

CHALMERS UNIVERSITY OF TECHNOLOGY

Development of an Environmental-Friendly Insulation System for the Next-Generation Sustainable Electric Drive Unit

Report on research project
performed in co-operation with Polestar Performance AB,
funded by Swedish Energy Agency

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This report presents the results of the experiments performed with model insulation systems representing rotor and stator subsystems of an electrical machine. Different combinations of materials for wire insulation and slot liners were evaluated by measurements of inception and extinction voltages of partial discharges in the insulation. The tests were conducted by stressing the insulation with bi-polar square shaped test voltages. The insulation systems were thermally aged in air and in oil at temperatures 150C and 180C, respectively. The obtained results provide solid ground for further analysis and materials selection for future environmentally friendly and recyclable insulation systems of electrical machines for electromobility applications.

1. Introduction

Electric propulsion is the focus of research and development in the automotive sector on various scales, from passenger cars to heavy trucks for transportation of goods. The demand for increasing the power of electric motors for electric vehicles has pushed the limits for their electric insulation to endure voltages above 800 V and short rise time pulses resulting from high switching frequency of converters, operation under oil-cooling condition which causes chemical stresses on the insulation, longer lifetime.

The electrical insulation system of electrical motors is typically comprised of a slot liner, potting resin, and wire coatings. The materials these components are made of, typically contain elements with some level of human toxicity and the production of these materials is not environmentally friendly. Additionally, the hard attachment of these chemicals to the metals used in the electrical machine structure makes it very difficult to have fully recycled electrical machine at the end of its lifetime. Therefore, it is important to design, develop and produce components in electric vehicle propulsion system, including electrical machines, with sustainable insulation components and minimum impact on the environment and human health. To achieve this goal, the effects of electrical, thermal and chemical stresses on performance of environmentally friendly materials constituting the insulation systems need to be investigated.

The targeted components in this study are conductor insulation and slot liner, which are used in the stator and rotor windings of electrical machines (Fig. 1). The project has been concentrated on experimental activities aiming at identifying insulation materials for each component and their combinations comprising the insulation system, which provide high resistance to thermal stresses and stability of electrical characteristics after ageing in air and in oil at elevated temperatures.

The work has been performed in collaboration between the High voltage engineering group at Chalmers University of Technology and Polestar AB. In the study, the materials from the world leading material manufacturers (Dupont, Solvay, Huntsman Advanced Materials, etc.) were utilized for building and testing prototypes of the insulation systems. The project has been funded by the Swedish Energy Agency (project P2022-01299).



Figure 1. Components of the insulation system of electrical machine: slot liner in the slot and insulating coating on the wires.

2. Methodology

2.1 Materials for testing

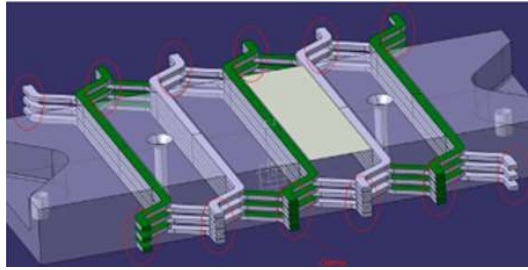
The activities in the project started by conducting a literature survey and an analysis of the market to identify suitable candidates for environmentally friendly materials for the insulation system and their availability. Technical characteristics, environmental impact, potential for recycling, etc. were considered. As a result of this step, the objects listed in Table 1 have been selected for further evaluation.

