aging test as presented in the last column of Table II.

TABLE II  
AGING TEST OF ENAMEL-EXTRUDED WIRES WITH AND WITHOUT SOL-GEL

Wires insulation composition	300°C Lifetime (h)	250°C Lifetime (h)
PAI + extruded layer of thermoplastic polymer with mineral micro fillers	60	708 <sup>1</sup>
PAI+ PAI/Sol-gel (18%) + extruded layer of thermoplastic polymer with mineral micro fillers	156	1428

The sol-gel insulated wire had been observed during the 250°C aging test, including classic wire samples, and PI enamel with a thermoplastic polymer extruded insulated samples. Eleven twisted-pair samples had been made for each insulation. The three insulations are described below:

- Wire insulated by the first layer of PAI enamelled, a second enamel layer of a mixed content of PAI and sol-gel in a concentration of 18%, and a topcoat of thermoplastic polymer on the extrusion layer.
- Wire insulated by a first layer of PI enamelled and an extruded layer of thermoplastic polymer. The proof test voltage was 1200 V for each sample, accordingly with its greater thickness compared with the others.
- A commercial wire insulated by enamel layers of PEI and PAI.

The graphic in Fig.2 shows the dielectric behaviour of each group of samples. Parallel capacitance and dissipation factors are measured by using an Agilent 4294A Precision Impedance Analyzer. The measurement frequency is 10 kHz to have the precision indicated on the accuracy chart of the equipment. The measurement of PDIV is achieved accordingly with the standard IEC 60270 [24]. These measurements are achieved before each thermal cycle and the proof test voltage is applied using the same device.

Despite the deviation between sample measurements indicated graphically in Fig.2, the commercial wire C shows an increase in parallel capacitance, which can be associated with accelerated aging of most parts of the samples compared with the other configurations of insulators. The classic wire may be observed in a longer aging test to affirm the increase of parallel capacitance expected in accord with the literature

<sup>1</sup> Result issue of Table I

previously exhibited [7-8] [10]. And wire B has stable values of parallel capacitance during the aging test, resulting from the high thermal stability characteristics of the PI in the first coat. Wire A had a variation in parallel capacitance values. That can be influenced by the sol-gel contents on the primer layer, in which the relative permittivity is not known. To understand this phenomenon, more tests are being done with sol-gel contents without PAI polymer to evaluate the permittivity and conductivity of the material.

The PDIV had been decreased during the aging for all insulators as expected. The extruded wires have higher values of PDIV compared with the commercial one, it's kept until its end life. The insulation B presented higher values of PDIV during the test.

The dissipation factor had different behaviours between the insulators. The most resistant insulators had stables values, and the commercial one got a visible increase just before the last proof test voltage, meaning that the dielectric parameters were already degraded. This can also be related to its low thermal resistance compared with the others. The high deviation for the last point of dissipation factor measurement of the commercial wire happens because part of the samples was degraded (dissipation factor > 1,0). The degradation of the dissipation factor coincides with the end of life when more than 50% failed during the last proof test voltage.

The curves finish at the end of the thermal aging when more than 50% of samples insulators broke down during the proof test. Wire A got a higher duration of resistance on thermal aging, which indicates that the sol-gel and filled resin influenced the improvement of the resistance on this test.

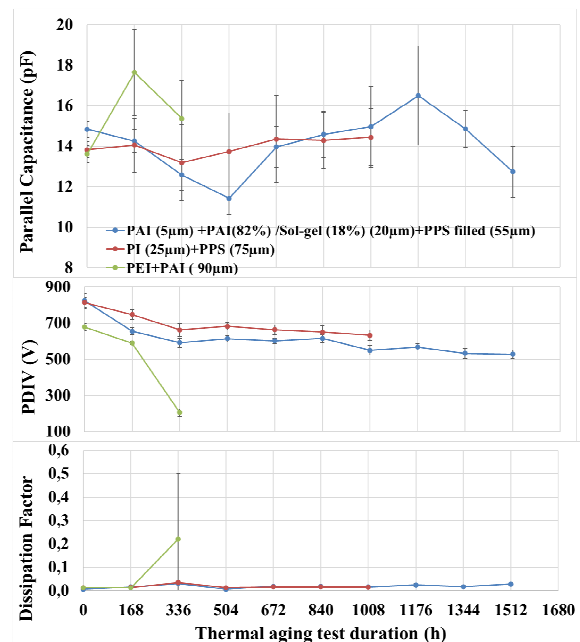


Fig. 2. Dielectric parameters collected between cycles of 250°C thermal aging

## CONCLUSIONS AND PERSPECTIVES

Different polymers have been tested on primer layer of enamelled wire to observe their influence on the thermal

resistance during the aging test. The sol-gel mixed with polymer insulation varnish, shows an increase in the thermal resistance on the aging test. The results obtained in this study show the positive influence of the sol-gel which doesn't need hazardous solvents for polymerization (sol-gel is water-alcohol based). This type of insulation can be an eco-friendly candidate to be used as insulation of enamelled wires. On the other hand, the basic mechanical properties of the wires are assured only when the concentration is very low (18%), and the polymer with organic solvent is still being required for that.

Although the enamel-extruded technology studied is far from being free of polymer enamel coat, it represents a possibility of reducing the enamel process and a greener solution for magnet wire manufacturers. Despite this possibility, many tests must be executed to confirm a replacement of the conventional enamelling process. We envisage defining the thermal index for the enamel-extruded wires developed, by thermal aging tests. Many other properties are still to be validated as required by the magnet wire standards (such as chemical resistance, abrasion resistance, and more).

The thermal class improvement depends on the thermal resistance of the insulators during the aging test. The commercial wire having a thermal class of 210°C, indicates that the enamel-extruded has better performance so a greater or equivalent thermal class.

We are testing different fillers to improve this thermal resistance. New formulations of sol-gel will be studied soon with the aim of increasing the concentration of sol-gel on the primer coat and evaluating if the properties for winding applications will be conserved.

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