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An Experimental Assessment of the Impact of High dv/dt SiC Converters on Insulation Lifetime of Electrical Machines

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***Abstract*— SiC MOSFETs, capable of operating at higher dc link voltages with faster rise times and higher switching frequency, are becoming more prominent in converter-fed drives. While they offer higher power density and high efficiency with improved performance, they also result in significantly increased voltage stresses to the insulation of machine windings. In this paper, the impact of SiC based converters on the insulation lifetime of a commercially available 2.8kW permanent magnet machine is assessed experimentally at elevated temperatures under a range of dc link voltages, rise times and switching frequencies. The lifetime of these samples and samples fed by a Si based inverter are compared, allowing the impact of SiC inverters to be studied. Specific focus is given to the quantity of partial discharge (PD) activity within the machine windings monitored throughout the experiments. It is shown that presence of PD during tests lead to very significant reduction in insulation lifetime.**

Keywords—* *Aging, Electric Machines, Materials Reliability, Partial discharges, Wide bandgap semiconductors,

I. Introduction

Advances in power semiconductor devices with fast turn on/off times provide great potential for significantly improved power density and efficiency in electrical drive systems. However, these improvements do not come without consequence. The potential issues for machine insulation which arise from utilising wide bandgap devices in inverter-fed drives are briefly outlined.

A. *Voltage Stresses*

The use of wide bandgap devices facilitates increased voltage stresses on the machine windings for two reasons. Firstly, the devices can support higher voltages, allowing the dc link voltage to be increased.

Secondly, the faster rise and fall times, which result in higher dv/dt can lead to higher levels of voltage overshooting at the machine terminals due to wave propagations and reflections in the cable and machine windings. If the cable length exceeds the critical length (which decreases as the rise time becomes shorter), the terminal voltages may reach up to, or even greater than, twice the dc link voltage [1]. This effect is particularly important to consider during the machine design process, as failure to do so may result in the winding insulation specification being exceeded, even though the dc link voltage is below the rated value for the insulation. In addition to this, due to the inductive nature of machine windings, fast switching events will lead to uneven voltage distribution in the winding turns. During these transient events the voltage across the first turns of the winding will be exposed to increased voltage stress.

It has also been shown in [2] that, in some cases under PWM excitation in a three-phase machine, the turns close to the neutral point may experience very high voltage stresses, potentially reaching up to four times the dc link voltage due to anti-resonant effects on the machine windings.

B. *Partial Discharge*

When the voltage stress applied to the winding insulation is above their partial discharge inception voltage (PDIV), partial discharges (PD) will occur within the machine windings. Repeated PD events will cause degradation to the machine insulation leading to premature insulation failure. While the influence of PDs on turn-to-turn insulation has been studied with twisted pairs of magnet wires in literature [3], the result is not representative of the machine insulation system for a number of reasons. First, there are three typical insulations in machines, phase-to-ground or main wall insulation, phase-to-phase insulations and turn-to-turn insulations. Depending on voltage stress distribution, PDs may occur in any of the insulations, not necessarily in turn-to-turn insulation.

To study the impact of excessive voltage stress and PDs, on lifetime of winding insulation, in this work machine stator samples were aged under accelerated life conditions while being excited by a SiC based, 2-level inverter under a range of

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different dc link voltages, rise times and switching frequencies. The stators used in tests are samples of a commercially manufactured machine, as it allows the winding insulation and potential PD occurrence during tests more representative of current state-of-the art insulation design and manufacturing. This differs from twisted pair or motorette samples, whose treatment/construction may not be entirely representative of a full machine and may not contain all the elements of the insulation system.

Samples of this machine, and its insulation lifetime have been studied previously, using a conventional Si based IGBT inverter [4], allowing the thermal index of the machine to be determined. The lifetimes recorded in this paper are compared to these known thermal index values, allowing the impact of the critical operating parameters of the SiC inverter to be assessed.

II. Test Methodology

A. Machine Samples

The machine under test is a commercially manufactured off the shelf three-phase 2.8kW permanent magnet servo motor, a photograph of its stator is shown in Fig. 1. The machine is random wound with each slot occupied by a single phase. The machine is wound with wire which incorporates a corona discharge resistant insulation material. To aid heat transfer and improve structural integrity of the windings the coils are also impregnated with polyester resin. The phase-to-ground insulation also includes a slot liner consisting of 0.25mm of Trivothermal N material between the windings and laminated core, and slot wedges manufactured from 0.35mm Nomex 410. To reduce manufacturing cost, the machine does not include any additional insulation between the phases in the end-winding, relying solely on the turn-to-turn insulation system for this purpose. By considering the entire machine stator it is possible to observe the impact of the whole insulation system on PD behaviour, rather than only considering a portion of the elements as would be the case if twisted pair samples were studied.

