Proceedings Paper:

Sundeep, S., Hewitt, D.A., Griffo, A. orcid.org/0000-0001-5642-2921 et al. (4 more authors) (2022) Detection of partial discharge activity in thermally aged SiC inverter fed stator winding samples and impact of partial discharges on their lifetime. In: 11th International Conference on Power Electronics, Machines and Drives (PEMD 2022). PEMD 2022 - The 11th International Conference on Power Electronics, Machines and Drives, 21-23 Jun 2022, Newcastle, UK (hybrid conference). IET Digital Library , pp. 271-277. ISBN 9781839537189

https://doi.org/10.1049/icp.2022.1062

DETECTION OF PARTIAL DISCHARGE ACTIVITY IN THERMALLY AGED SIC INVERTER FED STATOR WINDING SAMPLES AND IMPACT OF PARTIAL DISCHARGES ON THEIR LIFETIME

Shubham Sundeep[1], David A Hewitt[1], Antonio Griffo[1], Jiabin Wang[1], Fernando Alvarez-Gonzalez[2(1)], Mohamed S. Diab[3], Xibo Yuan[3]*

[1]*The University of Sheffield, Sheffield, United Kingdom*
[2]*Tecnalia Research & Innovation, Spain*
[3]*The University of Bristol, Bristol, United Kingdom*
**ssundeep1@sheffield.ac.uk*

Keywords: ELECTRIC MACHINES, PARTIAL DISCHARGES, INSULATION, ACCELERATED AGING, SILICON CARBIDE

Abstract

The rise in popularity of SiC devices in power electronic converters for machine drives has been driven by the potential to enhance power density and efficiency through higher DC link voltages and faster switching rates. These enhancements are not without drawbacks, however, as they result in high voltage stress on machine insulation and higher electromagnetic interference(EMI). Due to this, there is an enhanced potential for machine winding insulation to be exposed to stresses which exceed the partial discharge inception voltage (PDIV), leading to a significant lifetime reduction of winding insulation. In this work, the effect of SiC inverter operation on lifetime reduction is investigated. The stator samples are aged in an accelerated manner at 230°C while being driven by a SiC inverter. PD activity is detected using a custom manufactured high-temperature coaxial cable-based antenna, the selection of which is discussed in this paper, alongside the post-processing requirements of the signal required for reliable PD detection. Comparison is made between cases in which PD occurred, and cases in which it did not, allowing the impact of PD on the sample lifetime to be assessed.

1. Introduction

Electrical insulation systems used in the past were often not specifically designed to withstand partial discharge (PD). Although more recently, corona-resistant wires designed to resist PD have become available, it is still desirable to reduce PD activity. Many studies in the literature [1] [2] show that the fast slew rate voltage pulses impinging at the machine terminals, unlike line frequency (50-60Hz) voltage excitation, distributes non-linearly within the stator winding. Consequently, up to 80% of the voltage could be concentrated on the first few turns of the line end coil. In [3], it is shown that the voltage distributions with three-phase PWM voltage excitation, the turns close to the neutral point could be the most stressed. Under specific conditions, the peak-peak voltage stress across the main-wall insulation close to the neutral point may rise dramatically, reaching up to 4 times the DC link voltage. As a consequence, the voltage stress across the turn, main-wall, and phase-to-phase insulation may exceed the partial discharge inception voltage (PDIV). Several studies in the literature [4] [5] show that besides electrical factors such as fast slew rate and peak-peak voltage magnitude, environmental factors such as temperature, pressure, and humidity affects the PDIV. In [4], it is shown that the PDIV reduces with reduced pressure, reduced humidity, and increased temperature. The reduction in PDIV is measured with each environmental factor considered in isolation. In [5], a non-intrusive continuous online PD monitoring technique is used to detect the PD. However, the results do not provide sufficient information on the frequency of occurrence of PD over the lifetime of the machines. Many sensors have been proposed for PD detection in electrical equipment, including high bandwidth current sensors, coupling capacitors and antennas. The major challenges in the measurement of PD within the insulation system of the stator winding fed through a PWM voltage source are the interference from the commutation pulses of the inverter with the PD pulses. The requirement of a simplified, robust, and reliable yet automated process for detection of PD activity in the presence of commutation noise is of great importance for condition monitoring of the stator winding. In [6] [7] various measures such as antenna, filters, differential circuits, and software filtering techniques are introduced to improve the signal-to-noise ratio (SNR). In [6], an ultra-high-frequency (UHF) electric monopole antenna is used with a mid-band frequency of 1GHz directly connected to the signal cable and is placed inside the motor terminal box where the PD signal strength is strongest. To attenuate the commutation noise, several stages of analogue filters with cut-off frequency in the range of 100-800 MHz are connected in series with the signal cable. In another approach [7] an abrupt change in the standard deviation of the antenna acquired signal is used as an indication of PD activity. The aforementioned studies stress that the commutation noise and the PD activity are easier to distinguish in both time and frequency domains if the rise time of the voltage pulse is large. Therefore, these studies have specifically explored the PD activity due to PWM voltage pulse with a rise time of more than 60 ns. The rate of PD activity within winding insulation system during the thermal stress experienced in service life has not been reported in the literature, especially with SiC MOSFET based inverters which can have rise times as short as 20 ns and switching frequencies reaching 100kHz. Therefore, the experimental study presented in this paper will explore the impact of PD on machine samples driven by a SiC MOSFET based system at different DC link voltages using a low-cost PD sensor.

