

# Investigation of Traction Motor Windings' Insulation Capacitance at Switching Frequencies under Accelerated Thermal Stress

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**Abstract** – Machines in electric vehicles are driven by switching power electronic devices and undergo variable load cycling. In transient conditions high currents and temperatures develop, forcing the electric motor and particularly the insulation materials to undergo severe multi-stress. Insulation degradation will progressively lead to short-circuits which are harmful for the traction motor, vehicle safety and reliability. This paper focuses on the thermal assessment of insulation's capacitance at switching frequencies. For this, thin-film winding insulation samples were thermally aged at different temperatures and for various periods of time. Dielectric spectroscopy was applied and the capacitance information at different frequencies was extracted. The measurements were substituted to statistical analysis under three factors namely; ageing time, temperature and frequency. It is also evaluated how appropriate it is to use capacitance measurements as a means for reliable prognostic method. The statistical analysis depicts that the capacitance does not follow predictable ageing patterns, mainly because the material's dielectric properties are affected by a number of different degradation mechanisms that occur concurrently.

**Keywords** – capacitance, degradation, dielectric spectroscopy, insulation, thermal stress, traction motor

## I. INTRODUCTION

Part of an electrical machine's monitoring process is the statistical interpretation of data regarding the machine's components for purposes like predicting and preventing failure [1]-[14]. Meanwhile, electrical machines used in electric vehicles undergo a series of severe stresses due to transient state conditions [10], [15], [16]. As a consequence, the stator winding insulation material degrades and fails faster than expected, leading to inter-turn short-circuit and machine breakdown [13]-[20]. Various studies have been carried out to model and compare the behavior of insulating materials [1]-[8], and assess their properties under different stress conditions and tests [9]-[14].

Furthermore, in [1] the authors observed that polyamide-imide (PAI) insulating films exhibit changes in permittivity, loss factor and conductivity when the samples are subjected to changing temperatures. These changes were attributed to four different relaxation phenomena. Further, S. Diahm and M.-L. Locatelli analyzed the different types of relaxation phenomena [2], using broadband dielectric spectroscopy to evaluate the

thermal instability of the dielectric constant and the ageing mechanisms.

In [4] the dielectric characteristics of thermally aged PAI insulation films were studied for modeling the behavior of insulation resistance (IR). Continuing the work in [5], the authors also studied the impact of thermal degradation on the breakdown voltage of the insulation thin films. A very useful insight on the breakdown voltage behavior was also given by the authors of [3], [7], [8] and [11] justifying the direct dependence between the variation of dielectric or manufacturing parameters, the temperature and the time integral of ageing.

M. Farahani et al. attributed the changing patterns observed with the increase of the dissipation factor ( $\tan \delta$ ) and partial discharge (PD) during accelerated thermal ageing to the delamination effect [18]. In addition to that, air bubble formation and cracking caused unbalanced behavior in permittivity and loss of dielectric strength in [21]-[25]. The same authors underlined the significance of ambient conditions like humidity and erosion in such tests. This statement also appears in several other works [26]-[28]. All these aspects reflect the uncertainty of how dielectric parameters evolve with ageing. This is why since the 1980's [29]-[35], researchers in this field encounter obstacles in modeling the ageing mechanisms under different stress conditions.

In all studies involving samples subjected to stress, destructive or non-destructive, there exists the need for careful statistical analysis and implementation. Examples of similar modelling and statistically focused approaches have been carried out using simulation models, as well as analytical techniques [36]-[51]. However, it is crucial to be noted that experimental results did not always verify theoretical models with accuracy. Furthermore it is worth mentioning that, using stochastic and statistical models for prediction in [37], the authors suggested a prognostic model for reliability and lifetime assessment of the motor winding insulation. In [39] by correlating theoretical and experimental results and with the use of a random resistor-capacitor network model, under the assumption of a power law distribution, a simple formula to predict frequency-dependent ac conductivity and permittivity was proposed. Additionally, after applying multi-stress testing on stator bars, the authors of [40] observed elongation and gap spaces along the slot boundaries and underlined the fact that, aging effects of load cycling increase not only with the number

