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The Impact of Thermal Degradation on Electrical Machine Winding Insulation

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Abstract — Inter-turn stator short circuits can develop quickly leading to serious damage of an electric machine. However, degradation mechanisms of winding insulation are not yet fully understood. The main contribution of this article is analysis of the impact of thermal ageing on the electrical properties of winding insulation. The insulation samples have been aged thermally at 200 – 275 °C and for 100 – 1600 hours. After aging, impedance spectroscopy measurements were undertaken on the samples and equivalent circuit model (ECM) parameters fitted for each measurement. This allows the impact of thermal ageing on ECM parameters to be analysed, giving insight into the changes of the electrical properties of the insulation. Ultimately this will lead to development of new methods for remaining life prediction of electrical machine windings.

Index Terms — equivalent circuit model, electric machine, impedance spectroscopy, polyamide-imide, stator winding, thermal degradation

I. INTRODUCTION

STATOR faults are an important cause of electrical machine failures. The appearance of stator faults depends on the size of the electrical machine. According to [1], low voltage induction motor stator faults account for only 9% of total failures. In medium voltage induction motors, the percentage increases to 35-40%, whereas for high voltage it is more than 65% [2]-[6]. Amongst all possible stator faults, inter-turn stator faults are of particular interest because they are challenging to detect, especially at low severity levels [7]-[10], however they can evolve quickly leading to serious motor damage [11]. Moreover, these faults are difficult to discriminate from stator voltage supply imbalances. As a consequence, a variety of fault detection techniques including neural networks and envelope analysis have recently been applied [12]-[17].

Alternatively, other researchers have tried to understand

directly the physical mechanisms that lead to insulation degradation [18], leading to lifetime prediction and machine life prognosis models that may be used to improve performance and reduce cost. There have been many studies aimed at understanding insulation thermal ageing. An effort is made here to review and summarize some important past contributions.

Firstly, it has been noted that on-line thermal and chemical monitoring techniques are cost effective only in large machines [19]. Moreover, protective relays are triggered after the insulation has been seriously damaged and thus they cannot be considered to help towards the monitoring of the fault especially at low severity levels [20].

Furthermore, there are a variety of techniques which deal with the ageing mechanisms of the electrical machine windings insulation. In [21] a significant resin weight loss was observed around the winding in a failed induction motor. Additionally, it was found in [22] that after the initial ageing cycles, there was a shift of the dissipation factor and the capacitance at all voltage levels towards lower losses and capacitances because of the drying out and post curing of the insulation. Moreover, a new life span model was developed in [23], which presents an original relationship between the insulation life span and the stress parameters with the application of the Design of Experiments (DoE) methodology. Also, in [24] a new cable monitoring method was proposed based on impedance spectrum analysis in the high frequency range.

In the above papers the most commonly applied degradation technique is that of accelerated ageing, which deserves some further explanation. It has been reported in [25] that unstrained tests give overly optimistic information relating to long-term design data or predictions of expected lifetime. Furthermore, this type of testing has limitations. If the applied temperature exceeds some critical value then different chemical reactions are caused compared to the real ageing mechanisms. However, in [26] the application of multi-stress ageing on stator bars was successful in predicting the real ageing mechanisms of actual bars in applications working for 22 years. In the same work, the significant role of mechanical stress is highlighted because the loosening of the stator bars in the slots leads to vertical vibrations which enhance the degradation mechanism.

Here we analyze the impact of thermal ageing on the

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electrical properties of class H insulation (polyamide-imide or PAI), in particular with respect to the relationship between ageing temperature and time and the parameters of equivalent circuit models (ECM) of insulation materials.

