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Computer simulation and management of partial discharges in XLPE insulation of high-voltage power cable

Abstract: This study aims to investigate partial discharges (PD) occurring in micro-sized voids within the polymer insulation of high-voltage power cables, which serve as critical early indicators of internal insulation faults and potential failures. Accurate analysis and modeling of these PD phenomena are essential for improving the reliability and safety of power transmission systems. In this research, a detailed simulation of partial discharge behavior was conducted using MATLAB/Simulink

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software, focusing on the influence of void size, as well as the amplitude and frequency of the applied sinusoidal voltage, on PD characteristics. The simulation model incorporates key physical parameters to represent the micro-void environment and electrical stress conditions accurately. Key findings demonstrate that as the diameter of the gas-filled void increases, both the number of discharges within each voltage cycle and the charge transferred during individual partial discharges increase significantly.

Additionally, an increase in the amplitude of the applied voltage results in a greater number of discharges per period, indicating heightened insulation stress. The study also reveals a proportional relationship between voltage frequency and the average partial discharge current, where higher frequencies lead to increased PD activity. A novel aspect of this work is the ability to correlate partial discharge measurements obtained under high-frequency voltage conditions with those at the industrial standard frequency of 50 Hz. This correlation facilitates more accurate interpretation and prediction of insulation degradation and remaining service life in polymer-insulated cables and other high-voltage energy facilities.

Keywords: computer simulation, management of partial discharges, high-voltage power cables

Introduction

The need to improve the safety and reliability of the high-voltage (HV) insulation of the power cable lines, turbo- and hydraulic-turbine generators, high-power electric machines and other electric equipment of Ukrainian power facilities during the war period intensifies the relevance to develop the new approaches for mobile monitoring of the technical state of such insulation in order to determine the feasibility and conditions for further use of the power facilities. Deciding on additional maintenance, repair, and replacement of HV equipment to prevent emergencies and failures is primarily based on an objective assessment of the insulation state, including the detection of microdefects and prediction of the residual service life (safe operation time) of the insulation system (Shahsavarian et al. 2021).

As is customary in industrialized countries of Europe, America, and Asia, the technical state of insulation in HV cables and other power equipment is routinely studied in stationary laboratories. The researchers from the Institute of Electrodynamics of the National Academy of Sciences of Ukraine (Kyiv), Yuzhcable Works PJSC (Kharkiv), National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute” and National Technical University “Kharkiv Polytechnic Institute” developed the technological complex up to the world standard for serial production and certification of power cable systems with solid structurally reinforced, so-called cross-linked polyethylene (XLPE) insulation for voltage up to 400 kV (Zolotarev et al. 2017). Currently, Yuzhcable Works PJSC is the only Ukrainian manufacturer of up-to-date cable and wire products for voltage up to 400 kV intended for the electric power systems and facilities of critical infrastructure in Ukraine. The power cables and wires are also used to restore the operation of Ukrainian industrial and municipal utilities crushed by Russian aggression.

To test the power cables and wires with sinusoidal voltage up to 500 kV according to the National Standard СОУ-Н МЕВ 40.1-37471933-49:2011 (SOU-N MEV 40.1-37471933-49:2011) by determination of the electrical characteristics of XLPE insulation for international certification, the electrotechnical system with a series resonant LC-circuit having a quality factor from 20 to 40 when flowing the sinusoidal current of 50 Hz frequency was created at PJSC "Yuzhcable Works". In this LC-circuit, the capacitance of the HV cable with a length of 0,1–1 km and the adjustable inductance of two 18-ton inductors from Hipotronics (USA) are used (Zolotarev et al. 2017). This system is connected to a 380 V three-phase electric power network with a 50 Hz frequency. A Paschen autotransformer, along with a single-phase matching transformer, is applied for additional voltage stepping up.

ABB (Germany), Nexans (France), Brugg Kabel (Belgium), Sumitomo Electric (Japan), and Okonite (USA) have a similar structure for their electric systems in HV power cables (Zolotarev et al. 2017). Such systems provide a highly accurate measurement (error is less than two pC) of partial discharges (PD) in the HV insulation of modern power cables and wires. The systems are characterized by the parametric stabilization of current in load circuits, even in the presence of rapid changes in load resistance (Kumar et al. 2024). When the electric breakdown of HV insulation takes place during its testing by higher voltages in the electric system with the resonant LC-circuit having quality $Q = 40$, the voltage quickly becomes smaller by a factor of 40; accordingly, the current in the insulation is reduced, which prevents the emergency operation (Zolotarev et al. 2017).

The initiation of partial discharge (PD) in high-voltage (HV) insulation is one of the most reliable indicators of micro-sized defects within the insulation material. These defects typically include gas voids, microcracks, and post-treeing cavities, all of which can significantly compromise the insulation's structural integrity (Densley 2001). The presence of such imperfections leads to the localization of an electric field, which, in turn, promotes the early onset of PD activity (Eigner and Rethmeier 2016). This phenomenon not only reduces the dielectric strength of the insulation but also accelerates its overall degradation. As a result, the reliability and residual safe service life of HV insulation are substantially diminished (Shahsavarian and Shahrtash 2015). To better understand and predict these effects, researchers have developed a wide range of mathematical models (Kumar et al. 2024; Densley 2001; Eigner and Rethmeier 2016; Shahsavarian and Shahrtash 2015; Henry 1952). These models aim to simplify both the theoretical frameworks and the practical methodologies used to assess insulation aging and remaining service life. Their application is crucial in improving maintenance strategies and ensuring the long-term stability of high-voltage systems.

