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Assessment of Experimental Approaches for the Evaluation of Material Compatibility of E-fluids With the Insulation System of Low Voltage Rotating Electrical Machines

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***Abstract*—With the development of modern electric drive train systems, an effective cooling strategy is becoming a critical issue. Among various cooling methods, direct oil cooling is becoming more popular since it enables it to remove the heat directly from the heat source and subsequently improves the cooling performance. Aside from the cooling performance with direct cooling, the material compatibility of the coolant with machine components, particularly the electrical insulation system, is currently getting more attention. However, practical work regarding this issue is rare. Importantly, there still need to be widely recognised standards or instructions for compatibility evaluation. In the present work, the feasibility of conventional diagnostic approaches of insulation systems for compatibility evaluation is discussed. Particularly, a method to estimate the lifetime of the insulation system considering the compatibility issue is provided, and the role of mechanical stress during the compatibility study is analysed.**

***Index Terms*—electric drive, direct oil cooling, material compatibility, insulation system**

I. Introduction

The power density of the electrical drive system can be increased by reducing the volume requirement and increasing the allowable input power. An increase of the power limitation is usually an effective approach and can be achieved through more effective thermal management. Various cooling strategies and topologies have been developed in recent decades [1]–[4]. Among these cooling strategies, direct oil cooling is drawing more attention from machine designers. Its advantage over other cooling methods lies mainly in the direct contact of the cooling fluid with the heat source, which enables it to achieve a higher cooling efficiency [4], [5]. The concept of direct oil cooling is practised in different forms, such as end-winding spray cooling, splashing cooling, and combined lubricating and cooling in integrated electric drive trains.

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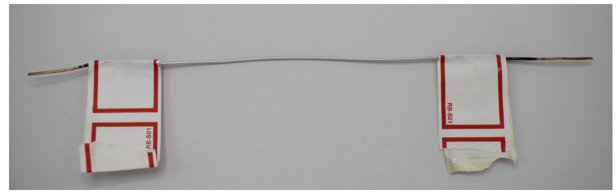
Parallel to the advancement of direct cooling technologies, side effects such as material compatibility of the cooling fluid with the inner components of the insulation system has been studied preliminarily [6]–[8] and immediately give rise to massive discussions. In [6], the poor material compatibility of various E-fluids with the enamelled wire depicts how urgent the compatibility issue is. Subsequently, more questions arise regarding the material compatibility study. For example, diagnostic tests for the compatibility study need to be developed since there are still yet to be widely accepted standards or guidelines for compatibility evaluation. As depicted in [6], the conventional diagnostic methods of the insulation system are not necessarily proper to evaluate the lifetime of the winding insulations.

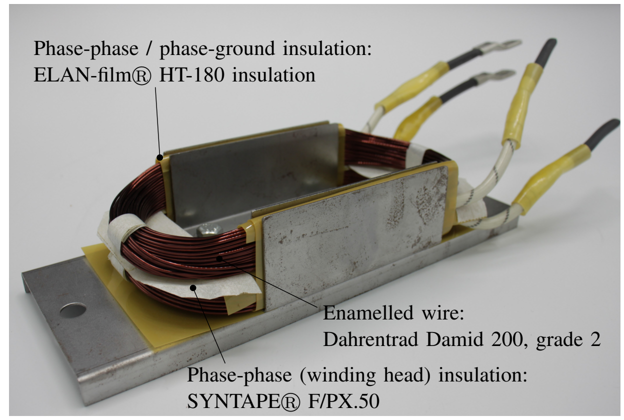
The present work focuses on the feasibility of various experimental approaches for the evaluation of material compatibility of E-fluids with the insulation system of low-voltage rotating electrical machines. The study is mainly focused on the characterisation of enamelled wires. In the following work, the state-of-the-art characterisation methods of winding insulations are overviewed first, and the feasibility of the individual characterising approach is discussed with experimental results. For a practical estimation of the lifetime of the insulation system with consideration of the E-fluid's effect, the lifetime of the insulation system is estimated by means of cyclic conditioning. The highlight of the present work is that, it provides valuable information on the topic of material compatibility, and it could work as a reference to study the material compatibility between various E-fluids and insulation materials.

