

Partial Discharge Behavior of Epoxy-Mica Insulation Systems under Superimposed AC and DC Voltage Stress

Thomas Linde*, Karsten Backhaus, Stephan Schlegel

Institute of Electrical Power Systems and High Voltage Engineering, Technische Universität Dresden

*jan_thomas.linde@tu-dresden.de

Sebastian Lengsfeld, Jonas Steffen

Fraunhofer Institute for Energy Economics and Energy System Technology, Karlsruhe

Joachim Krämer

Krämer Energietechnik GmbH & Co. KG

Klaus Schäfer

Flender GmbH

Abstract Recent technology advances in wind energy conversion systems include a new type of permanent magnet synchronous generator with a segmented stator that allows lightweight concepts with high efficiency and superior controllability. Each stator segment is driven by a separate power converter. The various cascaded power converters can be connected in series and in parallel, which ultimately leads to the superposition of a DC and an AC voltage stress in the insulation of the stator coils. The resulting DC-AC mixed voltage is an entirely new electrical stress for the epoxy-mica insulation system that is typically utilized as main insulation of rotating electrical machines. In order to resemble this stress, typical dielectric tests such as partial discharge (PD) measurements and long-term aging of model insulation systems have to be carried out under DC-AC mixed voltage stress. The mentioned investigations are presented in this contribution. The results indicate that the AC voltage is dominant with regard to the PD inception and influences the PD parameters such as the apparent charge and the repetition rate substantially when compared to the DC voltage proportion. The accelerated aging tests with significantly higher AC-DC mixed voltage stress than is expectable under operating conditions revealed no measurable PD deterioration of the investigated insulation systems.

1. Introduction

Wind turbines play a major role providing a significant share of the electrical energy of predominantly emission-free energy systems. The ongoing advancements of the electrical generators tend to higher powers and higher power density since weight and size are the principal factors in onshore and offshore wind power plants [1]. A novel gearless ring generator design with a segmented stator has a lower mass compared to conventional generators while providing additional flexibility to damp axial vibration and thus maintaining a higher lifetime of the mechanical parts and a higher fault reliability [2, 3].

Each stator segment is connected to an individual power converter. The flexible configuration of the converters makes it possible to connect them in series and thereby increase the DC link voltage. Thus, the advantages in cabling and interconnection within a wind farm can lead to a cost reduction of the wind turbine. However, the mixed voltage stress must be taken into account when designing the insulation of the generator [3] (Fig. 1). For example, the 48 commercially available 690 V three-

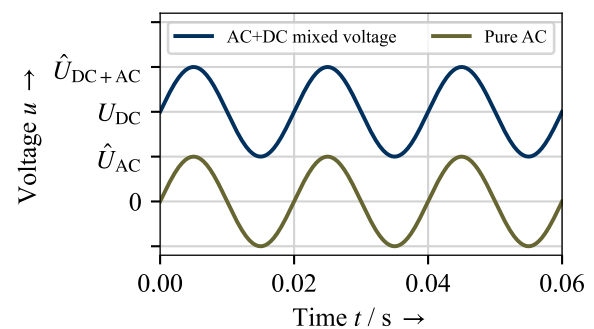


Fig. 1 – Voltage waveforms: pure AC and AC+DC mixed voltage. U_{DC} ... DC-voltage proportion. \hat{U}_{AC} ... AC-voltage proportion. \hat{U}_{DC+AC} ... peak of the mixed voltage.

phase two-level power converters, in the configuration 16 in series and 3 in parallel, result in a mixed voltage of 10.6 kV peak to ground. The voltage consists of half the DC link voltage superimposed with the converter peak voltage $\sqrt{2} \cdot 690 \text{ V} \approx 1000 \text{ V}$.

