Possibilities of Conventional PD Measurements with Non-Sinusoidal Waveforms for Electric Vehicles

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Abstract

Electrical traction machines in electric vehicles are normally fed by converters with DC link voltages up to 800 V. The resulting voltage pulses place particular stress on the insulating system of the drivetrain. In order to be able to investigate insulating material samples, e.g. twisted pair enameled wire, with voltages of different shapes and high frequency, a shielded experimental setup for the investigation of partial discharges (PD) at low voltages and high frequencies is presented. A medium frequency transformer with a frequency range up to 2500 Hz is used for this purpose, fed by a linear power amplifier on the primary side. The amplifier has a slew rate of 52 V/µs and is capable of sourcing various voltage waveforms such as sinusiodal, triangular or rectangular, with a maximum frequency of 30 kHz. Electrical PD measuring methods according to IEC 60270 as well as acoustic and optical measurement methods are applied for PD diagnosis. The experimental setup is intended to demonstrate the possibilities and limitations of conventional PD diagnostics for non-sinusoidal voltages. Focus is placed on the application of filters, the damping behavior of the step-up transformer and the rise times of the voltages.

1. Introduction

PD diagnostics is an established method for non-destructive evaluation of an insulating material and has been used in high voltage engineering for a long time. In the past, the main focus was on its usage for sinusoidal voltages with frequencies of 50 Hz or 60 Hz [1]. Besides conventional power engineering components such as transformers, medium-voltage motors can also be tested at these voltages. However, power electronics have now evolved to the point where machines are mostly powered by inverters instead of the mains. The use of inverters result in non-sinusoidal pulse voltages, which affect aging and the occurrence of PD. [2]

In the field of electric mobility, electric traction machines are also controlled by inverters. However, the voltage level of the DC link is significantly lower compared to the voltage level in conventional grid-connected applications with DC link voltages of up to 800 V. On the other hand, with the introduction of silicon carbide and gallium nitride semiconductors, the switching frequencies and pulse rise and fall times are increasing. Although the voltage level is rather low, PD can nevertheless occur in increasingly compact motors, which can damage the insulating materials and leads to a motor failure. For this reason, there is great interest in performing PD tests at low pulse shaped voltages. [2] [3]

IEC/TS 61934 already mentions some ways to detect PD at these voltage waveforms. In this work, it is shown what kind of possibilities for PD measurement at non-sinusoidal voltages and frequencies of 100...2500 Hz are possible with IEC 60270 compliant measurement equipment. This will allow further studies in the future on topics such as frequency dependence of PD inception voltage (PDIV), dependence of PD on voltage waveform, or electrical aging phenomena.

2. PD effects at different voltage shapes and frequencies

Table 1 gives a literature overview of the effects of different voltage shapes on PDIV and PD extinction voltage (PDEV). The table was inspired by [4] in which very interesting results for frequency dependent effects of PD were compiled. The focus in Table 1 is on both the test objects used and the voltage studied. For this purpose, selected references on sinusoidal and pulsed voltages of different frequency and rise and fall time were evaluated. In a further column the used measurement method is compared.

In the considered papers, frequencies from 0.1 Hz to 50 kHz are investigated for sinusoidal voltages. In general, it can be concluded that PDIV tends to increase with increasing frequency at lower frequencies. At higher frequencies, the frequency has less influence on the PDIV. For pulsed voltages, it was shown that the PDIV increases for increasing rise and fall times.

