Thermal Aging Investigation of Random Wound Compressed Stator Windings

M C Kulan*, N J Baker*

**Newcastle University, School of Engineering, Newcastle Upon Tyne, UK, NE1 7RU, m.c.kulan@ncl.ac.uk*

Keywords: Accelerated life tests, coil pressing, permanent magnet machine, thermal aging, thermal modelling

Abstract

Compression of windings is known to give thermal and performance benefits, but may also cause insulation failure. The aim in this paper is to investigate how stator winding insulation system is influenced by on-tooth coil pressing. Therefore, compressed stator windings have been aged by exposing them to high temperatures. Winding insulation resistance is monitored during this process to experimentally validate whether compressed coils are healthy in terms of electrical insulation. In this case, a single stress (i.e. temperature) model is used to predict the reliability of the compressed coils. Accelerated life tests are also conducted to inspect the life expectancy and thermal endurance of the compressed stator coils. The employed statistical model demonstrates that on-tooth coil pressing reduce the life expectancy dramatically due to reduced turn to ground wall insulation dielectric strength.

1 Introduction

The reliability of coil pressing is not clear in terms of stator winding electrical integrity. Mechanical deformation on magnet wire enamel and slot insulation system might result in reduced life expectancy in the compressed stator windings. Therefore, electrical machine designers must ensure that the proposed technique does not deteriorate electrical durability of stator windings and their insulation system.

There are two principal winding insulation systems in rotating machines: turn to turn insulation and ground wall insulation. Mechanical and thermal stresses due to magnetically induced vibration and I^2R losses in windings might cause in-service failure because of turn to turn short and/or ground wall short between the conductors and the grounded stator core [1]. Since compression of stator windings can lead to plastic deformation on magnet wires as discussed in [2], the life expectancy of compressed windings might be affected from the compression process. Therefore, thermal aging tests (i.e. single stress aging model) of compressed windings have been carried out to investigate if there is a rapid insulation degradation in stator windings in comparison to conventional random wound coils.

The operating temperature of a winding causes thermal stress due to copper losses and core losses. The expected life of the insulation will be shorter when machine is run at over operating temperature. For this reason, the aging process can be sped up to obtain a life data in a much shorter time if accelerated aging tests are performed [1].

The Arrhenius life–stress model is one of the most common life-stress relationship utilised in accelerated life testing when acceleration variable is temperature [1, 3]. By choosing at least two over operating temperatures, a set of compressed coils which are almost identical in terms of applied pressure, number of turns and insulation system are aged in an environmental chamber operating at up to 180°C. During the aging tests, off-line stator winding tests including insulation resistance (IR), high potential (HiPot) and high voltage surge tests have been conducted using 'Static Motor Analyser – Baker Instrument' to record failure time of each particular winding sample by testing coils periodically as depicted in Figure 1.

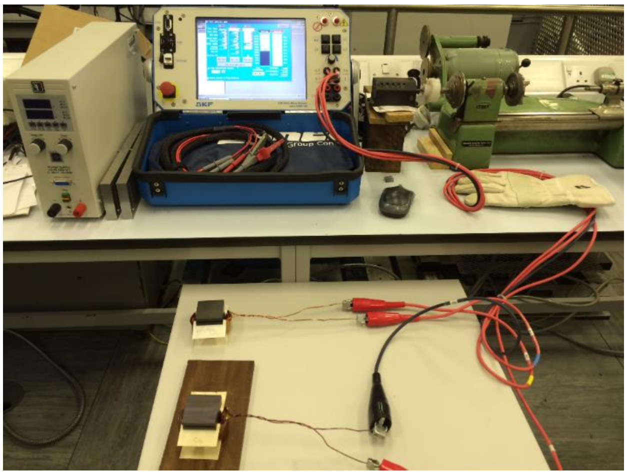


Figure 1: Static motor analyser – Baker Instrument

2 On-Tooth Compressed Coils for HEVs

On-tooth coil pressing in designs with a tooth tip necessitates stator segmentation. In the segmented machines, the stator consists of a multiple number of segmented pieces. Each piece is separately wound and the wound pieces are assembled together to form the machine stator [4].

