Experimental considerations on the possible impact of space charge accumulation on partial discharges activity for wire insulations

Hadi Naderiallaf
Power Electronics, Machine and Control Group (PEMC)
University of Nottingham
Nottingham, The United Kingdom
Hadi.Naderiallaf@nottingham.ac.uk

Paolo Giangrande
Power Electronics, Machine and Control Group (PEMC)
University of Nottingham
Nottingham, The United Kingdom
P.Giangrande@nottingham.ac.uk

Michael Galea*
Department of Industrial Electrical Power Conversion
University of Malta
michael.d.galea@um.edu.mt

2022 IEEE 4th International Conference on Dielectrics (ICD) | 978-1-6654-1833-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICD53806.2022.9863223

***Abstract*— The impact of space charge accumulation caused by unipolar square waveform excitation on partial discharge inception voltage (PDIV) and partial discharge extinction voltage (PDEV) for one Type-II insulated wire, i.e., Glass fibre and one Type-I insulated wire Polyether Ether Ketone (PEEK), are compared and investigated experimentally in this paper. Two rise times (i.e., 80 and 800 ns) and two impulse voltage repetition frequencies (i.e., 50 Hz and 2.5 kHz) are considered under different exposure times. Additionally, the influence of rise time and impulse voltage frequency on PDIV level of dispersion as a function of exposure time is compared for the two insulated wires, relying on the shape/slope parameter of the Weibull distribution.**

***Keywords*— partial discharges, space charge, electric machines, variable speed drives, pulse width modulation**

I. Introduction

It is widely known that using converter-fed electrical machines can result in better control, energy efficiency, power density and versatility [1-3]. However, they pose challenges for the insulation system, especially the turn-to-turn insulation [4]. Indeed, short rise times increase the non-linear partition of the jump voltage (potential difference between the line terminal and the star point) between the turns [5]. It increases the chance of partial discharges (PD) inception between adjacent turns, resulting in reliability reduction. PD is known as the main reason for the premature failure of the winding insulation. Type-I insulations are generally employed as winding insulation of low voltage electrical machines, where PD is considered an end-of-life criterion [6]. An alternative solution could be using Type II (i.e., mixed organic-inorganic materials) due to the more resistance against PD activity. Based on this paradigm shift, one commercially available Type II insulated wire (i.e., Glass fibre) and one Type I insulated wire Polyether Ether Ketone (PEEK) insulated wire are considered for this experimental comparative study.

The space charge accumulation under unipolar square waveform excitation (e.g., 3-level inverters) is inevitable even at high impulse repetition frequencies due to the presence of a DC component. It can affect the partial discharge inception voltage as a function of poling time [7]. Besides interfacial polarization, this phenomenon would be more plausible using Type II insulation due to mixed organic-inorganic materials, thus, different permittivity and conductivity values. Therefore, the space charge accumulation impact on PDIV and partial discharge extinction voltage (PDEV) as a function of exposure time are investigated experimentally in this paper.

II. Methodology

A. PD Measurement Setup

The PD sensor is typically an ultra-high-frequency (UHF) antenna that features the bandwidth of 100 MHz–3 GHz. A frequency shifter mitigates the frequency content of the UHF signals to the desirable range for the impulsive test synchronization module (ITSM) and the PD detection unit. The role of the ITSM is the generation of a digital synchronization signal synchronized to the pulse generator fundamental frequency via low pass filtering. The PD detection unit can perform the PD test under impulsive voltage excitation via this connection layout [8]. The PD detection unit is a Techimp PDBaseII featured bandwidth of 40 MHz and a sampling rate of 200 MSa/s. A high-pass filter can be connected between the UHF antenna and frequency shifter, improving the signal-to-noise ratio (SNR) [8]. The voltage waveform applied to the specimen under test is monitored by Lecroy WaveJet Touch 334 oscilloscope (350 MHz bandwidth, 2 GS/s sampling rate). The voltage waveform is measured by a CT4079-NA differential probe (50 MHz bandwidth, 2000:1 voltage ratio, 50 Ω impendence).