From the investigated literature in this section, it can be concluded that the PDIV and PDEV depend on many factors, including the frequency and geometry of the test setup. In addition, direct measuring circuits have already been used successfully for sinusoidal voltages with various frequencies. For pulsed and high-frequency voltages other measuring methods like photo multipliers

Research work	Test objects	Supply voltage parameters	PD measuring technique	Dependency of the PDIV (and PDEV) on the supply voltage parameter(s)
Mauseth, Tollefsen, Hvidsten [5]	Service aged cable joints	Sine voltage, 0.1...100 Hz	Direct test circuit with MPD600, Omicron	$0.1\,\text{Hz} \leq f \leq 0.5\,\text{Hz}$: PDIV, PDEV grow; $0.5\,\text{Hz} \leq f \leq 100\,\text{Hz}$: PDIV, PDEV approximately constant
Hauschild, Cavallini, Montanari [6]	Cavity in layered PE foils, sphere plane configuration	Sine voltage, 0.1... $\sim$ 500 Hz	Direct test circuit	PDIV, PDEV for internal and surface PD; non-monotone frequency dependency of PDIV, PDEV with a maximum at a certain frequency
Esfahani, Shahabi, Stone, Kordi [7]	Needle plane configuration	Sine voltage, 10...2000 Hz	Direct test circuit	Non-monotone frequency dependency of PDIV with a maximum at 50 Hz
Shuai, Feng, Jiangang, Bowen, Qingmin [8]	Needle plane configuration, polyimide films	Sine voltage, 1...50 kHz	Photomultiplier (PMT)	No distinct dependency of PDIV on frequency; in comparison greater impact of the frequency on the amplitude and rate of PDs
Wang, Xu, Wang, Zhou, Cavallini [9]	Twisted pairs	Repetitive pulse voltage, 50 Hz, $t_r, t_f =$ 20...1000 ns	UHF antenna	PDIV for different t_r, t_f and polarities; impact of t_r, t_f on PDIV highly dependent on the voltage overshoot
Hu, et al. [10]	Coil sample	Repetitive pulse voltage, $t_r, t_f =$ 100...800 ns	Antenna	No distinct dependency of PDIV on the frequency; PDIV grows for increasing t_r, t_f

Table 1 – Overview of research on the influence on PDIV and PDEV at different frequencies and pulse-shaped voltages.

or antennas are usually used.

3. Testbed

The schematics of the experimental setup is shown in Fig. 1. It consists of a voltage source, including filters, the high-voltage (HV) transformer, the PD measuring circuit with coupling capacitor C_c and coupling quadrupole CPL, and the test object C_t. The main elements are housed in a shielded cabinet and are explained in detail below.

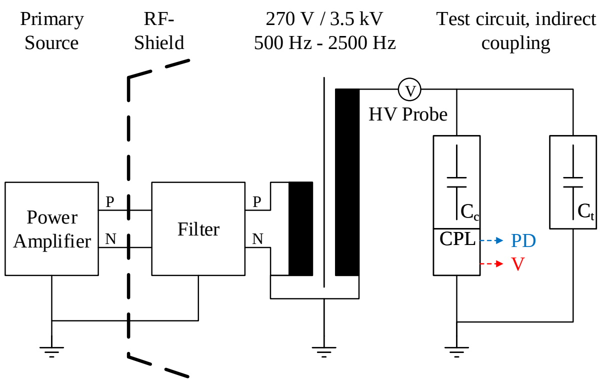

Fig. 1 – Schematic drawing of the experimental setup. Coupling capacitor C_c, coupling quadrupole CPL, device under test C_t, partial discharge signal PD and voltage signal V at CPL.

3.1. Voltage source

A linear amplifier (APS 5000, Spitzenberger und Spies) is used as voltage source. It amplifies a low level signal waveform to a voltage level up to 270 V. In order to exclude interference on the mains side, the linear amplifier was extended by a mains filter on the input side. The linear amplifier provides an integrated signal generator. In this work, however, an external signal generator (4064B, BK Precision) is used because it offers more adjustment possibilities for the voltage waveforms. Both the linear amplifier and the signal generator are controlled automatically via TCP/IP to achieve precise voltage rises and frequency changes. On the output side of the linear amplifier, a radio interference filter is applied to eliminate as much interference as possible that is generated by the amplifier. A 2500 VA medium frequency transformer (Tauscher Transformatoren) is applied to generate the high voltage. This allows voltages of up to 3.5 kV at frequencies of up to 2500 Hz. On the HV side, the voltage is measured by an active differential HV probe (TA042, Pico) and oscilloscope (MSO46, Tektronix). The oscilloscope is also automatically controlled and measures the voltage waveform at specific times in the test sequence.

