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BENEFITS OF PEEK INSULATION IN HIGH-VOLTAGE ELECTRICAL MACHINES

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Abstract— The selection of an insulation system for higher voltage electrical machines has a direct impact on both machine power density and lifetime. This paper highlights the benefits that can arise from the use of VICTREX XPI™ PEEK insulation in a higher voltage electrical machine when compared with a standard enamel. Multi-stress factor ageing testing has shown that XPI PEEK insulation delivers and maintains higher partial discharge inception voltages throughout its life. It is also more resistant to degradation when used at higher temperatures. The selection of XPI PEEK insulation for electrical machine applications therefore offers designers the opportunity to deliver a higher performance electrical machine with a more compact insulation system and increased lifetime when compared to conventional insulation solutions.

I. INTRODUCTION

The selection of an insulation material for use in electrical machines seeks to deliver the highest possible power density (by maximising the copper fill in the slot) while ensuring reliability over the required lifetime. The reliability of the insulation system is based around several factors that include the mechanical strength of the insulation (both during assembly of the machine and from dynamic operational factors such as vibrations and road impacts), the breakdown voltage and the partial discharge inception voltage. As these properties can change throughout the machine lifetime, it is necessary to fully understand the through life performance as well as the 'as new' properties of the insulation.

Electrical machines used in transport applications will inevitably be fed from a variable frequency drive that delivers a near squarewave voltage to the machine terminals. The use of a 800V DC bus is now commonplace in high performance automotive applications. A machine used on an electrical system with an 800V DC bus will see a peak-peak voltage of at least 1600V on the phase-phase insulation system with this increasing further because of overshoots / increases in system voltage above nominal. While the insulation must be selected in a manner that prevents breakdown from occurring, it is more likely that the risk of partial discharge will be the primary factor that determines the insulation thickness.

Partial discharges typically take place in electrical machines in locations where there is no or poor encapsulation. The voltage on the conductors creates an electric field in these air gaps that then leads to a discharge event. This discharge does not cause a complete fault / flow of high current but instead causes local damage to the insulation. In inverter fed machines where partial discharges can happen at high frequency, this can lead to times to failure in the region of a few hours. As such, the prevention of partial discharge in an inverter fed electrical machine throughout its lifetime is essential and particularly challenging at high altitude where a lower air density reduces the partial discharge inception voltage (PDIV - the voltage at which partial discharge starts) of the system. Additionally, some materials like enamels lose insulation thickness over life (particularly when operating at high temperatures) and this can result in the partial discharge inception voltage reducing as a function of time.

The primary means by which a machine designer can reduce the likelihood of partial discharge is to specify a thicker insulation or a lower relative permittivity insulation material. If the insulation system can be kept partial discharge free, the insulation system will most likely fail in the long term as a result of the thermo-mechanical stresses that will be imposed on it during use. A combination of thermal ageing that can cause embrittlement of the insulation, thermal cycling and vibration can lead to cracking in the insulation system that then dramatically reduces the breakdown voltage, particularly in humid conditions.

II. CHOOSING INSULATION THICKNESS TO AVOID PARTIAL DISCHARGE

A. Defining The Required Voltage Levels

The IEC 60034-18-41 standard [1] provides guidance that allows test voltages to be defined for use in insulation qualification testing. The voltage selection and the framework of testing described in the standard aims to ensure that the insulation system of the machine is partial discharge free until the end of life. If the insulation system cannot be shown to be partial discharge free, it must be assessed to confirm the lifetime in the presence of partial discharge (it is likely that this will be very low as a result of the high frequency at which partial discharges can occur when a machine is inverter fed). This would typically be achieved using the guidance described in IEC 60034-18-41 [2].

Table 1 illustrates the magnitude of the voltage that the 'phase to phase' and 'phase to ground' insulation system would have to withstand when tested 'as-new' in ambient conditions. Assuming a battery fed system (in which there are no transients), the test voltage is determined by multiplying the 'peak-peak' voltage seen on the insulation system with two enhancement factors. One enhancement factor relates to the effect of air density – when a machine is operated at higher temperature or at high altitude (low pressure), the PDIV will fall. The other relates to the effect of ageing and reflects the reduction in insulation thickness that can take place when the insulation is operated near the class temperature. Multiplying these factors by the system voltage allows the definition of the voltage at which a new insulation system should remain PD free when testing in ambient conditions.

