Lifetime of Machines Undergoing Thermal Cycling Stress

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***Abstract*— In modern applications, electrical machines are facing increasing thermal cycling and resulting mechanical stress due to harsh variable loading, however there is little information in literature that shows the impact of severe cycling conditions on insulation health. An accelerated aging test is performed in this paper on seven motor stator samples that are operated under various thermal cycling conditions at high temperature. It is shown that there is a severe but predictable lifetime decrease with increased thermal cycling stress. The impact of this must be considered at the design stage for applications requiring high temperature cycling to ensure fulfillment of the required lifetime.**

Keywords—Insulation, Condition monitoring, Electrical machines, reliability

I. INTRODUCTION

Insulation systems of electrical machines are subject to multiple stresses under operation during machines' lifetime, including thermal, electrical, environmental and mechanical stresses. Electrical damage to insulation has been studied extensively, especially in medium and high voltage machines where partial discharge (PD) is a significant contributor to machines' failures. Similarly, progressive degradation due to thermal effects is well known and extensively researched. Early research [1] recognized that insulation ageing can be modelled considering the degradation as a chemical reaction and therefore modelled using the Arrhenius equation:

$$L = L_0 e^{\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)} \quad (1)$$

where the predicted lifetime L of the insulation is exponentially decreasing with temperature T, L_0 being the reference lifetime at the temperature rating class T_0. E_a and R are the activation energy and gas constant, respectively, and can be considered as fitting parameters.

The Arrhenius model typically provides very accurate prediction of insulation lifetime when machines are operated at constant temperature T. Many machines, however, operate in applications with continuously varying conditions with complex duty cycles resulting in variable temperature profiles. It is well known that thermal cycling causes expansion and contractions of materials and that different materials have different coefficients of thermal expansions (CTE). Mechanical stress will result at the interfaces between materials with different CTE. This is the case in machine insulation systems which often have several interfaces between the copper windings conductors and stator iron including wire insulation, winding impregnation, phase-to-phase and ground-wall insulation materials.

Extensive evidence of the damaging effects of thermal cycling on electrical machines has been published. However, these studies have almost exclusively focused on large and typically high-voltage (>10kV) machines e.g. generators in hydropower plants [2]. It is concluded that a number of ageing processes are a consequence of thermal cycling including loss of adhesion, delamination between layers of insulation, abrasion at the surface, circumferential cracking of the insulation and damage due to distortion. International standards have recognized the importance of qualification of insulation subject to cycling stress, e.g. IEEE Std-1310-1996 provides guidelines for testing form-wound stator bars and coils for large generators subject to thermal cycling [3].

Relatively little research has been conducted on the effects of thermal cycling in smaller, typically low-voltage machines. Some studies have claimed that due to short winding lengths in smaller machines, thermal cycling produces relatively lower stress that might be too small to cause significant damage [4]. Due to the increasing use of low-voltage electric machines in high reliability applications with extremely variable duty cycles e.g. in electric vehicle traction and aircraft propulsion/actuation, interest has been shown in investigating insulation damage resulting from thermal cycling on smaller machines. A numerical method for predicting the lifetime of machines under variable temperature has been proposed in [5]. However, no explicit consideration has been given to the effect of thermo-mechanical induced damage with the risk of over-estimating the predicted machine lifetime. In [6]-[7] extensive numerical analyses are used to evaluate the fatigue of insulation in traction motors due to thermal and thermal induced mechanical stress, however, no experimental evidence is provided. Some limited experimental evidence of significant lifetime reduction due to thermal cycling effect is given in [8]. This paper presents data gathered on 11 low voltage machines conducted during an accelerated lifetime test. The aim is to evaluate the impact of thermal cycling on machine lifetime and evaluate lifetime modelling tools for machines operating under thermal cycling conditions.