In order to find a realistic tooth dimensions for coil pressing, a permanent magnet (PM) integrated starter generator (ISG) for hybrid electric vehicles (HEVs) has been employed. It is a 22 kW, 21 slot-16 pole V-shape PM machine for a crankshaft mounted ISG as depicted in Figure 2. The machine consists of segmented single tooth windings with a number of turns: 91. The stator windings are of thermal class of 200 (°C) and the conductor diameter is 1.25 mm. Grade 2 magnet wires with polyester-imide coating are utilised for the proposed machine.

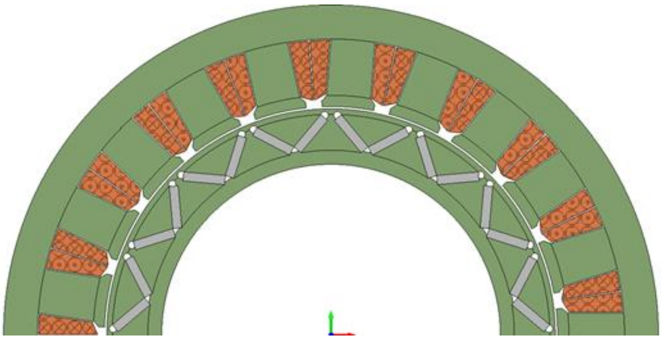
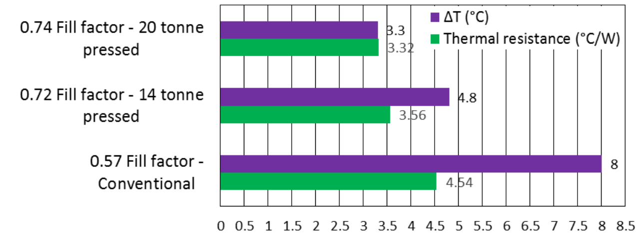


Figure 2: 21 slot – 16 pole buried V-shape PM ISG

2.1 The Effect of Applied Pressure on the Equivalent Slot Thermal Resistance

The random wound ISG coils have been compressed at 14 and 20 tonnes. Both steady state thermal tests and short time transient thermal tests have been conducted as proposed in [5, 6]. Slot thermal resistance of the ISG coils is determined by matching the experimental transient thermal results to first order RC thermal circuit model of the coils. It is shown that the higher the applied pressure, the smaller the thermal resistance between the winding and tooth. This leads to a lower temperature difference between the winding and tooth as shown in Figure 3. Thus, it is explicit that the thermal performance of the compressed windings is significantly better than random wound single tooth windings, yet the insulation system (i.e. magnet wire enamel and 0.25 mm thick Nomex 410 slot liners) damage on the compressed coils is not clear after the compression of the coils by means of a hydraulic press.



	0.57 Fill factor - Conventional	0.72 Fill factor - 14 tonne pressed	0.74 Fill factor - 20 tonne pressed
ΔT (°C)	8	4.8	3.3
Thermal resistance (°C/W)	4.54	3.56	3.32

Figure 3: The effect of applied pressure on the slot thermal resistance and winding to wall temperature difference

A 0.72 slot fill factor has been achieved experimentally by compression of the windings at 14 tonnes. From a macroscopic point of view, there was no insulation damage on the compressed windings. The lateral surfaces of the winding, however, flatten when a high pressure is applied as given in Figure 4.

The compressed coil specimen at 0.72 slot fill factor was cut into two pieces to microscopically investigate the deformation on the magnet wires as shown in Figure 4 (iii). The cross-sectional view indicates that the magnet wires are packed in a smaller volume in a quasi-hexagonal manner. It is anticipated that the thermal contact conductance between the compressed magnet wires increases due to the reduced air voids between the wires. Also, a significant plastic deformation occurs in the compressed winding segments as shown in Figure 4.