Table 1. Materials selected for testing

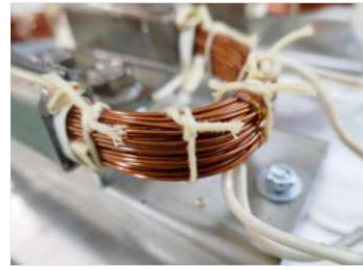
Purpose	Type	Insulation thickness, μm	Index (used in the text)
Stator subsystem	flat wire	150	A
Stator subsystem	flat wire	160	B
Stator subsystem	flat wire	95	C
Stator subsystem	flat wire	85	D
Rotor subsystem	round wire	50	W1
Rotor subsystem	round wire	50	W2
Main insulation	slot liner	150	SL1
Main insulation	slot liner	180	SL2
Main insulation	slot liner	500	SL3
Main insulation	slot liner	500	SL4
Main insulation	transmission oil		

For electrical testing, the stator and rotor subsystems have been modelled by using formette and motorette assemblies, respectively, as shown in Fig. 2. The former is essentially a stack of flat wires inserted in a slot in a stator whereas the latter is a random wound coil made of round wires inserted into a holder representing the slot in a rotor. In both assemblies, the wires are insulated from the slot by the slot liner.

The combinations of the wires and slot liners materials used in the tests are listed in Table 2. Formette and motorette assemblies have been thermally aged. For doing this, the test objects were placed in an oven and were kept at elevated temperature for required time as specified in Table 2. For aging in oil, the objects were placed in aluminum containers filled with oil and sealed with a high temperature adhesive tape 3M 363 to prevent oil evaporation, see Fig. 3. The electrical characterization of the test objects was conducted before ageing, in the middle of ageing period and after it has been completed.



(a)



(b)



(c)

Figure 2. Formette (a) and motorette (b) assemblies, preparation of formettes and motorettes for testing (c).

Table 2. Wires and slot liners tested.

Purpose	Wire	Slot liner	Ageing in oil 150C	Ageing in air 180C
Stator subsystem	A	SL1	500h (1 sample) 1000h (2 samples)	100h (2 samples)
Stator subsystem	B	SL2	500h (1 sample) 1000h (2 samples)	100h (2 samples)
Stator subsystem	C	SL4	500h (1 sample) 1000h (2 samples)	100h (2 samples)
Stator subsystem	D	SL3	500h (1 sample) 1000h (2 samples)	100h (2 samples)
Rotor subsystem	W1	SL1	500h (2 samples)	100h (3 samples)
Rotor subsystem	W2	SL1	500h (2 samples)	100h (3 samples)
Rotor subsystem	W1	SL2	500h (2 samples)	100h (3 samples)
Rotor subsystem	W2	SL1	500h (2 samples)	100h (3 samples)



Figure 3. Containers with formettes immersed in oil inside the ovens.

2.2 Electrical characterization of the insulation

In the present study, the insulation systems were stressed by applying test voltages of bi-polar rectangular shapes with the duration of 500 us and the repetition frequency of 1 kHz to reproduce the actual stresses acting on the insulation in a converter-fed electrical machine. The voltage was supplied to the test object as shown in the circuit diagram in Fig. 4. It gradually rose up to the magnitude at which the appearance of partial discharges (PDs) was registered by the DAQ system, and the corresponding value was recorded as the inception voltage PDIV. The voltage was raised further up to $1.1 \times \text{PDIV}$ and then was gradually reduced and the extinction

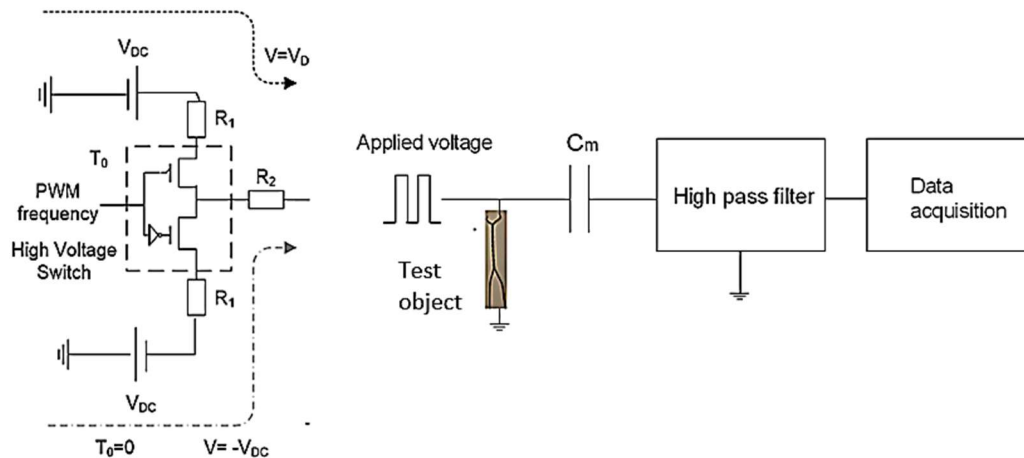


Figure 4. Circuit diagram of the experimental setup.