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II. LIFETIME MODEL UNDER THERMAL CYCLING CONDITIONS

The Arrhenius eq. (1) has been applied to evaluate the lifetime of transformers [9] and electrical machines [5] in variable temperature conditions. In this case, the temperature $T(t)$ in (1) becomes a function of time t. The rate of change of remaining insulation lifetime in a short interval of time dt is given by:

$$\frac{dt}{L(T(t))} \times 100\% \tag{2}$$

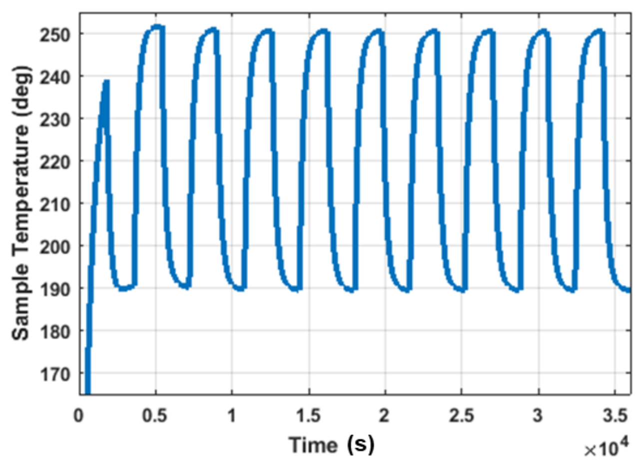
Therefore, the cumulative percent wear in the time interval $[t_1, t_2]$ is given by:

$$100\% \int_{t_1}^{t_2} \frac{dt}{L(t)}\ . \tag{3}$$

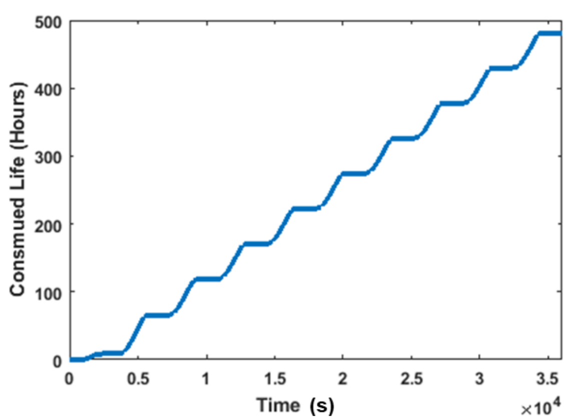
The cumulative loss of lifetime LoL at time t is given by:

$$LoL(t) = \int_0^t \frac{1}{L_0 e^{B\left(\frac{1}{T(\tau)} - \frac{1}{T_0}\right)}}\, d\tau \tag{4}$$

An illustration of the procedure is shown in Fig. 1, where 10 hours of cycling operation at elevated temperature of a class H insulation machine result in a cumulative consumed life of approximately 500 hours.



(a)



(b)

Fig. 1 Machine temperature (a) and cumulative consumed lifetime (b)

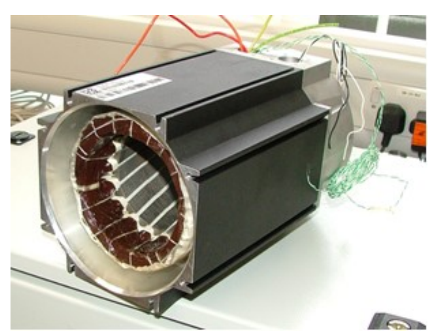
The paper experimentally investigates the validity of the lifetime calculation model (2)-(4) when applied to thermal cycling conditions, and proposes a novel lifetime estimation methodology that explicitly takes into account thermo-mechanical stress due to cycling.

