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Electrical Performance analysis of Enamelled-Extruded Wires based on Partial Discharges and Voltage Endurance

Giovana Pereira dos Santos Lima, Sonia Ait-Amar and Gabriel Vélú

Abstract— This study aims to explore an economically feasible enamelled wire technology based on sol-gel, offering enhanced performance compared to traditional enamelled wire. The evaluation involves assessing insulation configurations for copper wires designed for high-temperature applications, with a proposed configuration combining sol-gel solution on enamel and PPS extrusion resins. Electrical performance is compared across these insulation configurations, building upon their demonstrated higher thermal performance in prior research. Experimental data, including partial discharge parameters, dielectric strength, and electrical aging endurance, are collected from twisted pair samples for each insulation type. Promising results emerge from partial discharge studies, favoring hybrid technology (enamelled-extruded wires) over the classical approach (PEI+PAI enamelled wires). Measurements reveal a higher intensity of partial discharges for classical enamelled wires under 3 kV-50 Hz. Moreover, lifespan models under voltage stress indicate that enamelled-extruded wires with PPS extruded resin have advantages, withstanding 1525 minutes compared to 530 minutes for classical wires under 3 kV-50 Hz. A correlation between lifespan under voltage stress and partial discharge intensity is observed. Furthermore, microfillers on PPS show lower results compared to non-filled enamelled-extruded wire configurations.

Index Terms—apparent charge, dielectric strength, electrical aging, enamelled-extruded wires, PDIV, photon number, partial discharge.

I. INTRODUCTION

ROTATING electrical machines and power transformers are typically composed of windings made of copper or aluminum wire insulated commonly known as enamelled wire. The improvement of these enamelled winding wires is relevant for various industries such as automotive, aerospace, and equipment related to renewable energies (for example, wind energy) [1], [2], [3], [4]. The manufacturing of enamelled copper requires special attention to various technical aspects to ensure the

quality of the final product. The production of enamelled copper can be costly due to the complex manufacturing process (enamelling) and the special materials required to achieve effective insulation for electrical purposes. Currently, an annual production of over 100,000 tons of enamelled wire is generated in the northwest region of Europe [1].

This research is conducted within the framework of the Hi-Ecowire project (High Quality eco-efficient Magnet Wire), funded by European INTERREG funds. The project aims to develop insulated copper wires for electrical winding applications, focusing on manufacturing process and winding performance improvements. The first involves replacing traditional solvent-based enamelling with the extrusion of a polymer-based composite to improve environmentally the process; the latter is related to improving the overall properties of these new insulated wires compared to conventional ones.

The electrical insulations configurations (enamelled-extruded wires) studied in this paper have been previously studied concerning their thermal performance [5], [6], [7]. This paper focuses on their electrical performance evaluation. Its primary objectives are to identify potential advantages or drawbacks of the enamelled-extruded wires compared to classical enamelled wires and to understand the factors influencing electrical properties. The study includes the characterization of partial discharges using electrical (apparent charge) and optical (number of photons) measurements. This phase enables a comprehensive evaluation of the performance of enamelled-extruded and classical configurations with regard to partial discharges. Furthermore, the dielectric strength characteristics is compared based on breakdown voltage measurements under both ambient and elevated temperatures. Finally, the results of lifetime under electrical stresses are compared and analyzed for these insulation configurations.

II. METHODS AND MATERIALS

The insulation configurations studied in this work are presented in Fig. 1. These configurations include round copper magnet wires with a diameter of 0.95 mm, the corresponding increases in insulator diameters, as detailed in Table I. As the

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insulation coats were applied on a laboratory scale, some differences in thickness have been observed.

Regarding the classical wire, its composition consists of a first layer of Polyesterimide (PEI) and a topcoat of polyamide (PAI). The insulation diameter of this wire increases by applying 14 coats of varnish during the enamelling process.

The enamelled-extruded wires have 25 % of the insulation thickness obtained through the enamelling process (5 passes) and 75 % obtained by only one pass of the extrusion process.

The PAI + PPS configuration consists of a first layer of PAI enamelled coat covered by PPS resin, which constitutes the majority of the total thickness.

Regarding the insulation configuration PAI + PAI/Sol-2 + PPS, a first enamel coat of PAI has been applied to the copper, followed by a PAI-silica coat named "PAI/Sol-2". This hybrid PAI-silica composition was obtained via the sol-gel method, essentially comprising a solution of silica (in a hydrolyzed liquid state) incorporated into the PAI varnish and kept at room temperature for several days. Finally, the silica-PAI hybrid varnish was used in the enamelling process to achieve the insulating layer named "PAI / Sol-2". The extruded coat of Polyphenylene Sulfide (PPS) resin has been applied as a topcoat and constitutes the majority part of the insulation thickness.