With this setup, almost any voltage waveform can be generated at unusually high frequencies. Since interferences are reduced by the setup, direct conclusions can be drawn about the measurability of PD in connection with the voltage waveform, especially for low voltage amplitudes.

3.2. PD measuring circuit

The measurement setup is placed in the shielded area. Fig. 2 shows a picture of the setup. A commercially available partial discharge analysis system (MPD600, Omicron) is employed as the measuring device. The coupling capacitor $C_c = 1\,\text{nF}$ forms a unit together with the coupling quadrupole (MCC210, Omicron). The direct test circuit with coupling device in series with the coupling capacitor according to IEC 60270 is used as measuring circuit. A coupling device in series with the test object or bridge measurement can achieve a higher sensitivity compared to the measurement used. Nevertheless, the main reason for selecting this measurement setup is that the voltage span between the onset of the PD and the breakdown of the test object is very small at low voltages. With the indirect setup, the coupling quadrupole and the measuring device are protected against high currents in case of failure of the test object. Another reason is that in this case, the setup can achieve good sensitivity to reliably detect PD. To verify the inception of the PD safely, a directional microphone (SDT 170s) and an optical PD locator (DayCor UVolle-VX, OFIL) are used.

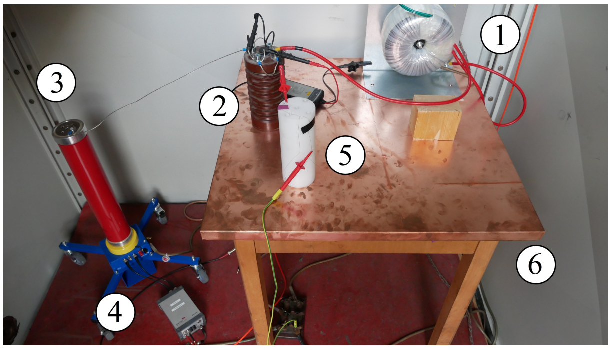

Fig. 2 – Picture of the experimental setup. 1 HV transformer, 2 HV connection point and voltage measurement, 3 Coupling capacitor with coupling quadrupole, 4 PD measuring device, 5 Mount for twisted pair test objects, 6 Grounded base plate.

3.3. Settings

In order to be able to perform PD measurements at pulse shaped voltages, the current pulse generated by the pulse shaped voltages must be filtered according to IEC/TS 61934. Therefore, the filter range of the measuring device may not be set too low, since otherwise the voltage form itself generates an interference spectrum that is not sufficient. However, the filter range should also not be set too high. Otherwise the amplitude spectrum of the PD is no longer approximately constant or no longer detectable. This leads to the fact that the integration error becomes too large. For a high pulse resolution time, the bandwidth should be set as wide as possible. However, this will also include more interferers in the spectrum. [1]

For this reason, deviations from the IEC 60270 guidelines are taken into account when selecting the filter range of the measurement device. Here, the center frequency is from $f_c = 4.0...4.5\,\text{MHz}$. The bandwidth is set to the highest possible value of $B = 1.5\,\text{MHz}$, providing maximum pulse resolution. This is possible because the shielded environment eliminates many interferers. The method of quasi-integration is used for charge determination.

3.4. Test Object

The test objects investigated were selected based on the field of application of low-voltage motors for electric vehicles. The design of the test objects should be as realistic as possible, but also simple. At the same time, it makes sense to achieve a PDIV as low as possible in the range of the nominal voltage of the inverters used.

For this reason, twisted-pair test objects based on IEC 60851-5 are employed. Enameled wire with a diameter of $0.250\,\text{mm}^2$ is taken as the base and twisted 33 times. Fig. 3 shows an example of a test object. The choice of such test objects for electric vehicle motors is made e.g. in [2] or [3] similarly.