Fig. 1. 2.8kW servo motor stator under test

B. PDIV of insulation system

1) Turn-to-Turn Insualtion

The machine turn-to-turn insulation consists of a combination of the wire strand insulation material and polyester resin. Due to the construction of the machine, it is not possible to directly measure the PDIV value of the turn-to-turn insulation within a machine, however it is possible to estimate this value based on a twisted pair sample. To this end twisted pair samples were produced using the same wire as the machine samples. To determine the PDIV of these samples an MTC2 winding tester manufactured by Schleich was used in the configuration shown in Fig. 2. In this configuration the PDIV of multiple samples were tested with values ranging from 931V to 1071V at room temperature, with an average value of 1001V. These results show a variation of ~15% which can be attributed to the stochastic nature of PD in addition to variations in the winding enamel coating. It is believed that this value should be representative of the PDIV value of the machine turn-to-turn insulation within the machine. In a random wound machine such as the one studied here it is not possible to control the position of the individual turns within the slot. Consequently, the worst-case scenario, in which the first and last turns of the coil are in contact may occur. In this case the stress applied to the turn-to-turn insulation will be approximately equal to the voltage across the full coil, which in turn, during transient switching events due to transient effects may be approximately equal to the phase voltage. This being the case, there is an obvious risk of PD occurring within the turn-to-turn winding insulation when utilising a 1kV dc link voltage. Further to this, due to terminal overshooting it is also possible PD will also occur in this region when lower dc link voltages are used. This will be explored further in the discussion section of this paper when considering the terminal voltages for each sample.

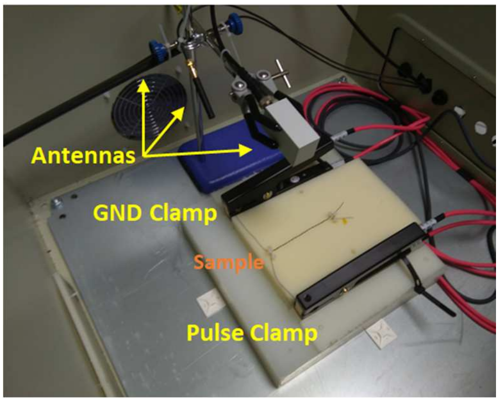


Fig. 2. Twisted Pair PDIV testing setup

2) Phase-to-Phase Insualtion

In the stator samples which are tested within this work, the ends of the three phases are connected together to form a neutral point which is buried within the end winding structure. Consequently, it is not possible to measure the phase-to-phase PDIV in these samples. To address this a special sample was manufactured in which the neutral point connection was not made, and the individual coil ends were led out separately; as this sample was otherwise identical to the other samples, it is not expected that this change will substantially alter the PDIV properties of the machine. The PDIV values for phase-to-phase insulation of the machine were measured using the MTC2. The resulting values are listed in Table I. It can be observed here that the PDIV value between the phases has an average value of 1086V. This value is similar to the measured value obtained for twisted pair samples. Such a result is to be expected as the machine does not employ additional phase separation materials. The phase-to-ground PDIV of this sample is also measured shows a ~25% increase compared to the phase-to-phase value. This can be explained by the inclusion of slot liner which increases the insulation thickness between the phases and ground. In these values a small amount of deviation can be observed between the different phase values. This can be attributed to small differences in the insulation system caused by the manufacturing process as well as the stochastic nature of PD.

TABLE I. MEASURED PDIV VALUES FOR MACHINE SAMPLE WITHOUT NEUTRAL POINT CONNECTION

	Case	PDIV	Average
Phase -to- Ground	PhA-Gnd	1253V	1355V
	PhB-Gnd	1443V	
	PhC-Gnd	1369V	
Phase -to- Phase	PhA-PhB	1053V	1086V
	PhB-PhC	1109V	
	PhC-PhA	1095V	

3) Phase-to-Ground Insulation

In the same way the MTC2 was used to measure the PDIV value of the phase-to-ground insulation for all ten of the experimental samples. For each sample this measurement was performed both before and after aging had occurred. The resulting PDIV values can be seen in TABLE II. Here the average PDIV value prior to testing is 1486V. The measured phase-to-ground value for the previous sample discussed with regards to the phase-to-phase measurements is consistent with the other samples suggesting that the alternative neutral point configuration does not impact the resulting PDIV of the machine. The PDIV was also measured for each sample at the end of testing, after the sample had failed. From this it can be seen that the PDIV for each sample is lower after failure. Factors which will have contributed to this include thinning of the wire insulation due to loss of volatile compounds and degradation of the ground wall insulation caused by the aging process.

TABLE II. PHASE-TO-GROUND PDIV VALUES OF TEST SAMPLES BEFORE AND AFTER TESTING

Sample	PDIV (Before)	PDIV(After)
1	1486V	758V
2	1397V	758V
3	1596V	364V
4	1436V	667V
5	1246V	1029V
6	1381V	761V
7	1685V	584V
8	1655V	625V
9	1352V	763V
10	1623V	350V

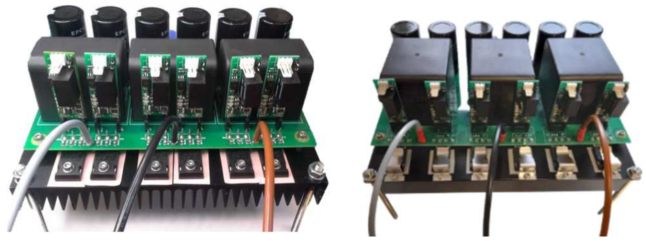
4) Temperature Effects on PDIV

The measurements which have been discussed in the previous section are applicable for machines at room temperature and pressure, however, the machines under test in the study will be operated at elevated temperature (230°C) during testing. In literature [5], a study on twisted pair samples is performed which generates an equation which allows PDIV to be calculated at differing temperatures and pressures. Based on this equation, it can be determined that the PDIV at 230°C will be ~86% of the room temperature value, at ambient atmospheric pressure. This fact should be considered when evaluating the PD activity observed within test samples.