of cycles but also with the magnitude of temperature swings. Also, they noted that, in some cases, accelerated aging tests yield break-down voltage data substantially higher than those obtained from actual measurements. In [41] an online method for broadband insulation spectroscopy was proposed using signal injection in order to trend the response of impedance over time, while the authors also reported variation and unstable behavior of capacitance in some frequencies. In [42] standards and multi-stress testing processes were reviewed noting that, in many cases results from accelerated tests are difficult to interpret and model, as also noted from [52], where different behavior of resistance and capacitance was observed during experimental destructive and diagnostic testing on different stator insulations.

The authors of [42] also explained how thermal aging contributes to faster occurrence of phenomena like the loss of adhesion and delamination, layer separation, cracking, mechanical damage and abrasion at the outer surface of the insulation. Furthermore, an overview of existing simulation modeling techniques regarding thermal degradation was given in [43], while a combination of FEA and CFD tools was presented in [45] to predict the lifetime of a machine. In [46] the authors presented a model for predicting a fault's progression using the correlation of the motor's monitored signals and apply Principal Component Analysis to the datasets in order to obtain features as indicators of a pattern leading to the motor's failure.

Another approach for the study of insulation degradation and prognosis was done from the aspect of material modelling for different insulation material cases [47]-[50]. In [47] accelerated degradation of insulation material was studied offering a deeper view into the effects of degradation mechanisms like partial discharges and polarization, stating once again that results from different authors on accelerated aging are often contrasting and need statistical evaluation. An attempt for prediction of polyethylene insulation degradation was presented in [48], based on chemical properties and electrical measurements under heat aging. Additionally, cable insulation monitoring for predictive lifetime modeling was applied in [49] for thermosetting polymers, while in [50] transformer and power grid insulating materials were examined and modeled using dielectric spectroscopy and statistics. Insulation monitoring and diagnostics along with multi-stress tests for different materials and coils were studied and thoroughly investigated in [51]-[56]. Finally, [57]-[61] contributed to this field of research with knowledge regarding the dielectric properties of new insulating materials for various applications, as well as diagnosis under a series of tests.

The aim of this work is to investigate how the capacitance of thin film insulation behaves, when the insulation samples are thermally aged for different hours under elevated temperatures. The analysis was carried out for the frequency range 1-10 kHz with special focus on 1 kHz. This is because electric motors operating in electric vehicles are coupled with variable frequency inverters and controllers, the majority of which operate in the switching frequencies range. The presented results are part of an ongoing study that focuses on aspects that affect thermal degradation of thin film windings' insulation material.

## II. EXPERIMENTAL SETUP AND PROCEDURE

Firstly, a population of rectangular copper wire bars (350 mm long) coated with thin film Class H insulation have been used, with the wire's cross-sectional dimensions being 15.5 mm wide by 2.5 mm thick. The insulation coating consists of two layers, an inner layer of polyester-imide (PEI) and the outer of polyamide-imide (PAI).

Six identical ovens were set up at fixed temperatures 200°C, 215°C, 230°C, 245°C, 260°C, 275°C to degrade 180 sample bars, sorted into 6 groups of 30 each, for the time periods of 100, 200, 400, 800 and 1600 hours at each temperature. At the end of each accelerated thermal aging period six samples were removed from the oven and each sample was placed in a specially fabricated plastic case for dielectric properties to be measured. Moreover, a population of 20 new unaged samples was tested. These new samples turned out useful not only as a baseline for evaluating the degraded ones, but also because they are indicative of manufacturing defects caused by impurities or imperfections during the manufacturing process.

The dielectric properties of all samples were measured at 6 different points on each sample. The measuring points were separated 3.8 cm from each other. The measurements were performed with a custom-built electrode and the PSM1735 equipment from N4L (impedance analyzer).