The most widely used model is the mathematical model with three capacitances, proposed by Whitehead in 1951 (Zhang et al. 2021). It is currently successfully used to study the transient processes occurring in high-voltage (HV) insulation during partial discharge (PD) activity. By analyzing these rapidly evolving electrical phenomena, researchers can gain valuable insights into the condition and behavior of the insulation material under stress (Pattanadech et al. 2023). This approach also enables the identification of early signs of insulation deterioration, which are critical for timely maintenance decisions. Moreover, it provides a practical means to estimate the residual service life of the insulation, thereby enhancing the reliability and safety of HV equipment (Pattanadech et al. 2023; Albarracin et al. 2020).

However, at present, the electric systems of all world manufacturers use the resonant LC-circuits at 50 Hz, when the capacitive reactance of XLPE insulation in the HV cables and wires is quite remarkable. That requires the creation of the reactor with the same significant inductive reactance at the same frequency (Niemeyer 1995). Therefore, the modern 500 m cable with XLPE insulation for voltages up to 330 kV at 50 Hz will have a capacitive reactance of approximately 13 kΩ. To realize the series resonant LC-circuit, it is necessary to create the reactor with the same inductive reactance of 13 kΩ for passing the current up to 40 A. At the same time, the cable and reactor should be able to pass power up to 20 MVAR. That is a rather complex technical problem (Zolotarev et al. 2017).

The transformer-type electric system is practically impossible to use for creating either mobile or stationary installations intended for partial discharge (PD) diagnostics of insulation in power facilities (Musa et al. 2023). This limitation is primarily due to the inherent characteristics of such systems, where the voltage applied to the insulation remains unchanged even when an electric breakdown occurs. As a result, the system cannot respond dynamically to the breakdown event, leading to uncontrolled energy release (Illias et al. 2012). This often results in the generation of an unacceptably large short-circuit current, which poses serious risks to both the diagnostic equipment and the power facility infrastructure. In fact, such a scenario is considered an emergency condition, making transformer-type systems unsuitable for sensitive PD measurement and analysis tasks.

It was found that, with an increasing frequency of applied voltage, a crucial characteristic – the average value of DC current – increases approximately proportionally with this frequency (Niemeyer 1995; Bleaney and Bleaney 1965). Accordingly, the obtained results concerning the effect of current frequency on PD characteristics allow, by measurement of PD level at high frequency, to recalculate these characteristics for 50 Hz frequency and then to predict the technical state and the rest of the service life of the insulation of power cables and other energy facilities at the voltage and current of industrial frequency (50 Hz).

The effective management of partial discharges (PD) in cross-linked polyethylene (XLPE) insulation of high-voltage (HV) power cables is a critical element in extending asset life and ensuring energy transmission reliability (Dychkovskyi et al. 2024). PD activity, which indicates localized electrical breakdowns in insulation, not only leads to premature aging of cables but also increases the risk of catastrophic failures (Beshta et al. 2023). From an environmental management perspective, addressing PD early reduces the frequency of cable replacements and minimizes the production of e-waste and harmful by-products associated with manufacturing and disposal (Myronova et al. 2025). Monitoring systems based on non-transformer pulse technologies, in combination with AI-based diagnostics, support a predictive maintenance strategy that aligns with ISO 14001 principles by reducing the environmental footprint of high-voltage infrastructure (Dychkovskyi et al. 2024; Beshta et al. 2023; Myronova et al. 2025; Fedoreiko et al. 2017).

Within the framework of advanced PD diagnostic systems, disk pulse devices (DPDs) play a crucial role in generating controlled high-voltage impulses without triggering damaging short circuits (Nikolski et al. 2020). The design and thermal regulation of such devices, particularly the management of heat exchange within their internal channels, directly impact measurement accuracy and operational safety (Lewicka and Lewicka 2019). Effective heat dissipation mechanisms prevent overheating and improve energy efficiency, aligning the system's operation with broader principles of energy conservation (Polyanska et al. 2024). Incorporating heat recovery or self-cooling solutions into DPD design can further enhance performance while reducing energy demand, offering a symbiotic interface between electrotechnical diagnostics and thermal process optimization (Vladyko et al. 2025).

The integration of PD monitoring technologies into the lifecycle management of HV power systems supports several key functions of industrial ecosystem sustainability (Vladyko et al. 2025; Golovchenko et al. 2020). By prolonging the functional life of XLPE-insulated cables and reducing raw material consumption, PD management contributes to resource efficiency, a cornerstone of the circular economy (Lewicka and Lewicka 2019; Nikolski et al. 2022). Furthermore, the reduction in maintenance-related environmental disruptions (e.g., excavation, cable disposal) supports ecosystem protection and restoration (Lewicka and Lewicka 2019; Magdziarczyk et al. 2024). From a sustainable development perspective, this approach not only meets the operational needs of today's power infrastructure but also preserves environmental integrity for future generations, aligning technical reliability with long-term ecological and economic resilience.