III. EXPERIMENTAL METHODOLOGY

Eleven 2.8kW 380V 3 phase 3000RPM servo drive motors, pictured in Fig. 2, driven by an M700 Unidrive inverter were used in the tests. These were selected as they are a good representation of a small size low voltage machine. The machine rotors have been removed in order to eliminate other non insulation related failure modes. High ambient temperature is maintained by placing the machine samples inside a temperature controlled oven. The thermal cycling is provided by increasing the machine current through inverter control, with the inverter drive applying sine wave voltage to stator winding with the amplitude and duty ratio of the voltage excitation controlled to achieve the required T_{peak} and **ΔT.** To represent a variety of operating conditions, four thermal cycling conditions were selected and seven samples were tested under cycling conditions with temperature cycles of $\Delta T = 20°, 40°, 60°, 80°\ C$. The accelerated aging was carried out with two peak temperatures of 240° and 250°C. All samples were tested from new until failure which resulted in all samples in phase-phase short circuits.

In addition, four samples were tested at constant temperatures of 205°, 215°, 230°, 250° to provide a reference for extracting the parameters of the Arrenhius model (1). Further details fot these tests are reported in [11] .

The machines temperature was monitored continuously using two K-type thermocouples placed in the middle of the winding and in the end windings, respectively. Temperatures are logged using the PICO TC-08 module over the lifetime of the machines. The mid-winding temperature was selected as the indicator of sample temperature. Thermal cycling conditions of each of the seven samples are summarised in Table 1. In practice, due to the lack of closed-loop temperature control, the peak temperature and temperature cycle will never be exactly as specified in Table 1. To classify the samples more accurately, a histogram of measured temperature over time is plotted as demonstrated in Fig. 3 for Sample 7. The difference between the peaks of the histogram is the true temperature cycle that the sample underwent over its lifetime. For sample 7 the actual ΔT was measured as 76.8°C and peak temperature of 235.1°C.



(a)

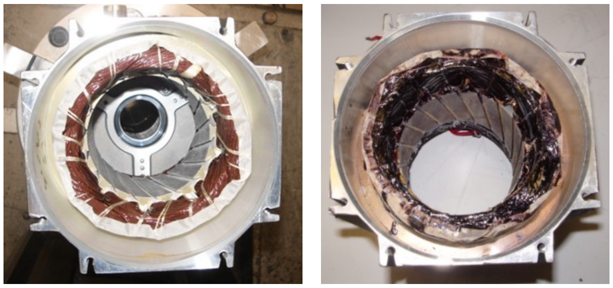


Fig. 2 Machine sample (a), prior to ageing (b) and after failure (c)

Table 1

		Peak Temperature	
		250	240
Temperature Cycle	80 ΔT	Sample 4	Sample 7
	60 ΔT	Sample 2	Sample 6
	40 ΔT	Sample 3	Sample 5
	20 ΔT	Sample 1	

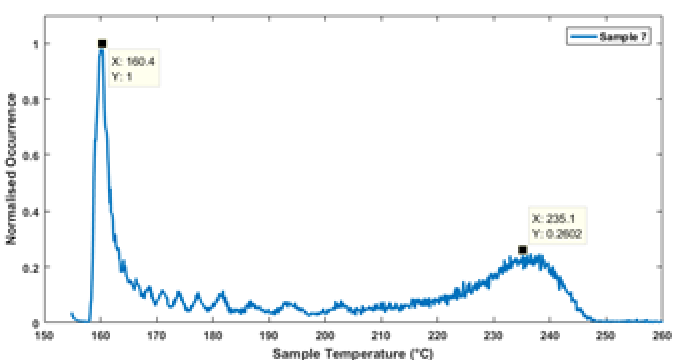


Fig. 3 Histogram of temperature distribution for sample 7 during its lifetime

IV. Experimental Results

The results of the four samples at constant temperature are summarized in Fig. 4 showing an exponential decrease (linear in logarithmic scale) of sample life with temperature. It can be concluded that the Arrhenius eq. (1) is valid for the analyzed samples. From the results of Fig. 4, the constants in (1) can be identified as:

$$L_0 = 3835.2\ [hrs]$$
$$T_0 = (215 + 273)[K]$$
$$B = 13497\ [K]$$

The results of the thermal cycling experiments are summarised in Fig. 5 for samples 2 to 7. To evaluate the thermal loss of lifetime of all samples, the temperature data was integrated using eq. (3). The results are illustrated in Fig. 4 with graphs showing the percent cumulative thermal loss of life. During operation, experiments on some of the samples were paused temporarily. This is most evident in Samples 3 and 5. It can be seen that when Sample 5 is operated at a low temperature there is little insulation life consumed.