II. State-of-the-art Characterisation of Insulation Systems

For the diagnosis of the insulation system, partial discharge inception voltage (PDIV) is commonly used to examine the



a) Single wire specimen.



b) Motorette.

Fig. 1: Employed single wire specimen and motorette.

state of health of the winding insulation of low-voltage electrical machines. A low-voltage electrical insulation system must be designed free of partial discharge (PD) since, under PD, the insulation system fails rapidly within several hours. The PDIV indicates until which voltage level the insulation is able to withstand during the operation. In the standards [9], [10], the parameter PDIV is usually used as a criterion for diagnostic tests and lifetime estimation. A minimum PDIV can be defined as the end-of-life (EOL) criterion, taking the safety and the overshoot factors into consideration [10], [11].

As supplements, the capacitance is also characterised to interpret the material degradation. An increased capacitance usually indicates a decrease of the dielectric strength of insulation materials. Particularly, the capacitance measurement is commonly applied to examine the state of health of the impregnation material. A loss of the impregnation material results in a decrease of capacitance. Besides, the relative permittivity of insulation materials determines the dielectric strength. A lower permittivity involves a higher dielectric strength. The widely-applied polyamide-imide (PAI) and polyester-imide (PEI) materials typically possess a relative permittivity in the range of 3 to 4 [12]. However, the permittivity can not be reduced arbitrarily. It is indicated in [13], [14] that water absorption of the insulation material results in an increase of the relative permittivity, since water has a much higher conductivity than insulation materials.

The insulation system must also be able to withstand the mechanical stress resulting from rotation and vibration during the operation of electrical machines. Typically, slot insulations such as insulation paper are required to possess proper mechanical strength to withstand tearing. Therefore, the laminated insulation materials are usually examined with tensile tests [7]. For the wire enamel, the peel strength test is typically used to examine the coating adhesion strength during the manufacturing process of enamelled wires. In the standard IEC 60851-3.5 [15], it is pointed out that elongation and adhesion describe the ability of the wire to withstand stresses such as stretching, coiling, bending or twisting without cracking or peeling of the insulation. The thickness of the coating layer of enamel wire is usually in the micrometer range. Taking the round enamelled wire of grade 2, with a conductor diameter of $1\,\mathrm{mm}$ for example, the coating thickness is required to be in the range of $31.5\,\mu\mathrm{m}$-$47.0\,\mu\mathrm{m}$, according to the standard IEC 60317-0-1 [16]. In [17], nanoindentation is conducted on the cross-sectional area of the wire enamel to compare the hardnesses of commercial corona resistance and conventional enamelled wires.

III. Methodology

In this section, the feasibility of compatibility evaluation with simple wire samples, such as twisted pairs and single wire samples, is discussed. Conventional characterisation methods such as PDIV and capacitance measurements are applied to twisted pairs, and their feasibilities to diagnose material degradation and compatibility with E-fluids are discussed. Relative permittivity measurement with single wire samples is conducted. Motorettes are employed during thermal ageing cycles for the lifetime estimation of the insulation system, considering the mechanical stress conditions.

In the following, specifications of employed materials and specimens, details of diagnostic and material characterisation methods, and procedures of lifetime estimations are introduced in detail.

A. Materials and Specimens

The enamelled wire Damid 200, grade 2, and one commercial automatic transmission fluid (ATF) are applied for the compatibility study. Damid 200 is a standard enamelled wire in state-of-the-art electric traction machines. The involved enamelled wire possesses a thermal class of $200\,^{\circ}\mathrm{C}$ and a conductor diameter of $1\,\mathrm{mm}$. A dual-coating system comprised of polyester-imide (PEI) as the base-coating and polyamide-imide (PAI) as the over-coating ensures a combination of thermal and mechanical properties. The specifications of the applied ATF can be found in [6].