2. Experimental setup

In this work stator samples of an off-the-shelf 2.83 kW servo motor are used. These stator samples are kept at an ambient temperature of 230°C to accelerate the ageing and shorten the test duration to give an expected thermal lifetime of 35 days. This lifetime is determined from previous work performed using samples of this type driving by a Si IGBT based inverter [8]. The high ambient temperature is maintained using a temperature-controlled oven. During testing, the stator samples are aged simultaneously under electrical and thermal stress until their failure. An abrupt increase in the phase current above the threshold limit is identified as a failure criterion. The PWM inverter is operated in constant current mode injecting 0.5A RMS current into the winding for the duration of the test. In this paper, we will discuss the testing of two samples, both of which were driven using a prototype SiC based two-level inverter that was developed for this work by partners at the University of Bristol. The conditions under which each sample was driven can be observed in Table *1*.

Table 1 Sample testing conditions

Sample No.	Rise Time (ns)	DC Link Voltage (V)	Switching Frequency (kHz)
1	**40**	**600**	**40**
2	**40**	**800**	**20**

2.1. SiC Inverter

Fig 1 800V SiC inverter prototype

The SiC inverter used in this work is a 2-level, 3-phase inverter shown in Fig *1*. It is based on six 2nd generation 1.2kV MOSFETs manufactured by Cree. These are controlled by a DSP chip manufactured by Texas Instruments. Gate drive signals are provided by gate driver daughter boards mounted onto the main power board. These boards incorporate a gate resistor, the value of which can be adjusted to configure the converter rise time. The controller also incorporates over-current and over-voltage protection which are used to detect sample failure.

3. Detection of Partial Discharge

As has already been mentioned it is possible to detect PD activity using an antenna. This section of the paper will discuss the different antennas which were evaluated for the purpose of monitoring PD, it will also touch on methods by which the antenna signal was processed to achieve automated PD detection.

3.1. Selection of Antenna

Fig 2 Experimental setup used for antenna evaluation

During the initial stages of this work the ability of three different antennas to detect PD was evaluated. These antennas were a PD antenna designed by Schleich for use with their MTC2 winding analyser, a monopole antenna, and a dipole antenna. The three antennas were placed inside a metal box with a twisted pair sample as shown in Fig 2. The twisted pair sample was then excited by the MTC2 winding analyser to generate PD events. The antenna signals were all captured using a high bandwidth oscilloscope. An example of the captured waveform is shown in Fig *3*. From this figure it is apparent that both the dipole and monopole antennas generate comparable signals to those obtained from the specifically designed Schleich antenna.