With the exception of sample 1, the results, summarised in Table 2, show that thermal ageing based on (3) only accounts for a fraction of the total expected life of each sample. The results, clearly illustrate that thermal ageing alone, as modelled by (1)-(3), cannot explain the reduction of lifetime when machines are subject to thermo-mechanical stress resulting from cycling operating conditions. Results are further processed in Figs. 6 and 7, where the percentage of calculated remaining and consumed lifetime due to temperature cycling are shown as function of ΔT. A linear relationship can be observed between thermal cycling and consumed lifetime, excluding the anomalous Sample 1 point. Further investigations are required to explain the behaviour of Sample 1. Nevertheless, the trend is clear where the fit line goes through near 100% lifetime when there is no thermal cycling, and lifetime sharply decreasing with increased thermal cycling.

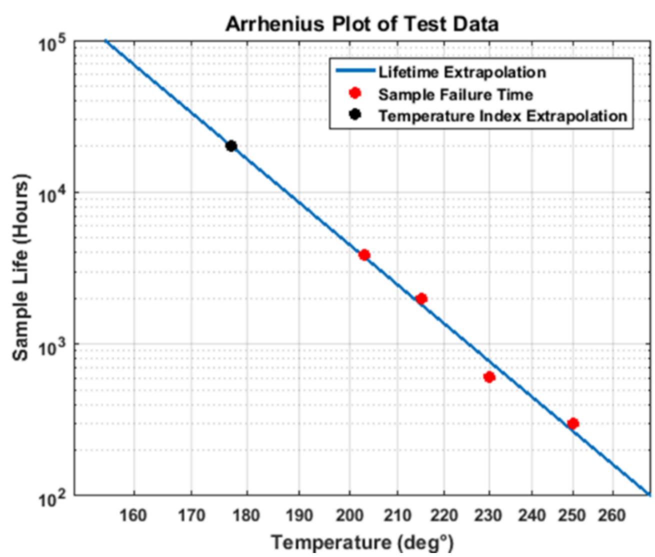


Fig. 4: Lifetime as function of temperature for 4 samples at constant temperature

Table II: Samples and test conditions

Sample	Peak Temp. (°C)	Cycle ΔT (°C)	Loss of life due to Thermal aging (%)	Loss of life due to thermal cycling (%)
1	250	20	150.3	0
3	250	40	45.6	55.4
2	250	60	34.3	63.7
4	250	80	13.2	86.8
5	240	40	51.5	48.5
6	240	60	30.8	69.2
7	240	80	9.6	90.4

