The Impact of Impregnating Resins in Ensuring the Reliability Of Inverter-Fed Machines

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***Abstract* - Impregnating resins are a key component of low voltage motor insulation but are not entirely designed keeping in mind their dielectric properties as they should withstand limited electrical stress. With power electronics, electrical stress can exceed the threshold for partial discharge inception leading to failure in short times. The reliability of the insulation thus becomes more dependent on the performance of the impregnating resins since impregnation raises the partial discharge inception voltage. We have investigated impregnating resins finding that, sometimes, perform in unexpected way at elevated temperatures. Besides, using an infrared camera, we have observed how impulse voltages having elevated slew rates impact on impregnated twisted pairs. The results suggest that bare twisted pairs do not change their temperature appreciably, whereas impregnated twisted pairs can display some increase in the temperature, signaling the presence of large dielectric losses.**

Keywords – Impregnating resins, partial discharges, wide bandgap inverters, thermal stress.

INTRODUCTION

Impregnating resins are a key component of low voltage motor insulation. An impregnating resin improves the windings mechanical stability, enhances heat exchange, and protects from the ingress of contaminants. However, impregnating resins are designed having a variety of targets besides electrical withstand properties, including e.g. viscosity, heat exchange, safety, and environmental protection. For long, this was not a problem, as impregnating resins were subjected to limited electrical stress levels.

Today, voltage surges produced by power electronics converters increase the electrical stress due to overvoltages associated with reflections at motor terminals and uneven turn voltage distribution. Large electric stress levels can undermine the reliability of the system when partial discharges (PDs) with repetition rates near the inverter carrier frequency are ignited within the insulation system [1]. PD are the principal degradation mechanism for the turn/turn insulation in inverter-fed machines [2].

A side effect of the impregnation is that it raises the partial discharge inception voltage (PDIV) as it fills the air gaps between the conductors. The reliability of the insulation thus becomes dependent on the performance of the impregnating resins. Accordingly, the properties of impregnated twisted pairs must be investigated. This paper shows experiments performed on impregnated twisted pairs showing that impregnating resin might not work as intended when PDIV improvement is the target.

I. TEMPERATURE IMPACT ON PDIV

As a first step, the impact of the impregnating resin on the PDIV (and PDEV) was evaluated at different temperatures, to quantify the improvement of PDIV.

A. *Test samples*

Sets of ten twisted pairs (TPs) were realized for three different magnet wires (Wire A, Wire B, Wire C). For each wire type two sets were assembled: (a) non-impregnated TPs and (b) TPs impregnated with a resin suspected of having problems at high temperatures. The wire types and the resin were not disclosed.

To the above six sets, two others were added one impregnated and one not, each composed of 6 samples. They feature a different magnet wire (Wire D) and a different resin.

All the sets of TPs used were manufactured out of grade 2 round enameled winding wires having a diameter of 0.56 mm (A, B, C) and 0.63 mm (D) with insulation thermal class 200, featuring polyester/polyester-imide basecoat and a polyamide-imide overcoat. The twisted pairs were manufactured according to [3]. The Vacuum Pressure Impregnation (VPI) technology was used for the impregnation. The resins for A, B, and C is disclosed due to confidentiality agreements. Wire D was impregnated using a polyester-imide resin. All resins are suitable for class 200 insulation systems. The sets are summarized in Table 1.

Table 1 – Number of failures in the aging cycles.

Set	Wire ∅	Wire producer	Resin
A	0.56 mm	Not disclosed	Not specified by manufacturer
B	0.56 mm	Not disclosed	Not specified by manufacturer
C	0.56 mm	Not disclosed	Not specified by manufacturer
D	0.63 mm	Damid 200	Polyester-imide

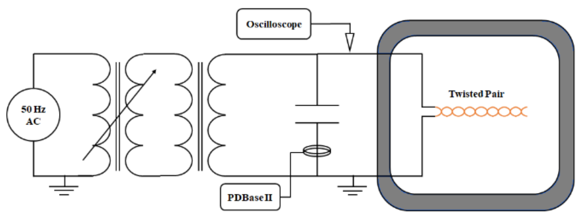

Figure 1: PDIV and PDEV setup scheme.