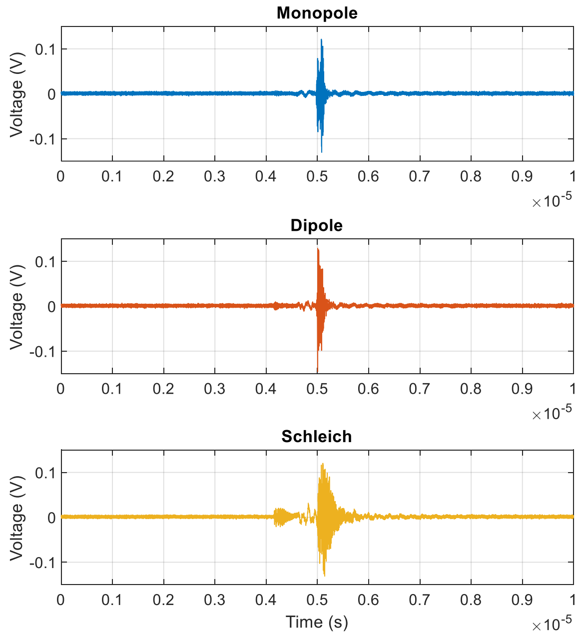


Fig 3 Response of different antenna types in the presence of a PD pulse

3.2. *High Pass Filtering*

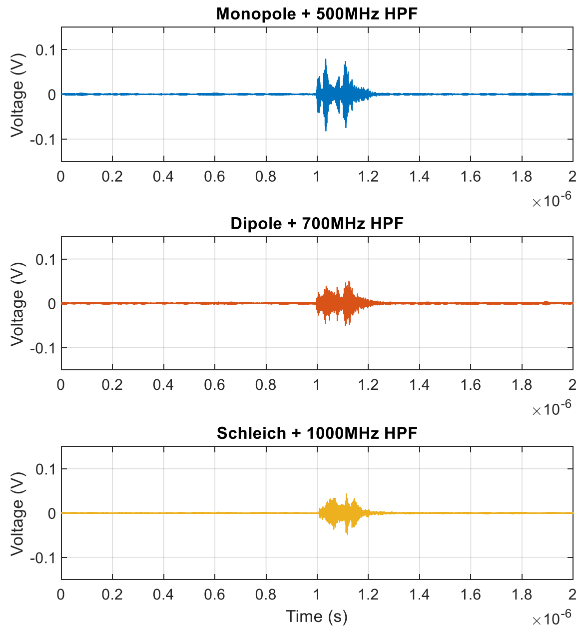
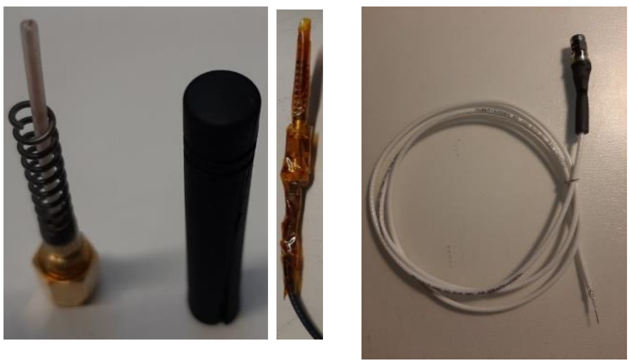


Fig 4 Response of different antenna types in the presence of a PD pulse (High pass filtered)

During inverter operation in addition to PD signals, there will also be other radiated signals detected by the antennas including switching and commutation noise. To reliably detect PD is it necessary to remove signals from these other sources. It has been shown in the literature [9] that commutation noise from PWM inverters is generally confined to frequencies below 100MHz, whereas PD signals generally exist within the GHz frequency range. Consequently, it is possible to suppress the effect of commutation noise by introducing a high pass filter to the system. For the desired functionality of this filter, it should be selected such that the filter removes the lower frequency commutation noise, while not impacting the higher frequency PD signals. The response of the three different antennas was tested with high pass filters of different cut-off frequencies, the results of this can be observed in Fig *4*. From this it can be seen that all three antennas still produce a noticeable response in the presence of PD, the three different high pass filter corner frequencies appear to have a little impact on the antenna response within the frequency range of interest for the detection of PD.

3.3. *High temperature antenna*

The antennas in combination with high-pass filtering evaluated in the previous section of this paper have been demonstrated to be suitable for the detection of PD events. As has been discussed, the samples will be exposed to a high temperature environment inside an oven. For the detection of PD, it is necessary to be able to also insert the PD antenna inside the oven. Unfortunately, none of the antennas tested up to this point is capable of operating within a 230°C environment. To address this, the alternative antenna constructions shown in Fig 5 are considered. These consist of an off-the-shelf monopole antenna with the outer plastic coating removed, and replaced with a layer of Kapton tape, and an unterminated length of high temperature coax cable which produces an approximation of a quarter-wavelength monopole antenna, based on the approach described in the literature [10].