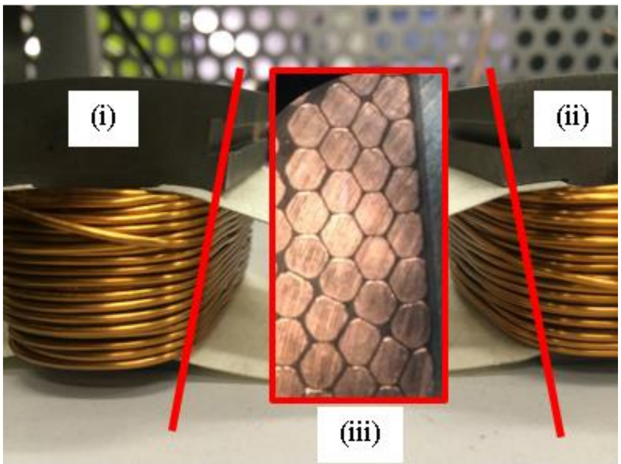


Figure 4: (i) Compressed coil at 0.72 fill factor, (ii) random wound coil at 0.57 fill factor, (iii) cross-sectional view of the compressed coil

After obtaining slot thermal resistances at 0.57 and 0.72 slot fill factors from short time thermal transient tests as tabulated in Figure 3, static DC thermal tests and transient thermal FEA simulations have been performed to determine the important thermal parameters of the ISG stator segments such as the tooth surface heat transfer coefficients and the thermal conductivity of the equivalent insulation system. The effective slot thermal conductivity of the compressed coil is found to be 0.52 $(W/m.K)$ and the effective thermal conductivity of the random wound coil at about 0.57 fill factor is 0.28 $(W/m.K)$. In order to show the accuracy of the thermal FEA model of a single ISG tooth, the calibrated FEA temperature variation and static thermal DC test results are plotted in Figure 5.

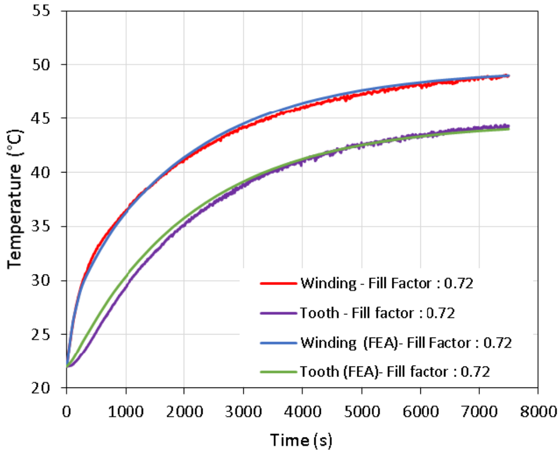


Figure 5: Transient temperature variation by thermal FEA and static DC thermal tests for a compressed ISG segment

3D transient thermal FEA simulations have also been conducted to compare hot spot temperature increase in the random wound coils and the compressed coils. Thermal boundary conditions for the performed FEA simulations are based on empirical formulations as given in [7]. The FEA models are identical in terms of internal heat generation (total losses ≈ 908.8 Watts) and thermal boundary conditions yet the effective slot thermal conductivity in FEA is based on previous experimental calibration. Thus, the maximum temperature increases in windings at 0.57 and 0.72 fill factors can be obtained for comparison. The temperature rises in the full thermal FEA models of the ISGs at different fill factors are given in Figure 6. It should be also noted that the surrounding temperature for the ISG is 95°C and it utilises a water jacket cooling system with a coolant temperature of 80°C. Water cooling is applied as a boundary condition directly onto the stator external surface for the simplicity.