B. Test Samples

A pair of Glass fibre wires wrapped in polytetrafluoroethylene (PTFE) tape and twisted pairs of PEEK insulated wires are implemented to model the turn-to-turn insulation for low-voltage electrical machines. PTFE tapes are used to make the wrapped pairs of Glass fibre since the insulation coating of wires might be cracked if they are twisted (because of the tiny bending radius). Thus, PTFE is used only to provide a complete fitting between the insulation surfaces (Fig. 1). The manufacturer of the Glass fibre insulated wires (2 Silix VSI) is Von Roll. According to the ASTM D2307 standard, the twisted pairs of PEEK insulated wires (manufactured by ZEUS) are made (Fig. 1). The samples features are summarized in Table 1.

TABLE I
Test Samples Characteristics.

Insulated wire	Length (cm)	Bare wire diameter (mm)	Insulation thickness (μm)
Glass fibre	22	0.9	100
PEEK	22	0.9	40

*: Also, with PEMC, University of Nottingham, UK

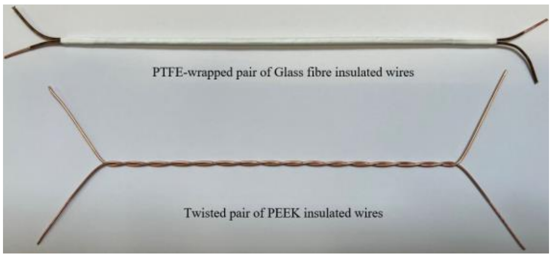


Fig. 1. Sample tests.

C. *Measurement Procedure*

A commercial variable pulse generator system (RUP6-18bip) is then used to generate positive and negative unipolar square voltage waveform excitations. The impulse width duration is set constant to 100 µs. Two impulse voltage repetition frequencies (i.e., 50 Hz and 2.5 kHz) and two rise times (i.e., 80 ns and 800 ns) are considered for the PD measurements.

The PD tests are carried out at room temperature (21°C), atmospheric pressure (1013 mbar) and relative humidity (28±5%). First, PDIV is measured for each specimen. Then, the peak value of the voltage is reduced to 0.85, i.e., as a steady poling voltage for two exposure time durations: half an hour and one hour. Eventually, PDIV and PDEV measurements are performed at the end of each exposure time. Five pristine specimens are tested for each considered case. The Weibull distribution of the five measured peak values is calculated. Then, a percentile in the tail of the distribution (i.e., B10) is used to draw the PDIV and PDEV trends as a function of exposure time. B10 is selected since the weakest link of the chain determines the reliability of the whole system in the insulation systems (thus, 90% reliability) [5].

The voltage is raised in steps of 25 V peak and the stop duration of 30 seconds, starting from the poling voltage [9]. Once the PD activity is triggered, the peak magnitude of the voltage is recorded as PDIV. The reason to consider the peak value is the PD-free criterion, where the peak voltage between the two adjacent turns must be lower than the minimum PDIV [6]. After recording PDIV, the voltage is reduced in steps of 25 V peak and the stop duration of one minute. When the PD activity is ceased, the peak of the applied voltage is registered as PDEV.

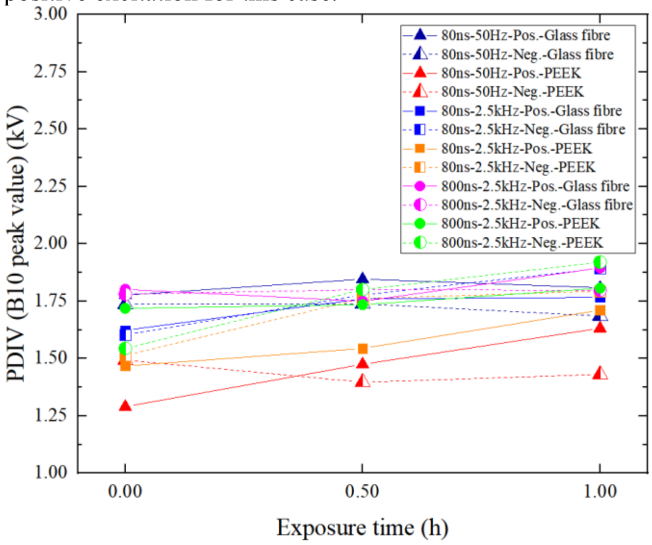
III. Experimental Results and Discussions