voltage of partial discharges was recorded as PDEV. The values of PDIV and PDEV were used for performance evaluation of the insulation – their higher magnitudes indicate higher resistance of the insulation to partial discharges.

3. Results

3.1 Ageing in oil

As indicated in Table 2, both formettes and motorettes assemblies were aged in oil. Most of the experiments were conducted for a duration of ageing of 500h. For formettes, additional tests were run for 1000h. The ageing was interrupted for conducting measurements of partial discharges, which typically took 1-2 days to allow for natural cooling of the containers to room temperature and doing the actual measurements. During the measurements period, the containers were kept sealed to prevent the exposure of the oil to the ambient air. Only a container with the sample to be tested was open for a short while to make necessary connections, and it was again sealed immediately after the test was completed. In the measurements, PDIV and PDEV values were obtained. Typically, four-five tests were run on each sample. In the plots below, the average values with standard deviations (STD) are shown.

The results for 500h ageing of motoretts are shown in Fig. 5. As seen, the thermal stress has led to the reduction of both PDIV and PDEV values. The differences in the magnitudes of both parameters are most pronounced for fresh insulation and at the end of the ageing period the differences between the four studied systems are rather minor. This indicates different ageing rates of the studied materials. Another observation is that the standard deviations are in general smaller for aged system that is more pronounced for PDIVs. Formettes samples exposed to longer thermal stress of 1000h show similar behavior of PDIVs and PDEVs as can be noticed from Fig. 6.

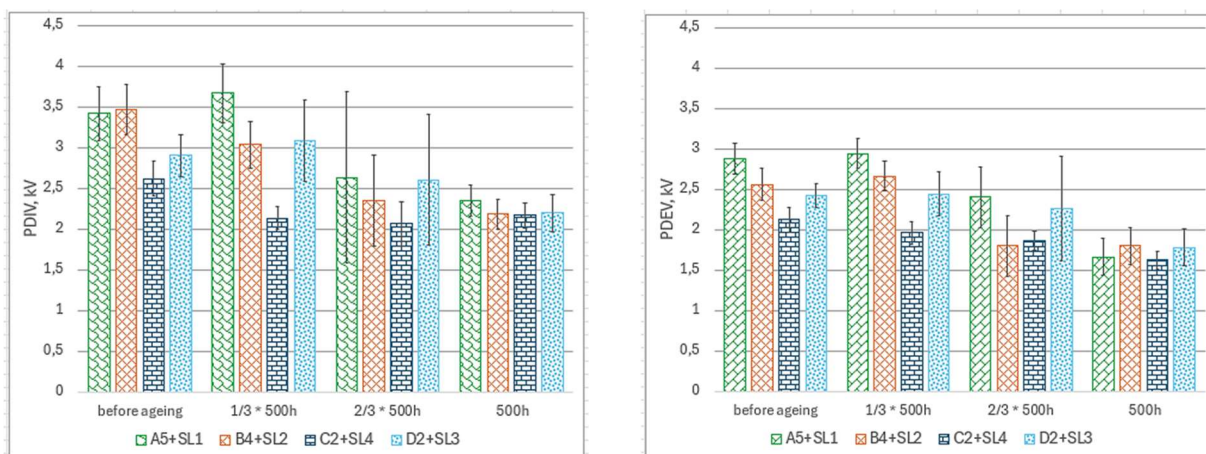


Figure 5. PDIV and PDEV measured on formettes samples of four materials combinations at various times during 500h ageing in oil at 150C.