(a) (b)

Fig 5 High temperature antennas (a) Stripped monopole, (b) unterminated coax antenna

Both antennas were tested with the MTC2 and twisted pair samples in the manner described in the previous section. The results of this can be seen in Fig *6*. It can be observed here that both antennas produce a clearly visible response in the presence of PD activity. Based on this, the unterminated coaxial cable antenna was selected for the monitoring of PDs within the experiment, because of its simplicity and ability to operate in high temperatures. The monopole antenna is designed for operation at low temperatures. Hence even with the cover being stripped, the effect of its long-term exposure to high temperature on PD detection is unknown. The combination of employing high temperature coaxial cable and the relative simplicity of the self-made coax antenna make such issues less likely for this configuration.

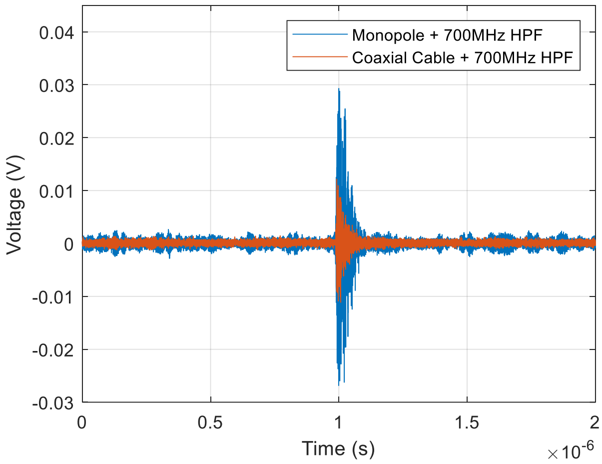


Fig 6 Comparison of monopole antenna and coaxial cable antenna (both include 700 MHz HPF)

3.4. Signal Processing

PD signals were captured using an oscilloscope with an analogue bandwidth of 4GHz and a sampling rate of 20GSa/s. The oscilloscope is set to trigger at the positive edge of the captured signal at a sampling frequency of 10GSa/s. At each triggered event, the recording length of the signal is equivalent to 4 switching cycles. The captured signal is then further processed to calculate the number of PD events. Before acquisition, the signal is passed through a 500 MHz high pass filter to remove commutation noise, as discussed previously.

The signal captured by the oscilloscope is processed by the user programmable processing unit using embedded MATLAB code to detect and record/count the PD events. The signal is processed once in every minute, assuming the frequency of occurrence throughout the time period is the same as in the captured signal. Any other captured signals within the minute are discarded without post processing. Examining the frequency spectrum of the PD signal it was observed that the components which relate to PD activity lie between 500MHz and 900MHz. To further isolate this region, a digital band-pass infinite impulse response (IIR) filter is used with 700MHz centre frequency and 400MHz bandwidth to reject the frequency components beyond this range. The digital band-pass filter ensures rejection of signals lying in very-high radio frequency range or beyond 900MHz. The moving standard deviation of the filtered signal is then calculated. Based on the peak of the MSD, the PD events can be identified.

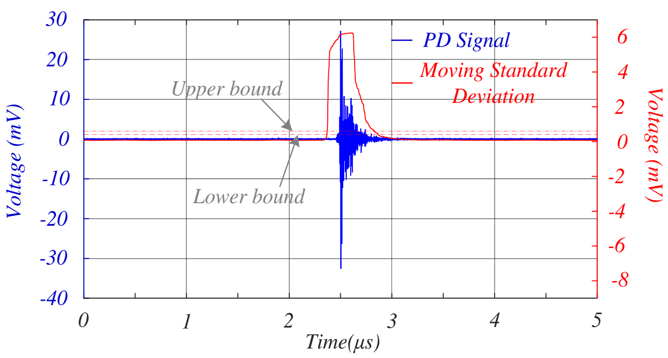


Fig 7 Example PD processing outputs

Each voltage pulse in one phase can trigger multiple PD events (on rising and falling edges) with different magnitudes. Additionally, switching in other phases can trigger multiple PD events, which may occur closely. As a result, the peak of the MSD of the filtered signal may occur closely. In addition, the MSD of the PD signal has high frequency ripples, which makes it difficult to count using a single threshold value. Therefore, to count the number of PD events, a hysteresis band is employed. An example of the signals generated from the antenna during the processing of a PD event can be observed in Fig *7*.