The same procedure was followed for the insulation configuration PAI + PAI/Sol-2 + PPS filled. The latter differs by the presence of barium sulfate microfillers comprising 25 % of the extruded resin, with these particles characterized by a mean diameter of 0.4 μm .

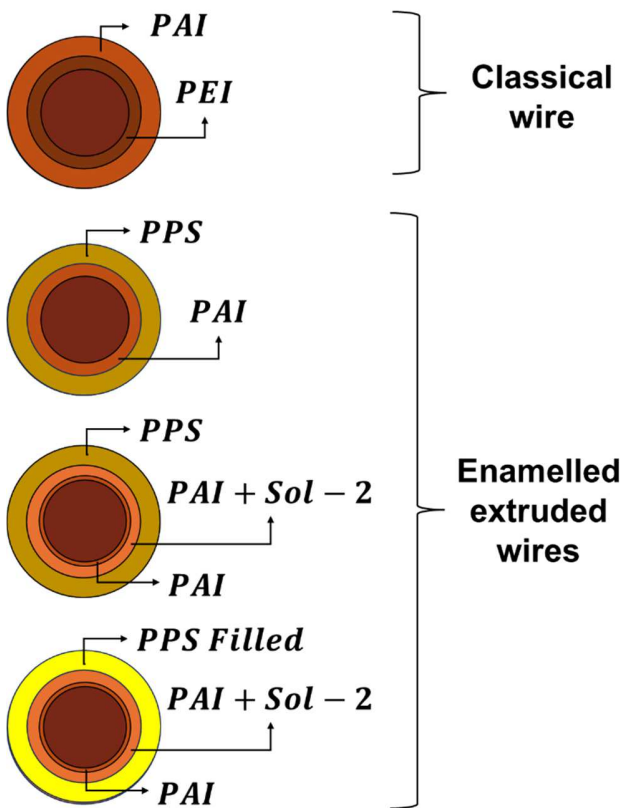


Fig. 1. Illustrative representation of the insulation configurations.

TABLE I

INSULATION COATS OVERDIAMETERS

Insulation configuration	Primer enamel coat (μm)	2 nd enamel coat (μm)	Extrusion coat (μm)	Total (μm)
PEI + PAI	48.9	32.6	-	81.5
PAI + PAI/Sol-2 + PPS filled	3.6	14.2	72.4	90.2
PAI + PAI/Sol-2 + PPS	5.1	18.2	43.8	67.1
PAI + PPS	18.1	0	73.9	92

III. BREAKDOWN VOLTAGE CHARACTERISTICS

A. Measurement of Breakdown Voltage Description

The dielectric strength parameter is evaluated by measuring the breakdown voltage. The measurement device used complies with IEC 60851-5 [8]. This measurement is conducted on seven (7) standard twisted pairs for each type of insulated wire. Fig. 2 illustrates the sample within the measurement apparatus; each wire of the sample is inserted into two tanks of spherical metal, ensuring contact between the copper conductor of the enamelled wire and the measuring apparatus. An alternating voltage (50 Hz) is applied to the sample, starting at 0 V and increasing until breakdown occurs. The rate of voltage escalation is consistent and defined by the standard based on the expected breakdown voltage amplitude. The test voltage must be administered between the two conductors of the sample at a rate of 100 V/s for a breakdown voltage ranging between 500 V and 2,500 V, or 500 V/s for a breakdown voltage exceeding 2,500 V. Upon breakdown, the voltage is recorded. The test is subsequently conducted on the remaining samples.



Fig. 2. Twisted pair in the breakdown voltage measurement device.

B. Dielectric Strength Performance Results

The Weibull law was used for the analysis of dielectric breakdown voltages as recommended by the IEC 62539 standard [9]. A measurement was carried out at ambient temperature (25 °C) initially, and another measurement has been conducted at 200 °C. The latter measurement was performed to evaluate the dielectric strength under thermal constraints.

Fig. 3 presents the Weibull distribution of the dielectric strength of the different insulated wires. Table II shows the summary of the dielectric strength collected by both measurements.

Regarding the shape parameter, beta (β) calculated from the breakdown data collected at 25 °C:

- There is a greater discrepancy between the experimental data for the groups of conventional enamelled samples (PEI + PAI).
- The breakdown voltages obtained seem to be closer to each other for the extruded enamelled wires.