The typical main insulation system of the stator windings of electrical machines consists of epoxy and mica and is partial discharge (PD) resistant. However, the insulation system is not immune to PD damage since PD slowly cause deterioration of the epoxy polymer. Up to now, this insulation system is typically utilized with AC voltages, while the new generator type leads to AC-DC mixed voltage stress in the main insulation. There is evidence that the mixed voltage stress alters the PD activity (Section 2.). Consequently, the PD deterioration and hence the insulation system lifetime is expected to change as well. In summary, this contribution presents

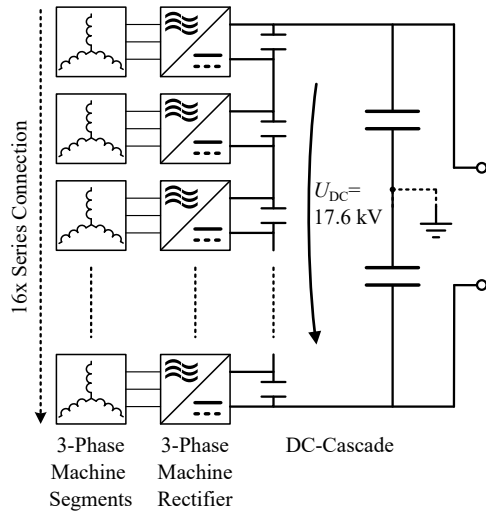


Fig. 2 – Exemplary configuration of 16 converters in series and 3 converters parallel leading to 17.6 kV nominal DC voltage and a mixed voltage of 10.6 kV [3].

results of the PD measurements and long-term aging of two independent insulation system types stressed with AC-DC mixed voltage.

2. Literature Review

The greater part of research regarding AC-DC superposition and PD is motivated by the AC ripple of voltage source converters of the HVDC transmission systems. Subsequently, typical defects such as voids in polymeric insulators [4–6], voids in oil-pressboard arrangements [7] and electrical treeing [8–11] were investigated. In general, it was found that the AC component dominates the PD behavior and the literature findings can be summarized as follows:

1. The influence of the DC voltage on the PD repetition rate and phase-resolved partial discharge (PRPD) patterns is less pronounced if the AC voltage is above PD inception [6, 7, 11].
2. The higher the AC proportion of the mixed voltage is, the lower the peak of PD inception mixed voltage [6].
3. The time between consecutive PD impulses strongly depends on the AC voltage proportion (see Fig. 1) [6].

The influence of mixed voltages on electrical aging is mostly investigated by electrical treeing. Measurements of the electrical tree inception under DC and AC composite waveforms confirm the dominance of the AC proportion [9]. The tree initiation and propagation seems to be accelerated when DC and AC voltages are superimposed, as compared to pure AC or pure DC [8, 10, 11]. Hereby, it was found that positive DC voltage

superimposed with AC voltage leads to the shortest breakdown times [9–11]. Consequently, positive DC voltage will be used in this work in order to investigate the worst-case conditions.

The measurement of PD in an artificial void in solid dielectrics revealed that the AC voltage is crucial for PD inception and generally dominates the PD activity over the DC voltage proportion [6]. It was also found, that after a period of mixed-voltage aging, the PD inception voltage (PDIV) increased and the measured apparent charge Q_{IEC} of the PD severely decreased [6]. This indicates that time-dependent processes such as space charge migration influence the dielectric behavior and should be considered when interpreting measurement results. In addition, an AC superposition on a high DC voltage apparently leads to increased space charge accumulation at electrodes or interfaces between multiple insulation layers [12]. The main insulation of electrical machines, that is subject of this investigation, has multiple interfaces between the epoxy impregnation and mica tape layers that will eventually be affected by space charge accumulation when DC voltages are present.

To the authors' knowledge, no research was carried out on AC-DC-superposition with epoxy-mica insulation. Since the main driver for electrical aging in machine insulation are PD and their deteriorating effect on the organic insulation materials [13], comparable results as in the literature review were expected for the PD and aging tests. The following hypotheses for these investigations are derived:

1. The AC proportion dominates the PD behavior in terms of inception voltage and PD parameters such as the apparent charge and repetition rate.
2. Electrical aging as a consequence of PD is accelerated, when DC and AC voltages are superimposed.