4. Insulation systems within sample machine

The machine samples used for testing in this work are from a commercial off-the-shelf 2.83kW servo motor. The single layer stator winding is a random wound with corona-resistant magnet wire. The winding is also impregnated with polyester resin. In addition to this insulation structure, the winding-to-ground insulation also includes a 0.25mm thick Trivothermal N slot liner between the stator core and windings and 0.35mm thick Nomex 410 as slot wedges. In this machine to reduce manufacturing cost, no additional insulation system is present between the machine phases, with inter-phase insulation being provided entirely by the turn-insulation system. The value of PDIV between machine phases will be lower than the phase-to-ground value because of this. Due to the random wound nature of the machine slots, turn position cannot be guaranteed. Consequently, the worst-case configuration may occur, this is when the first turn of the 1st coil is in direct contact with the last turn, resulting in voltage stress equal to almost the full coil voltage being applied to the turn insulation. Likewise, it is also possible that the two 1st turns of two phases are in direct contact with each other in the end-winding region. The inter-turn insulation may experience peak phase-to-phase voltage in this case.

5. Partial Discharge Inception Voltage of Samples

The PDIV value of the stator samples was tested prior to the ageing experiment. Due to the construction of the samples, which incorporate a star-point which is buried within the end winding, it was not possible to test each machine phase in isolation. Consequently, for these machines, it is only possible to measure the PDIV value of the phase-to-ground insulation system. To provide an insight into the phase-to-phase and turn-to-turn insulation values samples of the wire used to wind the stator were prepared in a twisted pair configuration. Given the lack of phase separation within the machine this method is believed to provide a value which will be representative of the turn-to-turn and phase-to-phase insulation systems.

5.1. Wire twisted pair samples

Ten twisted pair samples were prepared using the same wire used in the construction of the machine samples. Each of these samples was tested using the MTC2 winding analyser at room temperature. Of these samples, the highest value of PDIV was 1071V and the lowest was 931V, giving an average value of ~1000V. There is about 15% variation in the measure PDIV, which is attributable to the stochastic nature of PDs as well as uncertainties on the enamel coating thickness and contact distance of the twisted pairs. In addition, repetitive PDIV over 10 pulses can also be measured, which varies between 946V and 1213V for the samples tested. These measurements provide an indication of expected PDIV values in the turn-to-turn insulations. Since the machine does not employ additional insulation in the form of phase separators for the end winding between phases, the wires of two different phases are likely to be in close contact, in the end, winding region. Consequently, the PDIV of the phase-to-phase insulation is also likely to be close to the measured PDIV of the twisted pairs.

5.2. Phase-to-Ground PDIV

The PDIV of the machine phase-to-ground insulation was measured using the MTC2 winding analyser. Across multiple machine samples, a range of phase-to-ground PDIV values of 1246V to 1685V were observed, with an average value of 1486V. This value is ~50% higher than the value measured for the twisted pair samples, which can be attributed to the slot liner included within the ground wall insulation which increases the PD resilience of the phase-to-ground insulation system by increasing the separation distance by 0.25mm. After failure, the phase-to-ground PDIV was measured again using the MTC2, at this point, the PDIV was measured as ~760V for both samples. This reduction is potentially likely to contribute to an increase in PD activity over the lifetime observed for sample 2.

5.3. Temperature effects

The PDIV values quoted in this section were measured at room temperature. This is not representative of the conditions to which the samples will be exposed under testing, in which they will be placed in a 230°C environment. Work done by Lusuadri, et al. [11] performed on twisted pairs provides an equation for the calculation of PDIV with respect to temperature. This work suggests that increasing the temperature from room temperature to 230°C will result in a reduction of PDIV to ~80% of the room temperature value. Based on this it is expected that under experimental conditions the turn-to-turn/phase-to-phase PDIV will be ~800V and the phase-to-ground PDIV will be ~1189V.

6. Lifetime Testing Results

The machine samples were placed within the oven and driven by the SiC inverter under the conditions outlined in Table *1*. The operation was continued until the drive entered an overcurrent state indicating insulation failure. The resultant lifetimes for the samples can be observed in Table *2*. From this, it can be observed that sample 1 operated for approximately twice as long as sample 2.