II. EXPERIMENT DESIGN

One hundred and eighty polyamide-imide (PAI) insulation samples were divided into 6 groups of 30 samples each. Each group of samples was placed in a separate laboratory oven. These ovens were set to 200, 215, 230, 245, 260, and 275 °C. Each group of samples aged at the same temperature was further divided into 5 subgroups of 6 samples each. Each subgroup was aged for a different period of time at constant temperature. The time periods were 100, 200, 400, 800, and 1600 hours. After the thermal ageing, samples were placed in specially fabricated plastic cases and their impedance responses measured at 6 equally spaced points along the sample. The equipment used was the N4L PSM1735 Impedance Analyzer. Furthermore, impedance spectroscopy of 20 new (i.e. unaged) insulation samples was carried out in the same manner. Further details of the experiment design can be found in [27].

III. EQUIVALENT CIRCUIT MODEL

Impedance spectroscopy of an example insulation sample is presented in Fig. 1. The insulation exhibits capacitive behaviour for frequencies above 1 kHz, whilst for frequencies below 1 kHz the impedance is mainly resistive.

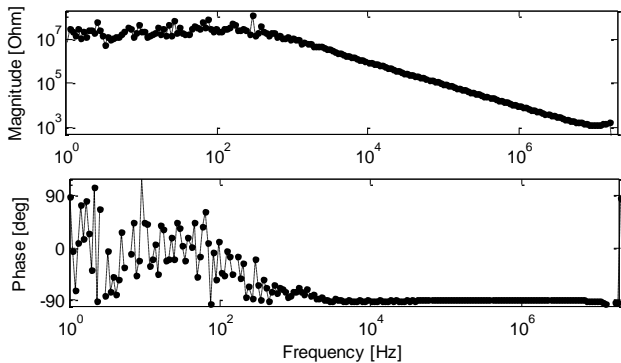


Fig. 1. Impedance spectroscopy of insulation sample

The insulation impedance response has been modelled using an equivalent circuit model comprising a capacitor C and resistor R connected in parallel

$$Z(j\omega) = \frac{R}{RCj\omega + 1} \quad (1)$$

where ω is the frequency expressed in radians per second and $j = \sqrt{-1}$. The R and C parameters of the equivalent circuit model have been fitted and their histograms are plotted in Fig. 2. Estimation uncertainties (assuming 95 % confidence bounds, see [28] for more details) of R and C are analyzed in the following subsections.

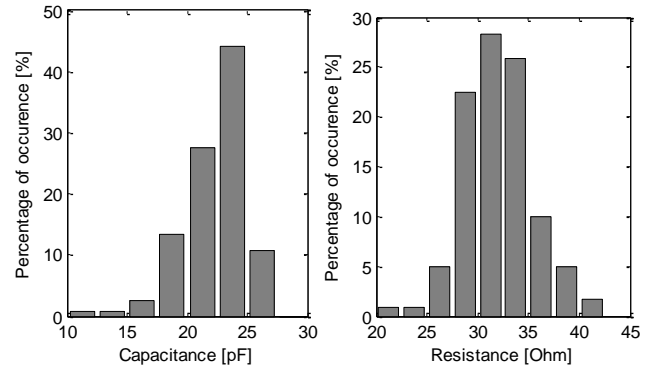


Fig. 2. Histograms of samples capacitance and resistance

A. Uncertainty of resistance estimation

Fig. 2 presents the uncertainty of the resistance estimation, denoted δR , vs. the fitted value of resistance for all measurements of the un-aged samples. It is observed that the resistance estimation uncertainty is proportional to the value of resistance R and has been obtained with $\delta R/R \cong 19\%$ accuracy on average. A similar observation has been made with respect to the aged insulation samples. This relatively high uncertainty is due to significant levels of measurement noise observed at low frequencies (where behaviour of the insulation is resistive, see Fig. 2) caused by the inability of the measurement equipment to drive the extremely small currents required for the measurements in this range.