On the basis of the presented findings, the insulation design can be optimized. The starting point for insulation dimensioning for a new voltage stress can, for example, be typical design parameters for AC voltage stress. Consequently, this investigation tackles following third hypothesis:

3. The insulation system design on the basis of operational experiences with AC voltage tends to be overstressed.

3. Experimental Methods

3.1. Test Objects

Two types of machine insulation test objects manufactured by two suppliers were utilized in these investigations. 13 test object samples from each supplier S1 and S2 are available. The main insulation is

made of resin impregnated mica-tape which insulates the aluminum conductor from a stator slot model with a length of approximately 270 mm. The test objects have no end winding corona protection because the superimposed DC voltage potential would be transferred along the surface of the insulation system which leads to lower flashover voltages. The total insulation thickness of the two systems are 1.9 mm and 1.5 mm for supplier S1 and S2 respectively.

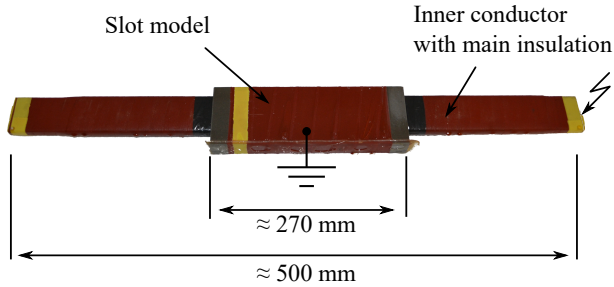
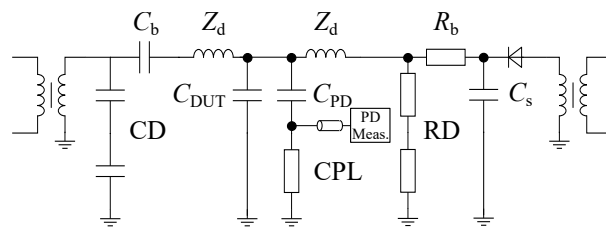


Fig. 3 – Exemplary test object

3.2. Test Setup

The PD and aging measurements are carried out with a superposition setup of AC and positive DC voltage (Fig. 4). The AC and DC voltages are measured separately via a capacitive divider (CD) and a resistive divider (RD) respectively. The mixed voltage at the test object is the summation of both separate voltages which was validated by measurements with a universal divider before the experiments. The DC and AC side are protected from each other's voltage with a blocking capacitor C_b and blocking resistor R_b . AC and DC sides are connected to the device under test and to the coupling capacitor C_{PD} via filter impedances Z_d . The filter impedances have an inductance $L \geq 40$ mH. The PD are measured with the measuring impedance CPL that is connected to a commercial PD measurement system. The noise level is below 1 pC.



$Z_d = 106 \text{ k}\Omega$	$R_b = 250 \text{ M}\Omega$	RD Resistive Divider
$C_b = 10 \text{ nF}$	$C_s = 10 \text{ nF}$	CD Capacitive Divider
$C_{PD} = 1 \text{ nF}$		CPL Measuring Imped.

Fig. 4 – Equivalent circuit for PD measurements under superimposed AC and DC voltage

3.3. Test Sequence

Several tests are carried out with the available 13 test objects of each supplier. All investigations are carried out at room temperature (23 ... 25) °C and a humidity of (40 ... 60) %.

1. Determining the PDIV for pure AC voltage $\hat{U}_{i,AC}$ (Fig. 5, 1.).
2. Determining the mixed voltage PDIV $\hat{U}_{i,DC+AC}$ with constant 1 kV AC peak voltage, representing the approximate peak voltage of a 690 V converter. (Fig. 5, 2.).
3. Recording the PRPD patterns and measuring of the apparent charge Q_{IEC} and repetition rate n_{IEC} according to IEC 60270 [14] for 1 min. Several voltage levels such as $\hat{U}_{i,DC+AC}$ and $\hat{U}_{i,AC}$ are investigated. Additionally, the DC proportion is varied while holding the AC voltage constant at $\hat{U}_{i,AC}$.
4. Long-term electrical aging up to 2841 h. Five test objects of both suppliers are utilized in each of the two separate aging tests. The aging tests have two voltage levels: 10 kV DC, which is a realistic value for application [3] and 20 kV DC. The voltages are superimposed with $\hat{U}_{AC} = 6.5 \text{ kV} \gg \hat{U}_{i,AC}$, so that PD occurrence is ensured.
5. Determining the breakdown or flashover voltage with a continuous voltage rising test for ten test objects of each supplier. The voltage consists of constant 1 kV AC peak voltage superimposed with the continuously increasing DC proportion (1 kV s^{-1}).