B. *Setup and Methods*

The AC PDIV was measured on all the twisted pair sets. The voltage was ramped at a rate of 5V/s and monitored though a Tektronix MDO3054D oscilloscope using an Agilent 10076A

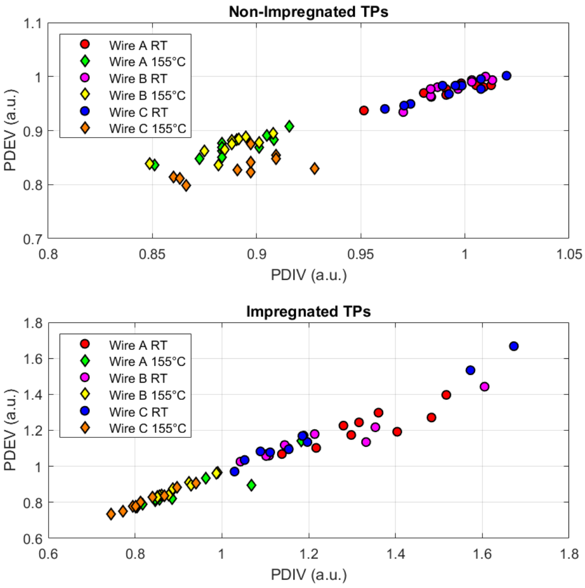

Figure 2: PDIV and PDEV of sets A, B, C. Impregnated and not twisted pairs, at room temperature and 155°C.

probe. When PD activity incepted, the peak value of the voltage was recorded (PDIV). Set A, B and C have also undergone AC PDEV tests where the voltage was decreased until PD extinction. The voltage source used is a simple step up 220/3000 V transformer whose output voltage was controlled by a 220:220 V autotransformer on the low voltage winding, fed by the power grid (50 Hz sinusoidal voltage, 220 V). TPs were connected inside an oven, with one branch grounded and the other connected to the high voltage source. Measures were done at RT (Room temperature) and high temperature (140°C or 155°C).

A conventional PD detection system was employed: a PDBaseII detector manufactured by Techimp HQ receiving the PD signals by a ferrite-core high-frequency current transformer (HFCT), also manufactured by Techimp HQ. The detector has a bandwidth of 40 MHz and a sampling rate of 200 MSa/s and provides the PD pulse pattern, a feature particularly useful to distinguish discharges from noise. The scheme of the setup can be seen in Figure 1.

For each wire type the results collected are normalized to the scale parameter of the Weibull distribution fitting the PDIV values of the non-impregnated samples at RT (base value).

C. Results and Discussion

Whatever the wire among A, B, C the impregnation resin helped improve the PDIV and the PDEV at RT, as it can be observed in Figure 2. For impregnated TPs at RT (circular markers) both are substantially larger than the ones measured on conventional non-impregnated TPs (diamond markers). However, the better performance is not consistent, with some samples having PDIV and PDEV 1.7 times the base value and others only of some percent points, indicating a large variance of the results.

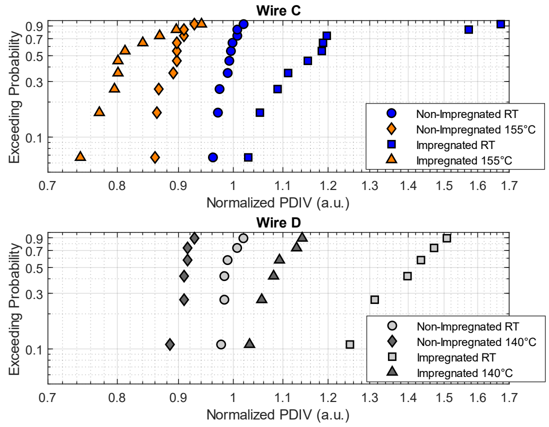

Figure 3: Comparison for Wires C and D in Weibull Plot for impregnated and not samples at different temperatures.

