Windings friendly environmental

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ABSTRACT. *The study presents a new enameled wire which production process reduces strongly its environmental impact. The paper presents also the study of a varnish made with very few volatile organic components (VOC). Both analyses present many mechanical and electrical tests showing that this new enameled wire is as good as the classic one. For several characteristics, such as partial discharge inception voltage (PDIV) it is even better. Finally we discussed the problematic of impregnation often made with vacuum and pressure to perform well. The use of a reactive monomer and a varnish pregelling with an UV lamp, greatly reduces mass loss and to improve all mechanical characteristics required for the operation of the motor in harsh environments.*

RÉSUMÉ. *Cette étude présente un nouveau fil émaillé dont le processus de production réduit fortement son impact environnemental. L'article présente également l'étude d'un vernis fait avec très peu de composants organiques volatiles (COV). Les deux analyses présentent de nombreux tests mécaniques et électriques, montrant que ce nouveau fil émaillé est aussi bon qu'un fil à émaillage classique. Plusieurs caractéristiques, telles que le seuil d'apparition des décharges partielles (SADP), montrent qu'il est même meilleur. Enfin, est abordée la problématique d'une imprégnation souvent faite avec vide et pression. Ici l'utilisation d'un monomère réactif permet de pré-gélifier par U.V. le vernis. Cette méthode originale réduit considérablement la perte de masse tout en améliorant les caractéristiques mécaniques requises pour le fonctionnement du moteur dans un environnement sévère.*

KEYWORDS: *environnemental impact, enameled wire, U.V. polymerisation, extrusion, impregnation.*

MOTS-CLÉS : *impact environnemental, fils émaillés, polymérisation U.V., extrusion, imprégnation.*

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1. Introduction

The Conventional enameling process consists in applying successively very thin organic coating layers on the copper wire performing several passages in the coating pan and in the enameling oven. This wire enamel is currently called ‘primary insulation’ while impregnation varnish is called ‘secondary insulation’. The polymerization of the insulating layers is obtained by the combined action of heat and solvents included in the original varnish. Therefore the method is has a high energy cost. In most cases the windings of electric motors are made with enameled wire and impregnated with a varnish. These varnishes are alkyd, polyester or epoxy solution in aromatic solvents, polyesters in the aqueous phase or unsaturated polyesters dissolved in styrene, vinyl toluene. Varnishes are between 30% and 50% solids and therefore it is necessary to recover solvents, very expensive and not always easy to achieve (Boughanmi *et al*., 2010).

Enameled wires used to make the windings of electrical machines and transformers are classified first by their thermal indexes, that is to say, they must resist to a given temperature for 20,000 hours without losing more than 50% their dielectric properties (validation method described in IEC 60172) (IEC 60172, 1995). Thus, there are class son 120°C, 155° C, 180°C, 200°C, 220°C and 240°C. In addition, each family must answer to mechanical requirements, electrical, and chemical severe requirements that suit international standards referenced by the International Electrotechnical Commission (IEC). The manufacture of enameled wire is a complex operation, energetically costly and relatively polluting implying substantial environmental impacts. The traditional enameling process is to apply successively very thin layers of varnish on the copper wire (typically 12 dips in the varnish tank and into the oven for enameling heated to a temperature of about 600 ° C) (Boughanmi *et al.*. 2010). It’s absolutely necessary to deposit and polymerize the enamel layer in several passages to obtain a high quality crack free enamel layer without bubble. Energetically, the process is expensive. The polymerization of the insulating layers is obtained by the combined action of heat and solvents included in the original varnish, which creates despite the effluent treatment, some pollution near the production units. The resins are monomers in solution in the solvents listed in noxious or carcinogenic (cresols, aromatic solvents such as xylene, N methyl pyrolidonne...). Several chemical families are used depending on the use of the wire: polyvinyl formal, polyurethane, polyester, polyester-imide, polyamide, polyamide-imide and poly-imide. The concentration of the resin in solvent is between 15 and 40%, that is to say that about 60% of the product used evaporates and must be treated, which does not prevent a little part of being rejected directly into the atmosphere, (Frezel, 2005). Furthermore, the exothermic reaction of these solvents naturally generates a lot of gas carbon dioxide, which we know the ecological impact. The annual consumption of enameling varnish in Europe is 40,000 tons, 26,000 tons of eliminating solvents. (Boughanmi *et al*., 2010)