In some cases, the insulation was aged to the point of destruction prohibiting measurements during some aging profiles. This can be seen in Table I where destruction of samples due to process of accelerated thermal ageing begun at 230 °C at 1600 hours and is dominantly present at 245 °C and 260 °C, while at 275 °C total loss of samples occurred after 400 hours.

TABLE I – Measurements Performed

State	Aging Period (hours)				
	100	200	400	800	1600
Unaged	120/120				
200 °C	36/36	36/36	36/36	36/36	36/36
215 °C	36/36	36/36	36/36	36/36	36/36
230 °C	36/36	36/36	36/36	36/36	13/36
245 °C	36/36	36/36	36/36	25/36	0/36
260 °C	36/36	36/36	33/36	4/36	0/36
275 °C	36/36	36/36	7/36	0/36	0/36

## III. ANALYSIS OF UNAGED SAMPLES

Fig. 1 depicts the capacitance values of all unaged samples in the frequency spectrum from 1-10 kHz and one can see the outlier values marked in red circle. The existence of such values is clearly indicative of a manufacturing defect, reflected in the minimum values of capacitance. This is of high importance since capacitance is a reflection of dielectric properties of the insulation material, in terms of being proportional to dielectric permittivity [1], [2], [40]-[42], [47]-[51]. In Table II, mean value, standard deviation and minimum values of capacitance are given for some selected frequencies from 0.5 kHz to 12 kHz.

Because of their importance, the minimum values of capacitance are also illustrated in Table II. Through Table II, it is concluded that the defects of the manufacturing process are

more intense at 520.06 Hz and 2.591 kHz. The reality of the manufacturing defects must be considered in the analysis of all measurements, since it may reflect to the low-frequency conduction contribution ( $\sigma/\epsilon_0\omega$ ) that corresponds to the imaginary part of dielectric permittivity [1], [2], [36]. It is interesting to compare these values with the ones of the samples under thermal stress, presented in the following Paragraph IV.

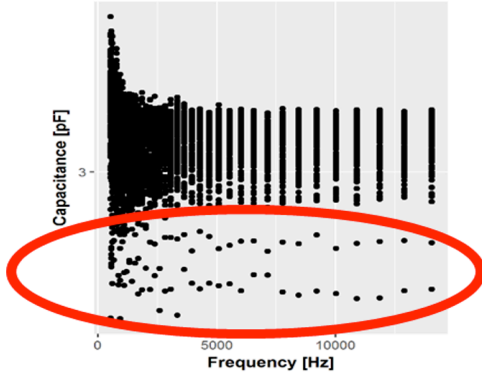


Fig. 1. Scatter plot of the unaged samples' capacitance versus frequency.

TABLE II – Capacitance Statistics of Unaged Samples

Frequency (Hz)	Mean Capacitance (pF)	Standard Deviation	Min Capacitance (pF)
520.06	27,5	4,7	10,5
1022.5	22,1	3,2	14,7
1560.3	22,7	2,8	13,4
2010.5	22,1	2,6	13,1
2590.7	22,6	2,6	10,9
3067.8	22,7	2,6	11,9
5093.8	22,7	2,5	12,1
10015	22,6	2,5	11,7
12906	22,8	2,5	11,9

#### IV. ANALYSIS OF THERMALLY DEGRADED SAMPLES

In this paragraph the samples subjected to accelerated thermal stress, as described in paragraph II, are analyzed and presented. In section A, the samples are examined in the frequency spectra range 1 kHz – 10 kHz, whereas in section B the focus is on the frequency of 1 kHz to study each ageing profile separately and to retrieve information about the distribution of capacitance at each temperature for all aging periods.

##### A. Capacitance Frequency Spectra

This section outlines the behavior of capacitance for the 180 degraded samples in the frequency spectrum. Note that Fig. 2 – Fig. 7 correspond to the aging profiles of 200°C, 215°C, 230°C, 245°C, 260°C, 275°C respectively, while letters a-e stand for 100, 200, 400, 800 and 1600 hours of thermal aging respectively. The y-axis depicts capacitance values (in logarithmic scale), while on x-axis lies the frequency.