In this table, the ageing factor is set to be 20%. This is the highest level possible from direct adoption of the method in IEC 60034-18-41 [1]. This method was introduced into the standard based on tests carried out on standard enamel wires. As such, it is not clear that this model is suitable for use with XPI PEEK based insulation systems.

The air density factor reflects the need to increase the test voltage at ambient conditions to cater for the reduction in PDIV that takes place as a function of temperature / altitude. Examples of the way altitude can change the required air density. Density correction factor are as follows:

- 2000m / 200°C = 1.24
- 5000m / 200°C = 1.38 (approximately highest road in the world / urban air mobility altitudes)
- 15000m / 200°C = 1.92 (commercial aircraft altitudes).

TABLE 1 - TEST VOLTAGES FOR MACHINE OPERATING ON 800V DC BUS WITH 50% OVERSHOOT

	Applied Voltage In Operation / V_{pk-pk}	Ageing factor	Air density factor	Test Voltage / V_{pk-pk}
Phase – Phase	2400	1.20	1.30	3744
Phase - Ground	1680			2621

The net result of the above is that an insulation system must be tested with a voltage that will be higher than what is seen in service. By providing a means by which the test voltages can be calculated, it is possible to estimate the required insulation thicknesses.

B. Converting PDIV Requirement To Insulation Thickness

There are a number of techniques to estimate insulation thicknesses and all rely on knowledge of the insulation thickness and the relative permittivity (dielectric constant) of the insulation. The higher the relative permittivity of the insulation, the higher the proportion of the electric field that will be found in any air gaps that could exist at the end-winding of a machine / within areas of the machine that have not been fully encapsulated and the lower the PDIV.

The chart below shows the equivalent insulation thickness required as a function of voltage (assuming this insulation system is being tested at atmospheric pressure / temperature). The equivalent insulation thickness is the summation of the insulation thicknesses provided by different materials divided by their relative permittivity. The chart is based on Halleck's method [3] – other methods such as the streamer inception method [4] could be used to provide similar results. The chart shows that higher voltages result in a non-linear increase in required insulation thickness.

This non-linear increase is likely to be a barrier to the use of conventional insulation systems at voltages higher than 800V, particularly in conjunction with operation at high altitudes. It is more likely that oil-flooded systems may provide solutions for operating at higher voltages / altitudes although the potential chemical compatibility issues

must be addressed. However, in any application it is highly desirable to minimise the insulation thickness needed in a machine by managing the level of voltage overshoot / rise in DC bus voltage above nominal.

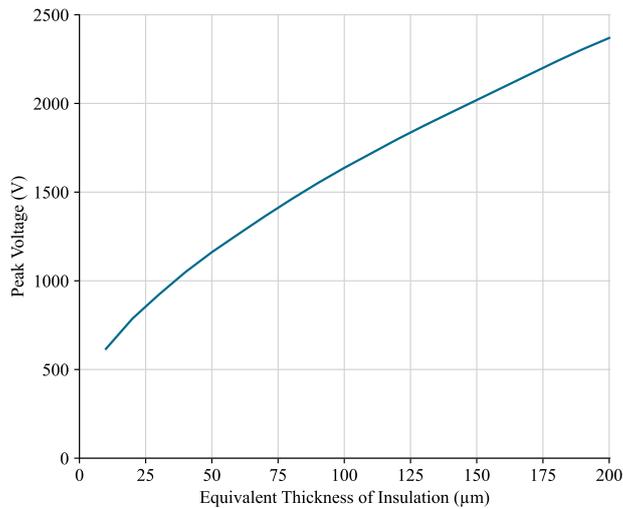


FIGURE 1 – PEAK PARTIAL DISCHARGE INCEPTION VOLTAGE FOR A SPECIFIC VALUE OF EQUIVALENT INSULATION THICKNESS (200M ALTITUDE, 20°C TEMPERATURE)