(a)

(b)

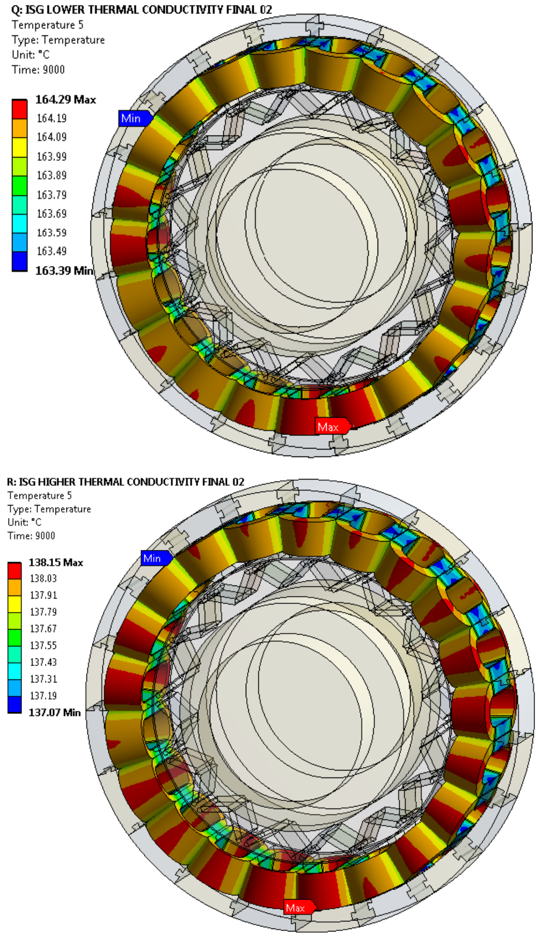


Figure 6: Temperature rise in the ISGs at steady state: (a) for the conventional random wound coils; (b) for the compressed coils – only coils are highlighted

As shown in Figure 7, the hot spot winding temperature at 0.57 slot fill factor is 26.1°C higher than that at 0.72 slot fill factor. Therefore, it is clear that the ISG with the compressed windings stays cooler than the ISG with the random wound coils at lower fill factors.

If 10°C temperature increase in windings temperature is assumed to reduce the machine life expectancy to one-half, as found in [8], 26.1°C temperature increase might be reducing the machine life more than one-quarter. Therefore, it is demonstrated that winding thermal conductivity is crucial parameter in terms of electrical machine life expectancy.

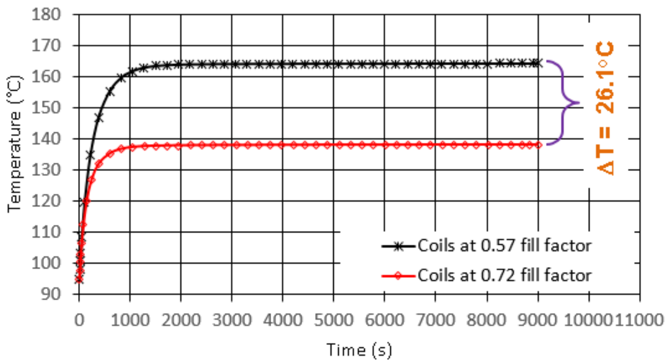


Figure 7: 3D-FEA temperature variations in the ISG coils at 0.57 and 0.72 slot fill factors

3 Accelerated Life Tests

Under normal service conditions, it may take several years for the insulation to fail. However, accelerated test conditions are an alternative model to estimate the life time characteristics of the insulations under thermal, electrical or humidity stresses. This technique is useful due to its effectiveness, timeliness and cost effectiveness [9].

Accelerated life tests can be performed on a certain AWG wire gauge with a specific type of insulations such as polyimide, polyester-imide or polyester enamelled copper wires. In this work, an experimental process has been set up and statistical methods are employed to estimate the life time characteristics of the compressed ISG coils under thermal stress.

3.1 Accelerated Life Test System

A model that predicts time-to-fail as a function of operating stresses is known as an acceleration model. A set of pressed ISG coils at similar slot fill factors can be considered to be samples for the experiment. Faulty specimens (coils) must be excluded from the data set. All coils therefore must be inspected, and if any faulty coils discarded. If all coils are healthy, then samples of pressed coils can enter the experiment.