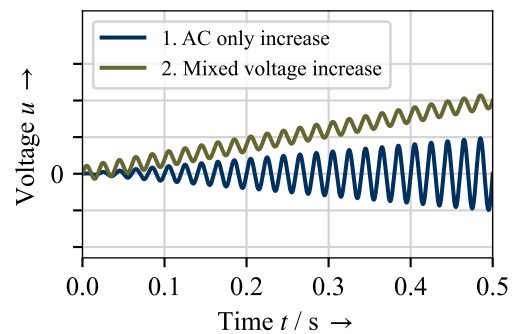


Fig. 5 – Pure AC and DC + AC mixed voltage increase for PDIV measurement

4. Results

4.1. PDIV and PRPD patterns

When stressed with purely sinusoidal voltage, the PD inception voltage $\hat{U}_{i,AC}$ of both test-object types is low, when compared with mixed voltages $\hat{U}_{i,DC+AC}$ (Table 1). The reasonably small 95 % confidence intervals show that the measurements are reproducible.

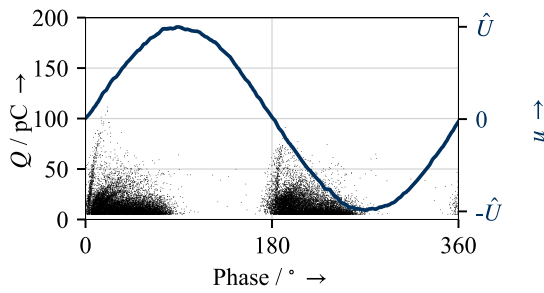
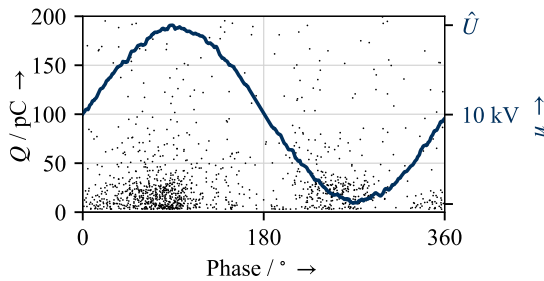
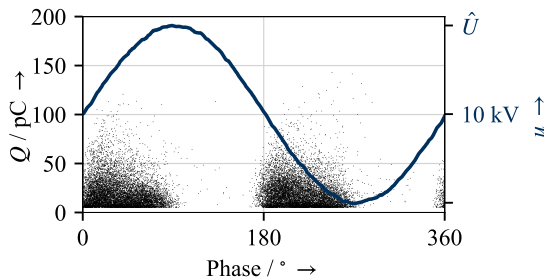
Additionally to the altered PDIV, the PRPD patterns reveal additional information. The Fig. 6 - 8 show patterns of different purely sinusoidal and mixed voltage stress for the same test object. The PRPD pattern of the test object for purely sinusoidal voltage above the

Table 1 – Mean PDIV with 95 % confidence interval

Supplier		S1	S2
$\hat{U}_{i,AC}$	kV	2.7 ± 0.5	4.4 ± 0.6
$\hat{U}_{i,DC+AC}$	kV	8.6 ± 2.2	11.0 ± 1.7

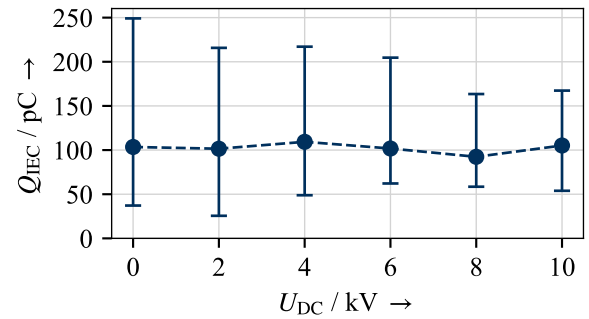
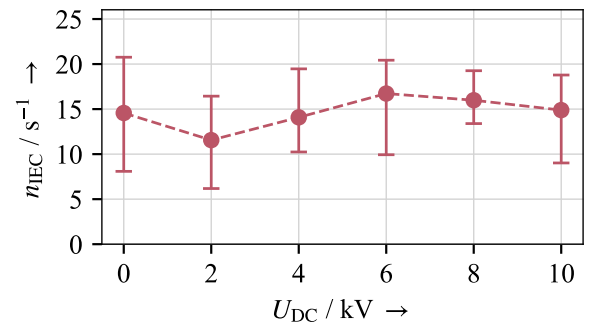
with $\hat{U}_{AC} = 1 \text{ kV} = \text{const.}$