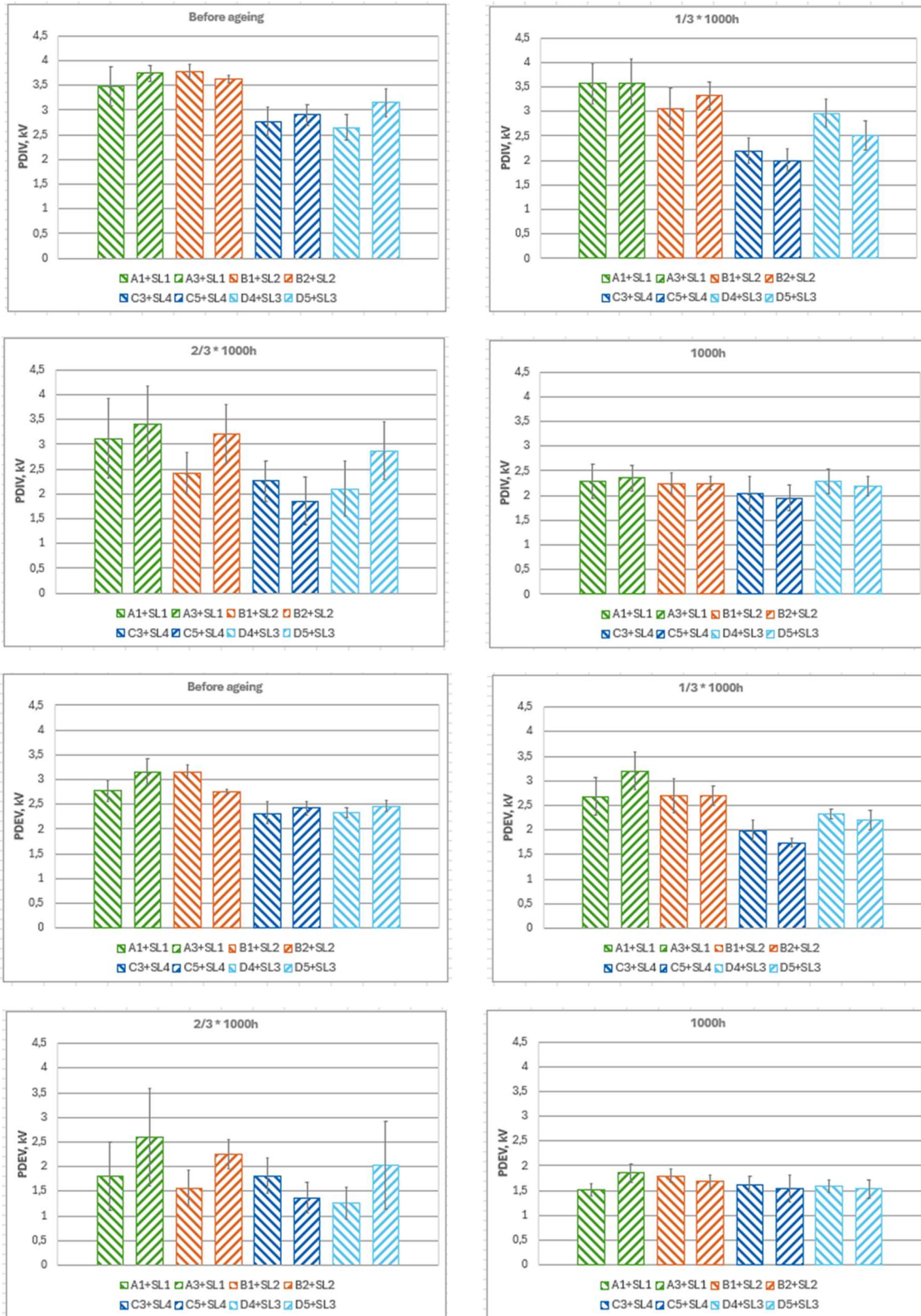


Figure 6. PDIV and PDEV measured on formettes samples of 8 different combinations of materials at various times during 1000h ageing in oil at 150C.