To analyze pulsed high-frequency electromagnetic processes in HV insulation during PD initiation, the numerical calculation of the electric field using the finite-element method is employed (Niemeyer 1995; Kolb et al. 2020). The advantage of this approach lies in determining the electric field distribution in the void and the possibility of revealing the insulation state before electrical breakdown. In such cases, the gas breakdown in the void is simulated by significantly increasing gas conductivity (Seheda et al. 2024). The limitation of this approach is the computational complexity and the time required for the computer system to work.

To improve the capacitive model of partial discharge (PD), it is effective to consider the coupled effect of several interrelated factors influencing discharge behavior (Kolb et al. 2020; Fedoreiko et al. 2025). These include the dependence of the inception and extinction voltages on the size of gas voids within the insulation, as well as the characteristic time required for the generation of free electrons in the void (Beshta et al. 2024). The presence of these electrons is a fundamental precondition for the initiation of subsequent discharges, particularly under high-frequency voltage conditions where electron availability and timing are critical. Incorporating these dynamic interactions into the model significantly enhances its accuracy in simulating real insulation behavior under stress (Pazynich et al. 2024). Nevertheless, despite their importance, this coupled effect is often neglected in published research, leaving a gap in the comprehensive understanding of PD phenomena.

Despite numerous studies on partial discharge detection in high-voltage cables, existing models often lack sufficient accuracy in simulating insulation degradation under real-world conditions, especially those involving high-risk or wartime operations. Many approaches do not fully incorporate critical physical parameters or adequately represent the complex void behaviors within XLPE insulation, thereby limiting their predictive capability and practical applicability (Pazynich et al. 2024; Fifield and Correa 2017). This study addresses these gaps by developing an enhanced Simulink-based model that integrates key physical factors and refines the void model to simulate partial discharge phenomena better. By doing so, it offers improved diagnostic accuracy and reliability, providing a valuable tool for monitoring insulation conditions in challenging environments.

The purpose of this article consists in 1) the development of improved mathematical model of electrical processes during PD in the micro-sized gas void of polymer insulation; 2) the computer realization of the model by Matlab/Simulink software and 3) the investigation of the effect of such parameters as the void size, the amplitude and frequency of applied voltage on PD characteristics.

1. Methodology and methods for partial discharges in XLPE insulation of high-voltage power cable

The methodology for investigating partial discharges (PD) in cross-linked polyethylene (XLPE) insulation is grounded in a systematic approach that combines experimental diagnostics, theoretical modeling, and data analytics (Zolotarev et al. 2017; Illias et al. 2012; Fifield and Correa 2017). It begins with the identification of insulation structures most susceptible to PD activity, such as gas-filled voids, interfaces between different material layers, and regions affected by thermal or mechanical stress (Zolotarev et al. 2017; Fifield and Correa 2017; Sobolev 2025). The study aims to characterize the initiation, propagation, and extinction of PD under varying electrical and environmental conditions, particularly in response to high-frequency voltages. A life-cycle-oriented perspective is adopted, with the goal of assessing long-term degradation mechanisms and predicting the residual service life of HV cables. This methodological orientation is aligned with preventive maintenance strategies and reliability-centered asset management.

The core methods involve non-destructive testing using high-sensitivity PD detection equipment, such as ultra-high frequency (UHF) sensors, time-domain reflectometry (TDR), and phase-resolved PD pattern (PRPD) analyzers (Fifield and Correa 2017; Zradziński et al. 2019). To simulate realistic stress conditions, high-voltage test platforms are employed with controlled frequency and amplitude modulation, enabling the study of PD behavior across a range of operational scenarios (Richert et al. 2024). Disk pulse generators or resonant test systems are used to apply standard or impulse voltages, with capacitive coupling techniques implemented for PD signal extraction (Zradziński et al. 2019). Advanced signal processing techniques, including wavelet transformation and machine learning algorithms, are utilized to distinguish partial discharge (PD) signals from background noise (Aakre and Ildstad 2020). These methods enhance the accuracy and reliability of PD detection, especially in complex operational environments.

Furthermore, they enable effective classification of different types of discharges based on unique signal features (Lee et al. 2019). In parallel, complementary sensing methods such as thermal imaging and acoustic emission sensors can be employed to provide additional verification. These tools facilitate the spatial localization of PD sites, providing a multimodal approach to insulation diagnostics (Aakre and Ildstad 2020; Lee et al. 2019; Wang et al. 2010).

Complementary to experimental diagnostics, numerical simulations are conducted using finite element methods (FEM) to model electric field distributions in defective insulation structures. These models incorporate variable parameters, such as void geometry, material permittivity, and charge accumulation, enabling a deeper understanding of field enhancement and discharge inception thresholds (Zolotarev et al. 2017; Fifield and Correa 2017). Coupled models integrating thermal, electrical, and chemical degradation pathways provide insights into the aging process of XLPE under PD activity. Collected data are analyzed statistically to derive trends, PD inception voltage (PDIV) distributions, and discharge repetition rates, which are then used to calibrate aging models and estimate insulation life expectancy. This integrated methodology ensures a comprehensive and multi-scale understanding of PD phenomena in HV XLPE cable systems, supporting the development of predictive maintenance frameworks and enhancing the reliability of power transmission infrastructure (Fifield and Correa 2017; Kuchinskii 1979).