C. SiC Inverter

In the tests, two different SiC based inverters were employed. The first of these is a 5kW 800V three-phase two-level inverter based on C2M0040120D SiC MOSFETs. Each MOSFET is driven by gate drivers which control the rise time of the converter through use of a gate drive resistor. The required gate resistance to achieve a given rise time are listed in TABLE III. This converter was used for testing at 600V and 800V dc link. PWM signals are supplied to the gate drivers from a DSP board driven by a TI TMS320F28335 allowing the converter to operate with a switching frequency of 20kHz, 40kHz and 60kHz. A photograph of the power board for this converter is shown in Fig. 3(a)

For 1 kV operation a second inverter is used. This is a 6kW 1kV three-phase two-level inverter based on C2M0080170P SiC MOSFETs. The topology of the converter is functionally identical to the previously described inverter, however the alternative MOSFETs provide sufficient headroom to allow the converter to be driven with a 1kV dc link voltage. A photograph of this converter is shown in Fig. 3(b).



(a) (b)

Fig. 3 Hardware view of employed SiC inverter. (a) – 800V Converter; (b) 1kV Converter

TABLE III. GATE RESISTOR CONFIGURATIONS USED TO ACHIEVE PRESCRIBED RISE TIME

Converter	Gate Resistor	Rise Time
800V	10 Ω	20ns
	25 Ω	40ns
	55 Ω	60ns
1 kV	10 Ω	20ns
	25 Ω	40ns
	55 Ω	60ns

D. Test Condition Selection

The focus of this study was to examine the impact of SiC converters on machine windings. SiC converters are desirable due to their ability to employ higher dc link voltages, faster switching speeds and higher switching frequencies than would be practical with conventional Si based devices. To this end, these three parameters will be varied when testing various samples. In this study the dc link will use the values 600V, 800V and 1kV, the switching frequency will take the values of 20kHz, 40kHz and 60kHz and the rise time will be 20ns, 40ns and 60ns. If we were to evaluate every potential combination of these factors it would be necessary to test 27 (3^3) samples. Unfortunately, due to resources and time constraints in this work this is not practical. For this reason, a full-factorial design approach, as described in [6] is employed. Details of how this approach is applied to this specific experiment is outlined in previously published work [7]. This approach allows the number of samples required to be reduced from 27 to only 9. Selection of the test cases is performed such that it is possible to mathematically reconstruct the entire experimental space covered by these samples by employing the processes outlined in [6]. The nine test configurations used in this work are listed in TABLE IV.

To ensure that the machine samples failed within an acceptable timeframe, all samples were tested within an oven operated at an ambient temperature of 230°C while being excited by the converter. By employing this ambient temperature, the expected thermal lifetime of the samples when no PD occurs is 840 hours (35 days).

TABLE IV. EXPERIMENTAL SAMPLE TESTING FACTORS

Sample	Factor		
	V_{DC} (V)	f_{sw} (kHz)	t_r (ns)
1	600	40	40
2	800	20	40
3	600	60	20
4	800	40	20
5	800	60	60
6	600	20	60
7	1000	40	60
8	1000	60	40
9	1000	20	20

III. PARTIAL DISCHARGE MONITORING

The use of higher dc link voltages combined with higher terminal overshooting increases the potential of PD activity within the machine winding. Such activity can lead to premature machine failure. To quantify the impact of this, PD activity was monitored for samples during testing. To achieve this, a PD detector made from a length of unterminated high temperature coaxial cable as explored and reported in [8] was used. This approach is particularly attractive in this application as it allows the construction of a very simple antenna which can be placed in close proximity to the sample under test at 230 ˚C. To prevent the PD antenna being influenced by other EMI generated by the converter (eg switching noise) a 500 MHz high pass filter was used.