An alternative, less polluting, has been developed in recent years. The manufacture of the enameled wire is then based on a UV polymerization process, which uses no solvent (Boughanmi, 2012). A new impregnating varnish based on reactive monomers is developed it does not evaporate any solvent during polymerization using a pre-gelation by UV lamp. This new insulation system, without VOC (volatile organic compound) is an important element in the design of low environmental impact electric motors. This new high performance product is consistent with the new European standards, could have an important part impact on electric motor future. The impregnation of windings and the chemical compatibility of all motor components are therefore two essential factors. Indeed, the impregnation of the windings provides significant advantages in terms of mechanical strength and thus the resistance to vibration phenomena (IEC61033, 1991).

This research may help to understand the turn-to insulation problems but also ground insulation. Our approach globalizes the tests to better assess the combinatorial effects of these two stages of winding manufacturing process. The electric vehicle is a good example: a gain, however small, got on the environmental manufacturing cost of each electric motor (propulsion and equipment) corresponds to a significant reduction of the global environmental footprint.

The paper presents the many tests of these wires and their varnish impregnation, then we show the interesting results obtained by comparing a wire and varnishes conventionally used in industry.

2. New insulation system

2.1. Description

The classic enameled wire has two insulating layers: the first, one, made of, polyester imide (PEI) provides good adherence on the copper, the external one, made of, polyamide imide (PAI) gives the mechanical properties required for the wire implementation. However, in a double layer enameled wire (PEI-PAI), the thermal resistance is higher than a single layer PEI. The insulating layers are obtained by a series of chemical operations of polymerization made in large vertical furnaces (30 meters) with a precise controlled temperature (Figure 1, left).

The new process is very different, the enameled wire is composed of a first 20 µm layer of polyester acrylate which provides adhesion on the copper, at the starting, monomer is contained in a solution, it is deposited on the copper and then the polymerization is obtained by radiation from UV lamps (Figure 1, right). The wire is then passed through an extruder which deposits a thicker layer of PPS (poly-phenylene-sulfide), or PPS/PPSU (Poly-phenyl-sulphone) heated at about 400 ° C (Figure 2). This second operation is made without any chemical reaction; the polymer enters the extruder in pellet form. The new process requires only one pass in each sector, it can operate at high speed; currently the prototype machine is running at 300m/min three times faster than the conventional process.

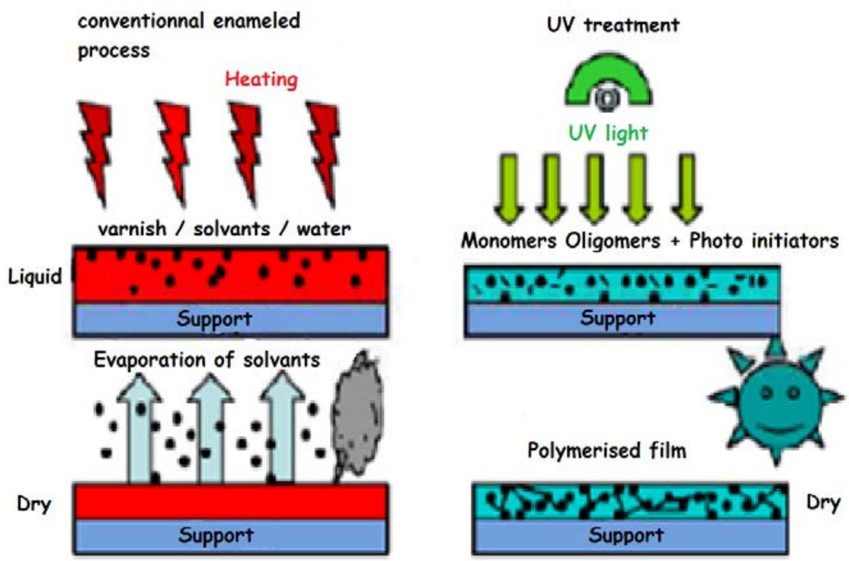

Figure 1. Illustrative comparison of enameling processes (Frezel, 2005)

2.2. Study of impregnation varnish

The impregnating varnishes currently used are mainly alkyd, polyester or epoxy in solution with aromatic solvents, polyesters in the aqueous phase or unsaturated polyesters dissolved in styrene, vinyltoluene. Varnishes are between 30 and 50% solids and therefore it is necessary to recover solvents, very expensive and not always easy to achieve. While VOC varnish is a varnish acrylate 100% of dry extract, which reacts by a radical reaction initiated by a photochemical route and / or by a thermal route.