III. ASSESSING INSULATION LIFETIME

To assess the lifetime of a Type I insulation system (as defined in IEC 60034-18-41 [1], one of two things are taken to cause failure:

- A drop in the partial discharge inception voltage of the insulation to a point where partial discharge then takes place. Given the time to failure of this insulation in an inverter fed machine is likely to be low, the point at which this happens is taken to be failure.
- Sufficient thermo-mechanical degradation (thinning of the insulation material or, as a result of embrittlement and subsequent vibration, cracking) that causes the insulation to no longer have sufficient strength to prevent breakdown.

To compare the expected life for different insulation systems, test campaigns are typically used that assess the behaviour of an insulation system (comprising all of the constituent parts such as winding wire, slot liner, encapsulation).

The test campaigns usually comprise of at least three sets of samples being thermally aged at increasing levels above their class temperature. After a period of ageing, these samples are subjected to vibration tests. This is followed by diagnostic tests that seek to confirm that the insulation can deliver its functional requirement (for higher voltage machines this both includes confirmation that it remains partial discharge free at the required test voltage and that it can pass a dielectric withstand test). This approach is based around the original requirements developed for low voltage electrical machines in IEC 60034-18-21 [5] with additional detail being provided in IEC 60034-18-41 [1] for converter fed machines.

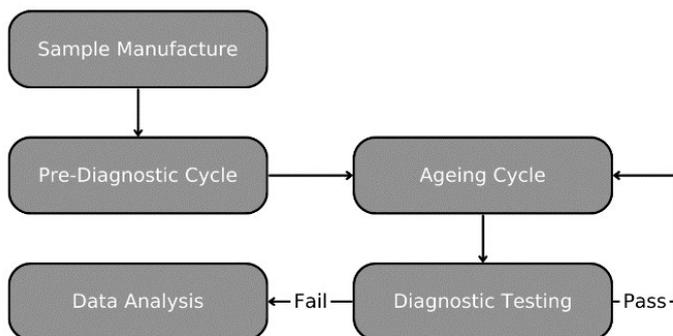


FIGURE 2 - FLOW CHART OF TESTING PROCESS

Following completion of the ageing / diagnostic cycles (when all or sufficient test samples have failed) , the lifetime of the insulation system can be estimated through the use of IEC 62539, 'Guide for the statistical analysis of electrical insulation breakdown data' [6]. Taking the failure point of the insulation to be halfway through the corresponding ageing cycle allows the production of a probability distribution of the time to failure for each ageing temperature. It is then possible to estimate the failure time at a lower operational temperature and scale this to account for the size of an actual product (the IEC 62539 standard provides guidance on the scaling of test data where measurements are taken on samples that are small-scale in comparison to the final product).

IV. EXPERIMENTAL COMPARISON OF XPI PEEK AND ENAMEL INSULATED WIRES

To illustrate the impact of material choice on the design of a machine and the lifetime of the insulation system, two types of wire were selected and tested using the framework described in section III. Additional tests were carried out to assess the comparative properties of a XPI PEEK and enameled wire to demonstrate the impact that wire choice can have on the machine design / lifetime.

A. Insulation Types Under Test

One wire selected was a standard PAI enamelled wire while the other was a XPI PEEK insulation (this being layered on top of a thin layer of enamel to promote adhesion). The typical dimensions of the wires (as measured using microscopy) are described below in Table 2.

TABLE 2 - MICROSCOPY WIRE MEASUREMENTS

	Copper Width / mm	Copper Depth / mm	Insulation Thickness / mm
XPI PEEK	4.40	1.82	0.150
Enamel	4.42	1.82	0.141

Images comparing the cross section of the two sample materials are shown in Figure 3. The first image shows the XPI PEEK insulated wire – the thin layer of the enamel can just be seen at the boundary of the copper. The second image shows a cross-section of the enamel coated wire.