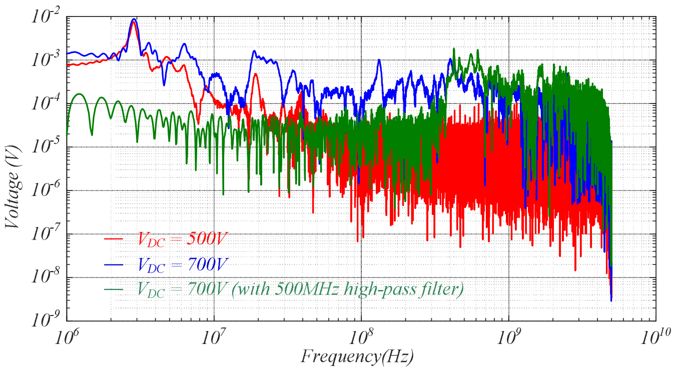


Fig. 4. Frequency spectrum of antenna signal captured for inverter voltages of 500V (No PD) and 700V (PD) dc link voltages

Literature shows that PWM based EMI is generally confined to frequencies below 100 MHz, whereas signals indicative of PD activity usually occupy the higher frequency region of the spectrum (GHz frequency range) [9]. This is also supported by the measurements shown in Fig. 4. Here the inverter was operated using dc link voltages of 500V and 700V, the frequency spectra of the signals captured using the antenna are shown. It can be seen that both signals contain frequency components below 100 MHz, however the 700V testing signal also contains a substantial component at frequencies above this threshold. These elements of the spectra are associated with PD activity. This figure also shows how the utilisation of a 500 MHz high pass filter removes the signal components associated with drive commutation, while leaving the PD related signals intact.

The signal from this antenna was captured using a 4-channel Teledyne Lecroy WavePro 404HD oscilloscope with 4GHz analogue bandwidth and 20G samples per second. This oscilloscope used the antenna signal to trigger signal acquisition. When triggered the oscilloscope would capture at least 4 PWM cycles. This signal was then processed online by the digital processing unit of the oscilloscope to calculate the moving standard deviation allowing the PD signals to be clearly extracted in the electromagnetically noisy environment [10]. The number of PD events within this processed signal are counted. The update rate of this process is limited to once per minute and it is assumed that the captured rate of PD within the signal is representative of the PD activity over the minute. An example signal obtained by this method before and after processing is shown in Fig. 5. The validity and accuracy of this method in detection of PD events was first confirmed by comparison with a commercial PD detection instrument, MTC2 winding tester from Schleich, before being deployed in the accelerated ageing tests.

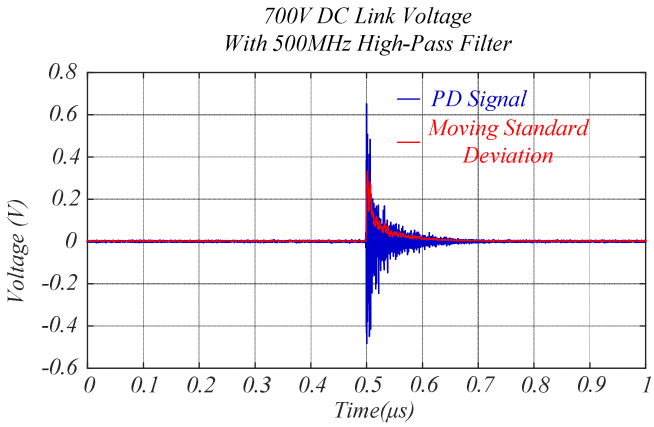


Fig. 5. PD signals captured by the antenna before and after process using standard deviation

IV. SAMPLE THERMAL INDEX AND EQUIVALENT LOSS OF THERMAL LIFE

The samples tested within this work are 2.8kW, 415V, 3-phase permanent magnet servo motors in mass production. The thermal index for these machine samples has been previously determined using a commercially available Si inverter [4], where no PDs occurred. The machine lifetime can be calculated using the Arrhenius equation (1) where L is the sample lifetime (in hours); L_0 is the reference sample lifetime (in hours) measured at reference temperature T_0 (K). T (K) is the temperature which corresponds to L, and B is a constant. L_0 at T_0 and B have been determined from accelerated aging tested samples and their values are listed in TABLE V. Based on these values and (1), the predicted thermal lifetime of the stator winding insulation at a temperature of 230 °C is ~840 hours (35 days).

$$L = L_0 e^{B(\frac{1}{T} - \frac{1}{T_0})} \quad (1)$$

TABLE V. MACHINE ARRHENIUS COEFFICIENTS

Coefficient	Value
L_0	1917.6 (hrs)
T_0	215+273 (K)
B	13497 (K)

Under the test conditions, the lifetime of the stator insulation will be influenced by both thermal and electrical aging mechanisms. To quantify thermal aging under varying temperature conditions, the Arrhenius equation (1) is rearranged to calculate the thermal loss of life of a sample for a given temperature profile using equation (2) where LoL_{therm} is the percentage loss of thermal life of the sample exposed to the temperature profile T(t) until failure time (t_f). Applying this equation to the measured temperature profiles for the test samples will allow the amount of sample lifetime lost due to thermal aging to be calculated. This value it is calculated using the temperature measured by a thermocouple embedded within the machine windings, allowing the effect of losses within the machine which will result in a temperature slightly higher than the oven temperature to be accounted for. Given that the coefficients for calculating this value for the samples in question were obtained using an IGBT drive which did not induce PD events, it can be concluded that any substantial reduction in life can be attributed to the use of the SiC converter. The equivalent lifetime in percentage, LoL_{elec}, is used in this paper to represent the proportion of life loss which it attributable to the influence of excessive voltage stress and partial discharge and can be evaluated by (3).