Fig. 3 – Picture of a twisted pair test object.

4. Investigated voltage shapes

In this work, the possibility of PD detection on three voltage waveforms, namely sinusoidal (Fig. 4), triangular (Fig. 5) and rectangular (Fig. 6 and Fig. 7) are examined in detail. These voltage waveforms are studied with different frequencies from 100 Hz to 2500 Hz. For the rectangular voltages, different voltage rise and fall times from $10\,\mu s$ to $100\,\mu s$ are also investigated. Due to the circuit design, overshoots in the rectangular voltages cannot be avoided.

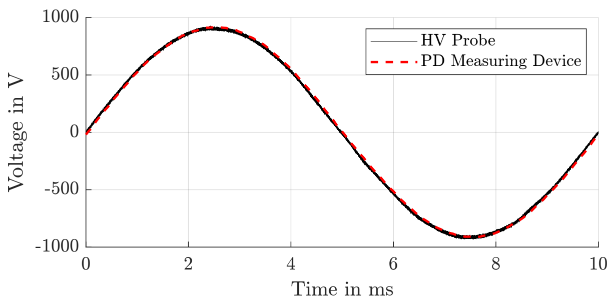

Fig. 4 – Sinusoidal voltage at a frequency of $f = 100\,\text{Hz}$.

First, the voltage measurement of the PD measuring device is compared with the voltage measurement of the high voltage probe. For this purpose, in Fig. 4 to Fig. 7 the voltage measured with the HV probe is shown in black and the voltage measured with the

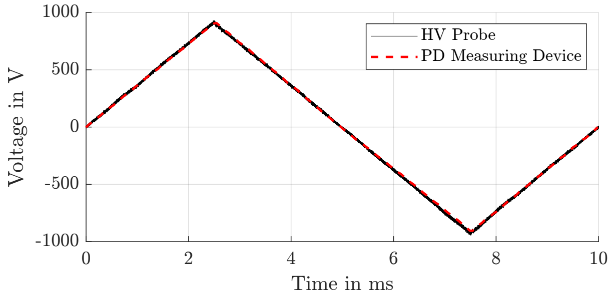

Fig. 5 – Triangular voltage at a frequency of $f = 100\,\text{Hz}$.

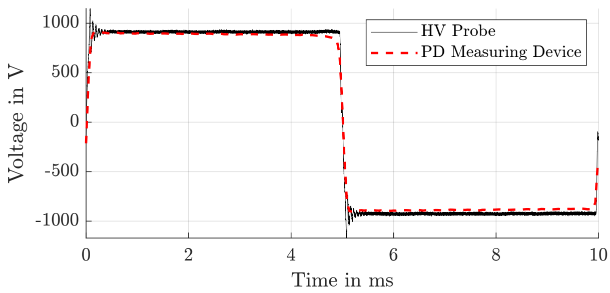

Fig. 6 – Rectangular voltage at a frequency of $f = 100\,\text{Hz}$ and $t_r = t_f = 100\,\mu\text{s}$.

PD measuring device in red. For low frequencies, the voltage measurement of the PD analyzer works sufficiently well. However, for rectangular voltages shown in Fig. 6 it becomes visible that overshoots cannot be measured satisfactorily even at low frequencies. This effect becomes more obvious when higher frequencies with shorter rise and fall times are investigated shown in Fig. 7. The voltage of the PD measuring device is smoothed due to its design for measuring sinusoidal voltages at low frequencies. In addition, sampling of the voltage is performed at a frequency of 20.83 kHz. The measurement of the clearly more transient overshoots is thus not possible. This makes the determination of the PDIV for rectangular voltages very difficult and must be taken into account during the evaluation.