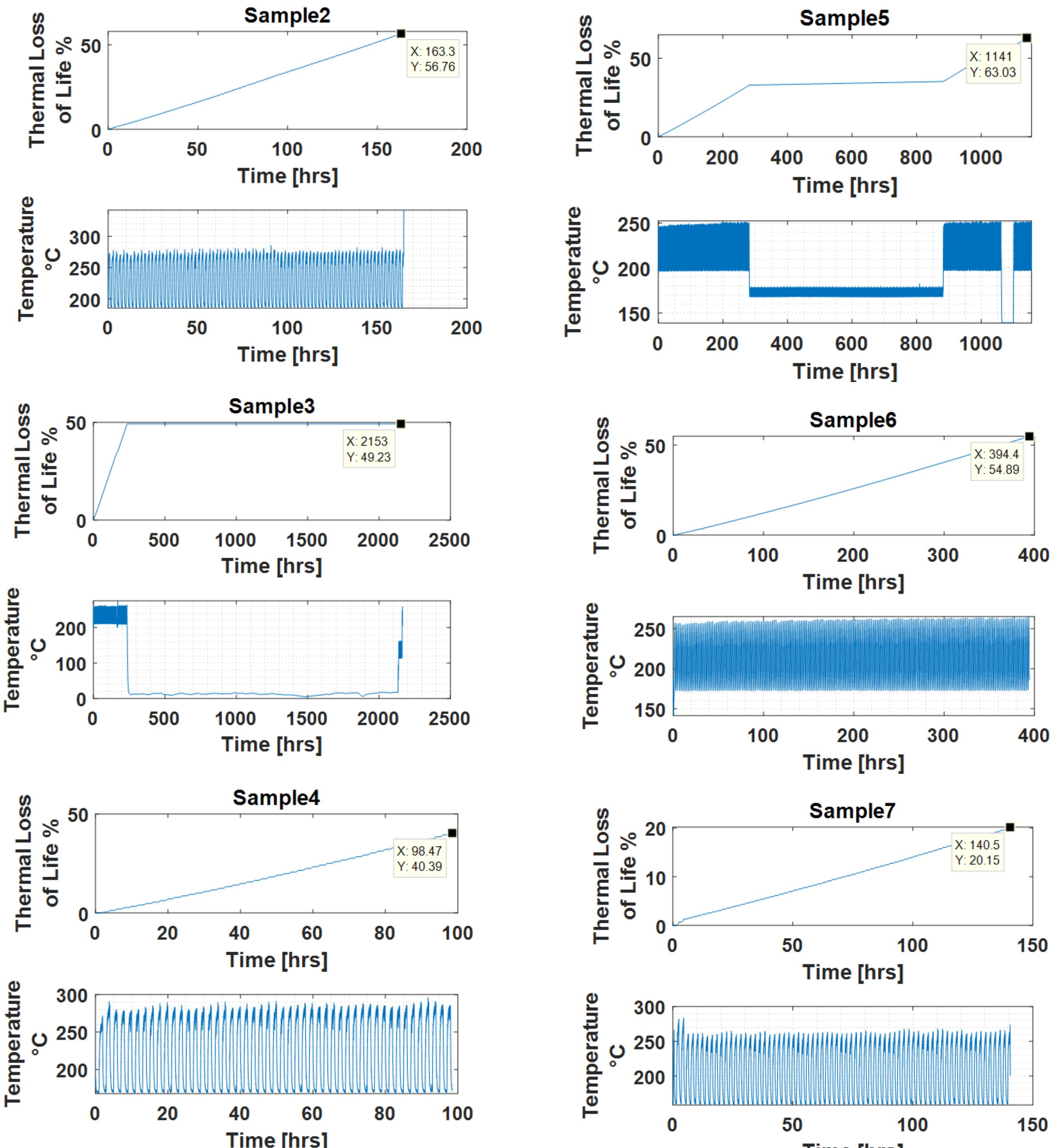


Fig. 5 Thermal cycling experimental results for Samples 2 to 7: samples' temperatures and thermal loss of life