3. Experimentation

3.1. Breakdown voltage

The breakdown voltage is measured applying a sinusoidal voltage on a twisted pair of wire made following an experimental protocol close to the one described in the IEC standard methods (IEC 60172, 1995). A high voltage (HV) probe is used to identify the value of the voltage that creates an arc breakdown between the twisted pair. Table 1 summarizes the results obtained for the different types of wire. For each type of wire tested, the value is an average of several samples.

Table 1. Breakdown voltage of different types of insulated wires

Enameled wire type	Description	Value kV
PE + PPS	PE (1,00mm) filled	10
PE + PPS	PE (1,00mm) unfilled	6
PE + PPS	PE (1,00mm) filled	3
PE + PPS	PE (1,01mm) filled	3
PE + PPS	PE (1,00mm) filled + AP[1]	5
PE + PPS	PE (1,00mm) filled + AP preeating @ 150°C/2H[2]	5,2
PE + PPS/PPSU	PE (1,00mm) filled	5
PE + PPS/PPSU	PE (1,01mm) filled	5
PE + PPS/PPSU	PE (1,01mm) filled + AP	5
PE	PE (1,00mm) filled	0,2
PE + PPS/PPSU	PE (1,00mm) filled + Plasma[3]	6,5
PE + PPS/PPSU	PE (1,00mm) filled + GB[4]	1,2

The tests showed significant variations in dielectric properties on the different types of manufactured wire. Indeed on the same coil and several lengths of wire, dielectric behaviors vary. For this analysis a metallographic study was planned on several samples of enameled wire in order to control the eccentricity of the enamel layer.

3.2. Resistance to thermal stresses

Figure 2 shows the numbers of non-defective specimens after each 3 days thermal cycle at 250°C for PE enameled wire + PPS. From this figure, the specimens using the PE wire unfilled PPS + and impregnated by the classic varnish ISO800 begin to age faster than others. After three cycles (9 days), the failing samples exceed 50%. Samples manufactured with filled PE wire + PPS and impregnated by GII 370 take up to 8 cycles (about 24 days). These samples have the best thermal endurance. We can also see that the non-impregnated wire has a resistance to thermal stresses better than impregnated by the classic ISO800 varnish.

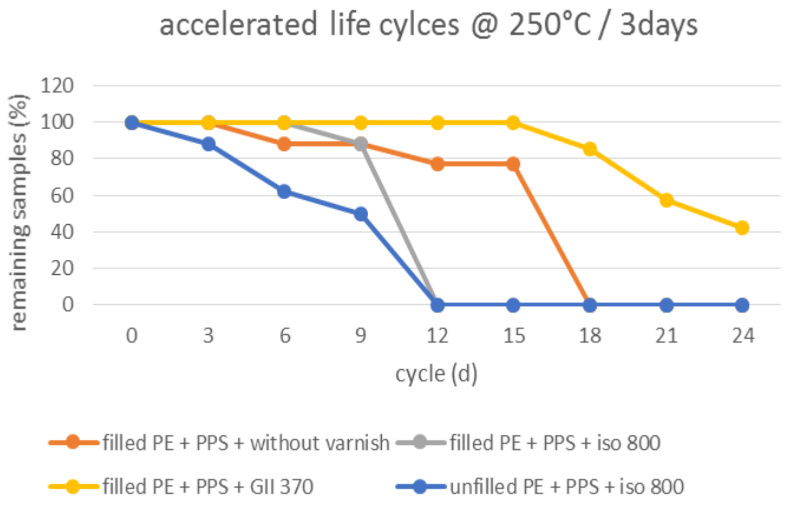

Figure 2. Accelerated life cycles @ 250°C/3days for wire PE+PPS

Thermal aging tests at 250 °C/3d, applied this time on the PE wire + PPS/PPSU show that the test samples impregnated by the varnish ISO800 live during 13 cycles (39 days). According to this study, the PE wire + PPS/PPSU either impregnated with varnish GII370 or not, has a significantly better than standard wire thermal endurance. After 20 cycles (60 days), there are still more than 80% of the specimens alive.