$$LoL_{therm} = 100 \int_0^{t_f} \frac{1}{L_0 e^{B\left(\frac{1}{T(t)} - \frac{1}{T_0}\right)}} dt \quad (2)$$

$$LoL_{elec} = (100 - LoL_{therm}) \quad (3)$$

V. Results and Discussions

The experimental lifetimes of the samples in each experimental condition are summarized in TABLE VI alongside the calculated loss of life values. Initially it is worth pointing out two things in these results. Firstly, when considering sample 1, this sample survived 21.8% longer than the thermal loss of life would predict, it was also the only sample in this experiment for which PD was not detected throughout the sample lifetime, therefore the lifetime would be expected to match the lifetime obtained when using a Si based inverter. Due to the statistical nature of failure it is not unreasonable that this sample exceeded the predicted lifetime, however it would be misleading to claim that driving the sample with a SiC inverter has resulted in the longer lifetime of the sample in this case; for this reason, the electrical loss of life value from this sample is listed as zero. It should be noted at this point that some degree of PD activity was detected during the lifetime of every sample which was tested except for sample 1.

TABLE VI. Sample lifetime and thermal loss of life

Sample	Factor			Lifetime (Hours)	LOL_{therm} (%)	LOL_{elec} (%)
	V_{DC} (V)	f_{sw} (kHz)	t_r (ns)			
1	600	40	40	802.0	121.8	0.0
2	800	20	40	402.8	74.6	25.4
3	600	60	20	412.6	55.5	44.5
4	800	40	20	350.8	42.3	57.7
5	800	60	60	53.6	13.4	86.6
6	600	20	60	119.3	17.1	82.9
7	1000	40	60	8.4	2.4	97.6
8	1000	60	40	1.1	0.15	99.85
9	1000	20	20	2.6	0.4	99.6
10	600	20	60	106.6	13.8	86.2

A further thing to note is the inclusion of a tenth sample, which was not included in the initial experimental plan, this sample was a repetition of sample six, which exhibited a lifetime much shorter than would have been expected given the test configuration, specifically the dc link voltage of 600V. Given that sample six and sample ten have lifetimes which are very close together (~half a day difference) confidence can be had that the result is accurate.

In the remainder of this section the factors which contribute to high electrical loss of life will be discussed and explanations for the resulting sample life provided.

A. Terminal Jump Voltage

For each sample during PD events the machine phase-to-core and neutral-to-core voltages were also captured by the oscilloscope. Based on this it is possible to analyse the magnitude of the jump voltage at both of these points. By comparing these values with the PDIV values of the machine for the different insulation systems of the machine it is possible to predict the occurrence of PD; using this data it is also possible to predict the likely location within the winding at which this occurred. Fig. 6 shows an example of these captured waveforms for sample 6 which had a dc link voltage of 600V.

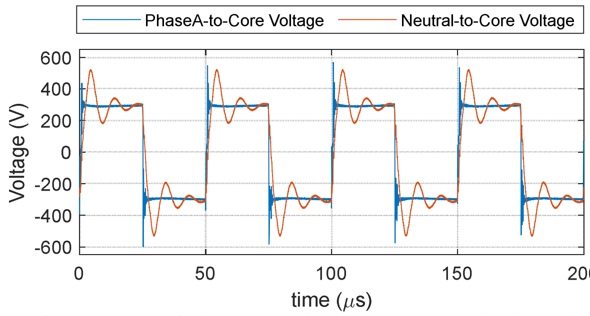


Fig. 6. Measured Phase-Ground and Neutral-Ground voltages in sample 6 (600V, 20kHz, 60ns)

TABLE VII. Measured Peak Jump Voltages at machine terminals and neutral point

#	DC (V)	fs (kHz)	tr (ns)	Terminal-GND Jump (V)	Neutral-GND Jump (V)
1	600	40	40	900	900
2	800	20	40	1191	1138
3	600	60	20	1241	971
4	800	40	20	1222	1294
5	800	60	60	1270	1297
6	600	20	60	941	819
7	1000	40	60	1448	1464
8	1000	60	40	1834	1616
9	1000	20	20	1494	1395
10	600	20	60	1090	806

A summary of the jump voltages captured for all samples during testing is provided in TABLE VII. Considering the values in this table it is interesting to note that the key parameter which influences the magnitude of the jump voltage is the dc link voltage. A much weaker link is observed between converter rise time and jump voltage in this dataset. While it is true that faster rise times result in slightly more overshooting than slower rise times, the difference between the rise times considered in this experiment do not produce a substantial amount of change to the peak terminal voltages. This can be attributed to the fact that all three of the considered risetimes are much faster than would be observed for a conventional Si based converter resulting in higher levels of terminal overshoot across the full range of samples. Consequently, under the specific conditions considered here, rise time does not have a substantial impact on terminal voltage overshoot, and by extension sample lifetime.

B. PD Occurance – Phase-to-ground insulation

By comparing the jump voltage with the PDIV values for the samples under test it is possible to evaluate the locations at which PD is likely to occur. Firstly, considering the phase-to-ground insulation system. Prior to testing the PDIV was measured for each sample at room temperature. In TABLE VIII the PDIV values for each sample are shown, here the values are adjusted to reflect the likely values at 230°C. This is achieved by multiplying the room temperature values by a factor of 0.86. This factor is derived from the PDIV, temperature relationship which is discussed in [5].