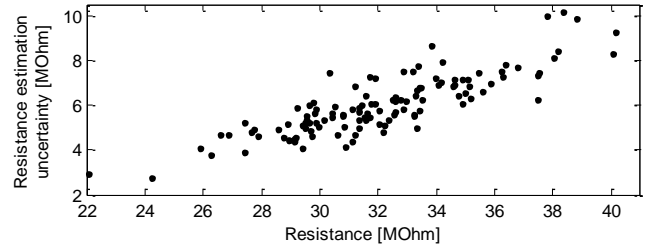


Fig. 3. Uncertainty of resistance estimation vs. resistance estimate

B. Uncertainty of capacitance estimation

The uncertainties of the capacitance estimation of the unaged samples, denoted δC , are presented in Fig. 3. For most of the cases, it occurs that $\delta C/C \cong 0.5\%$.

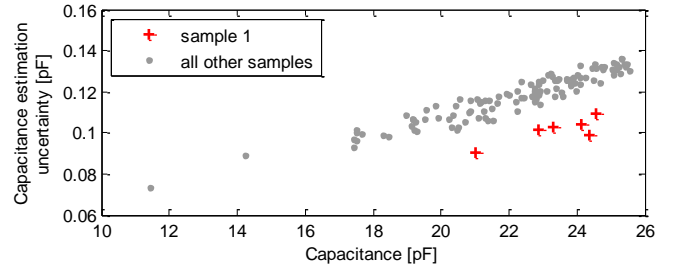


Fig. 4. Uncertainty of capacitance estimation vs. capacitance estimate

Interestingly, estimation uncertainty of all points on a single sample (sample 1 in Fig. 4) is slightly lower than the one of other samples.

IV. ANALYSIS OF UNAGED INSULATION

In this section the consistency of the insulation manufacturing quality is analysed. It is expected that the impedance measurements taken from each sample are characterized by comparable mean and standard deviation values. As the capacitance estimate is significantly less affected by measurement noise inaccuracies than the resistance estimate, the capacitance estimates have been used to assess the consistency of the manufacturing quality.

Firstly, the variance of the capacitance measurements taken for each sample has been considered. For every sample the mean value and standard deviation, denoted as μ_i and σ_i , respectively, of the six measured capacitance values have been calculated (the subscript i denotes the sample number). These are presented in Table I.

TABLE I
MEAN VALUE (μ_i) AND STANDARD DEVIATION (σ_i) OF 6 ESTIMATED CAPACITANCE VALUES (IN PICOFARADS) FOR EVERY SAMPLE

i	1	2	3	4	5	6	7
σ_i	1.3	1.3	1.5	4.5	3.5	1.6	2.1
μ_i	23.3	22.1	21.7	19.3	20.5	23.3	22.7
i	8	9	10	11	12	13	14
σ_i	2.4	2.8	2.1	1.7	2.2	2.1	1.9
μ_i	21.6	22.0	22.1	22.7	23.2	22.8	20.1
i	15	16	17	18	19	20	
σ_i	2.0	2.7	1.2	2.7	1.9	2.6	
μ_i	23.9	21.0	23.9	21.9	23.1	21.9	

Subsequently, for every pair of samples, i and j , a hypothesis that $\sigma_i = \sigma_j$ has been tested with the probability level of 0.05, cf. [29]. (Also all further hypotheses have been tested with the probability level 0.05). This hypothesis has been rejected for some pairs (i, j) , namely (1,4), (2,4), (3,4), (4,6), (4,11), (4,17), and (5,17). In order to eliminate number of potential false positives, Benjamini and Hochberg (BH) correction has been applied. Multiple hypothesis that all pairs $(4, i)$, $i = 1, \dots, 3, 5, \dots, 20$, have equal variances has been carried out applying BH correction with false discovery rate of 0.05. Subsequently the test has been repeated for all pairs $(17, i)$, $i = 1, \dots, 16, 18, \dots, 20$. The hypothesis has not been rejected for any of the pairs, hence it can be concluded that all samples have equal variance of capacitance values.

Then the procedure has been repeated to assess whether all samples are characterise with equal mean value. The multiple hypothesis that pairs $(14, i)$, $i = 1, \dots, 13, 15, \dots, 20$ have equal mean with application of the Benjamini and Hochberg (BH) correction indicated that samples 14 and 17 have distinct mean value. However, considering that false discovery rate is $\delta = 0.05$ it is expected that in 5 % of the

cases the hypothesis may be erroneously rejected¹. Consequently, it is concluded that the capacitance of new samples can be characterised by a single distribution with mean values of 22.17 and standard deviation of 2.46.