The results obtained for motorettes assemblies demonstrate somewhat different patterns. As can be observed in Fig. 7, PDIVs and PDEVs measured for fresh systems were extremely high for some samples, but their magnitudes drop to some average level already after ca 160h ($1/3 \cdot 500h$) of ageing and their further changes induced by the prolonged thermal stress were relatively small. The reason for such behaviour is unclear. It is also notable that for two systems (W1+SL1 and W2+SL1), the prolonged ageing led to even some improvements in the performance and both PDIV and PDEV magnitudes increased. Additional investigations are needed to understand this behaviour.

3.2 Ageing in air

As seen from Fig. 8, exposure of motorettes samples to temperature of 180°C for 500h didn't result in significant changes in the PDIV and PDEV magnitudes and this is a common trend for all studied insulation systems.

At the time of preparation of this report, the ageing of formette assemblies has been finished and measurements of PDIVs and PDEVs were ongoing. The results are to be presented in the updated version of the report.

4. Comments and remarks

The results obtained from the conducted experiments provide solid ground for further analysis and materials selection for the future environmentally friendly and recyclable insulation systems of electrical machines for electromobility applications. However, it is rather hard to emphasize any particular system considered in the present study based on the performed measurements only. To complete the analysis, additional electrical characterization needs to be done including measurements of leakage current through insulation, dielectric losses, breakdown withstand, etc. Finally, to make a conclusion about suitability of specific system, other factors need to be considered, including e.g. workability, cost, availability on a large scale, etc. For this reason, the conducted research is considered as the first step towards the claimed goal.

To get insight about feasibility of recycling the studied materials after thermal ageing, it is highly desirable to perform chemical and physical analyses of the samples used in the present study. As seen in Figs. 9-11, all elements of the insulation system have experienced changes after being exposed to thermal stresses that is indicated by changes of the colors of the wires coatings and especially oil.