3.3. Resistance to mechanical stresses

The Dexter's test is a compatibility test of insulating varnish with impregnating varnish. For impregnated engine applications, the wire used must satisfy this test.

Process sample's preparation:

The test specimens consist of helical coils of wire, which are wound with contiguous turns on 75 mm long on a mandrel of 6 mm in diameter. They are dipped in varnish for 10 s and then suspended. They are then polymerized in an oven at 90°C for 30 minutes, and outputs impregnated again in the other direction and returned to an oven at 90°C for 30 minutes and then 4 hours at 150°C. All samples are tested on a tensile machine by a bending system 3 points and a force is applied to rupture test specimens (see Figure 3).

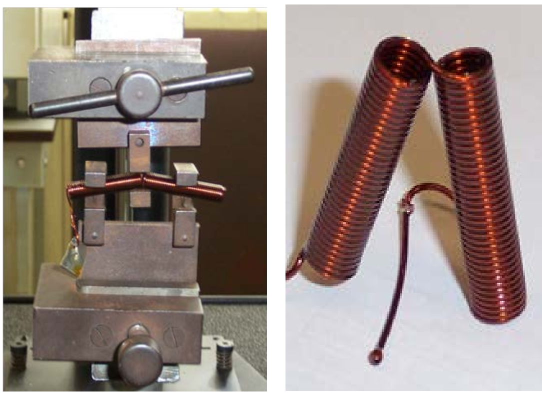

Figure 3. Setup and sample for Dexter test on tensile testing machine

The specimens were then observed with unaided eyes, at the location of the break and no exposed copper zone shall be observed (without varnish). The tests are performed with the following approved varnish:

Isopoxy 800 used at 20 ± 2% of dry extract (supplied by Elantas, Beck)

GII 368 ou 369 used at 100% of dry extract (supplied by Green Isolight).

For each test, five test pieces are subjected to testing Dexter, the average value represents the mechanical adhesion strength.

Dexter test results are summarized in Table 2 for two test temperatures: 20°C and 180°C. We recall that the wire used in this test is a classic type of wire (PEI + PAI).

Table 2. Results of mechanical adherence

Vanish/temperature	20°C	180°C
ISO 800	220 N	95 N
GII 368	195 N	115 N
GII 369	275 N	13 N

The observation with the unaided eyes specimens after the break shows that the separation occurs between the base enamel and impregnating varnish. This observation helps to ensure that the bond strength of the impregnating varnish is mechanically sufficient (> 150N @ 20°C) and not too high which will practice a peeling of the copper enameling varnish.

3.4. Optimization of impregnation varnish

The windings impregnation process is energy intensive and polluting. In order to adapt the proposed varnish (GII 370) for use for electrical machines, we proposed to optimize this varnish according to polymerization time and temperature. Thus, during polymerization, there is always loss in weight of varnish after the vaporization of the reactive monomers into the furnace. For this, we launched a series of Dexter test on helical coils using conventional wire and impregnated by ISO 800 varnishes and GII 370. The polymerization temperature is taken to 150°C and 170°C. The time required for the polymerization operation is varied from one hour to three hours. The test results are shown in the following figures (Figure 4 and Figure 5). The result is given in kilograms of load required to break the spiral coils impregnated during Dexter test.

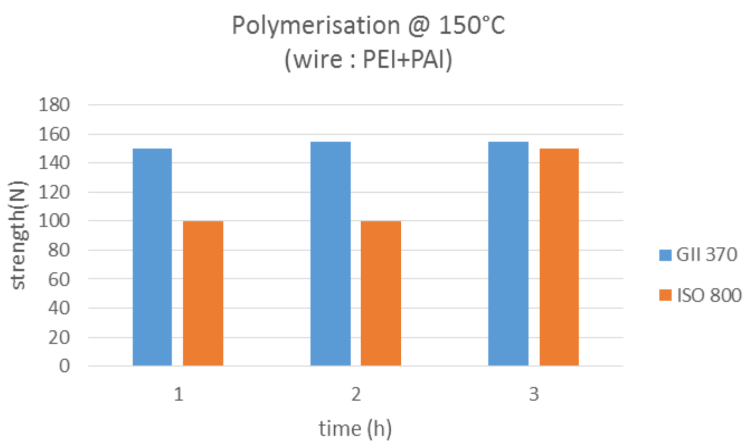

Figure 4. Dexter test on PEI-PAI insulated wire impregnated with 2 different varnishes and polymerized at 150°C

