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► **To cite this version:**

Giovana Pereira dos Santos Lima, S. Ait-Amar, G. Velu, P. Frezel. CHARACTERIZATION OF CLASSICAL AND EXTRUDED ENAMELLED WIRES. 14th International Electrical Insulation Conference (INSUCON 2023), Apr 2023, BIRMINGHAM, United Kingdom. hal-04150368

HAL Id: hal-04150368

<https://univ-artois.hal.science/hal-04150368>

Submitted on 4 Aug 2023

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CHARACTERIZATION OF CLASSICAL AND EXTRUDED ENAMELLED WIRES

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INTRODUCTION

Insulated wires are components of devices employed in different applications, such as in the automobile and aerospace industries, and renewable generation equipment (e. g. wind power). The interest in improving magnet wires is relevant to the industry sector, especially for electrical machine winding [1,2]. The performance of magnetic wires is fundamentally dependent on the quality of their Electrical Insulation System (EIS). Further knowledge of insulation properties may point to ways of improving this. Several properties as mechanical, thermal, chemical, and electrical must be considered for the manufacturing of magnet wires. Some standards establish protocols for the evaluation of those properties, such as IEC 60317-0-1 [3].

Many different stresses can contribute to the premature aging and damage of rotor and stator winding insulation. The coils are subject to electrical, mechanical, thermal, or environmental stresses. These constraints may be constant under the operating conditions, or they may occur for a short period, during a specific moment such as the start-up of the machine for example [2,4]. This work is focused on the thermal and electrical experimental characterization of insulation configurations for 0,95mm winding wires.

Previous works have shown some alternatives of insulation configurations less harmful to the environment with satisfactory basic properties of magnet wires [5,6]. Those alternatives have as principal composition:

- Thermoplastic polymer and mineral fillers on topcoat applied by extrusion process.
- Enamel coat on primer using mineral varnish obtained by sol-gel process and polyamide-imide.

In the proposed paper, new experimental tests are achieved on this new insulated wire and compared to the classical one. This latter is composed of polyesterimide (PEI) covered by Polyamide-imide (PAI), class 200 as the specifications of IEC 60317-13:2010 [7]. The influence factors of insulation performance are the speed enamelling process for conventional insulated wires class 200, and the type of material coat.

CHARACTERIZATION METHODS

The experimental tests used for this work characterize the electrical and thermal properties of insulated wires.

The thermal parameters collected are tangent delta characteristics and the lifetime of the insulated wires obtained by thermal aging tests following IEC 60216-1[8]. The samples prepared for the thermal aging test are presented in Figure 1.

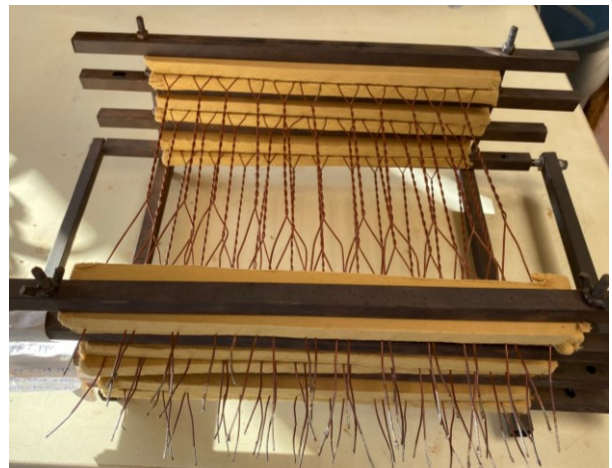


Figure 1 Samples for thermal aging tests

Tangent Delta

The tangent delta is a very used method of quality control for enamelled wire manufacture. This parameter represents the behaviour of internal bonds of the molecule's enamel [6,9]. The tangent delta related to the temperature is also part of the dynamic mechanical analysis (DMA) that studies the elastic and viscous behavior of materials under conditions of low force enough to not destroy the structure. The viscoelastic properties change under temperature variations. The tangent delta curve is commonly reported to indicate the glass transition temperature (T_g); for most polymers, the peak dielectric loss occurs on their T_g temperature [10].

The tangent delta temperature represents the phenomenon of irreversible deformation of the material depending on the molecular structure [11]. It is a thermomechanical indicator of intermolecular bonding. Concerning the enamel characterization, its

variation depends on curing characteristics, oven temperature, and the speed of the enamel process [9]. The tangent delta characteristic of the insulated wires presented in this work is obtained accordingly to the standards IEC 62631-1 and ASTM D 150—98 [12,13]. The dissipation dielectric loss is collected during the temperature rise in which the sample is subjected to an oven. It consists in measuring the dissipation loss factor of the sample during the variation of temperature 50°C to 350°C. The points of dissipation factor as a function of the temperature are plotted. The curve obtained presents one or more valleys at specific temperatures, which are called in this paper “tangent delta temperature”.