inception voltage of 3.7kV show PD clusters in the voltage increase after zero crossing (Fig. 6). When stressing with a high DC voltage, but leaving the AC voltage below the inception voltage $\hat{U}_{i,AC}$, no distinctive pattern unfolds. Instead, PD with low apparent charge and distributed across the entire period can be measured (Fig. 7). When increasing the voltage above the AC PDIV $\hat{U}_{i,AC}$ while leaving \hat{U}_{DC} identical, the patterns similar as in Fig. 6 appear (Fig. 8). The presented exemplary PRPD patterns were reproduced for several test objects with similar results considering the different PDIV of each test object.


Fig. 6 – PRPD pattern measured at $\hat{U}_{i,AC} = 3.7 \text{ kV}$

Fig. 7 – PRPD pattern measured at a voltage below $\hat{U}_{i,DC+AC}$. $U_{DC} = 10 \text{ kV}$, $\hat{U}_{AC} = 2.7 \text{ kV}$.

Fig. 8 – PRPD pattern measured at a voltage above $\hat{U}_{i,DC+AC}$. $U_{DC} = 10 \text{ kV}$, $\hat{U}_{AC} = 3.7 \text{ kV}$.

4.2. PD Parameters

The measurement of PDIV and the patterns indicate that more detailed evaluations of the apparent charge Q_{IEC} and the repetition rate n_{IEC} are worthwhile. While increasing the DC voltage stepwise from $U_{DC} = 0 \text{ kV}$ to 10 kV, the PD parameters are recorded for one minute at an exemplary selection of five test objects of supplier S1 (Fig. 9 and 10). In this measurement the AC voltage is held constant at $\hat{U}_{AC} \geq \hat{U}_{i,AC}$ so that a PRPD pattern as in Fig. 8 develops. The values of Q_{IEC} and n_{IEC} are recorded every 300ms and then averaged over the one-minute recording interval. The repetition rate n_{IEC} only accounts for the PD events that are relevant for the calculation of Q_{IEC} according to IEC 60270 [14, 15]. The measured values do not reveal any meaningful trend with increasing DC voltage. The large range of the measured values indicates strongly varying measurements between the test objects.


Fig. 9 – Apparent charge according to IEC Q_{IEC} as a function of the DC voltage with superimposed $\hat{U}_{i,AC}$ of each test object. Mean values and deviation. Sample size = 5.

Fig. 10 – PD repetition rate n_{IEC} as a function of the DC voltage with superimposed $\hat{U}_{i,AC}$ of each test object. Mean values and deviation. Sample size = 5.

4.3. Long-term Aging

Long-term aging tests are carried out in order to investigate if the altered PD behavior of DC and AC superimposed voltages influences the lifetime of the insulation system. 20 available test objects of the two suppliers are separated in tests with two different mixed voltages leading to five test objects per long-term aging

test (Table 2). The two mixed voltages are composed of an AC part to be significantly above the inception voltage $\hat{U}_{AC} = 6.5 \text{ kV} \gg \hat{U}_{i,AC}$ and above realistically expectable voltages. The DC voltage stresses are 10 kV, which is a realistic value in application, and 20 kV, to intently overstress the insulation system. None of the test objects broke down during the predetermined aging time of up to 2841 h (approximately 120 days).

A rising voltage test is carried out after the aging time to assess if higher DC voltages during aging have lead to faster deterioration. Hereby the DC voltage was increased continuously with 1 kV s^{-1} and the AC voltage was held constant at $\hat{U}_{AC} = 1 \text{ kV}$. The results show that for a significant share of the test objects no breakdown was registered but flashovers across the insulation system surface instead (Table 2). The test objects aged at a higher mixed voltage did not reveal lower breakdown voltages. The flashover voltages are significantly above the aging voltages, but do not carry any significant information on the insulation system performance since they are mostly dependent on the surface length and the outer geometry.