FIGURE 3 - IMAGES OF TEST SAMPLES, XPI PEEK (TOP) AND ENAMEL (BOTTOM)

B. Impact Of Thermal Ageing On Insulation Thickness

If an insulation loses thickness as it ages, there is a requirement to compensate with additional insulation material at the start of life – this being reflected by the ageing factor shown in Table 1. The ageing factors are increased, this results in a higher test voltage and therefore the need to use a higher insulation thickness when the machine is new.

The aim is to ensure that partial discharge does not take place in the machine once insulation thickness has been lost as a function of time. To compare the insulation loss of a XPI PEEK wire and an enamelled wire, the two wire types underwent exposure to a temperature of 200°C for a duration of 1000 hours. Control samples were measured alongside the aged samples for comparative analysis.

A total of 20 samples were aged with measurements of the insulation thickness before / after ageing being made by potting the samples in epoxy and polishing to allow microscope based measurement of the insulation thickness. This measurement was taken using a 8x zoom. A total of 100 measurements were taken. The results of this testing are shown in Table 3 and Figure 4 (this being in a box-plot format to show the range of measurements made).

TABLE 3 - INSULATION THICKNESS MEASUREMENTS

	Before Ageing / μm	After Ageing / μm	Percentage Change
XPI PEEK	150	152	1%
Enamel	141	132	-6%

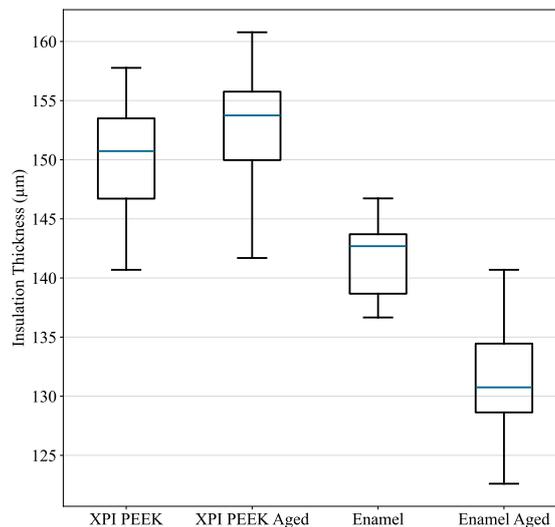


FIGURE 4 - INSULATION THICKNESS MEASUREMENT BOXPLOTS

The enamel wire loses 6% of insulation thickness after 1000 hours. This loss of life tallies with the tests described [7] that saw a loss in thickness of around 33% after being aged at . In this case, it is clear that selecting this type of insulation for use in a machine operating at / near to the class temperature will require consideration of a loss in thickness as a function of time.

In comparison, the XPI PEEK wire does not show any loss in insulation thickness. As such, there would be no requirement for an enhancement factor associated with ageing when selecting the machine test voltage as shown in Table 1. A drop in test voltage of 20% will correlate with a reduction in required insulation thickness higher than 20% given the relationship between PDIV and insulation thickness shown in Figure 1. This is a key benefit of XPI PEEK insulation when operated at the same temperature as an enamel insulation.

C. Permittivity Measurement

While the partial discharge inception voltage of the insulation is primarily driven by the insulation thickness, the relative permittivity of the insulation also contributes significantly. A higher permittivity of insulation leads to a higher electric field in any air gap in the machine. As such, a higher permittivity leads to a requirement for a higher level of insulation thickness to prevent damaging partial discharge.

The two wire types that underwent exposure to a temperature of 200°C for a duration of 1000 hours were taken and coated over a 125mm length using a copper-silver paint. Control samples were also coated with paint to allow for comparison against the aged samples. The wires were then kept in a 50% relative humidity environment for 48 hours. Following this, a 4 probe measurement method was used to determine the capacitance and dissipation factor of the samples as a function of temperature. The measurement was carried out using a BK891 LCR meter operating at a frequency of 1kHz. The results are shown in Figure 5.