Thermal Aging

Exposure to high temperatures leads to chemical changes in the materials, for example, a decrease in the molecular weight, and Tg of some polymers accordingly to recent works [14]. The thermal aging of enamelled copper wire involves loss of adhesion to the copper, inconsistent thermal shock, flexibility, and mechanical strength. It also results in accelerated aging of the EIS [15]. The thermal aging tests defined by the enamelled wires standards IEC 60216-1[8] are used to estimate the lifetime of the insulated wire, and its thermal index characteristics based on Arrhenius law.

This test uses eleven twisted pairs samples of each type of insulation as presented in Figure 1, under a temperature in an oven for a determined period. After each cycle of aging, a proof test voltage is applied to the samples; the amplitude of this voltage depends on the insulation thickness. The lifetime is determined after the cycle in which more than 50% of the samples failed the proof test.

Breakdown Voltage

Insulator breakdown results from a series of pre-breakdown events in the dielectric material. These pre-breakdown events can happen when [16]:

- the material has charges that can be released by applied energy (radiation, heating, increase of the electric field, etc.).
- ionization process occurs. Also called electrical pre-breakdown, it is the generation of charged particles from shocks between an accelerated charge and an atom. For crystals, the same principle of charge creation is considered, and it is estimated that ionized channels are formed inside the insulator, and the energy produced melts the material leading to its destruction. For less ordered materials, the ionization phenomenon is also possible, depending on the material.
- the physical structure weakening of the material occurs due to the pressure created by the application of strong electric field E. It is an electromechanical phenomenon.

- The material is characterized by "channels" with cumulative thermal power that leads to the destruction of the insulator.

The measurement is achieved by applying an alternative voltage (50Hz) to the sample and increasing uniformly its amplitude until reaches the electrical rupture of the insulation, the breakdown. For characterizing the properties of breakdown voltage on the insulated wires, the device in Figure 2 a), is used accordingly to the IEC 60851-5 standard [17]. The breakdown voltage (in RMS value) is collected from five twisted pairs samples.

Partial Discharge Inception Voltage (PDIV)

EIS must be carefully designed to avoid partial discharges (PDs) inception, to prevent accelerated degradation. The PDs are defined by the rupture of gases inside the insulation fault (e.g. cavity). It can be a short-circuit of a part of the insulation and not of its totality. The extent of the discharge will depend on the electric field applied to the insulation. Damages caused by the presence of partial discharge can result in[18]:

- Charged species in the cavities formed by the discharges can cause bombardment of the internal surfaces, resulting in volume erosion of the insulating material.
- The production of acidic substances because of interaction with atmospheric moisture.
- The appearance of weak points and high local temperatures.

The Partial Discharge Inception Voltage (PDIV) measurement consists in applying an alternative voltage on a sample and increasing it until obtaining the partial discharges phenomenon observed by the ICM compact device. The measurement setup is presented in Figure 2 b). This characterization of the PDIV was carried out following the IEC 60 270 standards [19]. Eleven twisted pair samples for each group of insulation configurations were tested, and the mean value of the PDIV is used to compare them.



Figure 2 Electrical characterization devices: a) Breakdown voltage measurement, b) PDIV measurement.

RESULTS AND DISCUSSIONS

The results are presented in two sections:

- An analysis of the speed of enamel application by the conventional wires. Their EIS is composed of enamelled coats of PEI and PAI.
- An analysis of the material influences by the alternative insulated wires. Their EIS is composed of the enamelled polyamide-imide coat with and without silica sol-contents produced by the sol-gel process and thermoplastic polymer extruded on the topcoat.

Speed of Enamelling Conventional Insulated Wires

The enamelling process is composed of three principal steps as illustrated in Figure 3. The bare copper is introduced into an annealing oven, where it's cleaned and softened. The second step is the varnish applied to the copper conductor surface, followed by a passage to the curing oven. The varnish application and the curing oven steps are executed many times until reach the desired diameter increase.

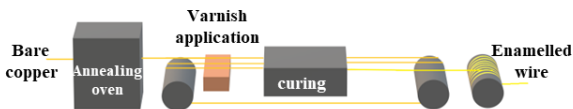


Figure 3 Enamelling process steps schematic adapted from [5]

The curing process is determined principally by the temperature of the curing oven and the speed of the enamelling process. In this work, the enamelling speed had been variated between the conventional wires presented in TABLE 1. The column "wire" refers to the speed of enamelling for each group of samples, 11m/min, 13m/min, and 15m/min. The final diameter increases for each wire had been measured with a micrometer and confirmed by a microscopic view. The significative difference is noticed between the bigger and the lower speed enamelled wire, slightly more than 10 μ m. This size variation implicates its dielectric strength.