5. Discussion

Based on the literature review, the hypothesis was derived that the superimposed AC voltage predominantly influences the PD inception and the PD parameters (Section 2.). The presented measurements confirm the hypothesis: The PRPD patterns are different once the voltage of the AC proportion increases above the previously measured purely AC voltage inception voltage. This is the case even if the mixed voltage peak is above the measured AC PDIV, but the superimposed AC proportion is small. This observation corresponds well to the findings in [6], where the DC proportion virtually played no role, once the AC proportion was above inception voltage. If the AC voltage is below PDIV, few sporadic PD events can be measured. The Q values are in the same order of magnitude compared to the measurements above PDIV, rendering the DC voltage insignificant for the PD activity as compared to AC voltage. These findings are confirmed by the PD parameter measurements that showed no statistically significant effect of the DC voltage, which confirms the previous findings cf. [11] with corresponding results. The second hypothesis is that DC and AC mixed voltages lead to faster electrical treeing, which implies faster

aging. While the presented findings of this contribution are not explicitly electrical treeing results, the aging phenomenology of epoxy-mica insulation is lead back to the progressing erosion through the organic materials of the insulation system [13]. The presented electrical aging tests at room temperature have lead to no breakdown of any test object although significantly higher than in reality expected mixed voltages were applied. On the one hand, this is a signal that the present insulation design based on the AC experiences works well even under the new AC+DC mixed voltage stress although it is possibly overdimensioned, refuting the third hypothesis. On the other hand, no reliable information about the DC voltage influence on accelerated aging can be provided. The AC voltage is set significantly above the inception voltage so that, at least at the beginning of the aging tests, PD should be present. However it is possible that the PD activity declines with the time as a result of the applied high DC field and consequently space charge phenomena as shown in [6]. More space charges are generated with mixed voltage stress than with pure DC stress [11, 12, 16] and their accumulation at interfaces such as the mica tape layers between the impregnation resin can eventually lead to the distortion of the electrical field. It is hence possible that the PD activity within the insulation changes with time, which was not investigated in this contribution.

The few measured post-aging breakdown voltages are twice as high as the highest mixed voltage in the aging test. The majority of the test objects flashing over at very high voltages rather than breaking down indicates that no substantial insulation system deterioration happened during long-term aging.

6. Conclusions

This contribution provides experimental data and experience regarding the influence of DC and AC mixed voltage on the PD activity and PD aging in epoxy-mica insulation systems. This untypical and non-standardized voltage stress can occur in an innovative power converter-driven segmented stator of a permanent magnet synchronous generator for wind turbines. Within the investigated parameter range, the PD behavior is largely dominated by the AC proportion of such a mixed voltage. The findings indicate that the DC proportion has no significant impact on PD parameters and insulation deterioration, given that the AC voltage amplitude is

Table 2 – Long-term aging tests and results of the subsequent voltage rising tests.

Supplier	Aging mixed voltage DC kV	AC kV	Aging duration h	Voltage rising test breakdown / flashover	Mean breakdown voltage w/ 95% confidence interval kV
S1	10.0	6.5	2841	4/1	44 ± 7.5
S1	20.0	6.5	2831	3/2	51 ± 16.5
S2	10.0	6.5	2841	0/5	-
S2	20.0	6.5	2831	0/5	-

above partial discharge inception voltage. This suggests that the main insulation design guidelines for pure AC voltage are considered to be conservative if used for AC+DC mixed voltages. It should be mentioned, that the presented findings are only applicable on the main insulation consisting of epoxy and mica. Other parts of the insulation such as field grading elements at the slot exit should be investigated separately. Furthermore, the temperature and humidity influence on the conductivity of the materials should be emphasized in the context of superimposed DC voltages. Space charges can influence the insulation system's performance and should be considered in prospective PD investigations. The comprehensive insulation design for mixed voltages requires additional long-term aging tests.

Acknowledgments

The authors would like to thank the German Federal Ministry for Economic Affairs and Climate Action as well as the Project Coordinator Jülich for funding the research project Magnetring III (support code 0324276A) leading to this article. Only the authors are responsible for the content of this publication.