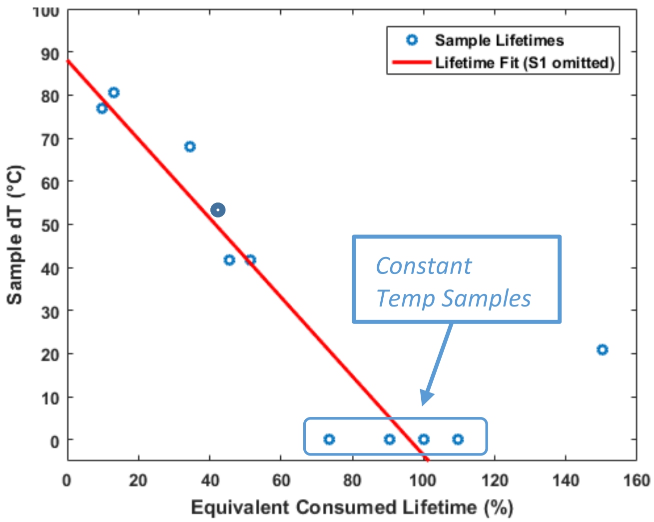


Fig. 6 Consumed lifetime at the time of failure as function of ΔT

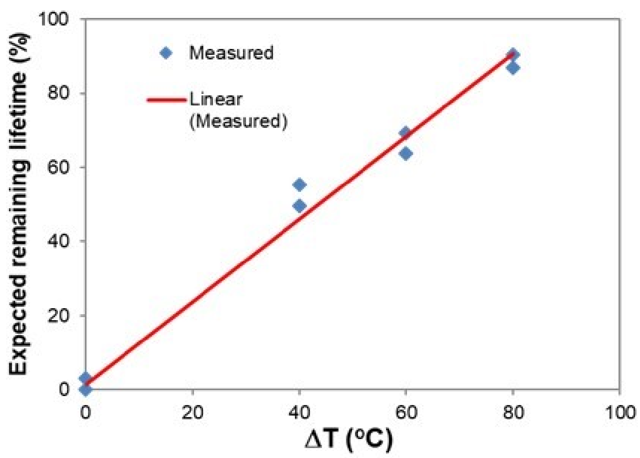


Fig. 7 Expected remaining lifetime at the time of failure as function of ΔT

Since extrapolation of the linear trend would imply that with thermal cycles greater than 90°C the machine will fail almost instantly, a linear fit is likely inapplicable at these extreme conditions. Results presented here are extremely important for machine manufacturers and users, as it is demonstrated that lifetime cannot be guaranteed based on temperature rating alone but is affected by temperature cycling which is dependent on applications.

V. Lifetime Model with Thermal Cycling

In order to provide a tool for quantifying machines' life in cycling condition a novel lifetime model is proposed. The method is based on a combination of the thermal ageing model (1)-(4) and the application of the Miner's rule through cycle counting methodology which is commonly used in the analysis of fatigue in materials and in reliability analyses of power electronics devices [10].

Miner's rule, assumes that the accumulation of damage produced by mechanical stress in a structure is linear. This means that when a material undergoes stress cycles with different stress levels, the damage caused by each cycle is linearly additive, independent on the order of each stress cycle. Let's assume that for a specific material the number of cycles to failure at the i-th stress level, is N_i. If the material undergoes a number of cycles n_i at the stress i-th level, then the ratio n_i/N_i is the cumulative damage fraction consumed by the i-th stress level. When the sum of damage fractions across all stress levels, given by:

$$\sum_i \frac{n_i}{N_i} \tag{5}$$

reaches 1, the sample reaches its end of life due to mechanical stress.

In a machine insulation system undergoing thermal cycling, the stress is caused by both thermally induced chemical damage and thermally induced mechanical stress due to repeated contraction and expansion cycles, which likely lead to micro-damages, cracks and delamination. Assuming that the chemical and mechanical stress are cumulative, and assuming validity of Miner's rule, the loss of life at time t of an insulation system is given by:

$$\begin{aligned}&\mathrm{LoL\%}\\&= 100\int \frac{1}{L_0 e^{B\left(\frac{1}{T(t)}-\frac{1}{T_0}\right)}}dt + \sum_{i,j}\frac{N_{cycles}\left(\Delta T_i, T_{peak_j}\right)}{N_{i,j}}\end{aligned} \tag{6}$$