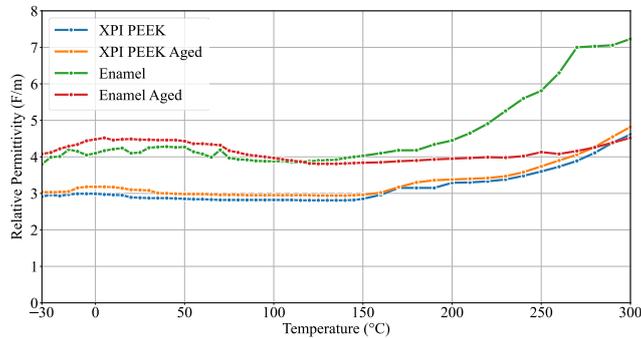


FIGURE 5 – RELATIVE PERMITTIVITY OF CONTROL AND AGED WIRES AS A FUNCTION OF TEMPERATURE

The XPI PEEK wire shows a consistent relative permittivity at temperatures below 150°C followed by a gradual increase. At a temperature of 200°C, a reasonable expectation for an electrical machine, the relative permittivity of XPI PEEK remains below that of the enamel wire.

Ageing was shown to have a more significant impact on the enamel wire although the effect is positive – in that the relative permittivity observed at high temperatures sees a significant reduction. As such, the differential between the enamel wire and the XPI PEEK is lower in the aged condition.

The data suggests that a relative permittivity of 3.4 can be assumed for XPI PEEK at the 200°C temperature while a value of 4.0 needs to be assumed for enamel. This would imply that the same thickness of XPI PEEK has an equivalent thickness that is 18% higher than that of the enamel and would deliver a resulting higher PDIV.

D. Partial Discharge Inception Voltage Measurement

The sections above show that a XPI PEEK wire retains insulation thickness after ageing and has a lower relative permittivity. That suggests the partial discharge inception voltage of aged wires should be superior, in turn allowing for a reduced insulation thickness to be utilised at the start of a build.

Partial discharge measurements were taken on 12 wire samples with a length of 125mm that were placed between two mesh sheets (these covering a 100mm length of the sample). An IEC 60270 [7] compliant partial discharge detection circuit using an Omicron MPD system was used with a 50Hz voltage that was automatically ramped from 0V to the target value. A noise level of 1.0pC was present in the PD detection circuit and the PD threshold set to 5V. The data captured from these measurements was fitted to a Weibull distribution using the guidance given in IEC 62539 [6]. The results of this analysis are as follows.

TABLE 4 - FITTED WEIBULL DISTRIBUTION SCALE AND SHAPE PARAMETERS

		Shape	Scale / V
Control	XPI PEEK	47.47	824.67
	Enamel	62.03	734.15
Aged	XPI PEEK	22.60	814.42
	Enamel	66.01	679.79

The shape factor of the aged samples indicated a higher standard deviation in the measurements made with the XPI PEEK material – something that would need to be confirmed with an increased number of samples. The scale factor (corresponding to the partial discharge inception voltage not being exceeded by 63.2% of samples) was stable for the XPI PEEK samples when comparing the control / aged values at around 820V.

When comparing the XPI PEEK and the enamel samples, there is a clear difference with the scale factor of the enamel samples being 11% lower than the XPI PEEK samples when unaged and 16% when aged. These results correlate with the measurements of insulation thickness before / after ageing and the relative permittivity values. The lower relative permittivity of the XPI PEEK provides benefit in both the un-aged / aged case with the benefit increasing as the enamel wires lose insulation thickness.

The data shows the stability of XPI PEEK over time and the ability XPI PEEK has to provide a higher PDIV with a smaller insulation thickness.

E. Breakdown Voltage Assessment

In the context of an 800V power converter, the highest peak voltage likely across any part of the insulation system is 1600V (this resulting from the presence of an overshoot) and any breakdown voltage measured on insulation samples should be considered in this context. As such, the measurement of breakdown voltage is usually most valuable when it is used to identify gross insulation defects such as cracks / holes in the insulation system.

The breakdown voltage of samples were therefore measured to confirm that the samples remained defect free after ageing and that there was no significant change in breakdown voltage. The test that was carried out used a power frequency voltage (50Hz) that was automatically ramped until the voltage at which breakdown took place. This tested was done with wires that had been aged at 200°C for 1000 hours and subsequently coated over a length of 125mm with copper-silver paint. The testing was carried out in oil to minimise the risk of surface flashovers at the end of the paint layer impacting the test results.