Simple configurational specimens, such as single wire specimens and twisted pairs out of aged enamelled wires, can only be analysed qualitatively. A demonstration of the single wire specimen is provided in Fig. 1a. Motorettes are usually applied, representing the stator for a precise estimation of the lifetime under specific conditionings. In the present work, motorettes, as shown in Fig 1b, are applied for the lifetime estimation of the winding insulation system in the ATF environment at $180\,^{\circ}\mathrm{C}$. It should be noted that the applied motorettes in the present work are designed without impregnation materials for the worst-case estimation. As a consequence, the interturn insulation made of Damid 200 comes in direct contact with the ATF.

B. Diagnostic Tests of the Insulation System

The PDIVs of twisted pairs are measured with the IEM HV generator at a switching frequency of 10 kHz. The detailed measurement technologies of PDIVs are provided in [18]. For the PDIV measurement of motorettes, the commercial stator testing device *Schleich MTC3* is applied with a sinusoidal voltage (50 Hz). During this measurement, a coupling capacitor is used to filter out high-frequency components of the current, and the PDIV is determined when the current reaches the threshold of 50 μA. When the current is over 0.1 mA during the increment of the applied voltage, a signal of over current occurs, and the measurement stops. The applied voltage for the PDIV measurement is with an initial value of 400 V and a maximum of 2000 V, in steps of 35 V. The capacitance is measured with a commercial LCR-bridge at 10 kHz. Additionally, the insulation resistances of motorettes are also measured under a dc-voltage of 1000 V after applying the voltage for 10 s.

The enamelled wire is regarded as a cylinder capacitor during the relative permittivity determination. The permittivity of the insulation coating ε_r can be calculated as:

$$\varepsilon_\mathrm{r} = \frac{C \cdot \ln(R_2/R_1)}{2\pi \cdot \varepsilon_0 \cdot l}. \quad (1)$$

Where C stands for the measured capacitance of the single wire specimen, ε_0 indicates the permittivity in the vacuum space, R_1 and R_2 are the copper radius and outer radius of the wire, respectively. The copper and wire diameters can be measured with microscopic photographs of the wire's cross-section. l denotes the effective length of the wire.

C. Thermal Conditioning & Ageing Cycle

During the compatibility study of enamelled wires with the ATF, enamelled wires are immersed in the ATF bath. Then they are thermally conditioned at 200 °C in an air-tight heating pot for 312 h, with five sampling points: 24 h, 96 h, 168 h, 240 h and 312 h, respectively. After sampling, the wires are cleaned before they are produced into twisted pairs and single wire samples in order to reduce the influence of oil residual on the measurement. It should be noted that ageing of twisted pairs directly in the fluid may result in large fluctuations of PDIV results due to random oil residuals between twisted turns. A reference group of wires is conditioned without the presence of the ATF under the same thermal condition.

Motorettes are subjected to thermal cycles according to the standard IEC 60034-18-21 [9]. In comparison with the defined cycles in the aforementioned standard, conditioning in a humid environment is removed in the present work, considering that the water content is usually detrimental to the dielectric properties of insulation oils. Motorettes are divided into two groups, and each group contains six pieces. Within one ageing cycle, two groups of motorettes are first thermally conditioned at 180 °C in the ATF bath and in air for two