The first term of (6) uses the Arrhenius eq. to describe the thermally induced chemical degradation as described in section II. The second term of (6) represents the thermally induced mechanical loss of life as expressed by Miners's rule, where $N_{i,j}$ is the number of cycles with ΔT_i temperature swing and T_{peak_j} peak temperature that results in additional loss of life due to thermally induced mechanical cyclic stress. The number of cycles to failure $N_{i,j}$ are determined based on experimental data. The procedure for estimating loss of lifetime can then be summarized as:

1. Determine ΔT_i and T_{peak_j} from the temperature history data using a counting algorithm such as the "rainflow counting" method [10] with i=1,2, …N, j=1, 2, …K
2. For a given (ΔT_i and T_{peak_j}), determine $N_{i,j}$ based on measured experimental lifetime data with variations of winding temperature swing and peak temperature
3. Compute the loss of lifetime according to the model

A 2D look-up table representing N_{ij} as a function of ΔT_i and T_{peak_j} can be used to determine $N_{i,j}$ in the lifetime model. Such a table for the experimental data collected in this work is reported in Table III. In the table, $T_{th,ij}$ represents the loss of life due to thermal effects only, as calculated by integration of the Arrenhius eq. The remaining fraction of life $1 - T_{th,ij}$ is attributed to the mechanical stress. Since under the proposed linear accumulation assumptions:

$$1 - T_{th,ij} = \frac{n_{ij}}{N_{ij}} \tag{7}$$

For the proposed accelerated life tests on seven samples, the number of cycles to failure n_{ij} are reported in Fig. 7. From these data and using (7), N_{ij} can be calculated as:

$$N_{ij} = \frac{n_{ij}}{1 - T_{th,ij}} \quad (8)$$

Table III: Samples and parameters of the lifetime model

Sample	Peak Temp°C	ΔT °C	$T_{th,ij}$(%)	1-$T_{th,ij}$	n_{ij} (cycles)	$N_{i,j}$
0	230	0	100%	0	0	NA
1	250	20	78%	0.22	298	1355
3	250	40	57%	0.43	119	277
2	250	60	49%	0.51	73	143
4	250	80	40%	0.60	51	85
5	240	40	63%	0.37	230	621
6	240	60	55%	0.45	197	438
7	240	80	20%	0.80	71	89

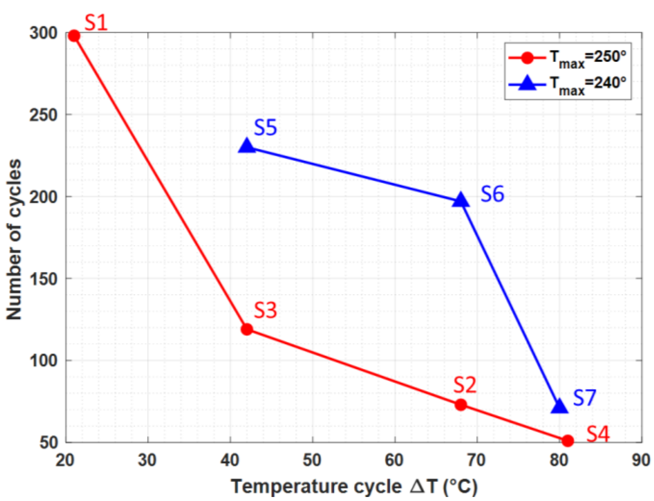


Fig. 8. Number of cycle to failure for the 7 samples as a function of temperature cycling and maximum temperature.

VI. Conclusion

Accelerated aging has been performed on machine stator samples using temperature and thermal cycling as accelerating factors. Clear evidence shows that considering thermal ageing alone significantly underestimates the damage to insulation when thermo-mechanical induced stress is present. Thermal cycling has been shown to be a significant accelerating factor in machines degradation. In applications that have extreme temperature cycles, the lifetime needs to be carefully evaluated taking temperature variations into account. To facilitate these reliability analyse, a novel methodology for evaluating lifetime under variable cycling condition is provided. Further experimental tests are required to validate the proposed methodology under variable cycling conditions.

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