Interestingly, in all studied cases (Figs. 2-7) it is evident that capacitance values tend to scatter as the hours of thermal stress increase. This is particularly clear if one observes the frequency spectra for thermal ageing 800 hours and 1600 hours. For 200°C and 215°C the samples present similar

behavior per group. A minor exception exists for the case of 200°C and 200 hours (Fig. 2-b), where it is clear that two measured points belong to the manufacturing tolerances group. No such points were observed in the case of 215°C and for ageing duration less than 400 hours.

The effect of temperature increase is more tangible at 230°C (Fig. 4), while during the aging process of 245°C and above, some samples experience catastrophic insulation damage due to apparently extreme thermal stress. A close inspection of those samples revealed damage such as cracking and treeing. Moreover, during aging at 230°C and 245°C, the capacitance exhibits the biggest dispersion especially for frequencies around 2.5 kHz and 10 kHz. Unlike that, at frequencies around 5 kHz a trend for smaller dispersion is noticed, which again increases after 10 kHz. This is probably because the point before catastrophic damage is reached. As a result, bubbles start to form before the cracking which cause the material's permittivity and consequently capacitance to fluctuate and, sometimes, reach very extreme values compared with values of the rest of the population.

Two more mechanisms that contribute to the loss of dielectric properties of our samples are the following: drying and weight loss as a consequence of the heating degradation. This behavior will also be focused on and discussed while analyzing the distribution of capacitance in the next paragraph for a specific frequency. Considering the manufacturing defects detected in the unaged samples, the fact that total decay of samples occurs in those temperatures, is an indication that heat shock tests and endurance test should be done at higher temperatures and for longer periods while temperature should be increased slowly in order to obtain more accurate results during test measurements.

Moreover, in Fig. 6, one can recognize the high number of samples that failed once they reach an age of up to 800 hours at 260°C. Even more samples were lost at 275°C, where no samples survive longer than 400 hours (Fig. 7). The last three cases of aging, given in Fig. 7, are also characterized by huge dispersion, but no proper conclusion can be conducted, because not enough samples survived. There exists a large dispersion of capacitance at around 2.5 kHz, like in all other cases, while a surprising reduction of it occurs at 5 kHz for 200 hours of aging to be risen again at 800 hours with outlier values around 7 kHz and 11 kHz.

At the onset of short circuits in rotating machines, the temperatures can increase very quickly [17]-[22] & [27]-[32]. Prior to the catastrophic breakdown of the insulating material, multiple other mechanisms initiate and take place, contributing to the degradation. This includes partial discharges, intrinsic charges and interfacial polarization [18]-[25] & [51]-[54]. When a coating consists of two layers of different materials, e.g. in thin film insulation cases similar to the one presented in this paper (inner PEI + outer PAI), the phenomena described above are more probable. In addition, the effect on the dielectric properties of the insulation and the evolution of degradation cannot be easily predicted due to the combined effect on the individual polymer dielectrics [52]. This provides with an explanation of the observed variability of the capacitance measurements.

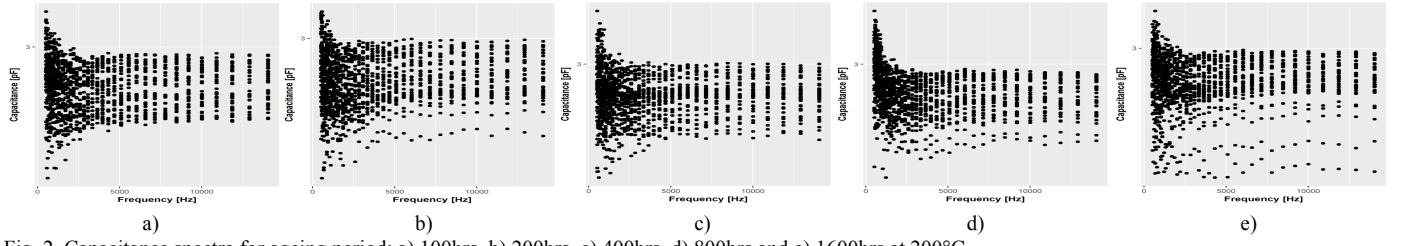


Fig. 2. Capacitance spectra for ageing period: a) 100hrs, b) 200hrs, c) 400hrs, d) 800hrs and e) 1600hrs at 200°C.