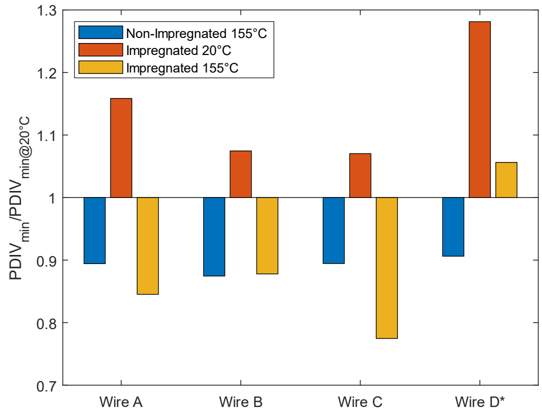

Figure 4: Performance of the different wires (minimum PDIV value) normalized to the minimum of non-impregnated at 20°C.

When the same samples are tested at elevated temperature (155°C), the non-impregnated TPs perform better than the impregnated ones. Impregnated samples not only have a mean drop in the PDIV larger than the non-impregnated, but the drop is so large that the actual PDIV is sometimes lower than the non-impregnated sample.

The wire D was tested for the PDIV at RT and 140°C. The results are reported using Weibull plots in Figure 3 together with the results of wire C (the worst among the others). The comparison highlights that the resin used for D is better: when the temperature grows the impregnated samples still outperform the non-impregnated ones. However, the PDIV drop in percent is larger. From Figure 3 it can be also appreciated the fact that a regression line would not capture correctly the PDIV data, hence the Weibull distribution does not model properly the sets of impregnated TPs. For this reason, the minimum recorded value is a better indicator, being around the value of the 10^{th} percentile of the distribution for a group of 6 to 10 samples. For this reason, in the bar plot in Figure 4 data are normalized to the minimum value of the non impregnated TPs. This might be the best option for evaluating the performance of the resins and summarizing the results found.

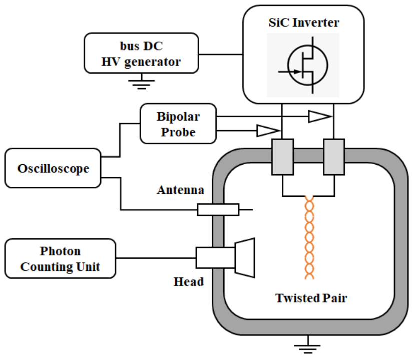

Figure 5: Setup for PDIV tests under SiC-converter voltage.

The phenomenon illustrated might be attributed to a substantial rise of the real part of permittivity of the resin at elevated temperatures, leading to a concentration of the electric field in the air and consequently inception of PD at lower applied voltages. Test at RT were repeated after the ones at high temperatures, obtaining the same results as before. Thus, it was assured that the chemical structure of the resin did not suffer a permanent change.

II. Converter Voltages and Aging

The natural question that arises is if a resin that manifests an acceptable behavior when new and under sinusoidal conditions maintains its properties when aged and stressed by converter voltages. In this framework, problems associated with thermal hotspots due to dielectric losses might become critical.

A. *Test Samples*

Two TP sets (non-impregnated and impregnated) manufactured using wire D were used. Each set was aged up to 42 days in sub cycles of 7/14 days at 230°C, as suggested by [4].

B. *Setup and Methods*

All the sets have undergone PDIV tests with sinusoidal voltage, identical to Sect. I.B and PDIV tests under converter-generated bipolar square voltage waveform at a frequency of 10kHz.