The Weibull probability plot on the right (Figure 6) produced according to the methods described in IEC 62539 shows that the XPI PEEK and enamel wires have similar breakdown voltages. The breakdown voltage at which 1% of samples would be expected to fail is approximately 8kV in the case of the XPI PEEK insulation and 10kV in the case of the enamel. In the context of automotive applications and existing / projected DC bus voltages, this would not appear to be a difference of any significance with both materials being fit for purpose.

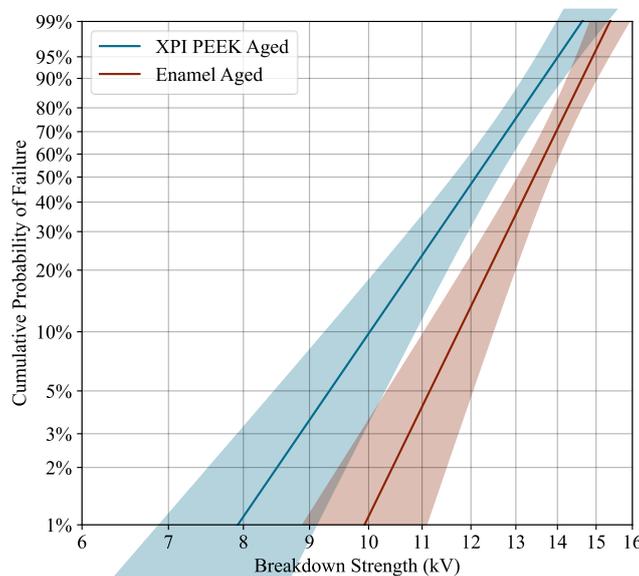


FIGURE 6 – PROBABILITY PLOTS OF THE BREAKDOWN VOLTAGES OF XPI PEEK AND ENAMEL WIRES AFTER AGEING

F. Comparative Lifetime Assessment Of The Insulation Systems

While the testing of individual wires gives an insight into the performance of the base materials and the required insulation thickness, an accurate determination of lifetime is best provided by considering their performance as part of an overall insulation system. For an insulation system that is expected to be Type 1 (i.e. partial discharge free) that typically sees failures resulting from thermo-mechanical degradation or a reduction of the PDIV below the required value as previously described.

As such, wire samples were placed along with 'APTIV 1000-100G' PEEK film slot liners, provided by Victrex, into a metallic block. Epiform E-9566-1 varnish was used in the construction of this motorette to ensure homogeneous thermal performance and stability during vibration ageing. The motorette block had dimensions of 205x155x50mm. An example of the type of block used is shown in Figure 7. Ten sets of wires are arranged in a stack of 4. This arrangement allows a single 'phase-ground' test per slot and two 'turn-turn' tests. No phase separator was used to mimic the arrangement seen in many hairpin motors where the turn insulation directly crosses in the end-winding area.