A. *PDIV and PDEV*

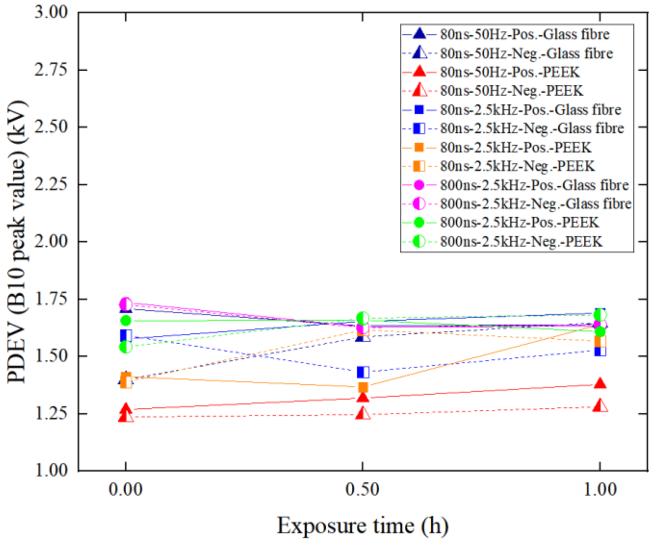
The PDIV and PDEV results as a function of poling time are illustrated in Figs. 2a and 2b, respectively. Overall, the variation of PDEV as a function of exposure time compare with PDIV is almost negligible, especially after half an hour. In addition, the Glass fibre insulated wire gives comparable PDIV values under positive and negative polarities for all cases. The two insulated wires are compared for each considered waveform characteristic in the following.

Glass fibre vs. PEEK @80 ns-50 Hz

Glass fibre delivers higher PDIV and PDEV than PEEK for both polarities in all exposure time durations. PDEV (under both excitation polarities) and PDIV (especially under negative excitation) reach stability after half an hour for both wires. There is a monotone increasing trend for PDIV and PDEV of PEEK insulated wire under positive polarity against exposure time. The increasing rate is more considerable for the former (PDIV). This rising trend of PDIV is likely due to the continuous heterocharge accumulation, leading to electric field reduction in the air gap versus poling time. However, PDIV and PDEV of Glass fibre remain almost constant under positive excitation for this case.



(a)



(b)

Fig. 2. (a) PDIV and (b) PDEV trend consequent to poling time for Glass fibre vs PEEK insulated wires using two different rise times and frequencies under unipolar positive and negative impulse voltage excitations, relying on the tenth percentile of the Weibull distribution.

Glass fibre vs. PEEK @80 ns-2.5 kHz

Glass fibre gives higher PDIV (under both polarities) and PDEV (under positive polarity) than PEEK insulated wire versus exposure time. The PDEV of insulated wires is comparable for both polarities after one hour. The PDIV and PDEV of Glass fibre reach a saturation level after half an hour under positive excitation. However, there is a steady growth trend for PDIV of Glass fibre under negative polarity. It can be associated with continuous heterocharge accumulation. There is an increasing trend for PDIV and PDEV of PEEK insulated wire under positive excitation after half an hour (probably due to heterocharge space charge accumulation). The opposite holds under negative polarity where PDIV and PDEV reach almost stability after half an hour.

Frequency Impact on PDIV and PDEV vs. Exposure Time

The comparing results between 80 ns-50 Hz and 80 ns-2.5 kHz can reflect the effect of frequency on PDIV and PDEV against exposure time. Considering the PEEK insulated wire, lower PDIV and PDEV for both polarities and in all exposure durations are attributed to lower frequency (i.e., 50 Hz). It can be ascribed to the higher permittivity of PEEK insulation at 50 Hz. It can increase the electric field in the air gap between the two adjacent wires, resulting in PDIV and PDEV reduction at 50 Hz. Regarding the Glass fibre insulated wire, PDIV is lower at 2.5 kHz under positive polarity in all exposure durations. The same holds under negative polarity before stressing the specimen. As a result, the frequency impact on PDIV depends on the wire insulation type. The lower PDIV at a higher frequency (i.e., 2.5 kHz) for the Glass fibre is likely due to the less chance for the depletion of deposited charges after subsequent PD when the frequency is higher [10]. Therefore, first electron availability to initiate PD would be more plausible for Glass fibre at a higher frequency. There are only two exceptions for Glass fibre where the PDIV is lower at 50 Hz. These are under negative excitation and after half an hour and one hour. This exclusion can be attributed to homocharge accumulation, which is more plausible at a lower frequency, leading to lower PDIV at 50 Hz. Considering the PDEV of Glass fibre under positive polarity, lower PDEV before stressing the specimen belongs to 2.5 kHz (same as PDIV). However, PDEV values are comparable for both frequencies after half an hour (thus, space charge accumulation). Under negative excitation, lower PDEV for Glass fibre is measured at 2.5 kHz after half an hour.