The behaviour of the dielectric loss factor as a function of temperature was also affected by the faster enamelling speed. The wire enamelled at the lowest speed (wire *a*) is characterized by a higher tangent delta temperature. Regarding the tangent delta curve in Figure 4, this type of wire has a thermal advantage of 36 $^{\circ}$ C compared to the wire enamelled at a higher speed. The tangent delta temperature peak is often taken as an indication of the thermal index. But the results of the thermal aging test of the wire *a* has got a shorter lifetime even if the tangent delta peak occurs at a higher temperature compared to the others.

TABLE 1 Conventional insulated wires

Wire Id	Process	Insulation layers		
	Enamelling speed	Primer	Topcoat	Diameter increase (\pm 4 μ m)
<i>a</i>	11 m/min	PEI	PAI	92
<i>b</i>	13 m/min	PEI	PAI	84
<i>c</i>	15 m/min	PEI	PAI	81

This tangent delta information indicates that the wire enamelled at a lower speed is more cross-linked, due to this lower enamel speed, its passage in the curing oven was longer. These curves indicate the curing characteristic of each enamelled wire. And for the PEI/PAI enamelled wire speeds lower than 13m/min can result in an over-curing of the enamel and have an impact on its lifetime at high temperatures. The wires enamelled in 13m/min and 15m/min still resisting the thermal aging test. Their lifetimes are more than double the lifetime of the wire *a* (enamelled at 11m/min).

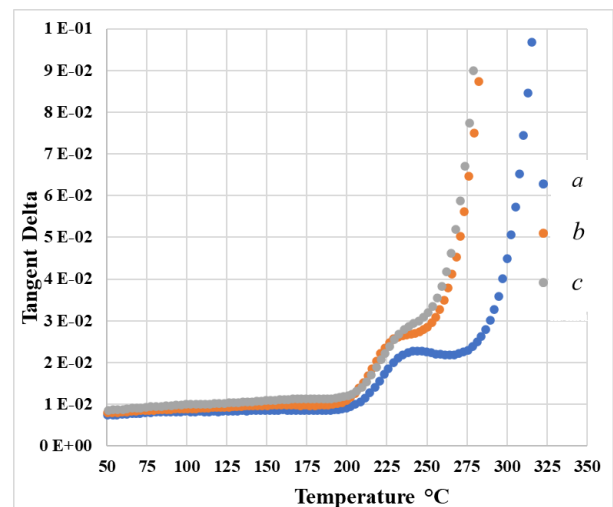


Figure 4 Tangent delta curve of conventional wires

The electrical properties have shown a significant difference in terms of PDIV. The lowest speed of enamelling had a positive influence on PDIV characteristics, with an advantage superior to 70V compared to the others. This advantage coincides with the higher diameter increase that this wire has over the other. But it can be also a material modification during the process of curing which changes this property of the enamel coat.

TABLE 2 Characterization of conventional insulated wires

Wire	Tan delta temperatures (°C)			Electric characterization (V)		Lifetime (H)
	T1	T2	T3	breakdown voltage	PDIV	At 250°C
<i>a</i>	-	206	299	7348	721	1020
<i>b</i>	-	207	272	7642	647	>2682*
<i>c</i>	-	201	264	7498	654	>2682*

Alternatives of Enamelled-Extruded Wires

The enamelled-extruded wires are characterized by the extruded coating beyond the enamelling process of insulation application. Three types of insulation configurations have been characterized. Their enamelling-extruded coating was made at a speed of 20m/min. These wires differ by the material of each coat composition as described in TABLE 3.

TABLE 3 Insulation configurations of the enamelled extruded wires

Wire Id	Insulation layers composition			
	Primer enamelled	2 nd coat enamelled	Extrusion coat	Diameter increase (µm)
A	PAI (20µm)	-	Thermoplastic (70µm)	90
B	PAI (20µm)	-	Thermoplastic filled (70µm)	90
C	PAI (5µm)	PAI + (18%) Sol Gel (20µm)	Thermoplastic filled (65µm)	90

The insulation configurations A and B, have the same kind of primer, composed of PAI. Their difference is the presence of mineral fillers on their extrusion layer of wire B. The insulation configuration C is composed of a thin primer of PAI, and a second enamel layer composed of sol-gel solution (concentration 18%) incorporated into PAI, with an extruded layer of 65µm thermoplastic filled resin. The analyse of the presence of mineral fillers on extrusion layers and the silica gel solution had been started by previous works [5,6]. In this case, the insulations configurations B and C had been exposed to different temperature stresses which allowed the estimate of the thermal index presented in Figure 5.