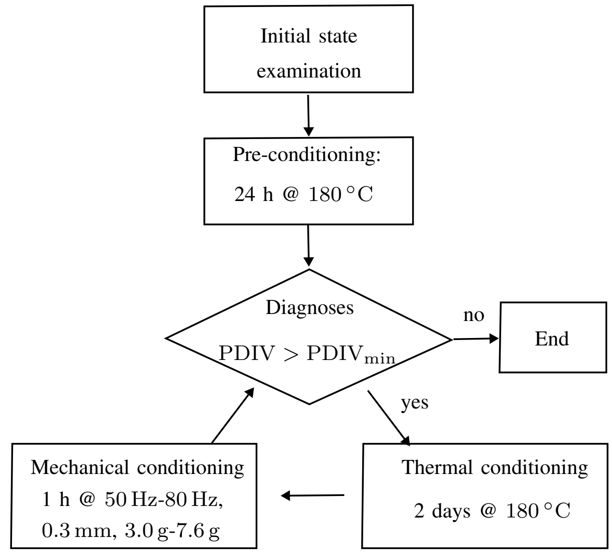


Fig. 2: Illustration of conditioning cycles.

days, respectively. Then the motorettes in the ATF bath are pulled out and dried in air and in the oven at 100 °C each for 1 h. After cooling down to room temperature, two groups of motorettes are mechanically conditioned on the vibrating table for 1 h, with a displacement amplitude of 0.3 mm, a vibrating frequency range of 50 Hz-80 Hz and acceleration of 3.0 g-7.6 g. After the mechanical conditioning, the motorettes are diagnosed with parameters of PDIV, capacitance, and insulation resistance at 10 s under a dc-voltage of 1000 V, respectively. The characteristics between the upper phase and ground (P1-G), lower phase and ground (P2-G), as well as between two phases (P1-P2), are examined until the measured value reaches the EOL criterion. Fig. 2 illustrates the ageing cycle. Eighteen cycles are conducted in the present work until six motorettes conditioned in the ATF fail, and the cyclic conditioning process stops for both groups.

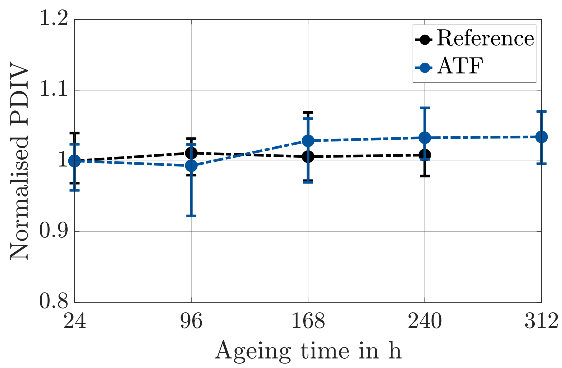
The material degradation generally obeys Weibull-distribution, which, therefore, can be used to estimate the lifetime. The cumulative distribution function of a two-parameter Weibull distribution can be expressed as:

$$P(U) = 1 - \exp(-(N/\alpha)^\beta), N > 0, \alpha > 0, \beta > 0. \quad (2)$$

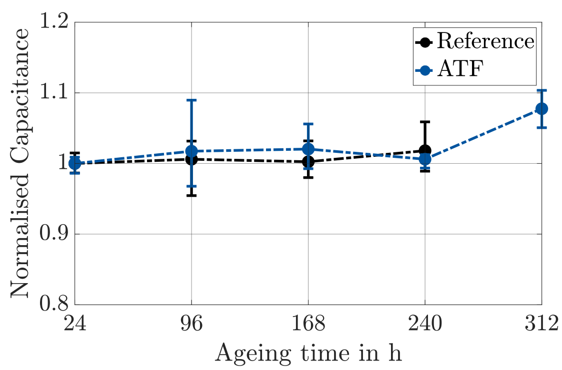
Where $P(N)$ denotes the probability of the occurrence of failure at the number of cycles of N, α and β are the scale parameter and the shape parameter, respectively. α depicts the characteristic lifetime in cycles, indicating at which ageing cycles a probability of 63.2 % of failure is obtained.

IV. Result Analysis and Discussion

In this section, the feasibility of multiple characterisation methods for a timely evaluation of the material degradation during the compatibility study is discussed. Besides, the lifetime of motorettes during the material compatibility study with the ATF is estimated, and the mechanical capability of motorettes during the ageing process is evaluated.



a) Normalised PDIV.



b) Normalised capacitance.