Glass fibre vs. PEEK @800 ns-2.5 kHz

Glass fibre delivers higher PDIV and PDEV for both excitation polarities (especially negative polarity) before stressing the specimens. The PDIV and PDEV of the wires are comparable for both polarities after half an hour. The superiority of Glass fibre under positive excitation is more evident after one hour when Glass fibre gives higher PDIV. However, PEEK insulated wire can provide higher PDIV under negative polarity after one hour of exposure time. Indeed, PDIV of PEEK increases monotone as a function of exposure time in this case (probably due to heterocharge accumulation), providing an exception where PEEK can finally deliver higher PDIV than Glass fibre insulated wire. PEEK shows a stable PDIV versus exposure time when the rise time is longer (i.e., 800 ns) under positive excitations. The same holds for the Glass fibre under negative excitation. The measured PDEV values at a longer rise time (i.e., 800 ns) are comparable for the two wires under both polarities after half an hour. Both insulated wires show low variations of PDEV versus exposure time under positive polarity when the rise time is longer. The same holds under negative polarity after half an hour.

Rise Time Impact on PDIV and PDEV vs. Exposure Time

The comparing results between 80 ns-2.5 kHz and 800 ns-2.5 kHz can reflect the rise time impact on PDIV and PDEV as a function of exposure time. The lower PDIV is associated with faster rise time (i.e., 80 ns) under both polarities and in all exposure durations for the PEEK insulated wire. The same holds for PDEV, while comparable values at both rise times are observed under positive excitation and after one hour. Regarding the Glass fibre insulated wire, the lower PDIV versus exposure time is attributed to shorter rise time under positive polarity before stressing the specimens and after one hour. PDIV values are almost comparable for both rise times under both polarities after half an hour. The lower PDIV is associated with a faster rise time (i.e., 80 ns) for both polarities before stressing the specimens. The reason to measure lower PDIV at a shorter rise time is likely due to permittivity escalation, resulting in an electric field increase in the air gap. This speculation is supported by higher measured capacitance for the stressed specimens by a shorter rise time (i.e., 80 ns) [12]. Indeed, effective permittivity can increase via more surface charge density caused by higher PD charge amplitude and PD repetition rate when the rise time is faster [11, 12]. However, this description may not set up a reasonable description for a significantly shorter rise time where the impact of first electron availability could result in higher PDIV [5].

The measured PDIV at a shorter rise time is higher than a longer one in one exceptional case. It is related to the Glass fibre insulated wire under negative excitation (80ns-2.5 kHz) after one hour. Indeed, there is a monotone increasing trend for PDIV as a function of exposure time when the rise time is faster. It is likely due to continuous heterocharge accumulation caused by faster rise time under negative excitation. Considering the Glass fibre insulated wire, the lower PDEV versus exposure time belongs to a shorter rise time under negative excitation. The same holds for the positive excitation before stressing the specimens. However, the measured PDEV values under positive polarity are comparable for both rise times after half an hour of exposure time.

B. PDIV Dispersion Level vs. Exposure Time

Fig. 3 illustrates the dispersion level of the measured PDIV for the insulated wires consequent to poling time resorting to the shape/slope parameter of the Weibull distribution (i.e., β).

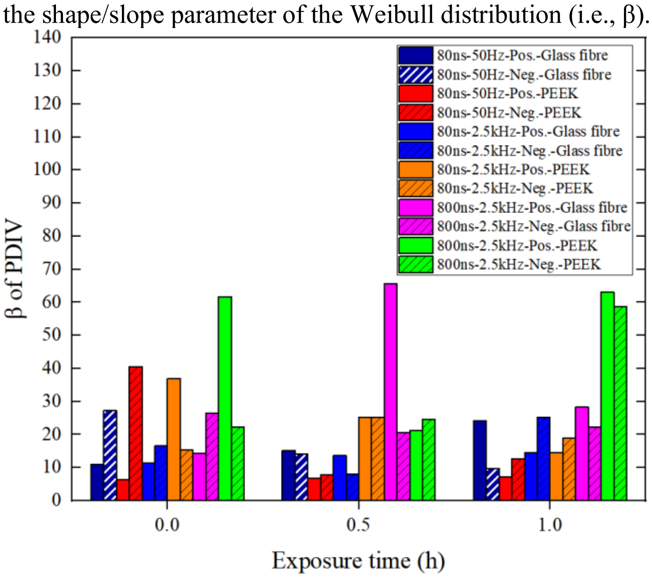


Fig. 3. The dispersion level of measured peak values of PDIV as a function of poling time under unipolar positive and negative impulse voltage excitations, using the shape/slope parameter of the Weibull distribution.