In addition, it can be determined that the transformation ratio of the voltage measurement of the PD measuring system is not frequency independent. This may be due to the filter elements used both in the coupling quadrupole and in the measuring device itself. This effect must also

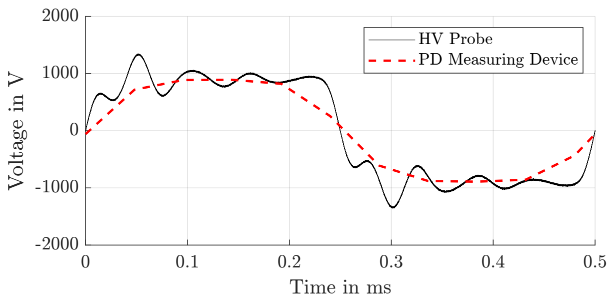

Fig. 7 – Rectangular voltage at a frequency of $f = 2000\,\text{Hz}$ and $t_r = t_f = 50\,\mu\text{s}$.

be kept in mind in practice for measurements at different frequencies. For example, it is possible to recalibrate the voltage measurement for each frequency step with the implemented calibration function. Another approach is the calculation of a correction factor for the evaluation below, which was applied here.

5. Experiments and Results

Experiments will be conducted to demonstrate the capabilities of conventional PD measuring instruments to determine partial discharges at unconventional voltage waveforms and frequencies. First, a test cycle is defined. The PDIV and PDEV is investigated at frequencies from 100 Hz up to 2500 Hz in 100 Hz steps. For this purpose, the voltage is increased in each frequency step until partial discharges have occurred on the test object. The voltage is then decreased. When the PD are safely extinguished, the frequency is increased by 100 Hz and the test starts again. This test cycle is performed for sinusoidal, triangular and rectangular voltages with a rise and fall time of $100\,\mu\text{s}$.

The results for the PDIV are shown in Fig. 8 and for the PDEV in Fig. 9, where the results for sinusoidal voltages are in magenta, for triangular voltages in cyan, and for rectangular voltages in blue. To make the voltages

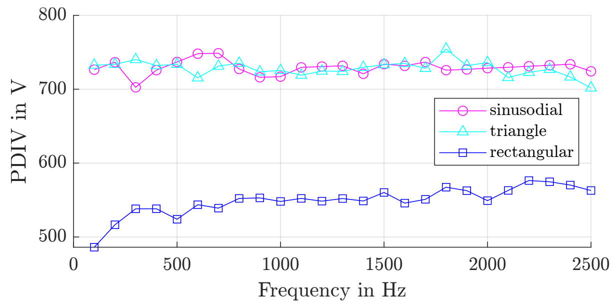

Fig. 8 – PDIV for different voltage waveforms and frequencies.

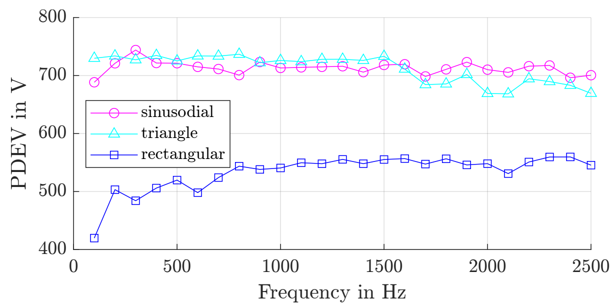

Fig. 9 – PDEV for different voltage waveforms and frequencies.

comparable, the PDIV and PDEV are given as peak values, measured by the PD measuring unit. The PDIV is almost constant for the respective voltage waveforms. However, more than one random sample would need to be examined to further evaluate the frequency dependence. It is noticeable that for the rectangular voltage, the PDIV and PDEV is significantly lower than the other voltage waveforms. This is mainly due to the voltage measurement of the PD measurement unit. Overshoots cannot be detected, but have a much higher voltage than the measured one. Because this work focuses on the conventional PD measurement device, the actual PDIV was not determined. Nevertheless, the relationship between pulse and PDIV is very interesting and can be investigated in the future with an extension of this setup.