By comparing the magnitude of the phase-to-ground voltages to the PDIV value it can be observed that in the cases of samples 5, 8 and 9 the terminal jump voltage exceeds the PDIV value for the turn-to-ground insulation, making it unsurprising that PD was detected in these cases. It should also be noted that the peak phase-to-ground jump voltage of sample 7 is essentially equal to the PDIV of the sample. Given the level of uncertainties in PDIV measurement, it is likely that PDs also occurred in phase-to-ground insulation of this sample.

TABLE VIII. COMPARISON OF MAXIMUM PHASE-TO-GROUND JUMP VOLTAGE AND PDIV AT 230°C FOR ALL SAMPLES

#	$V_{pgj\text{-}max}$ (V)	$PDIV_{pg}$ at 230°C (V)	$V_{pgj\text{-}max}$ > $PDIV_{pg}$?	PD Detected?
1	900	1278	No	No
2	1191	1201	No	Yes
3	1241	1373	No	Yes
4	1222	1235	No	Yes
5	1270	1072	Yes	Yes
6	914	1188	No	Yes
7	1448	1449	Yes	Yes
8	1834	1423	Yes	Yes
9	1494	1163	Yes	Yes
10	1090	1396	No	Yes

C. PD Occurance – Phase-to-phase insulation

Similar treatment was given to the phase-to-phase voltages in TABLE IX. Here it is assumed that the magnitude of the phase-to-phase jump voltage is equal to the phase-to-ground volage. This is entirely possible if the ends of the coil for adjacent phases are positioned next to each other. It is possible that this arrangement will occur within the end winding of the machine, however it cannot be guaranteed or prevented due to the nature of random wound machines. In the samples under test, it was not possible to measure the value of PDIV between the phases for each sample due to the presence of the neutral point connection within the winding structure. Consequently, the quoted value of PDIV is based on the measurements of the sample in which the neutral point is not connected as discussed previously. Again, the values quoted here are multiplied by a factor of 0.86 to represent the effects of temperature on the PDIV value.

It can be seen from TABLE IX that in all samples except sample 1 the phase-to-phase voltage exceeds the PDIV value. This is consistent with the observed PD activity of the samples, in which PD occurred in all cases except sample 1. It is also possible that PDs may occur in the turn-to-turn insulation, if the coil voltage greater than its PDIV is applied across the first and last turns of the first coil in the random wound machine.

TABLE IX. COMPARISON OF MAXIMUM PHASE-TO-PHASE JUMP VOLTAGE AND PDIV AT 230°C FOR ALL SAMPLES

#	$V_{ppj\text{-}max}$ (V)	$PDIV_{pp}$ at 230°C (V)	$V_{pgp\text{-}max}$ > $PDIV_{pp}$?	PD Detected?
1	900	934	No	No
2	1191	934	Yes	Yes
3	1241	934	Yes	Yes
4	1222	934	Yes	Yes
5	1270	934	Yes	Yes
6	941	934	Yes	Yes
7	1448	934	Yes	Yes
8	1834	934	Yes	Yes
9	1494	934	Yes	Yes
10	1090	934	Yes	Yes

D. Development of PD over sample lifetime

1) 600V Sample

The plots shown in Fig. 7 present a range of useful information about the test sample over its lifetime. Firstly, considering the common mode capacitance, it can be observed that the common mode capacitance of the winding increases slightly, before decreasing for the remainder of testing. The increase in capacitance can be attributed to the initial heating up of the sample at the beginning of the test. The following decrease can be attributed to the thermal aging process which is undergone by the machine insulation. Specifically, as the insulation ages chemical processes occur including oxidisation of the polymer chains and loss of volatile compounds. Due to the encapsulated nature of the windings, it can be assumed that the overall geometry of the coils remains constant throughout the sample lifetime, it can therefore be concluded that the aging influence results in a reduction in the relative permittivity (ε_r) of the insulation over the sample lifetime.

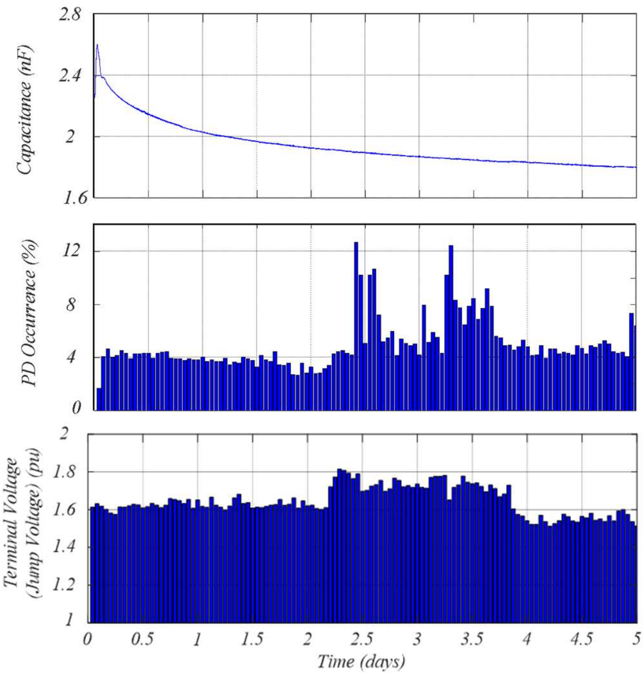


Fig. 7. 600V/20kHz/60ns sample (Sample 6) common mode capacitance and PD activity over sample lifetime