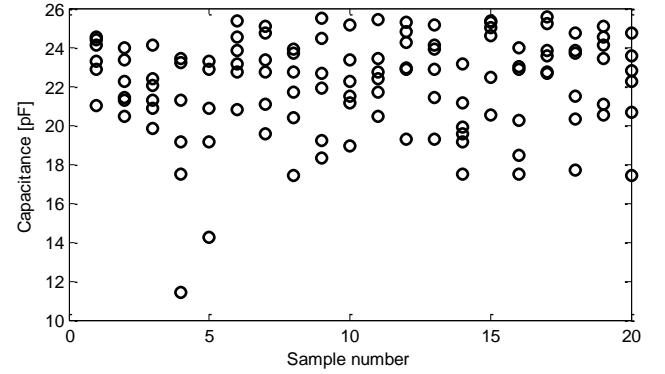


Fig. 5. Comparison of capacitance values measured at each sample.

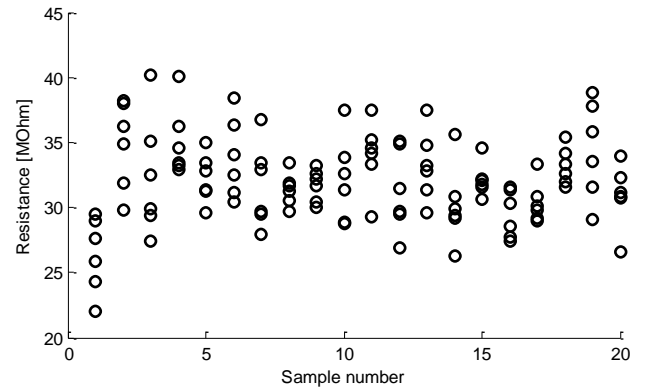


Fig. 6. Comparison of resistance values measured at each sample.

V. AGED INSULATION

We observed previously [27] that the capacitance of the majority of aged insulation samples is lower than 20 pF regardless of the length of ageing time. The only exceptions from this rule were insulation samples aged at 230 °C, where the capacitance drops from 22-24 pF to around 14 pF between 200 and 800 hours of ageing. Based on these observations a preliminary conclusion is made that the reduction of capacitance to $C < C_d \approx 20$ pF is an indicator of a thermal degradation. (Note that for 18 % of new insulation samples $C < 20$ pF, thus the absolute capacitance cannot be a sole indicator of degradation). Furthermore, the degradation mechanism seems to be dependent on the temperature at which the material is aged, which is indicated by different capacitance of samples aged at 230 °C.

As the most pronounced variations in the electrical properties of insulation were observed in the case of ageing at 230 °C, these results are presented first in Subsection A.

¹ The p-value is in the equal mean test (t-test) of samples 14 and 17 is 0.002 which is close to $\delta \frac{1}{19} = 0.0026$.

Subsections B and C analyse both the resistance and capacitance of the insulation aged at the other temperatures.

A. Thermal ageing of insulation at 230 °C

Fig. 7 presents insulation capacitance as function of time spent at 230 °C, denoted t . Mean values and standard deviations of the insulation capacitance for different values of t are presented in Table III.

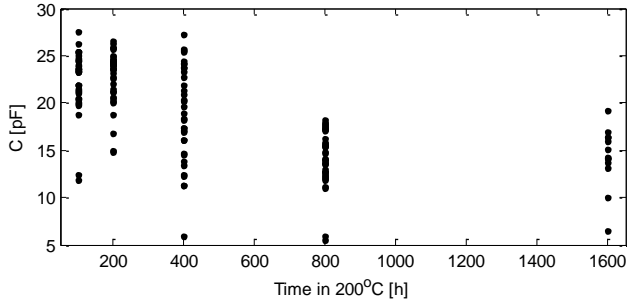


Fig. 7. Capacitance as function of time for insulation aged in 230 °C.