Since the voltage waveform cannot be accurately detected especially for rectangular voltages with overshoots, the phase resolved PD pattern (PRPD) is investigated in detail. For this purpose, in Fig. 10 the measured discharges at a frequency of 2000 Hz for a rectangular voltage with $t_r = t_f = 30\,\mu$s is shown. The overshoots have a frequency of approximately 18.3 kHz. The

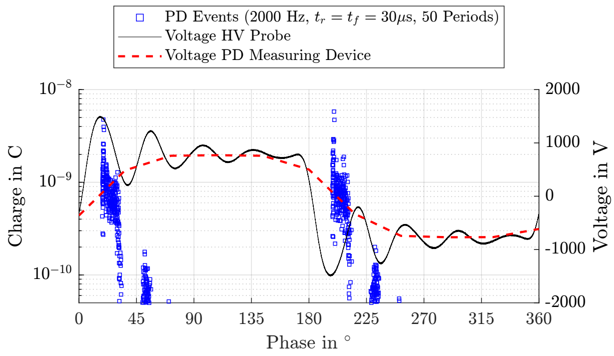

Fig. 10 – PRPD for rectangular voltage

discharges occurred are plotted in blue versus the phase angle. For orientation, the voltage measured by the PD measuring device is shown in red and the voltage measured by the HV probe in black. In the PD pattern, three clusters can be clearly seen in the slopes. These match very well with the overshoots measured by the oscilloscope. It is remarkable to point out that the PD caused by overshoots can be detected. However, sometimes the phase does not match exactly. One possibility for this effect is that the phase detection has difficulties for non-sinusoidal voltages. However, the PD measuring device used offers the possibility to subsequently adjust the phase in its software.

To investigate whether the PRPD changes for higher frequencies, it is calculated for sinusoidal voltage in Fig. 11 and for the triangular voltage in Fig. 12. Discharges for 100 Hz and 2000 Hz are shown in each case. In Fig. 11 phase width increases slightly. However, it should be noted that the PDs in this case are rather cloudy. An exact delimitation is therefore difficult. A clearer phase shift can be seen in Fig. 12. The PD pattern shows an abrupt decrease of the discharges as the peak is crossed. Here, increase of the phase width is clearly visible at higher frequencies. For these high frequencies it has always to be expected that the phase cannot be determined exactly by the PD measuring device.

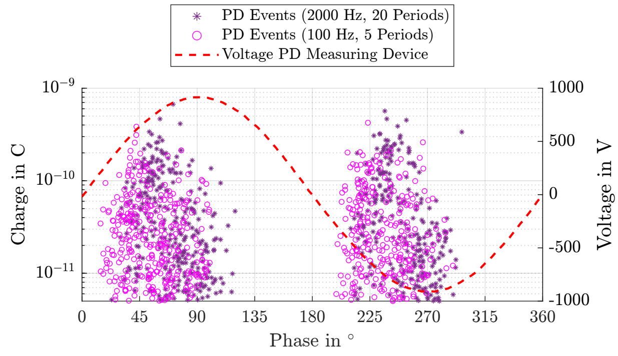

Fig. 11 – PRPD for sine voltage

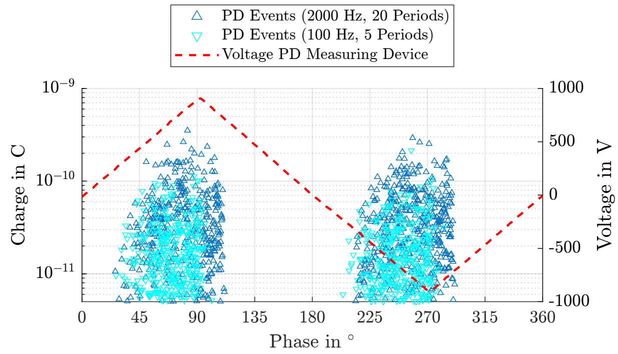

Fig. 12 – PRPD for triangle voltage

6. Conclusion

This paper investigates the possibilities of conventional PD measurement devices (represented by MPD600, Omicron) to determine the occurrence of PD at different voltage waveforms. For this purpose, sinusoidal voltages, triangular voltages and rectangular voltages with different rise and fall times at frequencies up to 2500 Hz are investigated. It can be shown that the voltage measurement outputs non-sinusoidal voltages, especially rectangular voltages with overshoots, in a highly smoothed form. On the one hand this is due to the sampling time of the measurement system and on the other hand to the design of the measurement for sinusoidal voltages at low frequency. In addition, the voltage measurement is frequency-dependent.