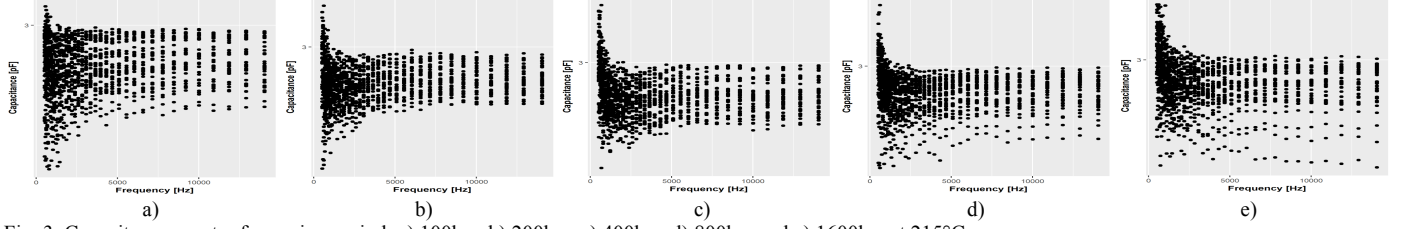


Fig. 3. Capacitance spectra for ageing period: a) 100hrs, b) 200hrs, c) 400hrs, d) 800hrs and e) 1600hrs at 215°C.

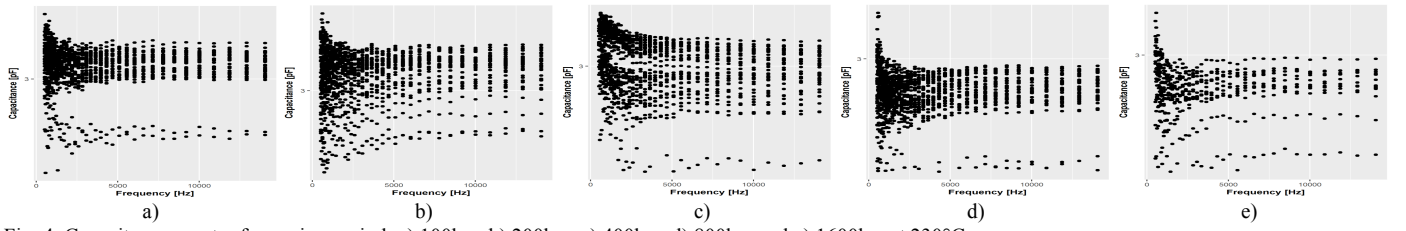


Fig. 4. Capacitance spectra for ageing period: a) 100hrs, b) 200hrs, c) 400hrs, d) 800hrs and e) 1600hrs at 230°C.

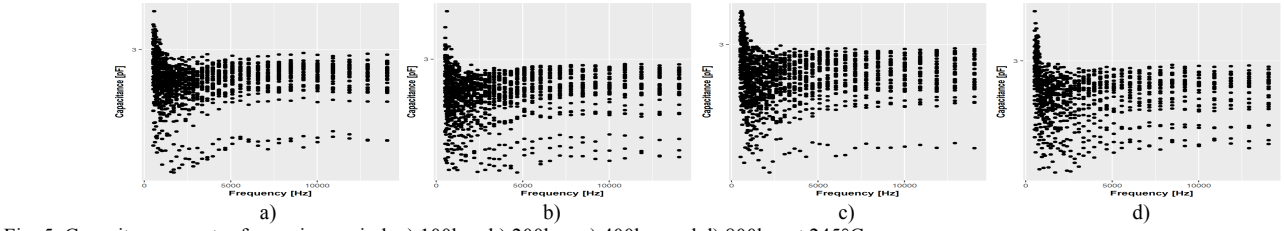


Fig. 5. Capacitance spectra for ageing period: a) 100hrs, b) 200hrs, c) 400hrs and d) 800hrs at 245°C.