Concerning the scale parameter, alpha (α), which represents the dielectric strength achievable with a probability of 63.2 % at 25 °C:

- Samples of the conventional wire PEI + PAI present an advantage compared to others.
- The extruded enamelled wires, ordered from highest to lowest alpha parameter, are as follows:
 - PAI + PAI/Sol-2 + PPS,
 - PAI + PPS,
 - PAI + PAI/Sol-2 + PPS filled.

Observing the 10th percentile makes the comparison more credible as specified in the IEC 62539 standard [9]. It is possible to observe in Fig. 3. a) at the 10th percentile, that:

- The difference between the wires PEI + PAI, PAI + PPS, PAI + PAI/Sol-2 + PPS is not significant as the confidence intervals overlap, making it impossible to identify the "best" among them.
- The wire PAI + PAI/Sol-2 + PPS filled exhibits the lowest dielectric strength compared to the others. At the 10th percentile, its confidence interval overlaps with that of the PEI + PAI wire. Therefore, the advantage of the latter in terms of dielectric strength is not significantly greater than that of the filled-extruded enamelled wire.
- The advantage of wires PAI + PPS, PAI + PAI/Sol-2 + PPS, compared to the wire PAI + PAI/Sol-2 + PPS filled, is confirmed, as the confidence intervals do not overlap at the 10th percentile.

Based on the results from Table II, the sample data is sufficiently linear ($R > 0.905$ for the 7 data points collected per insulated wire type), consequently compatible with the two-parameter Weibull distribution.

Previous studies on these extruded enamel wires have shown the beneficial effect on thermal properties through the use of inorganic particles via sol-gel enamelling and micro-barium sulfate fillers in extrusion [5], [7]. Therefore, in this work, the breakdown characteristic was observed under thermal conditions to compare wires and determine if the presence of inorganic particles can influence dielectric breakdown strength.

For the thermal constraint evaluation of the dielectric strength parameters, the samples were exposed to 200 °C in a ventilated oven before the measurements. This temperature is recommended for conventional PEI + PAI wire with a thermal class of 200 °C, according to the IEC 60317-13 standard [10].

Regarding the shape parameter, β (Table II):

- The most dispersed results are for PEI + PAI wires, followed by PAI + PAI/Sol-2 + PPS filled and PAI + PAI/Sol-2 + PPS.
- The PAI + PPS wire has the highest shape parameter, indicating the least dispersed results among the studied wires.

Regarding the scale parameter, α (Table II):

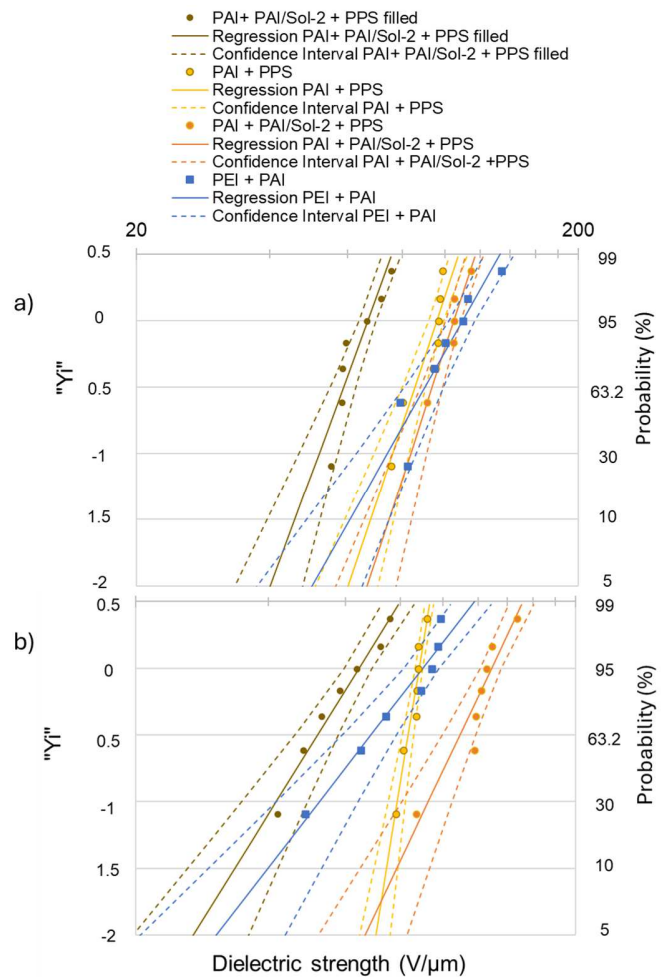


Fig. 3. Weibull distribution of breakdown data: a) at 25 °C and b) 200 °C.