TABLE III
MEAN AND STANDARD DEVIATION OF CAPACITANCE.

Time, t [h]	100	200	400	800	1600
Mean [pF]	22.4±1.1	22.7±1.0	18.9±1.7	14.2±1.0	14.3±1.8
Standard deviation [pF]	3.3 (2.2-4.8)	2.9 (1.9-4.3)	5.0 (3.3-7.4)	3.0 (2.0-4.4)	3.2 (1.7-6.6)

The capacitance appears to decrease with time. However, this relationship is nonlinear. Also, note that the capacitance of the unaged insulation is 24.0 ± 0.6 pF, which is close to the capacitance of insulation aged at 230 °C for $t \leq 200$. We therefore hypothesize that a degradation phenomenon occurred between 200 and 800 hours leading to the capacitance drop from around 22-24 pF to around 14 pF.

Fig. 8 compares histograms of capacitance measurements for ageing times greater and lower than 400 hours, i.e. before and after the aforementioned ageing phenomenon occurred. It is observed that the distribution of capacitance for $t < 400$ is negatively skewed. However, bearing in mind results from Section IV, it is assumed in the further analysis that the relatively low capacitance values obtained for $t < 400$ are due to manufacturing differences rather than thermal ageing. Distributions of capacitance values for $t < 400$ and $t > 400$ have been approximated with normal distributions $\mathcal{N}(23.1, 4.8)^2$ and $\mathcal{N}(14.2, 9.1)$, respectively, where $\mathcal{N}(\mu, \sigma^2)$ denotes normal distribution with mean μ and variance σ^2 . These are presented in Fig. 9.

Subsequently, a decision boundary $C_d = 19.1$ pF has been calculated for which the capacitance probability density functions for the two considered cases ($t < 400$ h and $t > 400$ h) are equal. Thus, it is further assumed that the decrease of the capacitance below 19.1 pF indicates that the aforementioned degradation phenomenon has occurred.

² In the case of $t < 400$, capacitances lower than 15 pF have been excluded from the estimation.

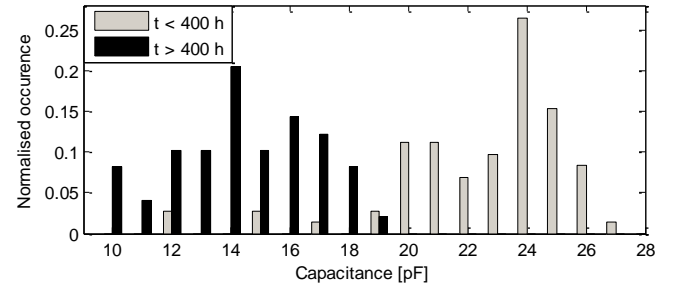


Fig. 8. Comparison of capacitance histograms for ageing time greater and lower than 400 hours

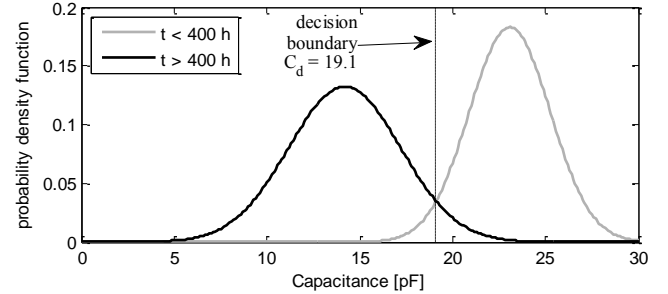


Fig. 9. Gaussian approximation of capacitance distributions for ageing time greater and lower than 400 hours.