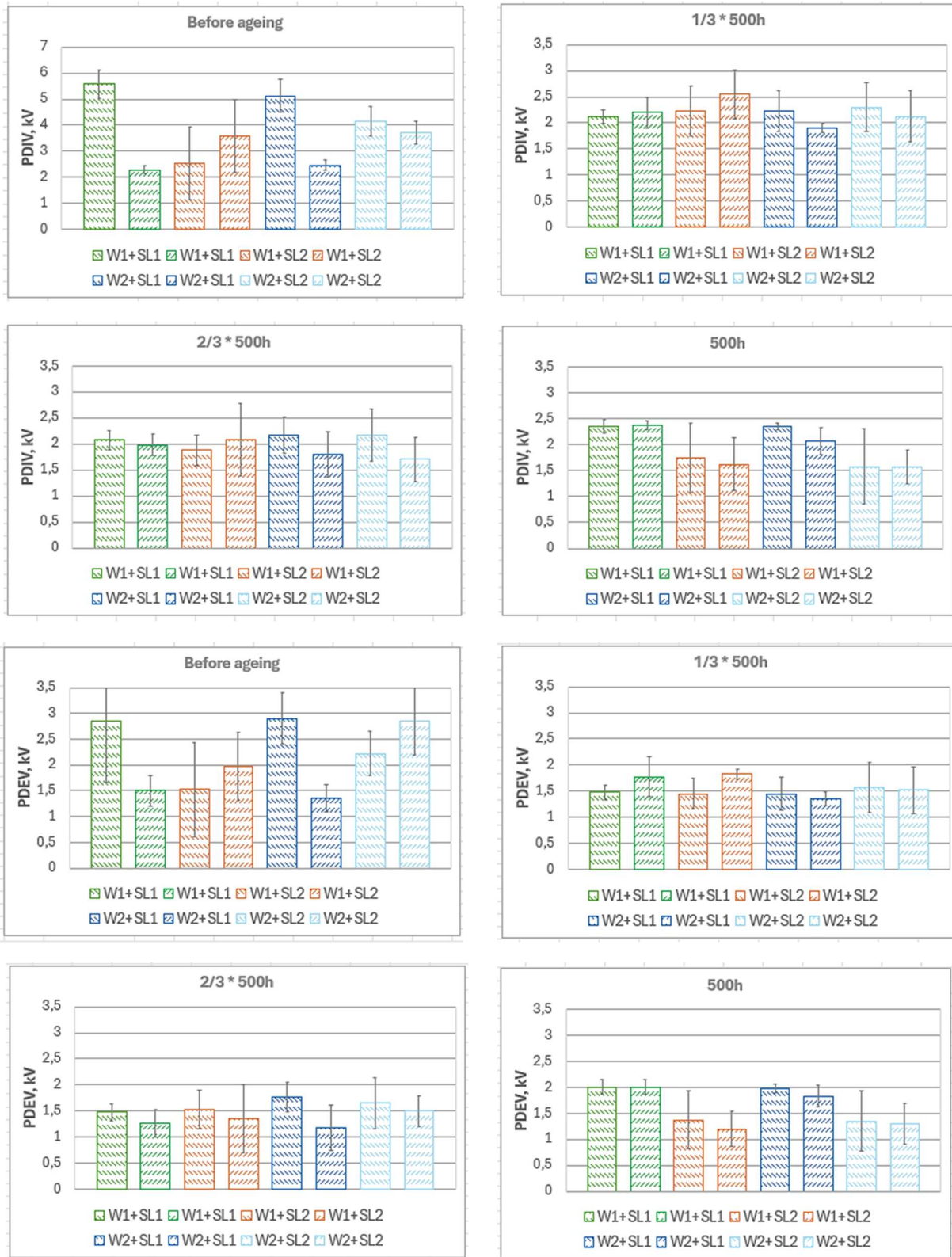


Figure 7. PDIV and PDEV measured on motorettes samples of 4 different combinations of materials (2 samples for each) at various times during 500h ageing in oil at 150C.