The converter used in the experiments is a bipolar (full bridge) SiC inverter designed and assembled by the University of Modena, Italy. The inverter switches are Wolfspeed C2M1000170D SiC MOSFETs, with blocking voltage of 1700 V. The rise time can be modified adjusting the gate resistance and for all the tests was set to 8 ns. The switching frequency can span between 10 and 100 kHz.

C. *PDIV Test under WBG converter waveforms*

A major obstacle for PD detection under power electronic converters is that large slew rate Wide BandGap (WBG) switches interfere with PD detection systems in a frequency band where PD have their spectral content [5]. As a result, it is generally hard, if not impossible, to distinguish between PD and interference. To circumvent this difficulty an optical system with proven sensibility was used [6]. It consists of two pieces manufactured by Hamamatsu Photonics: (a) a H11870-09 photon counting head, and (b) a C8855-1 photon counting unit.

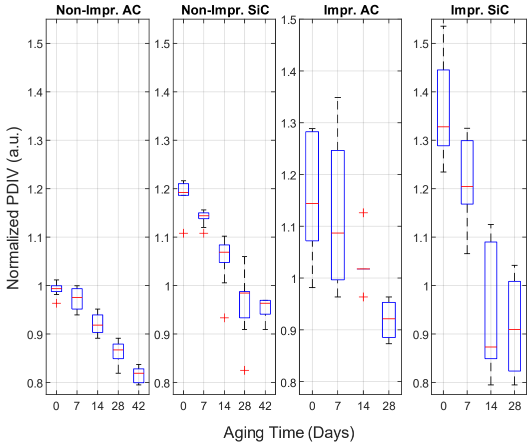

Figure 6: PDIV at different aging times for impregnated samples and not, for both AC and converter waveform tests.

The setup was completed with a Tektronix THDP0200 differential probe (200 MHz bandwidth) and Tektronix MDO3054D oscilloscope for the voltage measure, its scheme in Figure 5.

The voltage was raised in steps of 20V and its peak recorded as PDIV at the start of PD activity. Results collected are normalized to the scale parameter of the Weibull distribution fitting the results of new non-impregnated samples for AC tests.

D. *IR Camera*

Three TPs of each set were subjected to SiC waveforms with DC bus voltage of 540V at 100 kHz, to determine the temperature profile of their surfaces. The temperature profile was acquired using a FLIR infrared thermo-camera. Before the acquisition, the absence of PDs at 540 V was verified.

E. *Results and Discussion*

The results collected for the PDIV have been illustrated with box plots in Figure 6. Indeed, it was not possible to continue the tests after 42 aging days due to their failure. After only 7 aging days, enamel adhesion problems and embrittlement were already observed. The log of the failures is reported in Table .
For non-impregnated TPs the PDIV peak values under SiC voltage are greater than the ones in AC, for any aging time, result coherent with previous studies and is related to the large overshoot of the SiC impulse voltage [6]. This difference is very likely associated to the delay between the time the inception voltage is reached and the time the first PD is triggered.

Impregnated TPs perform better in SiC voltage only when they are pristine. As aging progresses, the PDIV obtained using SiC voltage impulses becomes lower than that using AC voltage waveforms. The lower PDIV value recorded for the square-waveform voltages at larger aging times could be attributed to an increase of the resin permittivity (real or imaginary) at high frequencies where the converter has significant spectral energy.

Figure 7 on left shows that the enamel is missing at the terminal parts of a twisted pair. The TP was not subjected to any specific mechanical test, it was just handled to connect it to the test fixture for PDIV measurements. A moderate

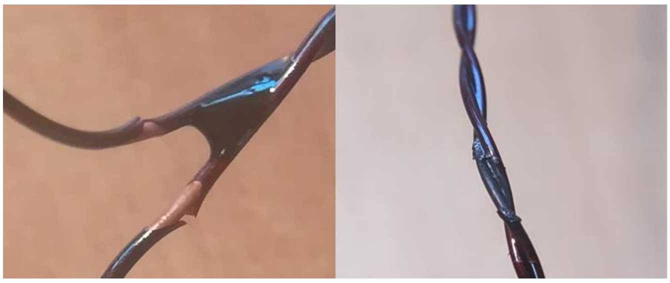

Figure 7: Crack due to handle (left) and failure during test (right).