TABLE 4 Characterization of enamelled-extruded wires

Wire	Tan delta temperatures (°C)			Electric characterization (V)		Lifetime (H)
	T1	T2	T3	breakdown voltage	PDIV	At 250°C
A	101	-	240	7000	804	420
B	107	-	268	7000	740	708
C	108	-	287	10066	725	1428

TABLE 4 show their electrical and thermal characterization results. It can be observed the higher temperature that characterizes de tangent delta temperature collected for wire C. The endurance under thermal aging is also an advantage for this kind of insulation compared to wires A and B. These thermal advantages were influenced by the presence of sol-gel contents in the enamel layer. The wires A and B have very similar thermal characteristics, but the filled extrusion had brought a slight advantage on the thermal endurance at aging tests. The thermal benefits of mineral charges and sol-gel contents in insulated wires are confirmed by 2 points of temperature aging (250°C and 300°C), that the presence of sol-gel at 18% of concentration can increase approximately 10 °C of the thermal index.

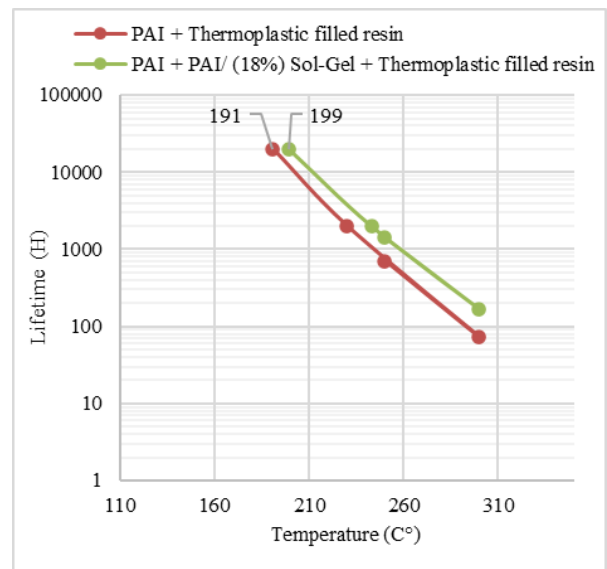


Figure 5 Thermal index (Temperature corresponding 20000h of lifetime estimated)

The PDIV characteristics are less advantageous for wires B and C. Wire A presented better PDIV, 70V more in comparison to the wire with filled thermoplastic resin on extrusion and sol-gel contents on the enamel coat (C). On the other hand, the breakdown voltage had better values for wire C.

The tangent delta curve of these insulation configurations presented a correlation with the lifetime obtained by the thermal aging tests. The dissipation factor peak occurs at a higher temperature for the more resistant to thermal aging.

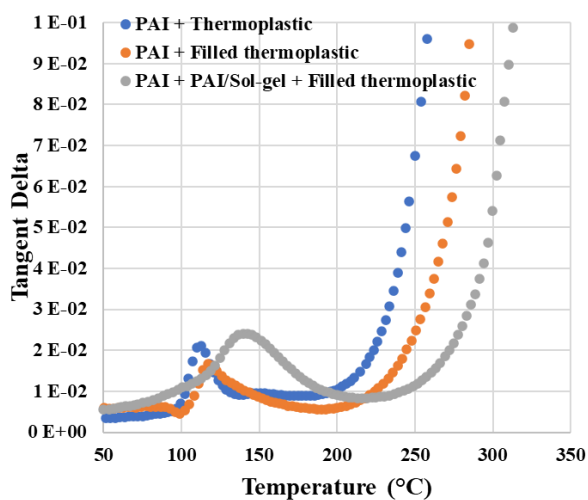


Figure 6 Tangent delta curve of the enamelled-extruded wires

CONCLUSIONS

The process conditions have a very significant influence on the thermal endurance of the materials. It could be observed the higher endurance of the enamelled wire processed at higher speeds (13 and 15 m/min) compared to the lowest speed (11m/min). It is essential to optimize this parameter at the good range of use. Is necessary to take into account the parameters of the process to compare materials performance of magnet wires.

The tangent delta curve cannot be an indicator of the thermal index as it is observed by the conventional wires' lifetime results.

Regarding the enamelled-extruded wires, the thermal index estimations had been deduced from two points of temperature exposition. More temperature expositions are being carried out to reinforce this hypothesis and confirm this thermal quantitative parameter.

The enamelled-extruded wires presented interesting performances compared to the conventional ones. Regarding the speed of enamelling, the thermal endurance can be twice increased in terms of lifetime, having a significant impact on thermal index. The optimization of the enamelling speed is still to be done to improve the thermal resistance of the enamelled-extruded wire.

For both types of insulated wire, conventional, and enamelled-extruded wires, the PDIV values are more advantageous for those less performant on thermal aging. Choosing materials and process parameters requires a global vision of the properties. In this case, the use of sol-gel contents and mineral fillers on the configurations brought thermal improvements, but slight decrease in PDIV

characteristic. Further studies are necessary to deeply understand this limitation.

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