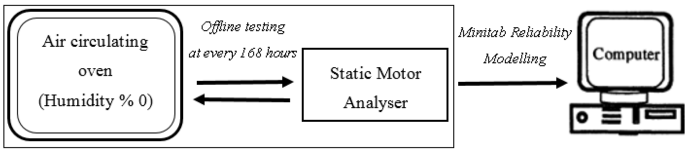


Figure 8: Schematic of the accelerated life tests system

In Figure 8, a schematic of the accelerated life testing system used is shown, including an air circulating oven that provides temperature and humidity control. Humidity was set to zero (in percent) since single stress (i.e. temperature) model is employed for the experiment.

3.2 Arrhenius – Weibull Life Model

Different types of life models can be used to estimate life characteristics of the pressed coils using statistical methods after collecting data from aging experiments. These life models are useful to calculate the life time at service level conditions. Statistical distributions such as Log-normal distribution, Weibull distribution are also needed to analyse test results. The main purpose of statistical distributions is to quantify the normal amount of variation in an outcome [1].

Here, the Arrhenius-Weibull statistical method has been applied to find a relationship between failure time of compressed windings and unreliability at certain accelerated temperatures. Also, a regression model can be derived to estimate how long the insulation will last at a given machine operating temperature when coils are pre-pressed. Using the outcome of statistical data after performing thermal aging tests in an environmental chamber, the life expectancy of compressed windings can be revealed. As it is not realistic to maintain life test indefinitely, aging tests were suspended before failure – so exact failure time could not be recorded. In this case, advanced statistical methods, known as data censoring (i.e. suspension of data), are required to treat this condition.

3.3 Parameter Estimation for Arrhenius- Weibull Life Model

The Arrhenius life stress model is formulated by assuming life is proportional to the inverse reaction rate of the process as given [3]:

$$L(V) = C\, e^{\frac{B}{V}} \tag{1}$$

where L represents a quantifiable life measure (i.e. mean life), V is the level of stress (e.g. temperature in °K), C is one of the model parameters to be determined ($C > 0$). B is another model parameter to be determined.
The probability density function (pdf) for the 2-parameter Weibull distribution is given by:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{n}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2}$$

By setting $\eta = L(V) = C\, e^{\frac{B}{V}}$ and substituting for η in the Weibull distribution equation, Arrhenius – Weibull model pdf can be obtained as given [3]:

$$f(t,V) = \frac{\beta}{C\, e^{\frac{B}{V}}}\left(\frac{t}{C\, e^{\frac{B}{V}}}\right)^{\beta-1} e^{-\left(\frac{t}{C\, e^{\frac{B}{V}}}\right)^{\beta}} \tag{3}$$

The parameter estimation can be carried out by using Maximum Likelihood Estimation Method. Maximum likelihood is one of the methods to estimate parameters (i.e. β, B and C) in statistical models. Parameter estimation is crucial in accelerated life models. The maximum likelihood estimation function was not given here as it can be found in [3] which considers data censoring. The logarithmic regression model can be attained using the relationship between temperature and failure time for the coil insulation system.

In order to estimate Arrhenius –Weibull parameters, a software package, Minitab has been used to numerically estimate the parameters. The software also provides Arrhenius-Weibull reliability modelling. Thus, probability plots with respect to failure time can be achieved in the software.

4 Experimental Results

The most important part of accelerated life data analysis is to conduct reliable thermal aging tests of ISG coils at an accelerated temperature and at 0% humidity. In the different phases of the accelerated life tests, 5 compressed (≈350 bar hydraulic pressure) coils at about 0.72 fill factor and 5 conventional coils at 0.57 fill factor have been simultaneously tested in an environmental chamber at 3 different pre-selected operating temperatures that are 175°C, 160°C and 140°C for 1182 hours (i.e. 49 days), Figure 9. The specimens of the experiment have been periodically tested by means of a Static Motor Analyser.

Figure 9: Conventional and compressed ISG coils in an environmental chamber operating at 175°C

It is worth to mention that although the magnet wires used in the ISG coils are of temperature class of 200, the accelerated temperature points are less than the thermal class of the wires. This is due to the fact that on-tooth coil pressing artificially reduces the thermal class of both slot liners and magnet wires as will be understood through the life test results in the following sections.