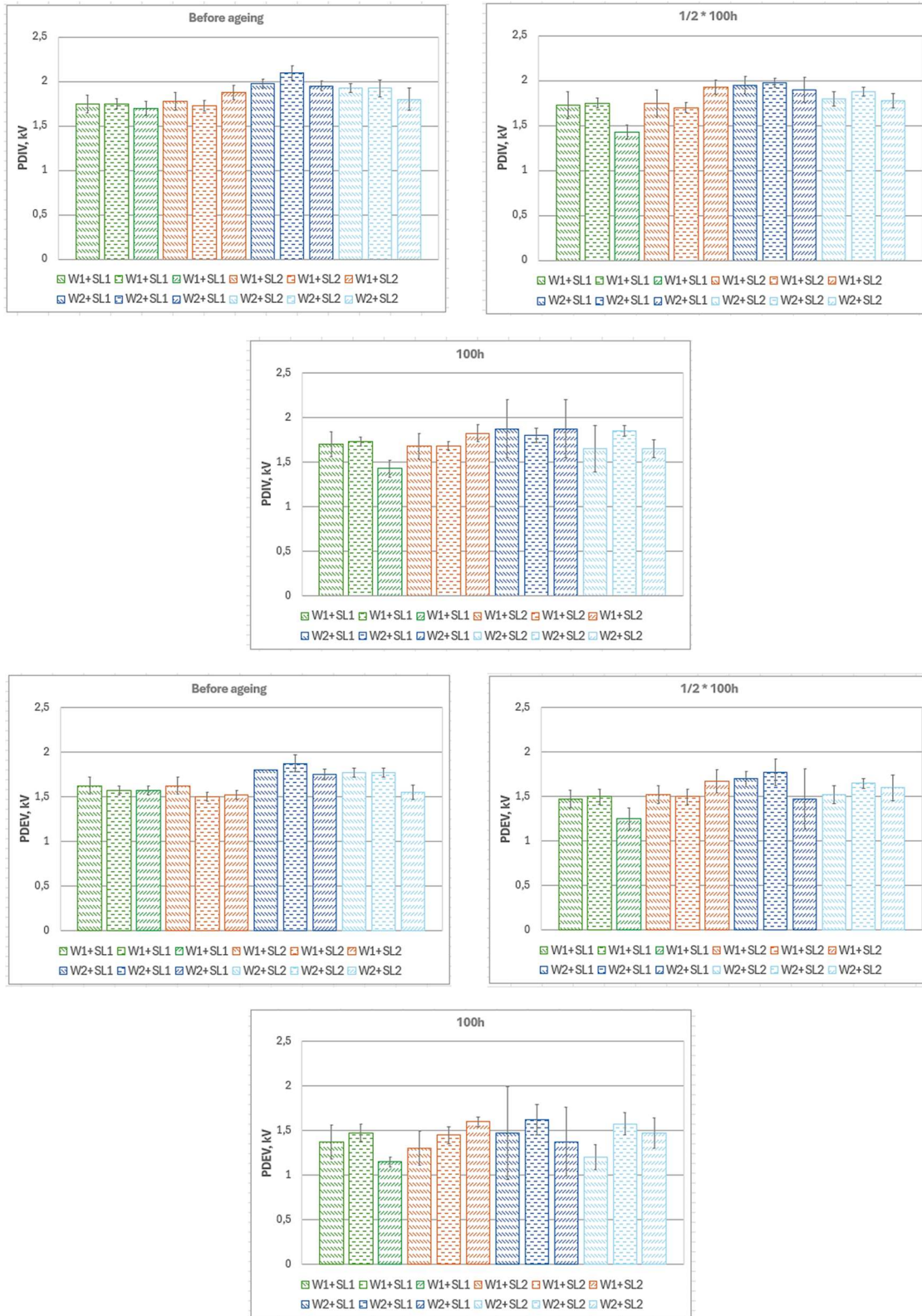


Figure 8. PDIV and PDEV measured on motorettes samples of 4 different combinations of materials (3 samples for each) at various times during 100h ageing in air at 180C.

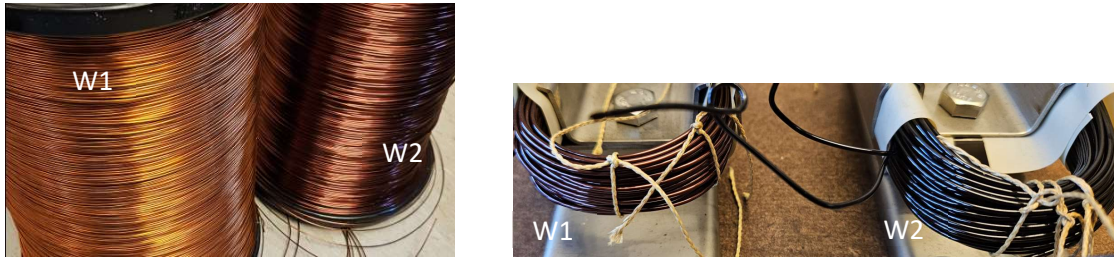


Figure 9. Tested wires before (left) and after (right) ageing in air for 100h at 180C.

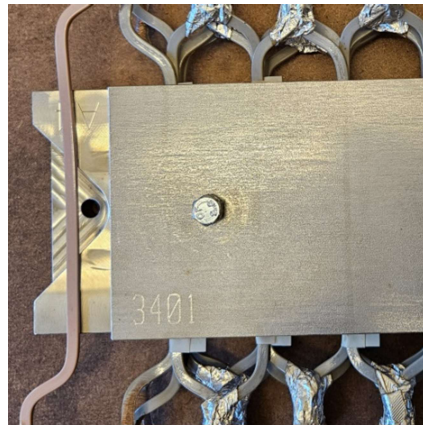


Figure 10. Formette assembly with wire A after ageing in air for 100h at 180C. A fresh wire is shown on the left side of the holder for comparison.



Figure 11. Degraded oil in the container with formette assembly after ageing for 288h at 180C.