Secondly, it can be seen that the PD occurrence is at least ~4% throughout the entire sample lifetime. Here the PD occurrence is defined as the number of PD events, normalised to the number of switching events. For a 3-phase converter there are six switching events in each PWM cycle.

As can be observed in this sample, the PD occurrence value increases at just after 2 days of testing, reaching a peak value of ~12%. This increase coincides with an increase in peak terminal voltage (caused by overshooting). This increase in overshooting is likely to be linked to the reduction in insulation ε_r value, as a reduction in insulation ε_r will result in a reduction in capacitance, contributing to an increase in machine surge impedance, which in turn leads to an increase in voltage overshooting. Further to this, changes in the insulation properties will result in changing levels of damping at the machine terminals, resulting in both the increase seen in terminal voltage at ~2 days, and the decrease at ~4 days.

Throughout the test the terminal-to-ground voltage remains below the PDIV value for the ground wall insulation. It does exceed the phase-to-phase PDIV value. This suggests that the PD activity which is measured is likely to occur between the machine phases in this sample.

2) 800V Sample

Fig. 8 shows the common mode capacitance and PD activity for sample 4 which was tested at 800V DC link, with a 40 kHz switching frequency and 20ns rise time. Considering the data in this sample, the lifetime can be observed to be ~13 days. One point to note regarding this sample, is that during testing an issue of data recording arose resulting in gaps in which the PD and peak voltage data for this test is missing. In these cases, the PD activity is believed to be similar to the surrounding data at these points, as the values either side of the gaps are relatively consistent, therefore it can be reasonably assumed that the actual PD behaviour in these periods is comparable to the available data shown.

Comparing this data to the previously discussed 600V case, a number of observations can be made. Firstly, the normalised terminal jump volage is of a similar value in both cases (1.6 to 1.8), despite the rise time of these two samples differing. This would support the previously made observation that in these tests, rise time is not a significant influencer on lifetime for the range of value tested.

Due to the increased dc link voltage in this test, the absolute value of the terminal voltages is increased. This increase can be observed to result in a corresponding increase in the level of PD occurrences in this sample. In the case of the 800V sample, PD occurrence reaches a peak value of ~30%, which is the equivalent of approximately two PD events per PWM cycle.

When considering the terminal voltage in this case, it can be observed that a similar increase is observed at the beginning of the test to that which was seen in the 600V case. However, here the corresponding decrease in jump voltage later in the test is not observed. This highlights the complexity of the mechanisms which influence jump voltage. As different mechanisms will work in opposition, the overall direction in which jump voltage will change is ultimately determined by which mechanism is dominant at a given time. In the case of the 800V sample, the terminal jump voltage initially increases, suggesting that the change in surge impedance may be the dominant factor at this point. After this initial increase, the value stabilises and remains relatively constant for the remainder of the sample lifetime, this suggests that at this point the two mechanisms are balanced, resulting in little change to the overall jump voltage. It is also worth nothing that the common mode capacitance value changes in an exponential manner, with most of the change occurring in the earlier portion of the testing. Consequently, it can also be inferred that the surge voltage and dampening of the system will also follow this trend, with most of the changes occurring in this early period of testing, as both relate to the insulation capacitance/permittivity.

In this sample the voltage is very close to the phase-to-ground PDIV voltage (99%) and exceeds the phase-to-phase PDIV value. Therefore, PDIV activity will have occurred within the phase-to-phase region of the machine. Given the closeness of the phase-ground voltage to the PDIV value it is also likely that PD will occur between the phase and ground of the machine, especially after the insulation undergoes a small amount of aging.

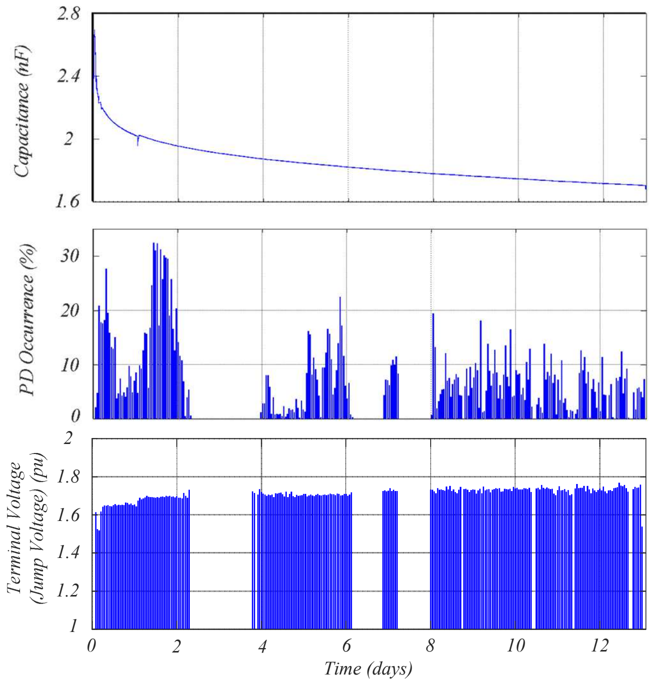


Fig. 8. 800V/40kHz/20ns sample (Sample 4) common mode capacitance and PD activity over sample lifetime