Fig. 3: PDIV and capacitance measurements with twisted pairs. Ten specimens are measured for each measuring point.

A. Feasibility of PDIV and Capacitance Measurements

In this section, the feasibility of conventional diagnostic methods: PDIV, and capacitance measurements, to the material degradation during the material compatibility is compared and discussed, and the results are shown in Fig. 3. The measured values at each ageing stage are normalised with respect to the value at the first measuring point at 24 h. Subsequently, the changes in percentages of parameters PDIV and capacitance during the entire ageing process can be drawn easily. As shown in the results, the PDIVs increase slightly with increasing ageing time until a plateau comes at 168 h. Generally, the maximum increment is approx. 5 % for the ATF group and even lower for the reference group. In comparison, the capacitance generally stays stable, and a maximum increment at the last ageing stage is approx. 9 % for wired aged in ATF, while the capacitance stays almost stable for wires aged in air until it mechanically breaks down. It should be noted that wires conditioned in the ATF partially and mechanically break down at 312 h during twisted pair preparation. Such a low increment cannot be utilized to predicate the material degradation, considering the inaccuracy of measurements resulting from the ability of the measuring devices and personal factors during the operation of measuring instruments.

During the PDIV measurement of motorettes, it is also observed that the PDIV stays almost stable until a sudden electrical failure occurs. And in the meanwhile, the capacitance values also stay stable with respect to growing ageing cycles. This phenomenon is consistent with the measuring results with twisted pairs. From this viewpoint, it can be concluded that PDIV and capacitance measurements are not able to interpret the material degradation in time.

B. Feasibility of Permittivity Measurement

It is proved in the last section that conventional diagnostic methods (PDIV and capacitance measurements) of twisted pairs cannot assess the material compatibility effectively. In one aspect, the dielectric properties of the insulation system are generally not impacted by E-fluids. In another aspect, these diagnostic methods are usually highly dependent on the configuration and geometry of the specimens. Single wire samples are applied to reduce the configurational effect on the characterisation of the dielectric properties. The relative permittivity of the coating layer is obtained through capacitance measurement. The relative permittivity of the wire enamel can be calculated according to (1). As shown in Fig. 4, the permittivity of wire enamels aged both in air and in the ATF at 200 °C increase slightly, while at the end of the ageing process, the total increment of the permittivity in both groups is within 10 %. The permittivity measurement results agree with the results of conventional diagnostic methods. However, the drawback of permittivity measurement is that it is much more time-consuming than indirect diagnostic methods due to the complex sample preparation process.

Besides, as mentioned above, water absorption may result in a significant increase of the relative permittivity of the coating layer due to the high conductivity of water. Since the applied ATF in the present work possesses a similar relative permittivity to the coating materials, absorption of the ATF will not result in a significant increase of the relative permittivity. When the involved E-fluids contain water, such as the so-called water-based lubricant, or when the material is conditioned under high humid environment, the relative permittivity is a suitable measure to examine the content of absorbed water of insulation materials.

C. Feasibility of Resistance Measurement

The resistances of motorettes conditioned in the ATF are measured until they electrically fail during the resistance measurement. As shown in Fig. 5, the relative resistances between two phases with respect to the value at cycle zero are plotted. Results show that the relative resistances decrease significantly at the first several ageing cycles, and in the following, the values reach gradually stable around 20 % of the initial value. The measuring results between one phase and the ground wall show similar trends and stay stable around 20 %.

Due to the application of E-fluids, the polarisation process of motorettes during the insulation resistance measurement is getting slower. And with increasing ageing cycles, the delay of polarisation is more significant.