- The conventional PEI + PAI wire and the two extruded wires, PAI + PPS, PAI + PAI /Sol-2 + PPS, exhibit very similar.
- The PAI + PAI/Sol-2 + PPS filled wire has the lowest dielectric strength.

TABLE II

DIELECTRIC STRENGTH PERFORMANCE DATA SUMMARY

Insulation configuration	PEI + PAI	PAI + PAI/Sol-2 + PPS filled	PAI + PAI/Sol-2 + PPS	PAI + PPS
$\alpha - 25\text{ °C (V/}\mu\text{m)}$	109.412	66.827	104.581	95.735
$\beta - 25\text{ °C}$	5.876	9.071	10.221	9.961
Correlation coefficient (R) - 25 °C	0.926	0.914	0.981	0.927
$\alpha - 200\text{ °C (V/}\mu\text{m)}$	89.767	64.319	128.761	88.154
$\beta - 200\text{ °C}$	4.256	5.317	6.945	20.338
Correlation coefficient (R) - 200 °C	0.975	0.987	0.942	0.961
Variation between $\alpha - 25\text{ °C (V/}\mu\text{m)}$ and $\alpha - 200\text{ °C (V/}\mu\text{m)}$	20	2	24	17

The distribution of dielectric strength data presented in Fig. 3. b) allows for a comparison of dielectric strength among each type of wire at the 10th percentile:

- The PAI + PAI/Sol-2 + PPS wire exhibits higher dielectric strength compared to others. At the 10th percentile, the confidence intervals of this wire overlap with those of the PAI + PPS wire.
- The PAI + PAI/Sol-2 + PPS filled wire also shows overlapping confidence intervals with the conventional PEI + PAI wire starting from the 60th percentile. Therefore, the conventional wire and the PAI + PAI/Sol-2 + PPS filled wire cannot be differentiated based on their dielectric performance for this test, unlike at ambient temperature. The measurement under thermal stress has shown a negative effect on the results of the conventional wire compared to others, despite demonstrating superiority over the PAI + PAI/Sol-2 + PPS filled wire in terms of dielectric strength at ambient temperature (25 °C).

IV. PARTIAL DISCHARGES STUDY

A. Measurement of Partial Discharge Parameters

The partial discharge (PD) measurement device is designed and implemented according to the IEC 60270 standard [11]. The ICM Compact allows for the measurement and visualization of partial discharge apparent charge pulses on the sinusoidal signal when a voltage is applied [12]. After connecting the sample to be tested, the control cabinet is powered on, and the sample is energized. The voltage is slowly increased until repetitive pulses characteristic of partial discharges appears on the ICM Compact software on the computer. This way, PDIV is collected, thereafter the voltage is increased up to 3 kV for the number photons and the apparent charge measurements. The setup of the photomultiplier tube (PMT) is integrated into the same power system as the partial discharge device, as shown in Fig. 4.

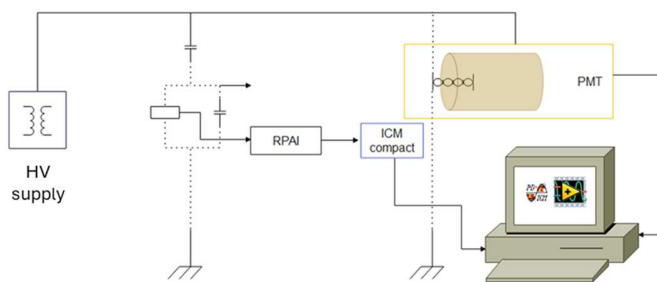


Fig. 4. Partial discharge measurement devices - Photomultiplier.

1) Optical measurements

The use of the PMT enables optical detection of the partial discharge phenomenon, due to the light emitted during the occurrence of partial discharges. The collected data corresponds to the amplitude of the discharges. For the measurements conducted in this study, the photomultiplier tube R943-02 is connected to a photon counter unit C8855-01 combined with a photon counting unit C9744 [13]. For each

sample measurement, 1,000 data points are collected over a duration of 20 seconds.

1) Electrical measurements

The apparent charge is measured at the same time as the photon number measurement, one measurement point is collected per second. For these characterizations the mean value of each parameter was determined from three measured samples. The ICM Compact measures apparent charges from partial discharges based on the current generated by charges moving between the electrodes. This represents the real charge, which differs from the apparent charge. The real charge occurs during the discharge and cannot be measured directly. The movement of the real charge causes a decrease in voltage across the test specimen, which is compensated by charge movement in the external circuit. These correspond to the apparent charges.