3) 1kV Sample

Fig. 9 shows data for sample 7 which was tested at 1kV DC link voltage, 40kHz switching frequency and 60ns rise time. The most significant point to note is that the lifetime of this sample is substantially lower than the other samples discussed to this point which were tested with lower dc link voltages, consequently it can be assumed that less thermal aging will occur in this sample. Observing the rates of PD in this sample it can be seen that the PD occurrence percentage is much higher than the previously discussed cases, with the peak PD occurrence reaching ~80% or 4.8 PD events per PWM cycle. In this sample the terminal jump voltage follows a similar trend to that observed in the 600V sample, initially increasing, before decreasing to a lower level and stabilising. This trend is mirrored in the PD occurrence percentage. In this case the terminal voltage is of comparable magnitude to the phase-to-ground PDIV, and well above the phase-to-phase PDIV consequently it is likely that PD activity occurred in all areas of the winding in this sample.

The sample considered here is the 1kV sample which exhibited the longest lifetime of all the 1kV samples, surviving for 2.4% of the expected thermal lifetime of the sample, this demonstrates the level of damage which is caused to machine insulation systems in the presence of PD.

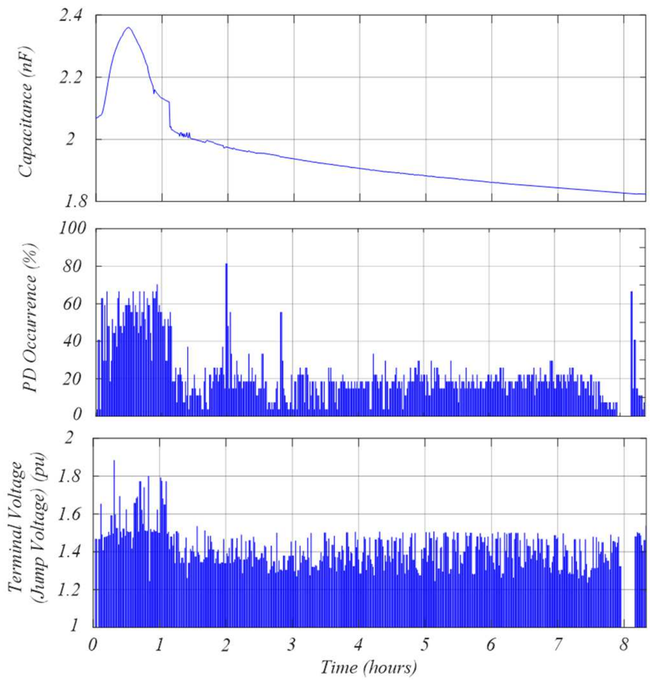


Fig. 9. 1kV/40kHz/60ns sample (Sample 7) common mode capacitance and PD activity over sample lifetime

VI. Conclusions

This paper has presented the lifetime of machine stator samples driven by a SiC based inverter under a range of dc link voltages, frequencies and rise times. From the results a number of conclusions can be drawn.

Firstly, the occurrence of PD has a significant impact on the lifetime of the samples. This can be most clearly observed by comparing the lifetime of sample 1 which did not experience PD with all other test samples which did. Doing this reveals that sample 1 had a lifetime approximately twice as long as any of the other samples tested.

Secondly, for the test conditions employed in these tests the DC link voltage and switching frequency are the most influential factors which contribute to electrical loss of life in the samples. Of these, the DC link was the largest contributor, as its increase enhances the likelihood that the peak voltage will exceed the PDIV of the insulation components.

In the sample under test the most vulnerable area of the insulation is the phase-to-phase insulation, due to the lack of a dedicated phase separator material within the end winding region of the machine.

Considering that PD occurred in the majority of samples tested at 600V, the insulation in this machine would need to be enhanced, to allow operation of this machine at 600V with a SiC based inverter. This could be achieved by enhancing the phase-to-phase insulation so that it is comparable to the phase-to-ground insulation. This is despite the fact that the machine has been shown to be capable of operating at 600V with a more traditional Si based inverter. The test result demonstrates the importance of validating the insulation system of a machine with the type of inverter which will be used to drive it, as failure to do so may result in the omission of increased voltage stress in the insulations which may cause premature in-service failure if overlooked. In the event that this machine was to be operated at DC link voltages above 600V it would be necessary to enhance the insulation in all areas to prevent the occurrence of PD.

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