References

- [1] H. Polinder, J. A. Ferreira *et al.*, "Trends in Wind Turbine Generator Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, 2013. DOI: 10.1109/JESTPE.2013.2280428.
- [2] A. Seibel, C. Stübig *et al.*, "Distributed Control of a Multi-Pole Permanent Magnet Synchronous Generator for Wind Turbine Application," presented at the 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), 2016. DOI: 10.1109/EPE.2016.7695355.
- [3] J. Steffen, S. Lengsfeld *et al.*, "Design of a Medium Voltage Generator with DC-Cascade for High Power Wind Energy Conversion Systems," *Energies*, vol. 14, no. 11, 11 2021. DOI: 10.3390/en14113106.
- [4] P. K. Olsen, F. Mauseth and E. Ildstad, "The Effect of DC Superimposed AC Voltage on Partial Discharges in Dielectric Bounded Cavities," presented at the 2014 ICHVE International Conference on High Voltage Engineering and Application, 2014. DOI: 10.1109/ICHVE.2014.7035408.
- [5] M. A. Fard, M. E. Farrag *et al.*, "Partial Discharge Behavior under Operational and Anomalous Conditions in HVDC Systems," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 3, 2017. DOI: 10.1109/TDEI.2017.006469.
- [6] M. Florkowski, M. Kuniewski and P. Zydrón, "Partial Discharges in HVDC Insulation with Superimposed AC Harmonics," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 27, no. 6, 2020. DOI: 10.1109/TDEI.2020.008966.
- [7] J. Li, X. Han *et al.*, "PD Characteristics of Oil-Pressboard Insulation under AC and DC Mixed Voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 1, 2016. DOI: 10.1109/tdei.2015.004650.
- [8] M. Tian, B. Du *et al.*, "Electrical Tree in Epoxy Resin under Combined DC-harmonic Voltage," presented at the Condition Monitoring and Diagnosis (CMD), Perth, Australia, 2018. DOI: 10.1109/CMD.2018.8535904.
- [9] I. Idrissu, S. M. Rowland *et al.*, "Electrical Tree Growth and Partial Discharge in Epoxy Resin under Combined AC and DC Voltage Waveforms," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 6, 2018. DOI: 10.1109/tdei.2018.007310.
- [10] I. Idrissu and S. M. Rowland, "The Impact of DC Bias on Electrical Tree Growth Characteristics in Epoxy Resin Samples," presented at the 2015 IEEE Conference on Electrical Insulation and Dielectric Phenomena - (CEIDP), Ann Arbor, USA, 2015. DOI: 10.1109/ceidp.2015.7352082.
- [11] H. Zheng, G. Chen and S. M. Rowland, "The Influence of AC and DC Voltages on Electrical Treeing in Low Density Polyethylene," *Electrical Power and Energy Systems*, vol. 114, 2020. DOI: 10.1016/j.ijepes.2019.105386.
- [12] A. A. Mulla, S. J. Dodd *et al.*, "The Effect of AC Ripple Voltage on Space Charge Accumulation in Double Layer Polymer Samples," presented at the IEEE Electrical Insulation Conference (EIC), Calgary, Canada, 2019. DOI: 10.1109/EIC43217.2019.9046596.
- [13] G. C. Stone, *Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair*. Piscataway, NJ, USA: Wiley-IEEE Press, 2004.
- [14] IEC 60270:2000/COR1:2001 - High-voltage Test Techniques - Partial Discharge Measurements.
- [15] K. Rethmeier, A. Kraetge and R. Hummel, "Untersuchungen zum praktischen Einfluss der TE-Wiederholrate auf die Scheinbare Ladung bei Teilentladungsmessungen nach IEC 60270," presented at the ETG Fachtagung Diagnostik elektrischer Betriebsmittel, Fulda, Deutschland, 2012.
- [16] F. Seifert, I. Porizka and C. Leu, "Charge Accumulation at High DC Voltage and Superimposed Medium Frequency AC Voltage," presented at the 2020 IEEE 3rd International Conference on Dielectrics (ICD), 2020. DOI: 10.1109/ICD46958.2020.9341963.