For the sake of brevity, the following β of PDIV for the Glass fibre insulated wire under positive and negative excitations are abbreviated as β_{GF}^{+} and β_{GF}^{-}, respectively.

Similarly, these quantities are denoted for the PEEK insulated wire like $\beta^{+}_{\mathrm{PEEK}}$ and $\beta^{-}_{\mathrm{PEEK}}$.

β of PDIV @80 ns-50 Hz Glass fibre vs. PEEK

It demonstrates $\beta^{+}_{\mathrm{GF}} > \beta^{+}_{\mathrm{PEEK}}$ in all exposure durations, particularly after one hour. Interestingly, β^{+}_{GF} increases as a function of exposure time, while the opposite holds for β^{-}_{GF}. However, $\beta^{+}_{\mathrm{PEEK}}$ remains steady as a function of exposure time. The collected data indicates the lowest dispersion level/highest β^{-}_{GF} and $\beta^{-}_{\mathrm{PEEK}}$ before stressing the specimens.

β of PDIV @80 ns-2.5 kHz Glass fibre vs. PEEK

It represents $\beta^{+}_{\mathrm{PEEK}} > \beta^{+}_{\mathrm{GF}}$ before stressing the specimens and after half an hour. However, $\beta^{+}_{\mathrm{PEEK}} \approx \beta^{+}_{\mathrm{GF}}$ after one hour of exposure time. Indeed, β^{+}_{GF} increases as a function of exposure time, while $\beta^{+}_{\mathrm{PEEK}}$ decreases.

Frequency Impact on β of PDIV vs. Exposure Time

The comparison of PDIV dispersion levels between 80 ns-50 Hz and 80 ns-2.5 kHz can reflect the effect of frequency on β of PDIV as a function of exposure time. Although $\beta^{+}_{\mathrm{GF(50\,Hz)}} \approx \beta^{+}_{\mathrm{GF(2.5\,kHz)}}$ before stressing the specimens, $\beta^{+}_{\mathrm{GF(50\,Hz)}} > \beta^{+}_{\mathrm{GF(2.5\,kHz)}}$ after one hour exposure time for the Glass fibre insulated wire. Indeed, both $\beta^{+}_{\mathrm{GF(50\,Hz)}}$ and $\beta^{+}_{\mathrm{GF(2.5\,kHz)}}$ increase as a function of exposure time. However, the increase rate of the former is higher, resulting in $\beta^{+}_{\mathrm{GF(50\,Hz)}} > \beta^{+}_{\mathrm{GF(2.5\,kHz)}}$ after one hour exposure time. $\beta^{-}_{\mathrm{GF(50\,Hz)}}$ decreases as a function of poling time, while the lowest dispersion level/highest $\beta^{-}_{\mathrm{GF(2.5\,kHz)}}$ is observed after one hour of exposure time. Considering the PEEK insulated wire, it is observed that $\beta^{+}_{\mathrm{PEEK(2.5\,kHz)}} > \beta^{+}_{\mathrm{PEEK(50\,Hz)}}$ in all exposure times. Although $\beta^{+}_{\mathrm{PEEK(2.5\,kHz)}}$ decreases as a function of exposure time, $\beta^{+}_{\mathrm{PEEK(50\,Hz)}}$ remains almost constant as a function of exposure time. The lowest dispersion level/highest $\beta^{-}_{\mathrm{PEEK(50\,Hz)}}$ is observed before stressing the specimens.

β of PDIV @800 ns-2.5 kHz Glass fibre vs. PEEK

It displays that the highest β^{+}_{GF} and lowest $\beta^{+}_{\mathrm{PEEK}}$ are observed after half an hour. In addition, $\beta^{-}_{\mathrm{PEEK}}$ increases as a function of poling time.