The measurement device includes an RLC high-pass filter to detect rapid pulses from partial discharges. The RPAI device has a bandwidth of 800 kHz, with an RPAI preamplifier amplifying low-amplitude signals from partial discharges, making the phenomenon visible during data collection.

B. Partial Discharges Performances Results

Table III shows the PDIV measurements obtained from the three samples per insulated wire type. The classical wire PEI + PAI exhibited the lowest value of PDIV compared to the others.

Among the enamelled-extruded wires, those without filled extrusion resin exhibited higher PDIV values, which is consistent with the breakdown results that also show lower performance for this type of insulation compared to the enamelled-extruded filled wires.

Fig. 5. a) presents the collected photon counts for each set of samples of each wire type. In this case, the ranking of wires exhibiting partial discharge activities from most energetic to least energetic based on photon count characteristics is as follows:

- PEI + PAI, with photon counts ranging between 2,000 and 3,000.
- PAI + PAI/Sol-2 + PPS, with photon counts mostly between 1,500 and 2,000.
- PAI + PPS, with photon counts between 1,000 and 1,500.
- PAI + PAI/Sol-2 + PPS, with photon counts between 400 and 600, thus characterizing the least energetic partial discharge activities.
- PAI + PPS exhibits a lower average photon count compared to the PAI + PAI/Sol-2 + PPS wire.

Fig. 5. b) allows to observe the values of apparent charges for each type of wire. The following assumptions have been drawn:

- The classical wire (PEI + PAI) exhibits significantly higher apparent charge values, reaching up to 2,000 pC.
- The apparent charge values of enamelled-extruded wire samples are maintained at less than 500 pC. The enamelled-extruded wire shows an advantage over the apparent charge parameter relative to partial discharge energy at 3 kV.
- The PAI+PAI/Sol-2 + PPS filled wire also exhibits a higher apparent charge characteristic, in the order of

TABLE III
PDIV MEASUREMENTS

Samples	PDIV	PDIV	PDIV	PDIV	Standard deviation (V)	Standard deviation (%)
	(V)	(V)	(V)	Mean Value (V)		
	Sample 1	Sample 2	Sample 3			
PEI + PAI	663	678	664	668.3	8.39	1.3
PAI + PPS	876	847	830	851.0	23.26	2.7
PAI + PAI/Sol-2 + PPS	779	772	793	781.3	10.69	1.4
PAI + PAI/Sol-2 + PPS filled	700	732	734	722.0	19.08	2.6

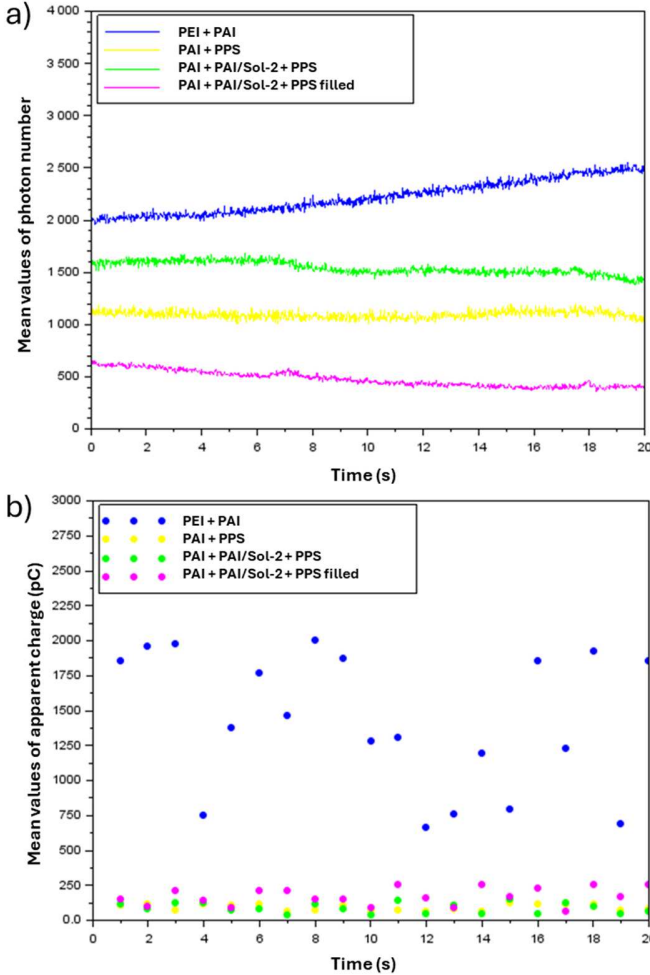


Fig. 5. Partial discharges parameters collected during 20 seconds at 3 kV (50 Hz): a) Photons number and b) Apparent charge.