Table 2 Experimental lifetime of test samples

Sample No.	DC Link Voltage (V)	Sample Lifetime (Days)
1	**600**	**33.4**
2	**800**	**16.8**

Sample 1 was tested at 600V DC link voltage. Under the SiC inverter operation, the measured peak phase-to-ground voltage is 1050V, 1.8 times greater than the DC link voltage. This value is ~10% lower than the PDIV of the phase-to-ground insulation. Although the expected peak phase-to-phase jump voltage of 1050V is greater than the PDIV of the turn-to-turn insulation, the worst-case condition, i.e., direct contact between two 1st turns in two phases does not appear to take place in this sample, as no PDs were detected throughout the ageing test and the lifetime of this sample is very closed to its expect thermal lifetime. Since each phase consists of 3 series of connected coils, the voltage across the 1st coil is below the turn-to-turn PDIV. Thus it is unlikely that PDs occur within the turn-to-turn insulation of a coil under this condition.

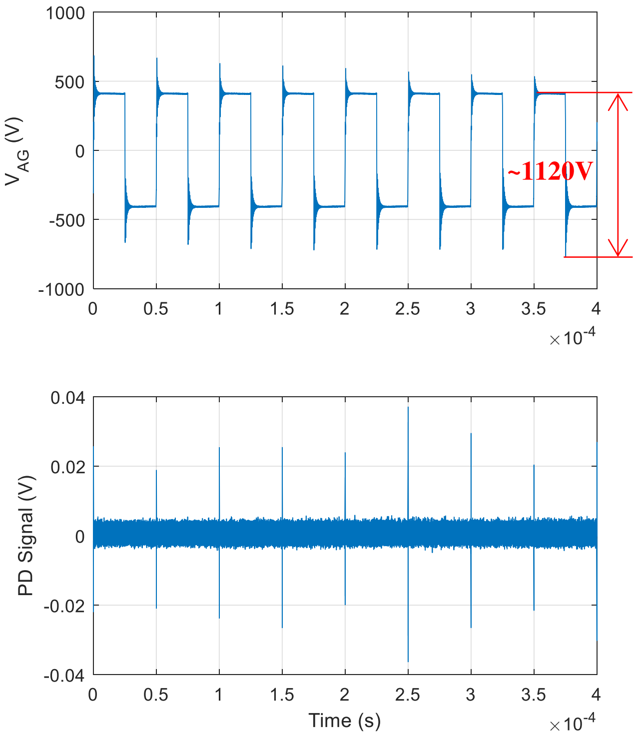


Fig 8 Sample 2 Machine Terminal-Ground voltage and PD signals measured on day 7

Sample 2 was tested at 800V DC link voltage. Due to the wave propagation effect of the cable-machine system, the terminal voltage of the sample exceeded the PDIV value. Consequently, PD activity was observed during the lifetime of the sample. At the beginning of the test, the PD occurs sporadically, with a repetition rate of several minutes. The frequency of occurrence of PD increases over the lifespan of 17 days. Thus, the occurrence of PD can be seen to increase over the course of the experiment, particularly in the closing stages of the sample lifetime. From the data are shown in Fig *8* it can be seen that the phase-ground voltage experiences a peak-to-peak value of 1320V. This value is higher than the PDIV of the phase-to-ground voltage insulation within the machine. The average peak jump voltage is 1120V slightly lower than the average phase-to-ground PDIV. Given the uncertainties in the PDIV measurements, the PDs may occur when the jump voltage is around 1120V, as evident in Fig. 8. The phase-to-phase voltage is also expected to be of comparable magnitude, exceeding the phase-to-phase PDIV value; this provides the scope of PD to also occur within the end winding region of the machine also.

7. Impact of PD activity on lifetime

When the lifetime of the two samples is compared it can be clearly seen that the sample which experienced PD had a substantially reduced lifetime when compared to the sample which did not.

It is worth noting that the samples used within this work are of the same design and construction as the samples studied in [8]. In the case of [8] the samples were driven using a commercially available Si based IGBT drive which did not generate PD events over the lifetime of the sample. It is therefore unsurprising that Sample 1 in this work exhibited a comparable lifetime to the sample which was also excited at 230°C.

Sample 2 experienced a lifetime of approximately half of that seen in Sample 1. This can be attributed to the PD activity which was detected within the sample during operation. It is important to note the fact that the DC link voltage during testing was below the PDIV values of the machine, however, due to the overshooting at the terminals, the voltage stress applied to the winding, particularly in the phase-to-ground and phase-to-phase end winding region will exceed the value of PDIV resulting in PD and causing the lifetime to be reduced, as has been demonstrated here.