The varnish GII 370 provides better adherence of the coils whether the time and the polymerization temperature. By adding 20 ° C during the stoving operation, it improves the adherence of the same coils for minimal stoving time whether the impregnating varnish used. So we can minimize the energy consumed during polymerization by reducing the baking time from 3-4 hours to 2 hours. This duration yields enough time to fully crosslink the polymer chains of the varnish allowing a more energy-efficient impregnation process. During all tests Dexter, peeling occurs in the coils between the impregnating varnish and the base enamel deposited on the conductive wire. The GII 370 impregnating varnish is well adapted for use in electrical machines in terms of grip strength. It remains to maximize the weight loss that can be lost during stoving. It is proposed to add the varnish with Photo-Initiators (PI) that will be excited by UV light to create as a gel coat on the sample surface. Samples of the helical coils are impregnated with the varnish (GII 370 + PI), then they are exposed to UV light using a UV lamp power of 4W/cm^2. The polymerization is performed at 170°C/3h in order to remain in the same conditions as the other samples which are impregnated and without being exposed to UV. Before placing the samples in the oven to reboot the polymerization thermally, the coils are weighed by a precision balance (0.005g accuracy error). They are also weighed just after the furnace outlet. The results, given in Table 3 show comparatively the weight loss of impregnating varnish during polymerization.

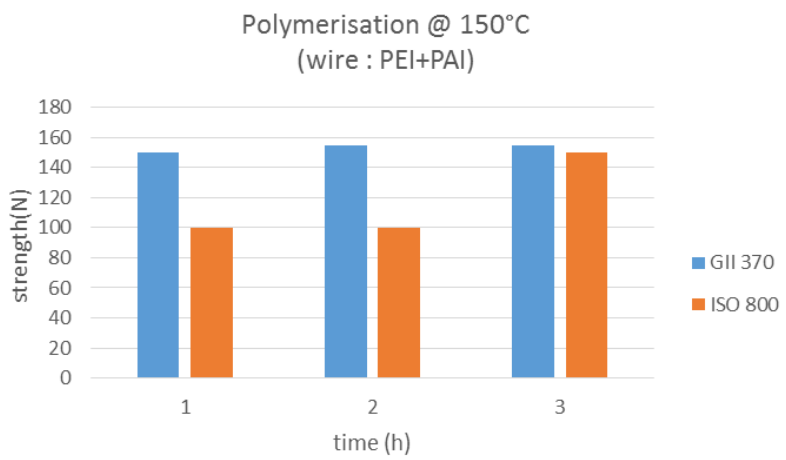

Figure 5. Dexter test on PEI-PAI insulated wire impregnated with 2 different varnishes and polymerized at 170°C

Table 3. Weight loss, with or without UV pre-treatment

	without pre-gelling	without pre-gelling by UV lights
wire : PEI+PAI	72%	17%
wire : PE+PPS/PPSU	68%	17%

It is noted that a substantial amount of varnish evaporates in the air during stoving if there is no pre-gelation UV coils. Indeed, UV exposure creates a kind of a skin on the surface of samples that prevents reactive monomers in the varnish starting the air during stoving. Note that the varnish smell is much weaker when stoving when samples are pre-gelled.

Table 4. Force of adherence of vernis GII 370 + PI,

	without pre-gelling	without pre-gelling by UV lights
wire : PEI+PAI	17 daN	5,5 daN
wire : PE+PPS/PPSU	12 daN	6 daN

To verify that the addition of the PI in the varnish GII 370, does not deteriorate the adhesion properties, the Dexter tests are once again redone. The result is shown in Table 4.

The result shows that adherence is lower for samples that are pre-gelled with UV. In effect, pre-gelation is effected by UV maximum power tube 4w/cm^2 and at a distance very close to the sample. That leads to the initiation of polymerization of the polymer prior to passing it into the furnace. So we decided to launch a second weight loss test by influencing the power emitted UV and thus the distance between the UV light and the sample. Several tests at different pair “power/distance” are carried out, we present below (Table 5) the test result done with a couple “P=2W/cm^2/D=50 cm”.