200 pC during most of the collection. However, the three enamelled-extruded wires are very close, making it difficult to assert a difference between them in terms of apparent charge.

Measurements at 3 kV showed a correlation between photon number and apparent charge data based on the wire insulation material. The wire observed with the highest apparent charge also exhibited the highest photon count, namely the classical wire PEI + PAI.

V. ELECTRICAL AGING PERFORMANCES

A. Electrical Aging Test Protocol

The electrical aging test is set up for three voltage levels between the PDIV and the breakdown voltage, as stipulated by the IEC 600034-18-32 standard [14].

The accelerated electrical aging test conducted in this phase of the study allows for qualitative analysis of different insulation configurations. The tested voltages are much higher than those applied in actual use conditions, with one of them being 3 kV.

The most commonly used model that describes the effect of electrical stress on lifetime is expressed as follows (1):

$$L = c \times E^{-n} \quad (1)$$

Where:

- L represents the insulation lifetime, expressed in units of time (hours, minutes, seconds).
- E represents the electrical stress, which can be the electric field (kV/mm, V/ μ m, etc.) or the voltage (in kV or V).
- c and n are constants.

The voltage amplitude has been chosen to obtain a difference between the three voltages, aiming for sufficiently varied lifetimes (in the order of hours, minutes, and seconds). Measurements are collected from 7 samples of each insulation configuration. The Weibull distribution was obtained for one of the aging tests (3 kV – 50 Hz) to compare the electrical endurance of the different wires. Three voltage-level tests were carried out, allowing us to obtain the lifetime model under voltage stress for each type of insulated wire.

The same breakdown voltage measurement device was used to power each twisted pair (sample). This device includes a feature that allows programming a voltage amplitude and counting the time until breakdown, thus enabling the collection of the lifespan of each sample. The voltage was kept constant until breakdown occurred, and the duration was measured.

B. Electrical Aging Endurance Results

Table IV shows the Weibull parameters for the electrical aging test at 3 kV. The correlation coefficient for all sample groups is close to the critical value indicated by the IEC 62569 standard [9] for this sample size.

Regarding the shape parameter (β), it is observed that:

- The enamelled-extruded wires exhibit smaller values, representing more scattered data.
- The samples of the classical wire PEI + PAI show significantly higher β values.
- The β parameters are very close among the enamelled-extruded wires, which does not allow

assuming the influence of the presence of inorganic particles on the dispersion of results.

Regarding the scale parameter (α), the wire samples corresponding to lifetimes at a 63.2 % failure probability are ranked in descending order of this lifetime:

- PAI + PAI/Sol-2 + PPS
- PAI + PPS
- PEI + PAI
- PAI + PAI/Sol-2 + PPS filled

Two enamelled-extruded insulation configurations surpass the classical enamelled wire. The insulation compositions PAI + PAI/Sol-2 + PPS and PAI + PPS have the highest α values, respectively. Once again, the presence of inorganic particles weakens the insulation's endurance to electrical aging at 3 kV-50 Hz. This is also evident in the distribution of lifespan data in Fig. 6. From this graph, is apparent that:

- It is apparent that the wires PAI + PAI/Sol-2 + PPS and PAI + PPS have very close data sets, with overlapping confidence intervals and almost identical regression lines. Thus, determining the 'best' insulation configuration between the two is not possible.
- The data from the samples of wires insulated with PAI + PAI/Sol-2 + PPS are shifted to the left compared to all other configurations. However, the lower confidence intervals of PAI + PAI/Sol-2 + PPS and PAI + PPS overlap with the confidence intervals of the PAI + PAI/Sol-2 + PPS filled wire for percentiles lower than 5%. However, at the 10th percentile, they differ, suggesting that the PAI + PAI/Sol-2 + PPS filled configuration is the least performing.
- The classical wire shows lifetime values shifted to lower values compared to PAI + PAI/Sol-2 + PPS and PAI + PPS, although from the 30th percentile onwards, the confidence intervals overlap. Thus, a test with a larger number of samples would be necessary

TABLE IV

WEIBULL PARAMETERS OF THE ELECTRICAL AGING LIFESPAN DATA OBTAINED AT 3 kV – 50 HZ

Wires	Weibull parameters	
PEI + PAI	Beta β	5.078
	Alfa α (minutes)	529.729
	Correlation coefficient (R)	0.923
	10th percentile	340.075
PAI + PPS	Beta β	2.231
	Alfa α (minutes)	1524.076
	Correlation coefficient (R)	0.932
	10th percentile	960.210
PAI + PAI/Sol-2 + PPS	Beta β	2.347
	Alfa α (minutes)	1616.697
	Correlation coefficient (R)	0.914
	10th percentile	619.622
PAI + PAI/Sol-2 + PPS filled	Beta β	2.569
	Alfa α (minutes)	265.238
	Correlation coefficient (R)	0.900
	10th percentile	110.449