Simulink-model of electrical processes at PD in the polymer insulation of power cable with gas void. The part of a 20 kV power cable with polymer insulation is considered as a model sample schematically shown in Figure 1. As assumed, the insulation has a micro-sized spherical gas void with a diameter d, in which partial discharge initiates when connecting to a sinusoidal voltage source. Figure 1 shows the capacitive equivalent circuit of the cable part. Here C_{Void} is the void capacitance, C_1 is the capacitance of the insulation between the void and electrodes, C_i is the capacitance of the working insulation of the cable fragment.

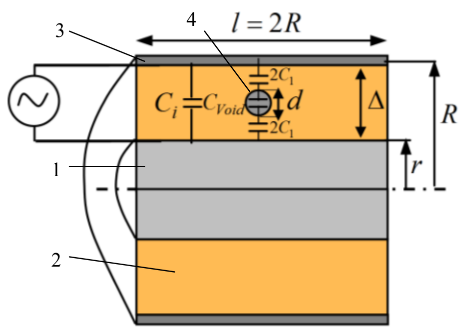

Fig. 1. Part of the power cable with spherical gas void:
1 – core, 2 – polymer insulation, 3 – external screen, 4 – gas void

Rys. 1. Fragment kabla zasilającego z kulistą pustką gazową:
1 – żyła, 2 – izolacja polimerowa, 3 – ekran zewnętrzny, 4 – pustka gazowa

The following expressions are used (Bleaney and Bleaney 1965):

$$C_{Void} = \varepsilon_0 d,\ \ C_1 = C_{Void} k / (1-k), \quad \text{where}\ \ k = 1.23d / \Delta,\ \ C_i = \frac{2\pi\varepsilon_0\varepsilon_r l}{\ln(R / r)} \qquad (1)$$

The value of capacitance C_1 is chosen provided that the voltage across the void at different diameters d is equal to the voltage drop across the spherical air void located in an infinite volume of the polymer insulation with permittivity $\varepsilon_r = 2.3$ in homogeneous electric field.

The Simulink model incorporates a range of input parameters that define the behavior and performance of the high-voltage generation system. Key parameters include the inductance and capacitance values of the resonant circuit (L = 2.5 mH, C = 100 nF), which determine the resonance frequency and energy transfer efficiency. The input voltage amplitude (V_{in} = 24 V) and frequency (f = 5–50 kHz) are adjustable, allowing for the simulation of different operating conditions and assess frequency tuning effects. Additionally, the model includes resistive losses (R = 1.2 Ω) to represent practical components and thermal effects (Illias et al. 2012; Wang et al. 2010; Kuchinskii 1979). These parameters are explicitly defined in the model setup and documented in the updated manuscript to ensure reproducibility and facilitate adaptation in related research.

The Simulink-model of the cable part with defect is presented in Figure 2. The general model contains the model of HV power supply of harmonic voltage, the model of cable fragment with

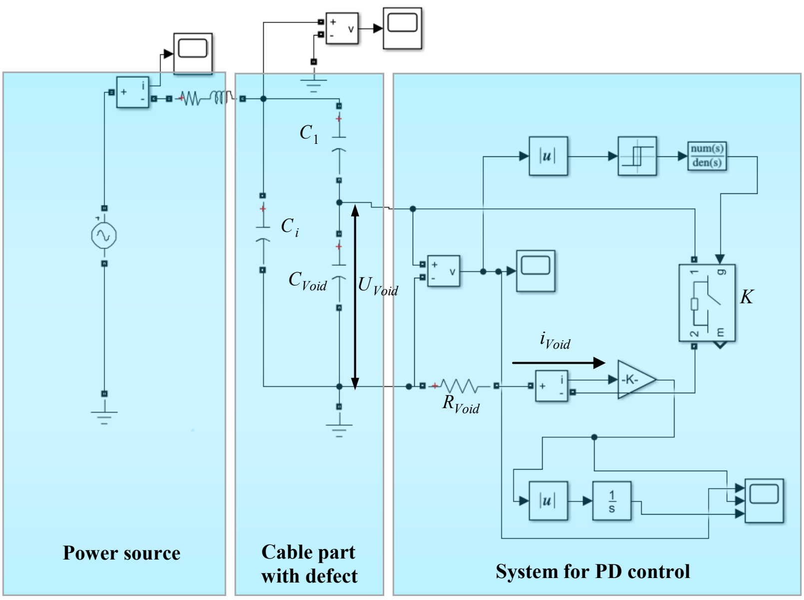

Fig. 2. Simulink-model for study of partial discharges in gas void

Rys. 2. Model Simulink do badania wyładowań częściowych w pustkach gazowych defect as a spherical void and the control system for the processes of the PD inception and extinction in this void. This is realized by switch K. At turning on the switch, the capacitor corresponding to C_{Void} is discharged to the equivalent resistance R_{Void}. When switch K is turned off, the capacitor with capacitance C_{Void} is charged from the power source.

The following conditions should be considered to control the switch. As it is known, the two causes for PD inception in a gas void of dielectric take place (Illias et al. 2012).

Firstly, the electric field strength in the void E_{Void} should exceed a certain initial field of breakdown in the gas medium E_{inc}. This value is calculated by the next empirical expression (Niemeyer 1995; Musa et al. 2023):

$$E_{inc} = 24.2p(1+8.6/\sqrt{pd}) \quad (2)$$

where:

E_{inc} – electric field strength [V/m],
p – gas pressure in the void [Pa],
d – diameter of the void [m].