Table 5. Test with pre-gelling by UV treatment with P= 2W/cm^2; D=50 cm

	weight loss	adherence
wire : PEI+PAI	22%	10 kg
wire : PE+PPS/PPSU	24%	11 kg

From Table 5, the setting of the UV lamp power can improve varnish adherence (GII 370 + PI) in the same time reducing the loss of weight. In order to have even better results from the perspective of the adherence of impregnated coils, we had the idea to add in the varnish black dyes that increase the absorption of UV light and thus to have a just pre-gelling to the outside surface of the samples. The test result is shown in Table 6.

Table 6. Test with pre-gelling by UV treatment on varnish (GII 370+PI+ black dyes)

	weight loss	adherence
wire : PEI+PAI	22%	17 kg
wire : PE+PPS/PPSU	27%	12 kg

We deduce that adhesion properties are well improved and we find the same values initially obtained with varnish GII370 without pre-gelling. Knowing that the weight loss during stoving is reduced from 72% to 22%. In conclusion, the varnish 370 GII contains of photo-initiators and black dyes may be an alternative solution to conventional varnish currently used to reduce the energy consummation during its polymerization. It has thermal properties, adhesion and significantly better thermo-gravimetric analyze. In addition, it reduces the weight loss during drying, consequently the environmental pollutants during its processing.

3.5. Resistance to electrical stresses

The enameled wire used in an electrical machine fed by static converters may be subject to electrical stresses (Nguyen *et al*., 2009). These are related to partial discharges that may occur in the insulating enamel. As most of electrical machines are fed by a PWM inverter that induce high dV/dt, the voltage spikes can be up to 2 times the value of the DC bus and partial discharges may be occur in the electrical insulation system (EIS). In order to have a first comparative idea on the occurrence of partial discharge (PD), it was decided to measure the PDIV depending on the temperature, representing the occurrence of DP threshold. Twisted pairs are also used to perform comparative tests by varying the type of wire and varnish impregnation. Figure 6 shows the measurement results of PDIV depending on the temperature of the non-impregnated specimens based wire (PE + PPS), (PE + PPS/PPSU) and (PEI + PAI). The figure shows that for any type of wire, PDIV decreases according to the temperature. The wire has a classic PDIV lower than that of the UV wire, whether with the PPS or PPS/PPSU overcoat.

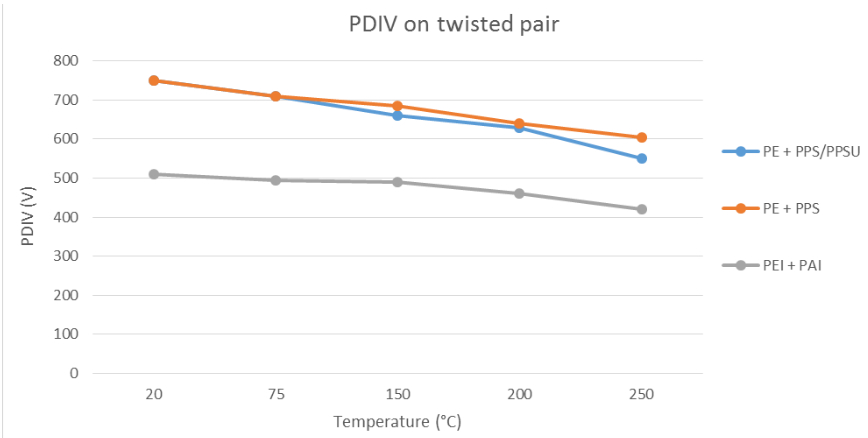

Figure 6. PDIV measured on twisted pairs (non-impregnated) as a function of temperature

Figure 7 shows the PDIV in function of temperature for the samples impregnated by the standard Isopoxy 800 varnish. There is the same as above except this time, the fact that impregnated twisted pairs, it slightly increases the PDIV. This phenomenon is well known and is explained by the fact that you filled with varnish the critical area were are ignited the partial discharges.