4.1 Insulation Dielectric Strength Tests

IEEE 43-2000 identifies minimum values for insulation resistance of rotating machines. This standard states that for most machines built after 1970 with random wound stator coils rated below one kV, the minimum insulation resistance is five mega-ohms [10]. All of these minimum values are based on a winding temperature of 40°C.

Mega-ohm tests are carried out to detect insulation resistance (IR) between windings and ground wall. If any insulation weakness exists between the coil windings and ground, high leakage current is detected during the tests. According to IEEE 43, insulation resistance measurement is taken after the test direct voltage has been applied for 1 min [10].

For the 21 slot 16 pole V-shape PM ISG machine, the peak phase voltage ($\hat{V}_{phase} = 200\ Volts$) is less than 1000 Volts meaning that Mega-ohm test voltage is 500 Volts. The static motor analyser shown in Figure 1 has been used to carry out IR tests.

In addition to IR tests, surge tests have also been carried out periodically during thermal aging tests. A surge test is based on applying a high current impulse to a winding using a fast rise time that will induce a voltage difference between adjacent loops of wire within the winding [11]. If the voltage difference between the magnet wires is high enough, an arc occurs between the wires. The arc can be detected by observing a shift in the surge waveform as depicted in Figure 10 for a faulty specimen that could not enter the experiment:

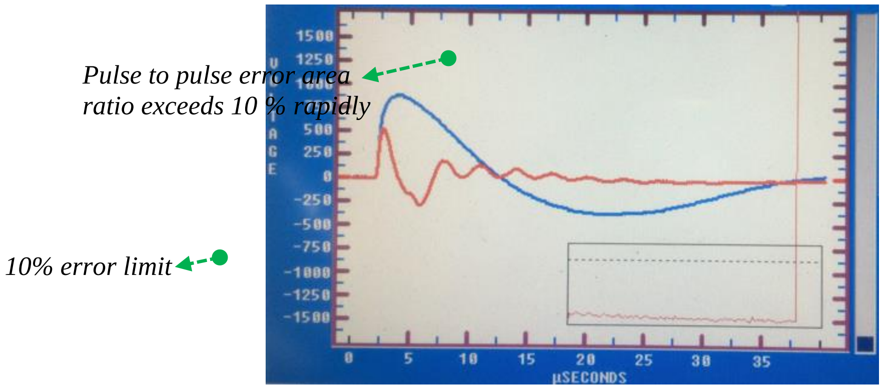


Figure 10: Faulty condition during 1400 Volts surge test due to turn to turn short

As shown in Figure 10, the surge waveforms are different from each other showing that surge tests run on lead 1 and lead 2 of a winding detect a turn to turn fault in one of the compressed ISG coils, which was hence omitted from the lifetime tests.

4.2 Accelerated Life Test Results

The ISG coils have been aged at 175°C, 160°C and 140°C for a minimum of 49 days and off-line turn to turn and turn to ground wall insulation tests have been performed every 168 hours (7 days) to monitor insulation resistance and catch failure time intervals in hours (hr). The results are shown in Table 1.

The failure criterion is that turn to ground wall insulation resistance must be higher than 5MΩ as reported in IEEE 43-2000 standards. Turn to turn short has not been observed for any coil surge tested throughout the thermal aging period.

Temp (°C)	Arrhenius Temp	Failure Interval Start (hr)	Failure Interval End (hr)	Frequency
175	25.894	168	336	2
175	25.894	336	504	1
175	25.894	1182	*	2
160	26.791	672	840	1
160	26.791	840	1008	1
160	26.791	1182	*	3
140	28.087	1008	1176	1
140	28.087	1512	1686	1
140	28.087	1686	*	3
* denotes that a number of coils is right censored (suspended) implying that no insulation failure recorded within the time period of the aging experiments.				

Table 1: Interval Censored and Right Censored time to failure data from the experiments

The frequency column in Table 8.5 indicates the number of failures recorded within given time interval. The pure experimental data given in Table 1 is sufficient to estimate life expectancy of the on-tooth compressed coil. The conventional random wound coils did not fail during the aging tests. Turn to ground wall insulation failure was observed only in the compressed ISG windings.