The PDIV and PDEV behave almost constant with increasing frequency, whereby in this case only one sample was used. This is because the initial focus was on the measurability of PD at high frequencies and non-sinusoidal voltages, rather than the frequency dependence of PDIV. A further investigation of the frequency dependence will be investigated in a future study. It is noticeable that in the results of this work, the PDIV and PDEV for rectangular voltages are significantly lower than those for sinusoidal and triangular voltages. This is mainly due to the voltage measurement, which cannot measure the overshoots. The dependence for PDIV between pulse shape, overshoot and voltage level will also be highlighted in further investigations. Some PD effects which have already been observed with pulse shaped voltages or different frequencies are summarized in this work.

Overall, it can be shown that with a interference-free source or if appropriate filter actions are taken, the conventional indirect PD measurement circuit according to IEC 60270 is quite suitable for detecting partial discharges at non-sinusoidal voltages with frequencies up to 2500 Hz. However, compromises have to be made with respect to the exact PDIV and phase position. In future work, the voltage source with transformer will be replaced by a HV inverter and other methods for measuring PD at pulse shaped voltages will be investigated.

References

[1] K. Schon, *High Voltage Measurement Techniques: Fundamentals, Measuring Instruments, and Measuring Methods*, Springer, Cham, 2019.

[2] K. Müller, *Entwicklung und Anwendung eines Messsystems zur Erfassung von Teilentladungen bei an Frequenzumrichtern betriebenen elektrischen Maschinen, "Development and application of a measuring system for the detection of partial discharges in electrical machines operated on frequency converters"*, Dissertation, Universität Duisburg-Essen, 2003.

[3] A. Berbic, *Teilentladungsmessung als Prüfverfahren in End of Line-Prüfungen elektrischer Traktionsmotoren, "Partial discharge measurement as test method in end-of-line tests of electric traction motors"*, Dissertation, kassel university press GmbH, 2015.

[4] C. Nyamupangedengu and I. R. Jandrell, "Partial discharge spectral response to variations in the supply voltage frequency", *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 2, 2012, pp. 521-532.

[5] F. Mauseth, H. Tollefsen and S. Hvidsten, "Effect of test voltage frequency on PD inception in service aged cable joints", *ICHVE International Conference on High Voltage Engineering and Application*, 2014, pp. 1-4.

[6] W. Hauschild, A. Cavallini and G. C. Montanari, "Effect of supply voltage frequency on testing of insulation system", *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 13, no. 5, 2006, pp. 1189-1191.

[7] A. N. Esfahani, S. Shahabi, G. Stone and B. Kordi, "Investigation of Corona Partial Discharge Characteristics Under Variable Frequency and Air Pressure", *IEEE Electrical Insulation Conference (EIC)*, 2018, pp. 31-34.

[8] H. Shuai, W. Feng, B. Jiangang, Z. Bowen and L. Qingmin, "Impacts of the frequency effects on partial discharge characteristics of the high frequency power transformer insulation", *International Conference on Electricity Distribution (CICED)*, 2016, pp. 1-4.

[9] P. Wang, H. Xu, J. Wang, W. Zhou and A. Cavallini, "The influence of repetitive square wave voltage rise time on partial discharge inception voltage", *IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 2016, pp. 759-762.

[10] B. Hu et al., "A Partial Discharge Study of Medium-Voltage Motor Winding Insulation Under Two-Level Voltage Pulses With High Dv/Dt", *IEEE Open Journal of Power Electronics*, vol. 2, 2021, pp. 225-235.