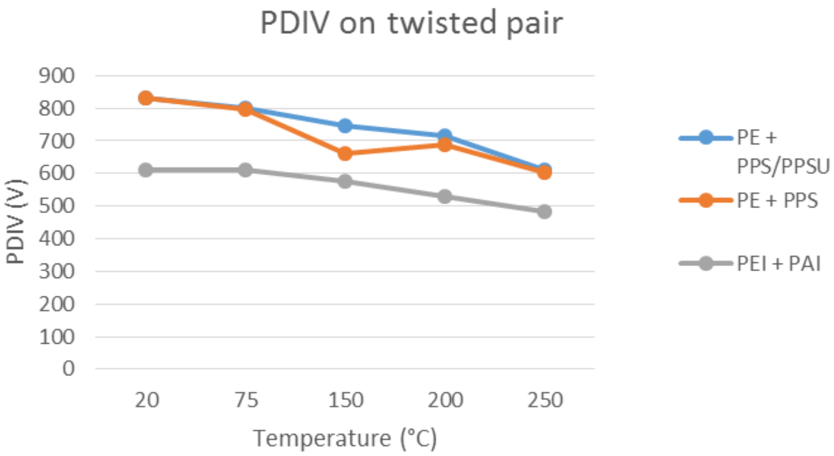

Figure 7. PDIV measured on twisted pairs (impregnated with varnish isopoxy 800) as a function of temperature

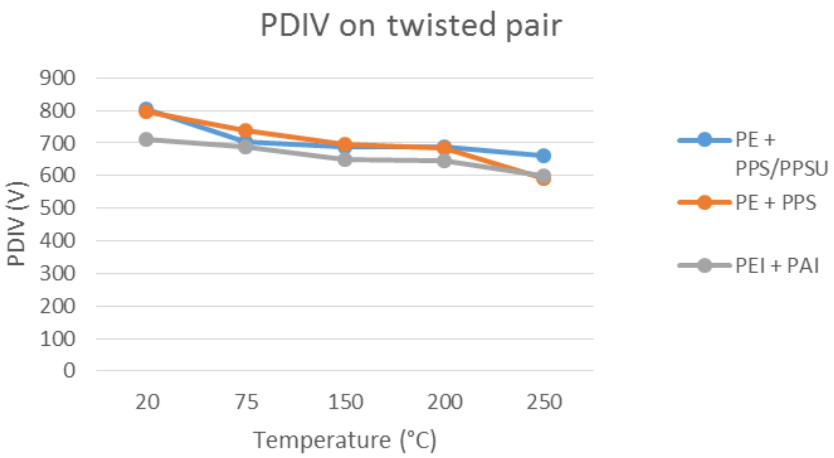

Figure 8. PDIV measured on twisted pairs (impregnated with varnish GII 370) as a function of temperature

Figure 8 gives the PDIV twisted pairs impregnated with the varnish GII 370. This time the PDIV values are similar for the three types of wire. This is explained by the fact that the varnish 370 GII can greatly improve the resistance to DP insulation due to its lower viscosity. It penetrates between the twisted pairs and fills the existing air where the electric field is intense.

4. Conclusion

The study was focused on the characterization of the new wire manufactured by UV polymerization process by comparing the standard enameled wire. Several types of wire have been fabricated and tested, but also interested in the different impregnating varnish. Wires tested are based on PE (filled or unfilled) + PPS or PPS /PPSU with thicknesses in each case different.

Tests of thermal accelerated aging, demonstrate that the PE wire + PPS / PPSU has a temperature index much higher than that of PE + PPS wire. The varnish GII370 is perfectly compatible with enamel wire tested. Therefore, it can extend the life of the samples. Instead, the standard Isopoxy 800 varnish does not appear from these tests compatible with the enamel UV since the non-impregnated samples either some type of wire, resist better the heat stresses than the test samples impregnated with the varnish Isopoxy 800. One explanation may be provided by the presence of solvents in the varnish may degrade the extruded layer.

By all tests conducted in this study, we deduce that the enamel-based PE wire (filled) + PPS/PPSU offers a much higher temperature rating of 200°C. It has better mechanical properties between 20°C - 240°C. Under electrical stress, this wire has a PDIV higher depending on temperature. Strong dielectric variations are directly related to the stability of the manufacturing process. The impregnating varnish GII 370 offers better adhesion of the winding. This varnish reduces during polymerization mass loss due to UV pre-gelling and energy loss through the optimization of the "Temperature / Time" exhibition. Under thermal stress, GII 370 has a significantly better thermal endurance in comparison to other types of varnish.

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