4.3 Life Expectancy of the Compressed ISG Coils

The experimental time to failure data collected from '3 Phase' Accelerated Life Tests at 140°C, 160°C and 175°C have been used to predict life expectancy of the on-tooth compressed coils. 3 different temperate point enables to extrapolate thermal life plot to estimate the life expectancy of the compressed ISG coils at operating temperature which is found to be 138°C from 3D thermal FEA simulations as reported in Figure 6 (b). Arrhenius-Weibull life model parameters for the conducted aging tests are tabulated in Table 2.

Acceleration variable	Temperature			
Distribution :	Weibull			
Estimation:	Maximum Likelihood			
Relationship with accelerating variable:	Arrhenius			
Right censored data:	8			
Interval censored data:	7			
Number of data (coils):	15			
Regression Table				
Predictor	*Coefficient*	*Standard Error*	*95% Normal Confidence Interval - Lower*	*95% Normal Confidence Interval - Upper*
Intercept	-4.83446	7.633	-19.79	10.12
Temperature	0.456644	0.286	-0.10	1.01
Shape	1.59653	0.548	0.81	3.12
Log-likelihood = -23.661				

Table 2: Arrhenius-Weibull Life Data Analysis

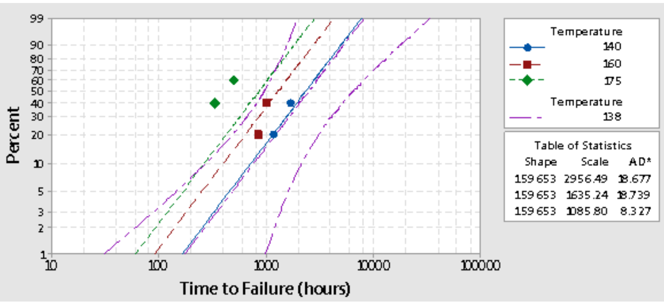
From the regression table given in Table 2, the coefficients for the regression model are obtained. For a Weibull distribution, this model describes the relationship between temperature and failure time for the insulation as given by [12]:

$$log_e(failureT) = -4.83446 + 0.456644(Arrh.Temp) + \left(\frac{1}{1.59653}\right)\varepsilon_p \qquad (4)$$

where ε_p is the p[th] percentile of the standard extreme value distribution.

The probability plot given in Figure 11 can help determine if the distribution at each level of accelerating variable (i.e. temperature) is appropriate or not. If the fitted lines are approximately parallel, the probability model becomes more accurate. According to Figure 11, 99% (probability) of the compressed ISG coils fail in 8190.35 hours (mean life) if they operate at 138 °C.

The 50^{th} percentile is a good estimate of insulation life expectancy. Therefore, 2501.34 hours life in average is expected from the coils running at 138°C. This states that the dielectric strength of turn to ground wall insulation for the compressed ISG windings is significantly affected negatively from on-tooth compression method.



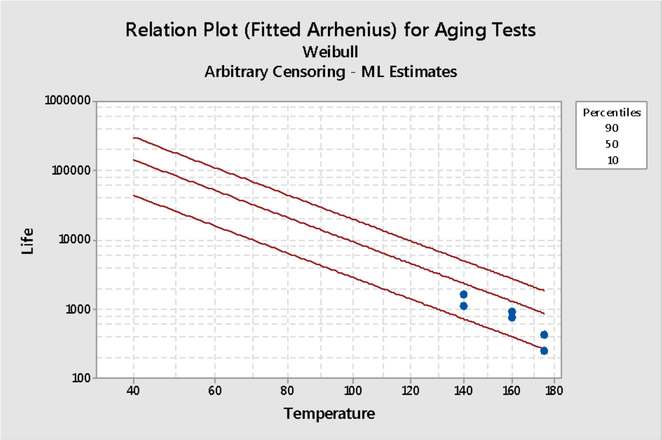


Figure 11: Arrhenius-Weibull probability plot (upper), life time extrapolation to lower temperatures (lower)

4.4 Reliability of Commercial Magnet Wires

ASTM D 2307 standard determines the thermal index of magnet wires. The magnet wires used in the ISG stator windings are of temperature class 200°C. This means that it has 20,000 hour life at maximum 200°C. This information is based on ASTM D 2307 specimen testing methodology. The preparation of specimens are given in [13]. The specimens for aging tests usually consist of twisted pair of wires with film insulations and a holder.