Secondly, the partial discharges are initiated with sufficient electrons to ionize the gas in the void. They result from photoionization in the gas, photoionization in the insulation material, and due to electron emission from the insulation surface into the void. The certain time ($\tau_e = 0.1$–3 ms) is required for the origin of the electrons (Niemeyer 1995; Illias et al. 2012).

These two conditions are taken into account in the computer model of PD. To estimate the voltage applied to the gas void in the insulation of an energized cable, the expression for the electrical field in a spherical void of dielectric in a homogeneous field (Bleaney and Bleaney 1965) is used:

$$E_{Void} = \frac{3\varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} E_0 \quad (3)$$

where:

ε_1, ε_2 – the values of relative permittivity of the void and dielectric, respectively.

When $\varepsilon_1 = 1$, $\varepsilon_2 = 2.3$ (polyethylene), $U_{Void} = E_{Void}d$, $U_0 = E_0\Delta$ we obtain from (3):

$$U_{Void} = 1.23\frac{d}{\Delta}U_0 \quad (4)$$

Using expression (4), the value C_1 in (1) is calculated under the condition that for different void diameters, the voltage at the void relates to voltage U_0 as in expression (4). This is the first refinement of the improved PD model, which allows investigating the effect of the void size on the basic characteristics of PD.

The second refinement is associated with the voltage at the inception and extinction of PD. Taking into account expression (2), the voltage at PD inception is equal to:

$$U_{inc} = E_{inc}d = 24.2pd(1 + 8.6/\sqrt{pd}) \quad (5)$$

The developed Simulink model effectively simulates the electrical processes associated with partial discharges (PD) in the polymer insulation of high-voltage power cables, which contain micro-sized spherical gas voids. By incorporating a capacitive equivalent circuit and control logic for PD inception and extinction, the model accurately reflects the physical behavior of insulation under sinusoidal voltage. Key refinements include the dependence of PD characteristics on void size and the dynamic voltage thresholds for discharge initiation and extinction, which are based on both the electric field strength and the time required for electron generation. These enhancements enable a more realistic analysis of PD behavior in dielectric materials, leading to a deeper understanding of insulation aging mechanisms. Overall, the model serves as a valuable tool for optimizing insulation design and diagnostic strategies in high-voltage power systems.

2. Results of the research and discussion

The simulation results obtained using the refined Simulink model of a 20 kV power cable segment with a spherical gas void in XLPE insulation demonstrate a strong correlation between the void diameter and the electrical parameters of partial discharge (PD) activity. The model accurately reproduced the dynamics of PD inception and extinction by incorporating both the electric field threshold and the time delay required for electron availability within the void. It was shown that as the void diameter increases, the voltage across the void decreases in accordance with the field redistribution described by the refined capacitive model, thereby lowering the inception voltage for PD. Additionally, the model confirmed that both the permittivity ratio between the void and insulation and the delay in electron generation significantly influence the timing and frequency of discharge events. These results validate the effectiveness of the improved PD model for assessing insulation reliability and provide a reliable computational tool for evaluating the influence of micro-defects in HV polymer cable insulation systems.

Figure 3 gives the dependences of voltages according to expressions (4) and (5) on void diameter for different voltages U_0 applied to the cable. The figure illustrates the critical void size (~0.2 mm) below which PD does not occur at 20 kV, as the electric field in the void does not reach the breakdown threshold. For larger voids, the inception condition is fulfilled, and PDs are initiated. As shown, there is a critical value of the void size (approximately 0.2 mm for the cable under consideration), when at rated 20 kV voltage, PD in smaller voids do not occur, since the voltage at the voids according to (4) does not exceed the voltage at PD inception presented by (5). For the greater voids, the condition of PD inception $U_{Void} \geq U_{inc}$ is always fulfilled and discharges are initiated. The voltage at PD extinction is specified as U_{ext} = (0.3–0.9)$^{U_{inc}}$ (Kuchinskii 1979).

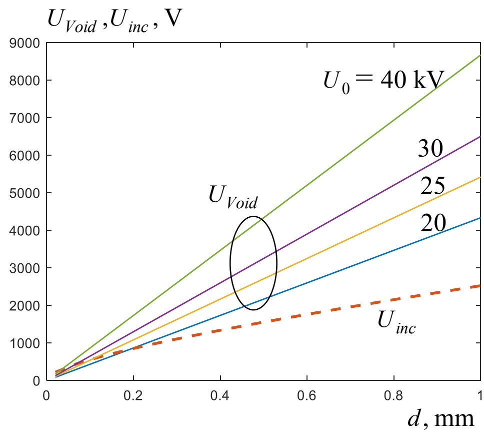

Fig. 3. Dependence of the voltage across the gas void at partial discharge (PD) inception on the void diameter for different applied voltages U_0

Rys. 3. Zależność napięcia w pustce gazowej w momencie powstania wyładowania częściowego (PD) od średnicy pustki dla różnych napięć przyłożonych U_0

The third refinement is related to the characteristic time τ_e required for the emergence of initial electrons within the gas void, which serve as the primary initiators of partial discharge (PD). This parameter is critical because, without enough free electrons, the ionization process in the void cannot begin, even if the electric field exceeds the breakdown threshold. The origin of these electrons may result from photoionization in the gas, surface electron emission, or ionization in the surrounding polymer matrix. This refinement is significant for accurately simulating PD behavior under high-frequency voltage conditions, where the time available for electron generation is significantly reduced. Therefore, taking into account the delay in electron formation enhances the realism and predictive capability of the PD model, especially when assessing insulation behavior under rapidly changing electrical stress.