Rise Time Impact on β of PDIV vs. Exposure Time

The comparison of PDIV dispersion levels between 80 ns-2.5 kHz and 800 ns-2.5 kHz can demonstrate the rise time influence on β of PDIV as a function of exposure time. It is observed that $\beta^{+}_{\mathrm{GF(80\,ns)}}$ increases slightly as a function of exposure time. However, $\beta^{+}_{\mathrm{PEEK(80\,ns)}}$ decreases monotone as a function of exposure time, while the opposite holds for $\beta^{-}_{\mathrm{PEEK(800\,ns)}}$. Although the maximum of $\beta^{-}_{\mathrm{GF(80\,ns)}}$ is measured after one hour of exposure time, the highest $\beta^{-}_{\mathrm{GF(800\,ns)}}$ is observed before stressing the specimen.

IV. Conclusions

The results reported here show that PDEV is less affected by exposure time (i.e., space charge accumulation) than PDIV for the two insulated wires. Overall, Glass fibre delivers higher PDIV and PDEV than PEEK except for one case (800 ns-2.5 kHz-Neg.) where PDIV of PEEK is higher due to heterocharge accumulation after one hour.

Regarding the impact of frequency and rise time on PD activity, PEEK gives the lowest PDIV and PDEV at 80 ns and 50 Hz. The same holds for Glass fibre, delivering lower PDIV when rise time is faster. However, the frequency impact is reversed for Glass fibre, where lower PDIV is observed when the frequency is higher. It is valid for Glass fibre under positive excitation (in all cases) and the negative polarity before stressing the specimens. The space charge accumulation for Glass fibre is observed under negative polarity at a faster rise time, providing an exceptional case when PDIV at a shorter rise time can be higher than a longer one after one-hour exposure.

V. Acknoledgment

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 807081.

References

[1] A. Cavallini, D. Fabiani and G. C. Montanari, "Power electronics and electrical insulation systems - part 1: phenomenology overview," *IEEE Electr. Insul. Magazine*, vol. 26, no. 3, pp. 7-15, May-June 2010.

[2] M. Lukic, P. Giangrande, A. Hebala, S. Nuzzo and M. Galea, "Review, challenges, and future developments of electric taxiing systems," *IEEE Trans. Transp. Electrific.*, vol. 5, no. 4, pp. 1441-1457, Dec. 2019.

[3] IEC 60034-18-42, *Rotating electrical machines - Part 18-42: Qualification and acceptance tests for partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters*, 2008.

[4] P. Giangrande, V. Madonna, S. Nuzzo and M. Galea, "Moving Toward a Reliability-Oriented Design Approach of Low-Voltage Electrical Machines by Including Insulation Thermal Aging Considerations," *IEEE Trans. Transp. Electrif.*, vol. 6, no. 1, pp. 16-27, March 2020.

[5] A. Rumi, J. G. Marinelli, and A. Cavallini, "Converter stress impact on thermally aged resin for low-voltage machines," *Annu. Rep. Conf. Electr. Insul. Dielect. Phenom. (CEIDP)*, 2021, pp. 40-43.

[6] M. Galea, P. Giangrande, V. Madonna and G. Buticchi, "Reliability-oriented design of electrical machines: the design process for machines' insulation systems must evolve," *IEEE Industrial Electronics Magazine*, vol. 14, no. 1, pp. 20-28, Mar. 2020.

[7] D. Fabiani, G. C. Montanari, A. Cavallini and G. Mazzanti, "Relation between space charge accumulation and partial discharge activity in enameled wires under PWM-like voltage waveforms," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 11, no. 3, pp. 393-405, June 2004.

[8] L. Fornasari, A. Caprara and G. C. Montanari, "Partial discharge measurements in electrical machines controlled by variable speed drives: from design validation to permanent PD monitoring," *9th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED)*, pp. 384-390, Aug. 2013.

[9] 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, Feb. 2021.

[10] D. R. Meyer, A. Cavallini, L. Lusuardi, D. Barater, G. Pietrini, and A. Soldati, "Influence of impulse voltage repetition frequency on RPDIV in partial vacuum," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 3, pp. 873-882, 2018.

[11] H. Naderiallaf, P. Seri, and G. C. Montanari, "Effect of voltage slew rate on partial discharge phenomenology during voltage transient in HVDC insulation: the case of polymeric cables," *IEEE Trans. Dielectr. Electr. Insul.*, pp. 1-8, Jan. 2022.

[12] H. Naderiallaf, P. Giangrande, and M. Galea, "A contribution to thermal ageing assessment of Glass fibre insulated wire based on partial discharges activity," *IEEE Access*, vol. 10, pp. 41186-41200, Apr. 2022.