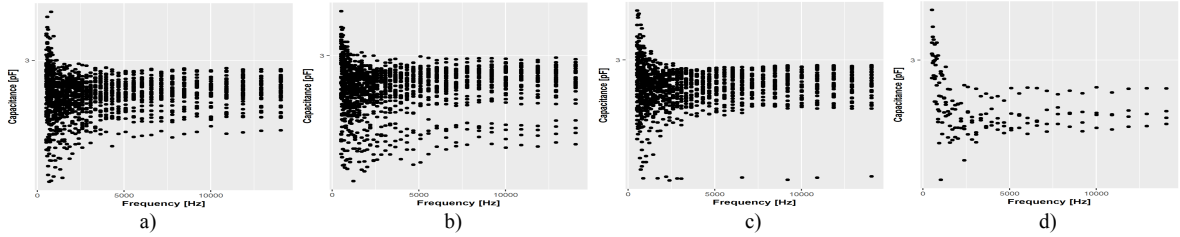


Fig. 6. Capacitance spectra for ageing period: a) 100hrs, b) 200hrs, c) 400hrs and d) 800hrs at 260°C.

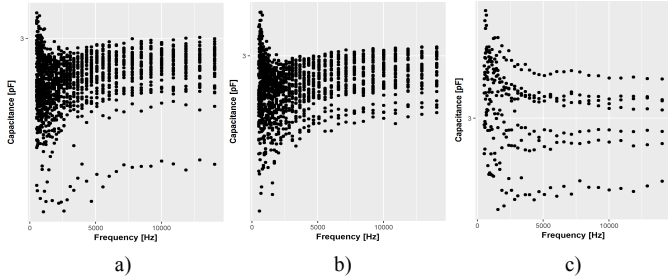


Fig. 7. Capacitance spectra for ageing period: a) 100hrs, b) 200hrs and c) 400hrs at 275°C.

The results are also explained by the fact that relative permittivity and loss tangent of PAI (measuring surface is PAI in our case) undergo a series of relaxation phenomena [1], [2] and the breakdown mechanisms' nature changes after some temperature critical limit (e.g. from thermal to electromechanical due to melting) [1], [2], [36], [47]-[51]. Finally, local delamination might be responsible for the fluctuation of capacitance values as well.

### B. Capacitance Statistics at 1kHz

In this paragraph each aging profile is studied separately at the frequency of 1 kHz. Also, the distributions of capacitance are presented and analysed at this frequency. The average

capacitance of every sample group and the probability density functions are presented to show how capacitance evolves during thermal aging.

Tables III-VIII illustrate the statistical information extracted from the measurements of all thermally degraded samples. For every temperature, the mean and minimum value of capacitance are given as well as the standard deviation for all degradation periods. Moreover, the normal distribution has been created for all studied cases and the results are shown in Fig. 8.

For the sample group degraded at 200°C it can be seen from Fig. 8-a that, the increase of aging time shifts the average capacitance slightly to the left. However this is not monotonic as one can see from the capacitance value at 800hrs. This is also observed in Table III. Compared to the 22.1 pF of the unaged samples, the average capacitance is lower but with higher standard deviation. This implies that capacitance values spread and scatter during thermal stress for long time periods.

TABLE III – Capacitance Statistics for 1 kHz, 200 °C

Ageing (hours)	Mean Capacitance (pF)	Standard Deviation	Min Capacitance (pF)
100	14.5	4.3	5.9
200	13.7	3.6	6.5
400	13.1	4.2	5.9
800	14.8	3.1	6.6
1600	12.5	3.4	6.1

Furthermore, concerning the samples degraded at 215°C, it can be seen from Table IV and Fig. 8-b that, while the aging time increases, the average capacitance is shifted to the right with respect to the first aging period of 100 hours (red colour). Despite the higher temperature, the values of capacitance are found to be higher than the values of the previous aging profile (Table III), except for the case of aging 200 hours where the capacitance is almost the same for the two cases (13.7pF and 13.6pF).