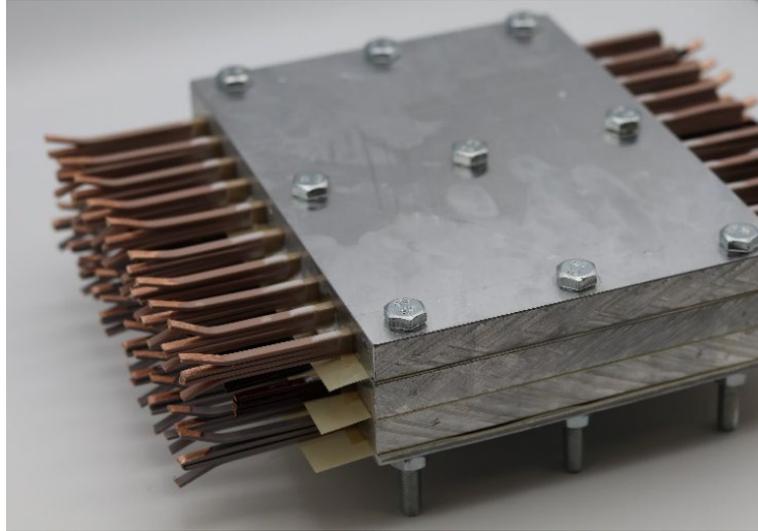


FIGURE 7 - MOTORETTE BLOCK USED TO CARRY OUT THERMOMECHANICAL AGEING TESTS

Three blocks were manufactured and all of these underwent initial diagnostic testing. A dielectric withstand test was performed 'phase-ground' and 'turn-turn' using a 50Hz voltage at 690V as per the recommendations in IEC 60034-18-21 (in this case the turn-turn insulation would also act as phase-phase insulation in most real systems). Once the benchmark performance had been established through partial discharge measurements and dielectric withstand tests, these three blocks were thermally aged at temperatures of 220°C, 240°C and 260°C. The duration of the ageing cycles was 10 days, 5 days and 2.5 days respectively.

Following each ageing cycle, the samples were placed on a vibration shaker and a random vibration profile applied for an 8-hour period according to requirements drawn from the GB/T-28046.3 standard [9]. Following this, the samples were partial discharge tested to determine their turn-turn PDIV before being placed in a high humidity environment for 48h before a final dielectric withstand test was carried out. Failure was indicated by either the PDIV falling below a target level (set using the IEC 60034-18-41 criteria for an 800V DC bus application) or failure of the dielectric withstand test.

Taking a failure criteria of 1026V (this being an RMS voltage determined through the use of an 800V DC bus voltage, a 3000m altitude and an overshoot of 0.25) saw all enamel samples fail during the test campaign. In the XPI PEEK samples, only 11/20 failed at 220°C before the test was truncated. Similarly, 18/20 failed at 240°C and 12/20 at 260°C. In comparison, all of the enamel samples failed at the two lower ageing temperatures and 18/20 at 260°C.

Using the data generated in the test programme, the lifetime predictions below have been made on the basis of the insulation systems operating continuously at the stated temperatures. In transport applications this is extremely unlikely with high temperatures only being expected on rare occasions. XPI PEEK demonstrates a higher lifetime than enamel when operated at these high levels of temperature.

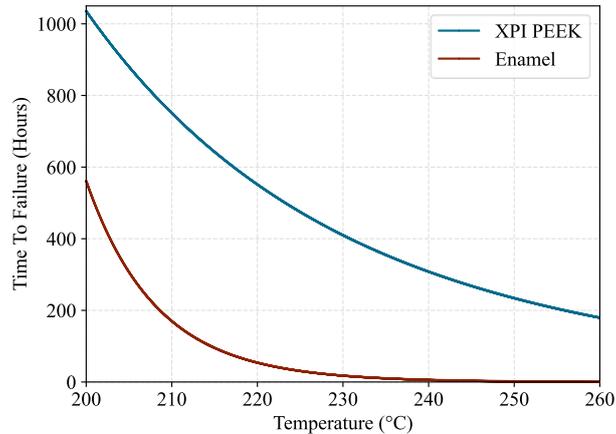


FIGURE 8 - FAILURE TIMES FOR FITTED XPI PEEK AND ENAMEL DISTRIBUTIONS DEMONSTRATING THE TIME TO FAILURE FOR 1% OF SAMPLES

V. CONCLUSIONS

VICTREX XPI PEEK insulation has been shown to deliver a higher PDIV compared with an equivalent enamel coated wire. This higher PDIV is retained for longer as XPI PEEK does not see a reduction in insulation thickness when aged. Both of these factors contribute to an ability to specify a XPI PEEK wire with a reduced insulation thickness in an electrical machine when built. The testing work carried out shows there is no significant difference in respect of the breakdown performance of the two wires with both wires having a breakdown voltage well above application requirements when aged.

The XPI PEEK insulation then shows an improved resilience to thermal-mechanical ageing with predicted failure times at standard operating temperatures being well above their enamel equivalent. Taken together, the use of XPI PEEK insulation appears to offer the prospect of significant benefits for a machine designer.

VI. REFERENCES

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