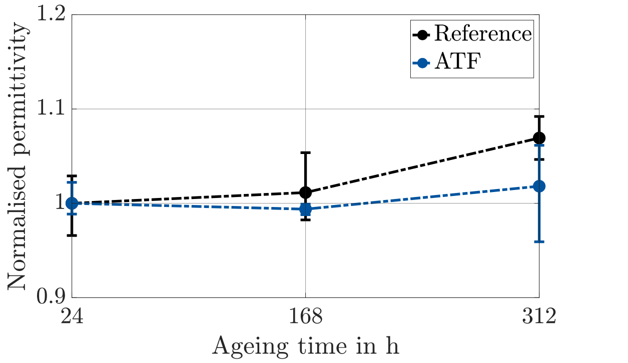


Fig. 4: Relative permittivity measurement of wire enamels, with five specimens of each measuring point.

D. EOL Criterion & Lifetime Estimation

During thermal conditioning, the motorettes are diagnosed after each cycle with multiple parameters. Mainly, the PDIV measurement is used to determine the lifetime. However, as mentioned above, the PDIVs of motorettes that are conditioned in the ATF stay stable generally during the ageing process until it suddenly fails electrically during the PDIV measurement. This phenomenon is consistent with the PDIV measurement of twisted pairs. Therefore, The motorette is determined to be failed when it electrically breaks down during the PDIV measurement. The number of failures with increasing thermal cycles is plotted in Fig. 6a. As shown in the results, electrical failures are prone to happen between two phases, and the insulation between phase II and the ground wall is at least to be damaged during the ageing process. Therefore, the failure distribution between the two phases is applied for further lifetime estimation.

The characteristic lifetime of the motorettes is calculated as 12.4 cycles, with 95 % confidence the lifetime lies between 10.9 and 14.2 cycles according to (2). With two days per ageing cycle and the failure distribution with respect to ageing cycles, the characteristic lifetime and lifetime range with 95 % confidence are summarised in TABLE I.

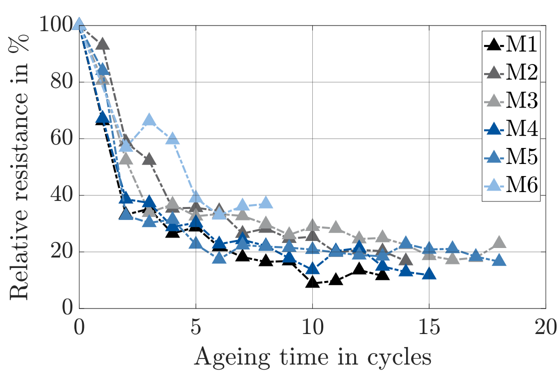
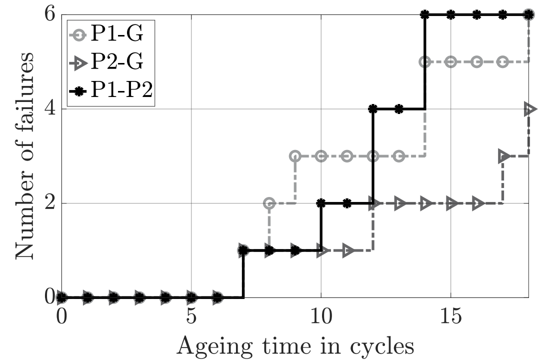
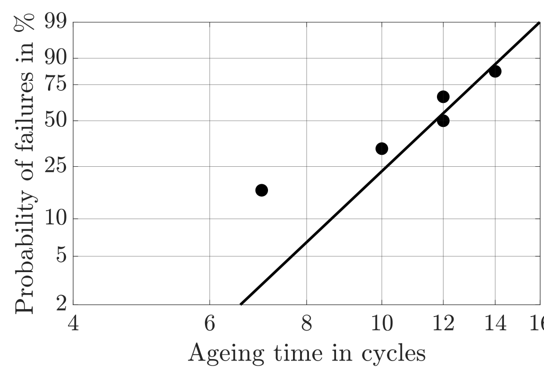


Fig. 5: Influence of ageing cycles on the insulation resistance between two phases of six motorettes conditioned in the ATF.



a) Accumulative number of failures.



b) Accumulative probability of failures between P1-P2.