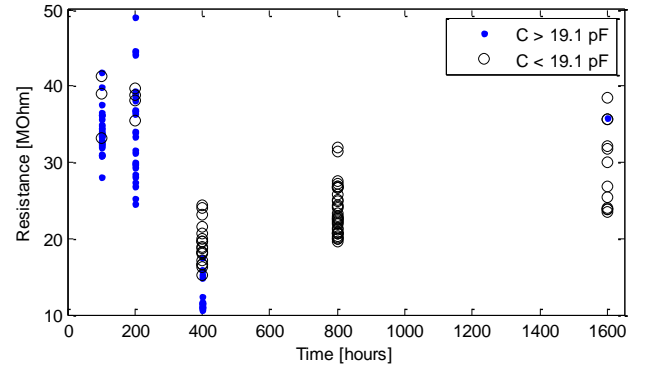


Fig. 10. Insulation resistance as function of time of ageing at 230 °C. Measurements for which capacitance exceeds 19.1 pF are denoted with blue dots, whilst points for which $C < C_d$ are denoted with black circles

Fig. 10 presents the insulation resistance as function of time of ageing at 230 °C. It is observed that for the first 400 hours the resistance decreases. (Note that the uncertainty of the resistance estimation increases with R , and that the four outliers visible in Fig. 10 for $t = 200$ h, for which the estimated resistance is greater than 44 M Ω , have estimation uncertainty of 11.7 M Ω on average, whilst the average estimation uncertainty for the remaining measurements for $t = 200$ h is 6.7 M Ω .) Subsequently, after 400 hours of ageing the resistance reaches its minimum (the average resistance estimation uncertainty for $t = 200$ h is 2.1 M Ω), then the resistance increases.

Furthermore, after 400 hours of ageing there is a clear separation between the resistance of points with $C > C_d$ and $C < C_d$, see Fig. 10. This is also visible in Fig. 11, where

measured capacitance has been plotted against resistance for $t = 400$ hours.

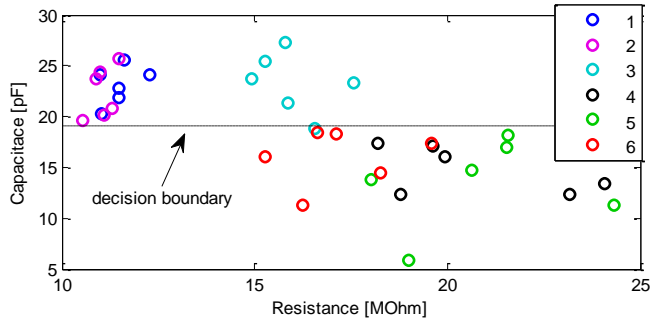


Fig. 11. Resistance and capacitance of insulation aged for 400 hours at 230 °C. Different colours denote measurements taken from different samples

The differences between the electrical properties of different points measured at a single insulation sample aged at 230 °C for $t = 400$ are much smaller than the differences between measurements taken at different samples, see Fig. 11. This could be due to the differences between insulation samples due to manufacturing quality. Therefore, it is expected that the whole area of an insulation sample ages at approximately the same rate, whereas degradation rates may differ amongst insulation samples. It is observed that the capacitance measured at samples 1, 2 and 3 aged for 400 hours is greater than C_d (except for a single point in sample 3 which has capacitance of 18.4 pF which is close to 19.1 pF), whilst the capacitance of samples 4, 5 and 6 is lower than C_d .

Fig. 12 compares the resistance and the capacitance of insulation for $t = 400$ with the electrical properties of the insulation aged for times less than and more than 400 hours. Comparing Fig. 11 and Fig. 12 the following degradation mechanism is observed: for the first 200 hours of ageing at 230 °C no significant change of electrical properties of insulation are noted; the expected values of resistance and capacitance of insulation are ≈ 35 M Ω and ≈ 23 pF. Then the resistance drops to $R_{min} \approx 11$ M Ω . Following the rapid reduction of resistance the capacitance drops to expected values of ≈ 14 pF, whilst the resistance slowly increases.