Figure 12: Damaged magnet wire after 49 day thermal aging at 175°C – not a pressed winding sample

However, the magnet wires with a temperature class of 200°C used in random wound un-pressed ISG windings fail at 175°C as shown in Figure 12. This was noticed when wires have been un-wounded from the tooth. This shows that commercial magnet wires might not be used at their temperature limit and also emphasise that keeping the temperature low for stator windings is vital.

5 Conclusion

A three stage (140°C, 160°C and 175°C) thermal aging tests of the ISG coils enable to perform Arrhenius –Weibull life model. The employed statistical model proves that on-tooth coil pressing reduce the life expectancy dramatically due to reduced turn to ground wall dielectric strength. It is reported that if windings are directly pressed on the tooth, the life expectancy will be about 2500 hours. Therefore, this suggests that stator windings should be pressed off tooth (on a dummy tooth) and then placed into the original stator with un-damaged Nomex 410 (by DuPont) slot liners.

References

[1] G. C. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical insulation for rotating machines: design, evaluation, aging, testing, and repair*. John Wiley & Sons, 2004.

[2] M. C. Kulan, N. J. Baker, J. D. Widmer, and S. Lambert, "Mechanical and Thermal Properties of Compressed Stator Windings," in *IET International Conference on Power Electronics Machines and Drives (PEMD 2016)*.

[3] Accelerated Life Testing Reference Tuscon, Arizona: ReliaSoft Corporation, 2015, p. 247. [Online]. Available: http://www.synthesisplatform.net/references/Accelerated_Life_Testing_Reference.pdf. Accessed on 02/07/2017.

[4] K. H. Nam, *AC motor control and electrical vehicle applications*. CRC press, 2010.

[5] A. Boglietti, E. Carpaneto, M. Cossale, M. Popescu, D. Staton, and S. Vaschetto, "Equivalent thermal conductivity determination of winding insulation system by fast experimental approach," in *Electric Machines & Drives Conference (IEMDC), 2015 IEEE International*, 2015, pp. 1215-1220: IEEE.

[6] M. C. Kulan, N. J. Baker, and J. D. Widmer, "Design and Analysis of Compressed Windings for a Permanent Magnet Integrated Starter Generator," *IEEE Transactions on Industry Applications*, 2017.

[7] G. D. Demetriades, H. Z. De La Parra, E. Andersson, and H. Olsson, "A real-time thermal model of a permanent-magnet synchronous motor," *IEEE Transactions on Power Electronics*, vol. 25, no. 2, pp. 463-474, 2010.

[8] J. R. Hendershot, Miller, T.J.E., *Design of Brushless Permanent-Magnet Motors*. Magna Physics & Oxford Science Publications, 1994.

[9] S. Grzybowski, S. Bandaru, N. Kota, and C. F. King, "Lifetime characteristics of magnet wires under pulse voltage [wire insulation multistress effects]," in *Electrical Insulation and Dielectric Phenomena, 2004. CEIDP'04. 2004 Annual Report Conference on*, 2004, pp. 145-148: IEEE.

[10] "IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery - Redline," *IEEE Std 43-2013 (Revision of IEEE Std 43-2000) - Redline*, pp. 1-75, 2014.

[11] SKF Static Motor Analyzer User Manual, Fort Collins, Colorado: Baker Instrument Company, 2013. [Online]. Available.

[12] "Minitab 17.0 Support," Accessed on: 05/12/2017Available: https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/reliability/how-to/accelerated-life-testing/before-you-start/overview/

[13] *Standard Test Method for Thermal Endurance of Film-Insulated Round Magnet Wire D2307*, 2013.