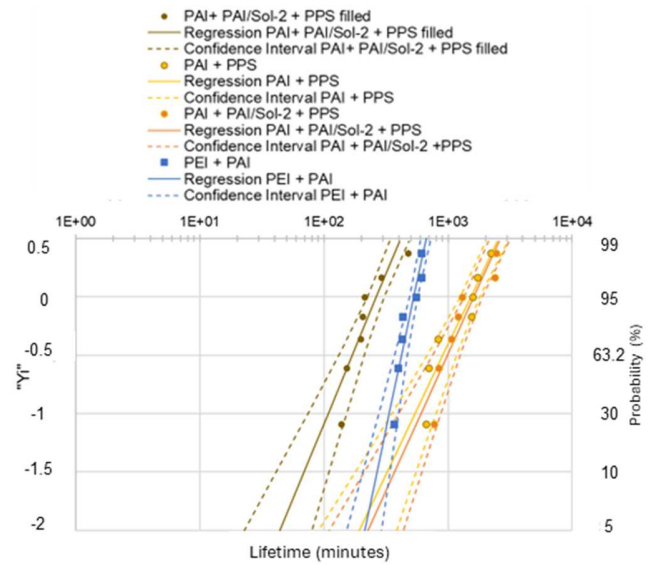


Fig. 6. Weibull distribution of 3 kV (50 Hz) electrical aging lifespan data.

to confirm which is the best configuration.

Based solely on the results of this test, the negative influence of inorganic particles on the aging resistance of the insulation configuration remains a hypothesis at 3 kV-50 Hz.

Two additional voltage tests were applied to observe the endurance behaviour and confirm this hypothesis. For the wires that withstood longer during this initial electrical aging (PAI + PPS, PAI + PAI/Sol-2 + PPS, PEI + PAI), additional voltage tests were conducted at 4 kV and 5 kV. Since the breakdown voltage of the filled-extruded wire (PAI + PAI/Sol-2 + PPS filled) is close to 5 kV, the applied voltages were set at 3.5 kV and 4 kV. Fig. 7 presents the mean values of the experimental lifetimes and the extrapolated curves obtained from them.

According to the lifetime curves, it can be noted that:

- Enamelled-extruded configurations have an advantage over the classical configuration at voltages below 2 kV.
- At voltages below 1 kV, the enamelled-extruded wires with the longest lifetimes are PAI + PAI/Sol-2 + PPS filled, followed by the PAI + PAI/Sol-2 + PPS, and lastly the PAI + PPS.

The constants of the lifespan model under voltage stress are presented in Table V. The higher the constants c and n , the greater the influence of electrical stress on insulation lifetime. Considering that, the wires whose lifetime is most affected by the voltage increase are respectively:

- PAI + PAI/Sol-2 + PPS filled
- PAI + PAI/Sol-2 + PPS
- PAI + PPS
- PEI + PAI

It suggests that at lower voltages, such as those typically used in operational machines, the PAI + PAI/Sol-2 + PPS filled wire may be less affected by electrical aging compared to the other wire configurations. This is consistent with the lowest voltage range in the graph (< 1 kV), which shows higher lifetimes for the enamelled-extruded wires compared to the classical one (PEI + PAI), particularly the PAI + PAI/Sol-2 + PPS filled wire.

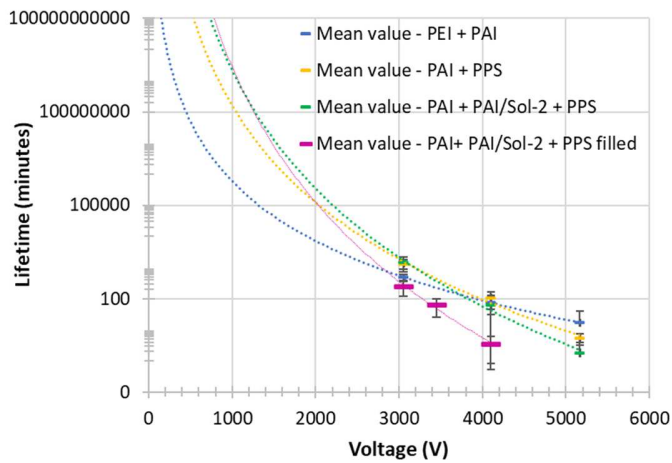


Fig. 7. Lifespan versus electrical stress (Voltage) at 50 Hz.