Basic characteristics of PD. The following PD characteristics are considered: 1) n_T is the number of PD during the time that is equal to the period of applied sinusoidal voltage $T = 1/f$; 2) q_T is the total charge in the void due to PD in period T; 3) $q_{PD} = q_T/n_T$ is the PD charge corresponding to single partial discharge in the void; 4) $I_{PD} = f\mathrm{q}_T = fn_Tq_{PD}$ is the average value of the electric current flowing in the void due to PD. The nature and pattern of dielectric destruction due to PD depend on this current.

Parametric analyses of electrical processes during PD. The computations are carried out at different parameters of equivalent electric circuit using Simulink-model (Fig. 2). It is taken into account that the capacitances C_{Void} and C_1 depend on void diameter d (according to (1)) and PD is initiated when the voltage at the void $U_{Void} \geq U_{inc}$, where U_{inc} is determined by (5), and PD are attenuated when $U_{Void} \leq U_{ext}$ at $U_{ext} = (0.3–0.9)^{U_{inc}}$. The values of these two voltages are specified in Simulink-model (Fig. 2). The minimum permissible time τ_e is defined in the time-delay unit in Figure 2.

The following values are set in the model. For the cable: r = 6.5 mm, R = 14.5 mm, Δ = 8 mm (Fig. 1). The capacitance values are calculated by expressions (1). The value of R_{Void} is defined under the condition that $\tau_{PD} = C_{Void}R_{Void}$ = 1 μs. The pressure in the void is determined according to (5): $p = 0.43 \cdot 10^5$ Pa. The applied voltage U_0 = 25 kV (effective value) and frequency f = 50 Hz.

Effect of extinction voltage on PD characteristics. Figure 4 presents the results of PD simulation for $U_{ext} = 0.3U_{inc}$ and $U_{ext} = 0.6U_{inc}$ at d = 0.3 mm, U_0 = 25 kV. The blue plots show the time-varying voltage U_{Void} at the void, the voltage without PD is displayed by red line for comparison. Here the time-dependent electric current and charge $q = \int_0^t |i_{Void}|\,dt$ are plotted too.

As determined by Fig. 4, when $U_{ext} = 0.3U_{inc}$ the PD characteristics are as follows: n_T = 4, q_T = 8.5 pC, q_{PD} = 2.1 pC, and when $U_{ext} = 0.6U_{inc}$, n_T = 8, q_T = 10.5 pC, q_{PD} = 1.3 pC. The blue

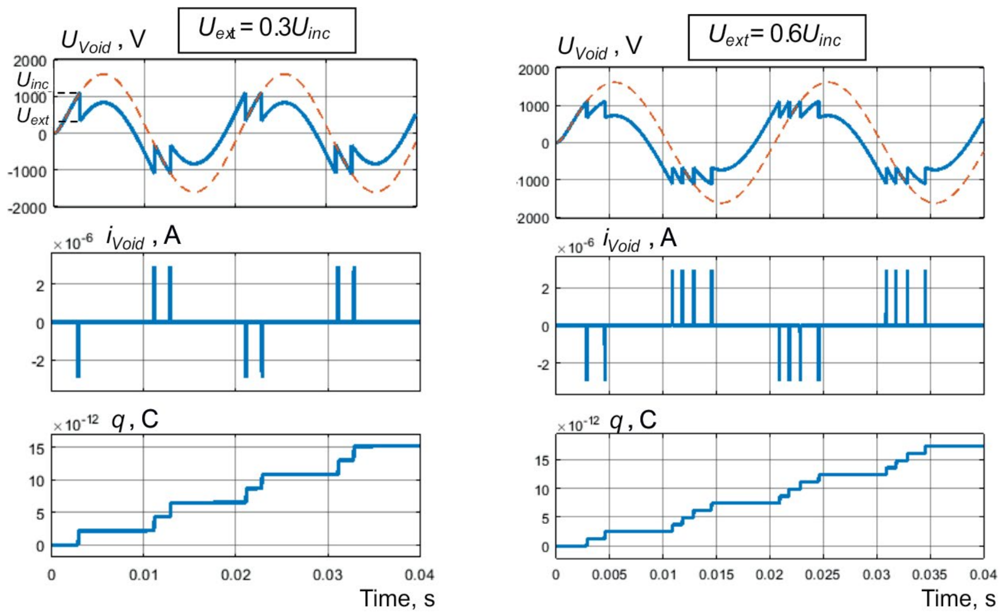

Fig. 4. Simulation results of partial discharges (PD) in a gas void with d = 0.3 mm diameter under U_0 = 25 kV applied voltage for two different extinction voltage coefficients $U_{ext} = 0.3U_{inc}$ and $U_{ext} = 0.6U_{inc}$

Rys. 4. Wyniki symulacji wyładowań częściowych (PD) w pustej przestrzeni gazowej o średnicy d = 0,3 mm przy napięciu przyłożonym U_0 = 25 kV dla dwóch różnych współczynników napięcia wygaszania $U_{ext} = 0,3U_{inc}$ i $U_{ext} = 0,6U_{inc}$

curve represents the voltage across the void during PD activity, while the red curve shows the reference voltage without PD. The plots also include the time-dependent PD current and accumulated charge. The results demonstrate that increasing the extinction voltage coefficient leads to more frequent discharges within one voltage period, reducing the charge of each individual PD while increasing the total charge, thus intensifying the overall degradation effect. Consequently, when increasing U_{ext}, the number of PD n_T within period T grows. That leads to a decrease in the charge of single PD. The total charge q_T, which characterizes the dielectric destruction, increases.