This capacitance increase is also met during aging at 230°C for the first 400 hours, but during the last stages of this profile it suddenly drops again. This happens from 800 hours and on (Table V) and values drop lower than the corresponding values at 200°C and 215°C. After 400 hours at 230°C a significant increase in the standard deviation is observed, which confirms the scattering of values due to thermal stress and manufacturing defect. Specifically, the standard deviation is 7.8 for the highest value of average capacitance (24.7 pF) in this degradation

profile. Another interesting observation derived from Fig. 8-c, is that the average capacitance value at 1600 hours, is almost identical to the average value of 1600 hours at 200°C, while the scattering surprisingly decreases (standard deviation 2.9 compared to 3.4 at 200°C and 5.4 at 215°C).

TABLE IV – Capacitance Statistics for 1 kHz, 215 °C

Ageing (hours)	Mean Capacitance (pF)	Standard Deviation	Min Capacitance (pF)
100	11.8	3.0	6.3
200	13.6	2.6	7.0
400	14.0	3.0	9.2
800	15.6	3.0	8.0
1600	17.9	5.4	11.4

TABLE V – Capacitance Statistics for 1 kHz, 230 °C

Ageing (hours)	Mean Capacitance (pF)	Standard Deviation	Min Capacitance (pF)
100	23.4	3.7	14.1
200	22.5	3.1	13.4
400	24.7	7.8	10.3
800	13.0	2.7	5.2
1600	13.1	2.9	7.9

For this aging profile of 245°C no samples survived at the age of 1600 hours. Interestingly, the capacitance recurs to values similar to those of the first aging profiles (values around 13 pF) and this can be seen in Table VI and Fig. 8-d. The normal distribution curves consolidate around almost the same average value with no particular scattering of the values. Standard deviation is between 3.0 and 3.5 for all periods of aging, in contrast with all the others profiles where scattering is observed with increase of the aging period.

Thermal degradation at 260°C is a case, where samples did not survive for more than 800 hours. Although capacitance has the tendency to increase during 100 hours and 800 hours, it drops during 200 hours and 400 hours (Table VII). Standard deviation increases with very small steps giving no indication of a special scattering, whereas this changes at 800 hours of aging. However statistics are unreliable in this case since only 4 out of 36 expected points were measured (Table I).

For aging at 275°C, some samples are lost at 400 hours while none survives after that point. Surprisingly, the capacitance follows an increasing trend (Table VIII). The average capacitance is 12.9pF during 100 hours with 3.2 standard deviation, increases to 15.8pF during 200 hours with