TABLE V
CALCULATED CONSTANTS OF THE ELECTRICAL STRESS
(VOLTAGE) LIFETIME LAW

Samples	n	c
PEI + PAI	6.35	7×10^{24}
PAI + PPS	10.34	2×10^{39}
PAI + PAI/Sol-2 + PPS	12.57	1×10^{47}
PAI + PAI/Sol-2 + PPS filled	14.44	6×10^{52}

VI. ELECTRICAL PERFORMANCE SUMMARY

Table VI summarizes the results of insulation configurations from the electrical tests presented in this work. Positive points are highlighted in green, intermediary points in yellow, and negative points in red. It was observed that:

- The wire that combines a greater number of advantages is the PAI + PAI/Sol-2 + PPS wire, followed by the PAI + PPS wire and the PAI + PAI/Sol-2 + PPS filled wire.
- The least energy-intensive partial discharges at 3 kV were observed for samples of the PAI + PAI/Sol-2 + PPS filled wire. The most energy-intensive ones were observed for the classical PEI + PAI wire.
- The dielectric strength was higher for the PAI + PAI/Sol-2 + PPS wires. The degradation of this characteristic under thermal stress was more evident for the classical PEI + PAI wires, while others did not show significant variation in their performance compared to their results at ambient temperature.
- The PAI + PAI/Sol-2 + PPS wire demonstrated greater resistance to electrical aging than others.

Enamelled-extruded wires have significantly more advantages compared to classical wires in terms of electrical characteristics. The fact that extrusion is carried out with a single application of the insulation layer reduces exposure to impurities compared to classical enamelling, which involves the application of multiple layers (more than 15 to achieve its thickness).

TABLE VI
ELECTRICAL PERFORMANCE COMPARISON SUMMARY

Parameters	PD data under 3 kV (50 Hz)		Dielectric strength (50 Hz)		Electrical aging endurance	
	Photon number	Apparent charge	Ambiant Temp.	Reduction under 200 °C	at 3 kV (50 Hz)	<1 kV (50 Hz)
PEI + PAI	++++	++++	+++	++++	++	+
PAI + PPS	++	++	+++	++	++++	++
PAI + PAI/Sol-2 + PPS	+++	++	++++	+	++++	+++
PAI + PAI/Sol-2 + PPS filled	+	++	+	++	+	++++

The second advantage could be that extrusion involves no solvent and therefore does not generate any solvent evaporation that could create micro-cavities as in classical enamelling. This characteristic of the process could explain the advantage in partial discharges and, consequently, in the aging performance of the insulation of enamelled-extruded wires.

VII. CONCLUSION

The breakdown voltage evaluation at room temperature favored the classical wire, while the filled resin wire showed the lowest performance. Under thermal stress, enamelled-extruded wires had higher dielectric strength than the classical wire, which performed poorly below 200 °C. The PPS-filled wire maintained consistent performance at elevated temperatures.

The classical PEI + PAI wire consumed more energy in apparent charge and photon count during partial discharges compared to all enamelled-extruded wires, with PAI + PAI/Sol-2 + PPS filled showing the lowest photon count. Despite slight composition and thickness differences, PAI + PPS and PAI + PAI/Sol-2 + PPS exhibited similar performance.

Electrical aging results, analyzed with the Weibull model, revealed that the filled resin wire underperformed, while the enamelled-extruded wires without fillers demonstrated endurance comparable to the classical wire. PAI + PAI/Sol-2 + PPS had the highest voltage aging endurance, and wires that lasted longer under aging tests showed lower partial discharge activity, suggesting a link between discharge intensity and electrical endurance.

The results suggest that mineral particles in the insulation may reduce electrical performance under high stress, possibly due to cavities accelerating dielectric breakdown. However, the exact cause remains to be confirmed.

Enamelled-extruded wires without fillers outperformed the classical PEI + PAI wire, especially in PDIV measurement, PD

behavior, and electrical aging at 3 kV. This technology shows promise for electrical properties and offers a low-solvent, energy-efficient alternative for wire insulation in winding applications.

The enamelled-extruded wires presented in this work are composed of materials that do not exceed the cost of traditional materials used in conventional wires. Additionally, applying the maximum insulation thickness in a single-pass extrusion process is economically advantageous, as it reduces production time and simplifies the manufacturing process compared to the enamelling process. The study of a 100 % extruded insulation solution is promising, given its environmental and economic benefits. This method would be completely solvent-free and much easier to implement, despite the challenge of ensuring proper adhesion to copper.

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