Effect of void diameter on PD characteristics. Analyzing the effect of void diameter d, it should be noted that when the diameter increases, the voltage at the void and the voltage at PD inception increase too (see Fig. 3). In this case, the voltage at the void increases more quickly, that causes the increase in PD charge q_{PD}. To study the dependence $q_{PD}(d)$, let us take into account (1) and (5) and write the following expression:

$$q_{PD} = C_{Void} U_{inc} = 24.2 \varepsilon_0 p d^2 (1 + 8.6 / \sqrt{pd}) \tag{6}$$

Expression (6) reveals how the charge of a single partial discharge (q) depends on the void diameter (d). The term inside the brackets reflects the interplay between capacitance and electric field strength in the void. Specifically, the first component of the bracketed term corresponds to the capacitive energy storage capability, which scales with the void size. The second component accounts for the influence of the electric field at PD inception, which is also affected by the void geometry. As the void diameter increases, both the capacitance and the inception voltage change, resulting in a nonlinear increase in the charge. Depending on the relative magnitude of these effects, the total charge can be scaled approximately as d^2 or even as d^3, indicating a strong sensitivity of PD characteristics to void size. This behavior is critical in assessing insulation degradation, as larger voids lead to significantly higher energy discharges.

Expression (6) reveals that depending on the components in the brackets, the charge increases either as $q_{PD} \approx d^{1.5}$ or as $q_{PD} \approx d^2$. Figure 5 shows the computational results obtained for two different void diameters: 0.3 mm and 1 mm. These simulations illustrate how the size of the gas void significantly affects the voltage distribution and the characteristics of partial discharge activity within the insulation. Specifically, the larger void exhibits a lower PD inception voltage and altered discharge dynamics due to its greater influence on the local electric field.

Table 1 lists the basic PD characteristics at different diameters d. As can be seen, the increase in the defect size d leads to the increase in all PD characteristics in table 1 (current $I_{PD} = fq_T$ also increases due to the increase of q_T). That corresponds to expression (6).

Effect of the voltage amplitude and frequency on PD characteristics. Figure 6 shows the computational data for three effective values of applied voltage U_0 = 20, 30 and 50 kV at 50 Hz frequency. As seen, with the increase of the voltage, the number of PD over period T rises. At the same time, the charge of single PD q_{PD} remains almost invariable. Then with the increase of the voltage, due to the increase in the number n_T, the total charge q_T and PD current also increase, current $I_{PD} \sim q_T$.

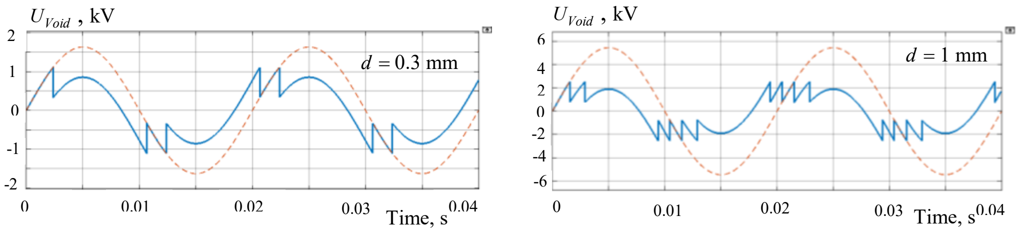

Fig. 5. Results of PD simulation for void diameters d = 0.3 and 1 mm

Rys. 5. Wyniki symulacji PD dla średnic pustych przestrzeni 0,3 i 1 mm

Table 1. Basic characteristics of PD at different void diameters d

Tabela 1. Podstawowe cechy PD przy różnych średnicach pustych przestrzeni d

d [mm]	0.2	0.3	0.6	1
n_T	4	4	8	8
q_T [pC]	4.5	8.5	57	150
q_{PD} [pC]	1.1	2.1	7.1	18.7