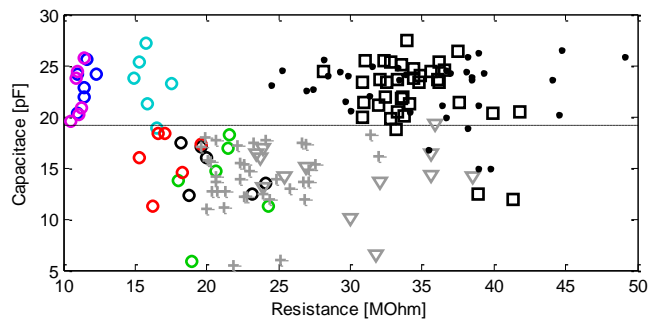


Fig. 12. Electrical properties of insulation with respect to ageing time at 230 °C. Black squares – $t = 100$ h, black dots – $t = 200$ h, grey crosses – $t = 800$ h, grey triangles – $t = 1600$ h, coloured circles – $t = 400$ h (cf. Fig. 10).

In this regard, it can be assumed that amongst the six samples aged for 400 hours (Fig. 11 and 12), degradation of sample 3 is the least advanced; samples 1 and 2 are at a similar stage of ageing and their capacitance is likely to reduce, whilst degradation of sample 5 is most advanced.

Note that the exact mechanism of ageing is not known at this stage, and further examination of the chemical properties of the aged insulation material is required to validate the above empirical results. Additionally, the resistance and capacitance values in the above degradation results are provisional and approximate. For example, since measurements are taken every several hundred hours it is not known whether $R_{min} \approx 11$ M Ω is the minimum resistance throughout the degradation period.

B. Thermal ageing of insulation at $T < 230$ °C

In this subsection thermal ageing of insulation at $T = 200$ °C and $T = 215$ °C is considered. It is observed that the insulation capacitance does not depend on the time of ageing (mean value of 14.5 pF and standard deviation of 2.7 pF). Analogously to the procedure presented in Fig. 8 and 8, distribution of the capacitance of unaged samples has been compared with the capacitance distribution of insulation aged in $T < 230$ °C and the decision boundary $C_d = 18.9$ pF has been obtained³.

On the contrary, the resistance varies with time. The resistance of the insulation aged at 215 °C firstly drops and then increases (see Fig. 13). A similar observation has been made with respect to ageing at 230 °C; however, without chemical analysis of the aged samples, it is not known whether these similar observations are due to the same phenomenon. Furthermore, the fact that the capacitance behaves differently at 230 °C suggests that these might be different phenomena.

Note that in the case of insulation aged at 200 °C for 400 hours (Fig. 13) there is a significant spread of resistance. Fig. 14 compares resistance values measured at different samples (aged at 200 °C for 400 hours). It is observed that the relatively large spread of resistance values is due to sample 6, whose resistance measurements were all relatively low. This might be an outlier, or sample 6 is at a different stage of the ageing process than samples 1-5.

C. Thermal ageing of insulation at $T > 230$ °C

The resistance of insulation aged at higher temperatures than 230 °C exhibits different behaviour compared to the previous cases (see Fig. 15). Firstly, all insulation samples were catastrophically destroyed after 1600 hours at 245 °C and 260 °C, and 800 hours at 275 °C. It has also been observed that during ageing at high temperatures, the insulation delaminates, which leads to increased resistance, see Fig. 15. Reduction of resistance after 800 hours at 260 °C is probably due to fact that the insulation was partially burned, hence it becomes thinner.

³ Sample 9 (see Fig. 5) has been excluded from this calculation.

Similarly to the low temperature case, the capacitance does not vary with ageing time (for $T = 245, 260$ °C the mean value and standard deviation are 14.8 and 2.8, respectively. In the case of ageing at 275 °C the capacitance is slightly elevated (mean value: 17.3, standard deviation 2.7), yet it does not depend on the ageing time.