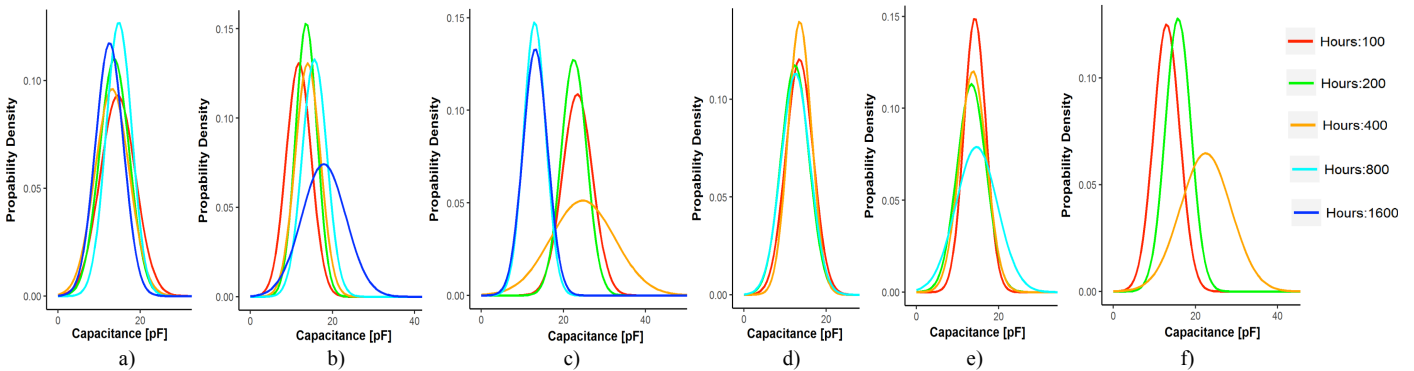


Fig. 8. Normal distribution of capacitance at 1 kHz for all aging periods at: a) 200 °C, b) 215 °C, c) 230 °C, d) 245 °C, e) 260 °C and f) 275 °C.



3.1 standard deviation, while suddenly reaches 22.5pF after 400 hours with almost double standard deviation (6.2). However, the last case (400 hours) is statistically unreliable since only 7 out of 36 measurements could be performed.

TABLE VI – Capacitance Statistics for 1 kHz, 245 °C

Ageing (hours)	Mean Capacitance (pF)	Standard Deviation	Min Capacitance (pF)
100	13.5	3.3	5.6
200	12.4	3.4	5.3
400	13.6	3.0	6.9
800	12.5	3.5	5.3

TABLE VII – Capacitance Statistics for 1 kHz, 260 °C

Ageing (hours)	Mean Capacitance (pF)	Standard Deviation	Min Capacitance (pF)
100	14.2	2.7	9.0
200	13.4	3.5	6.7
400	13.8	3.3	6.2
800	14.6	5.0	7.4

TABLE VIII – Capacitance Statistics for 1 kHz, 275 °C

Ageing (hours)	Mean Capacitance (pF)	Standard Deviation	Min Capacitance (pF)
100	12.9	3.2	5.1
200	15.8	3.1	8.7
400	22.5	6.2	14.3

Finally, it is to be noted that the total capacitance of a motor's winding is strongly influenced by the local weak capacitance points. After all, those weak points will probably be the ones where the short circuit will develop. So, Fig. 9 illustrates the minimum capacitance behavior for all thermal stresses versus the degradation time.

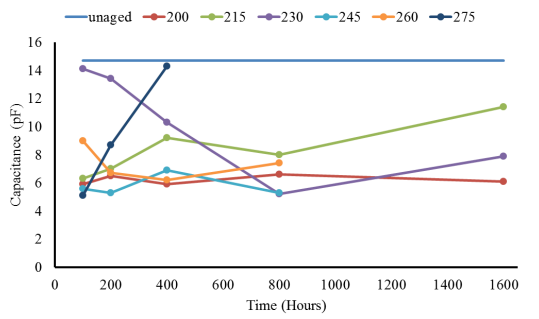


Fig. 9. Measured minimum capacitance values over time for all cases.

It seems that for low degradation stress conditions, the minimum capacitance values do not significantly vary. However an increase is observed for 1600 hours at 215°C. On the other hand at 230°C and 260°C a general decrease is observed. Despite that, a monotonic increase is observed at 275°C. The results indicate the strong impact of the manufacturing imperfections, which in addition to the degradation, may cause significant non-linear capacitance response.

## V. CONCLUSION AND FUTURE WORK

In this paper the capacitance spectra of traction motor winding insulation material samples, substituted to various

thermal stresses were studied. The results indicate that special care should be given when using the capacitance as a diagnostic mean to assess the winding's health. This is due to the strong non-monotonic relation of the capacitance to the thermal stress as well as the manufacturing imperfections impact. Analysis of the samples' capacitance at 1 kHz has shown that the minimum capacitance can significantly vary between different ageing profiles without following a distinct pattern. Our ongoing and future work focuses on the relation of the capacitance to the breakdown characteristics of the insulation trying to extract a relating mechanism between the capacitance changes and the drop of the thin film insulation resistance.

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