Fig. 6: Distribution of failures: a) accumulative number of failures with respect to ageing cycles and b) accumulative probability of failures obeying 2-parameter Weibull-distribution.

TABLE I: Lifetime of Motorettes Conditioned in the ATF at 180 °C.

Parameter	Number of cycles	Hours
Characteristic lifetime	12.4	595.2
Lifetime with 95 % confidence	10.9 - 14.2	534.1 - 681.6

E. Mechanical Boundary Conditions of Electrical Machines

In [6], the same type of enamelled wires are conditioned at the same conditions, peel strengths of aged wires during 1008 h are tested regularly, and the relative peel strength with respect to the initial state is shown in Fig. 7. The results show that the peel strength of the wire decreases significantly and rapidly after 336 h, and after that, it decreases continuously but slowly until the end of the ageing period. During the ageing period of 772 h and 1008 h, the peel strength of wires is lower than 10 % of the initial value. Whether such a low peel strength of the insulation winding will survive during the regular operation of electrical machines becomes the main concern.

In the present work, besides the motorettes of the ATF group, motorettes of the reference group are conditioned without the presence of the ATF. the characteristics of the

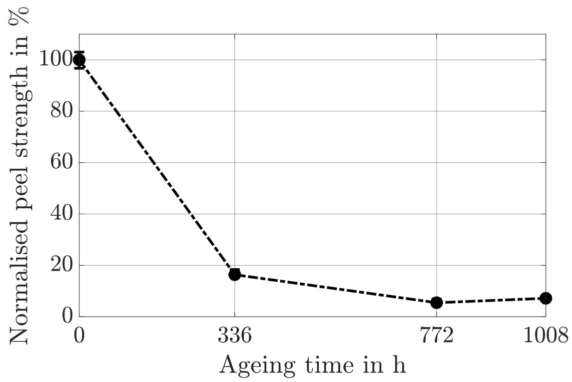


Fig. 7: Peel strength of the enamelled wire aged at 180 °C in air, with three specimens of each measuring point [6].

motorettes are examined as well. Until the end of ageing at 18 cycles, namely after 864 h, motorettes of the ATF group fail completely. While the properties of the reference group stay almost the same as the initial state and there is no mechanical or electrical failure observed. From this viewpoint, the peel strength test is only feasible to examine the adhesion strength of the new wire. The wire in the completed winding system is stressed significantly less than during the machine production process. As a consequence, a detachment of the wire enamel does not take place during the regular operation of the electrical machine, even if the results of peeling tests are not satisfactory. In this perspective, the winding insulation is highly overstressed with the peel strength test. In realistic electrical machines, mechanical stress mainly results from the rotation and vibration of the machine during operation.

V. Conclusions and Outlook

In the presented work, the material compatibility of the ATF with the enamelled wire is conducted, and it is focused on the feasibility of multiple characterising approaches for a timely diagnosis of the material degradation during the compatibility study. Results show that conventional diagnostic methods, such as PDIV and capacitance measurements, are not able to properly predict the degree of material degradation during the ageing process. This is true for both twisted pair and motorette samples. Relative permittivity measurement is also not suitable to evaluate the material compatibility of E-fluids with insulation materials, especially when the relative permittivity of the applied E-fluid is similar to that of insulation materials. By utilizing motorettes for the conduction of cyclic conditioning cycles, the lifetime of the insulation system can be estimated. Insulation resistances of motorettes that are conditioned in the ATF, decrease significantly during the conditioning process. Therefore, it can be appropriately utilized for the prediction of material compatibility. During the conditioning process, mechanical capability can also be examined by adding mechanical conditioning to the ageing cycles. And results show that the mechanical capability of the insulation winding is significantly underestimated with the peel strength test.

In future work, more attention will be paid on the characterisation of mechanical properties of enamelled wires, such as by means of nanoindentation. In addition, it is also meaningful to study the compatibility of E-fluids with other insulation components, such as impregnation and insulation paper.

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