This observation highlights the importance of the design of insulation systems to prevent the occurrence of PD by considering the potential peak voltage values due to terminal overshooting, as even a small amount of PD activity can result in a substantial reduction in machine lifetime. A collection of PD mitigation measures may include ensuring adequate rated winding insulation; inclusion of phase separation insulation to reduce the impact of phase-to-phase voltages; ensuring encapsulation is of high quality and is free from voids which could act as catalysts for PD activity; designing systems to reduce the impact of cables on terminal voltage overshoot. By ensuring these factors are suitably considered it should be possible to reduce/mitigate the impact of PD on the machine's lifetime.

8. Conclusions

The results presented here highlight a potential issue which can arise when using SiC based inverters which would not have been significant for traditional Si based inverters due to the operating limits of Si based technology. The higher voltages and faster switching speeds of SiC based inverters generate the potential for machine voltages to exceed the PDIV value of the winding insulation. This in turn can lead to PD activity occurring and premature machine failure. This effect is caused, not only by the increase in DC link voltage but also by terminal overshooting due to the transmission line effect within the machine cables exasperated by the fast switching action of the SiC based devices (when compared to their Si counterparts).

This work demonstrates the importance of ensuring the PD does not occur within the machine winding insulation, as even a small amount of PD can result in a substantial reduction in machine lifetime.

9. Acknowledgement

The authors acknowledge the funding from the UKRI under grant EP/S00081X/1 for the work presented in this paper.

10. References

[1] M. K. Hussain and P. Gomez, "Modeling of machine coils under fast front excitation using a non-uniform multiconductor transmission line approach," in *Proc. IEEE North American Power Symposium (NAPS)*, Denver, CO,, 2016.

[2] R. Beeckman, "Inverter drive issues and magnet wire responses," in *Proc. IEEE Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Conference (EICEMCW)*, 1999.

[3] S. Sundeep, J. Wang, A. Griffo and F. Alvarez-Gonzalez, "Antiresonance Phenomenon and Peak Voltage Stress Within PWM Inverter Fed Stator Winding," *IEEE Transactions on Industrial Electronics,* vol. 68, no. 12, pp. 11826-11836, 2021.

[4] E. Sili, J. P. Cambronne, N. Naudé and R. Khazaka, "Polyimide lifetime under partial discharge aging: effects of temperature, pressure and humidity," *IEEE Trans. Dielectr. Electr. Insul,* vol. 20, pp. 435-442, 2013.

[5] G. C. Stone, H. G. Sedding and C. Chan, "Experience with online partial-discharge measurement in high-voltage inverter-fed motors," *IEEE Trans. Ind. Appl,* vol. 54, no. 1, pp. 866-872, 2018.

[6] A. Cavallini, G. C. Montanari, A. Contin and Y. Qinxue, "Techniques for off-line measurement and analysis of PD pulses in inverter-fed induction motors," in *Proc. IEEE International Conference on Properties and Applications of Dielectric Materials (ICPADM)*, Nagoya, Japan, 2003.

[7] R. Ghosh, P. Seri, R. E. Hebner and G. C. Montanari, "Noise rejection and detection of partial discharges under repetitive impulse supply voltage," *IEEE Trans. Ind. Electron.,* vol. 67, no. 5, pp. 4144-4151, 2020.

[8] A. Griffo, I. Tsyokhla and J. Wang, "Lifetime of Machines Undergoing Thermal Cycling Stress," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Baltimore, MD, USA, 2019.

[9] T. Billard, T. Lebey and F. Fresnet, "Partial Discharge in Electric Motor Fed by a PWM Inverter: Off-line and On-line Detection," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 21, no. 3, pp. 1235-1242, 2014.

[10] T. Billard, F. Fresnet, M. Makarov, T. Lebey, P. Castlan, P. Bidan and S. Dinculescu, "Using non-intrusive

sensors to detect partial discharges in a PWM inverter environment: a twisted pair example," in *2013 Electrical Insulation Conference*, Ottawa, Ontario, Canada, 2013.

[11] L. Lusuardi, A. Rumi, A. Cavallini, D. Barater and S. Nuzzo, "Partial Discharge Phenomena in Electrical Machines for the More Electrical Aircraft. Part II: Impact of Reduced Pressures and Wide Bandgap Devices," *IEEE Access,* vol. 9, pp. 27485-27495, 2021.