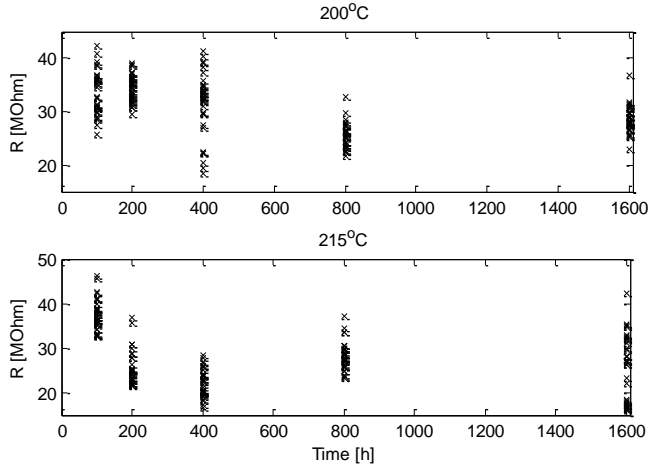


Fig. 13. Resistance of insulation aged in 200 °C and 215 °C as functions of time

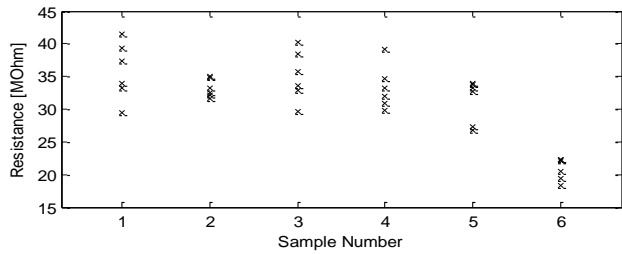


Fig. 14. Resistance of different insulation samples aged at 200 °C for 400 hours.

VI. CONCLUSIONS AND FURTHER WORK

Impact of ageing temperature and time on the electrical properties of the PAI insulation was analysed. It is observed that during ageing at temperatures lower than or equal to 230 °C, the insulation resistance exhibits a particular trend: it decreases at first, followed by an increase after approximately 400 hours. On the contrary, while ageing at temperatures of 245 °C and higher, the insulation resistance rather increases, which may be an effect of delamination [27]. Furthermore, for almost all aged samples the capacitance of the equivalent circuit model is lower than 20 pF, whilst the average capacitance of new samples is 22 pF.

Moreover, the study of new (un-aged) insulation samples has been carried out for comparison purposes. The capacitance of new samples can be characterised by a single distribution with mean value of 22.17 and standard deviation of 2.46.

Future work includes Fourier transform infrared spectroscopy of the new and aged samples in order to determine the possible material changes of the insulation and to validate the models derived in this paper.

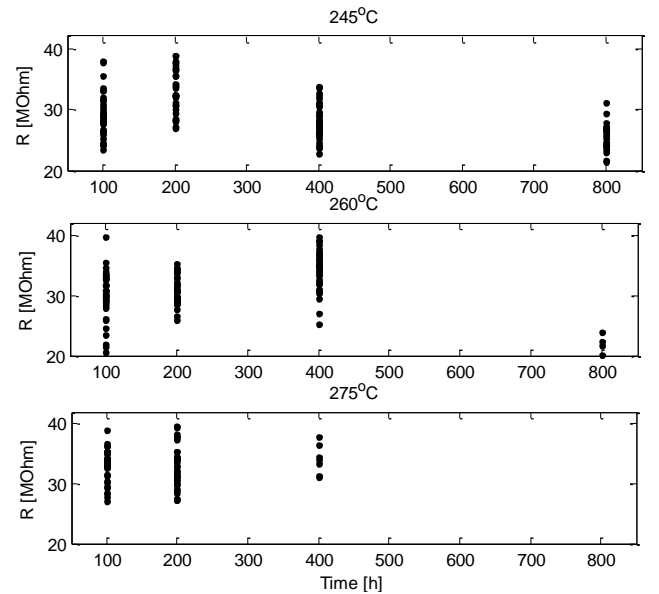


Fig. 15. Resistance of insulation aged at 245 °C, 260 °C and 275 °C as functions of time

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