Table 2 – Number of failures in the aging cycles.

Aging (Days):		0	7	14	28	42
Impr.	**Fails in Cycle:**	0	+3	+2	+2	+3
	Total Fails:	0	3	5	7	10
Non-Impr.	**Fails in Cycle:**	0	0	0	0	+2
	Total Fails:	0	0	0	0	2

Table 3 – Temperature Increase for Impregnated TPs

Aging (Days):	0	7	14	28	42
Sample 1	+4	+4	+4	+4	/
Sample 2	+5	+4	+4	+4	/
Sample 3	+4	+4	+5	+4	/

mechanical stress was enough to crack the insulation and expose the copper, that was extremely brittle. On the right shows the insulation failure occurred during a test.

The possible increase in imaginary permittivity was investigated indirectly with IR camera acquisitions. The temperature of non-impregnated TPs subjected to 100 kHz square waveform does not rise above the ambient temperature. On the contrary, the temperature of impregnated TPs is always 4°C above the room temperature, for pristine and aged samples, as it can be seen in Table . One of these acquisitions is reported in Figure 8. Since doubts existed on the reflectivity of the resin in the IR range, acquisitions were repeated for a lower switching frequency (10 kHz). In these latter tests, none of the samples displayed a significant temperature increase.

The only reason for this heat dissipation are dielectric losses that, at a given frequency, the can be estimated per unit volume as $p = 2\pi f E^2 \varepsilon''(f)$. The phenomenon was found to be observable even for new sample, so contributing from the start to the reduction of the PDIV and in a wider view the aging and lifetime of the machine.

IV. Conclusions

The impregnation resin role in preventing PD inception was evaluated on twisted pairs obtaining relevant results. The PDIV (and PDEV) improvement provided by the impregnation is remarkable at room temperature, but very much reduced at higher temperatures (e.g. 140/155°C). For some resins, non-impregnated TPs present larger PDIV than the impregnated ones at elevated temperatures. This could be attributed to a substantial rise of the real permittivity of the resin with temperature.

Under thermal aging, impregnated TPs show a significant decrease of PDIV when tested using WBG converter voltages.

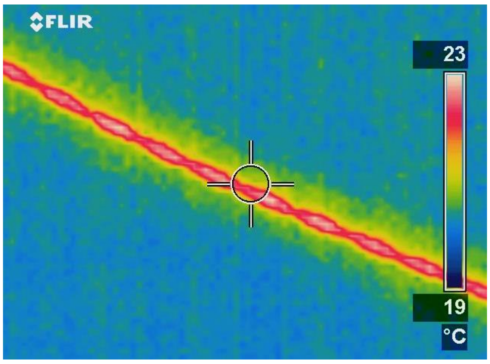

Figure 8: IR Camera acquisition of an impregnated TP (Sample 2, Aging 14 Days).

Using 50 Hz sinusoidal voltage waveforms, the reduction is much less important. In comparison, the PDIV of thermally aged non-impregnated twisted pairs shows much lower reduction under thermal aging and the same trend (same PDIV values) using either voltage impulses or sinusoidal waveforms.

This is a hint that thermal aging might influence in different ways the resin permittivity at 50 Hz and at high frequencies typical WBG converters. Furthermore, dielectric losses, measured though an IR camera manifest only for converter-voltages at high frequencies (e.g. 100kHz). These losses are active for both pristine and aged samples. So, they might contribute from the start to the reduction of the PDIV and in a wider view to the aging and lifetime of the machine.

V. Acknowledgments

RAISE project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 785513.

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