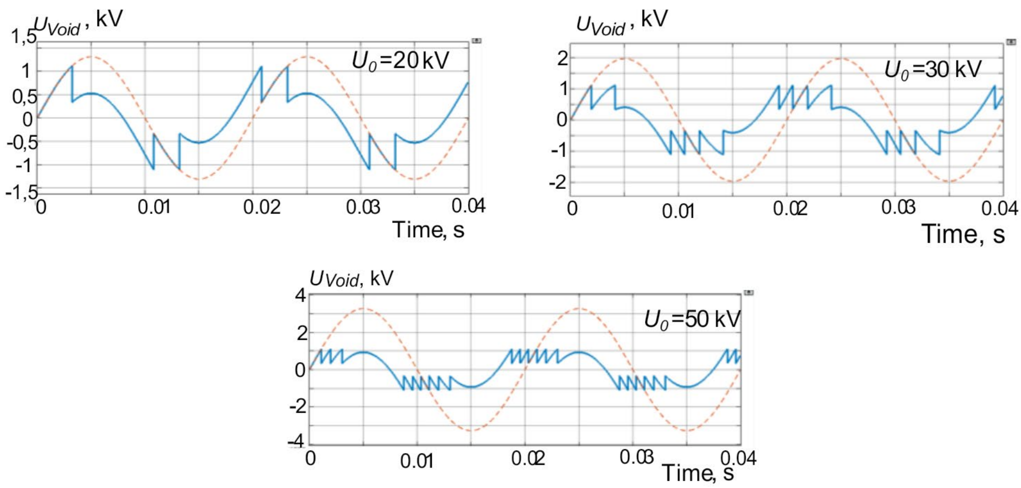

Fig. 6. Computational results for r.m.s. voltages U_0 = 20, 30, 50 kV at 50 kHz

Rys. 6. Wyniki obliczeń dla napięć r.m.s. U_0 = 20, 30, 50 kV przy 50 kHz

Figure 7 presents the simulation results for three different values of applied voltage frequency: f = 1, 20, and 50 kHz, under the conditions of a peak voltage amplitude U_0 = 25 kV, void diameter d = 0.3 mm, and electron origin time τ_e = 1 µs. The figure illustrates how higher frequencies reduce the time between voltage peaks, influence the timing of PD initiation, and result in higher average PD current due to increased charge accumulation. These results demonstrate that the frequency of the applied voltage has a significant impact on the timing and repetition rate of partial discharges within the gas void. At higher frequencies, the time intervals between voltage peaks become shorter, which affects the availability of initial electrons and the initiation of discharge. Consequently, the discharge dynamics become more sensitive to the timing of electron generation, highlighting the importance of including this parameter in PD modeling.

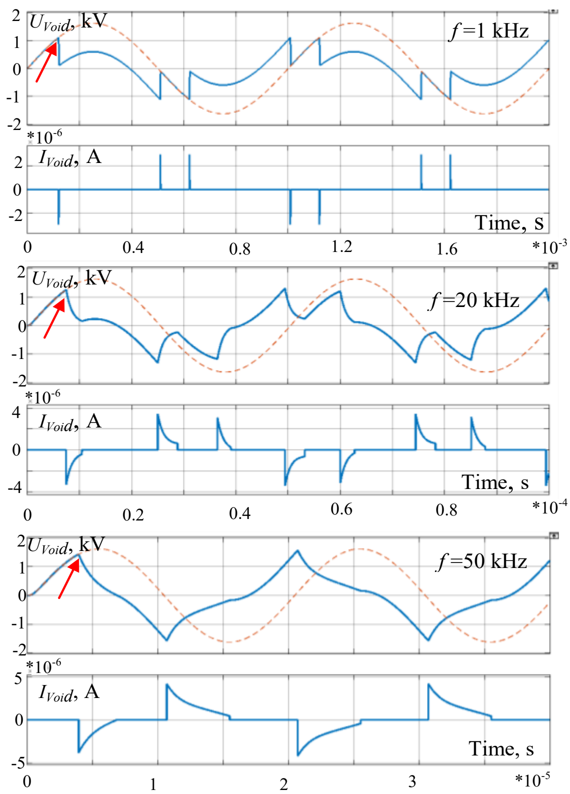

Fig. 7. Simulation results of the influence of applied voltage frequency (1, 20, and 50 kHz) on the characteristics of partial discharges (PD) in a gas void with diameter 0.3 mm at 25 kV peak voltage and 1 µs electron formation delay

Rys. 7. Wyniki symulacji wpływu częstotliwości przyłożonego napięcia (1, 20 i 50 kHz) na charakterystykę wyładowań częściowych (PD) w pustej przestrzeni gazowej o średnicy 0,3 mm przy napięciu szczytowym 25 kV i opóźnieniu tworzenia się elektronów wynoszącym 1 µs

It should be noted that the passage of partial discharges (PD) in a dielectric is characterized by two inherent time constants: $\tau_{PD} = C_{Void}R_{Void}$ and τ_e. These time constants reflect the physical processes that govern the initiation and extinction of PD events. The first is related to the rate at which the electric field in the void is restored after a discharge, while the second determines the duration and shape of the current pulse during the discharge itself. Understanding and correctly modeling both time constants is essential for accurately simulating the transient behavior of PD and assessing its impact on long-term insulation degradation.

Provided that τ_e, $\tau_{PD} << T$, the voltage frequency has a weak effect on the number of PD n_T in period T and on the value of q_{PD}. At high frequency, when these time constants approach the period T, the number of PD in the period decreases. This can be seen on Figure 7. The values of q_T vary weakly, since at high frequency due to the time delay, the capacitor corresponding to the void is charged to higher voltage. This is displayed by red arrows in Figure 7. The average value of PD current increases approximately proportionally with frequency: $I_{PD} = fq_T$. Accordingly, in comparison with the current at 50 Hz, it can be written that:

$$I_{PD}(f) \cong I_{PD\_50\,Hz} \frac{f}{50\,Hz} \tag{7}$$

Note that the characteristics given in this expression, based on the measurement of PD level at high frequency, can then be recalculated for 50 Hz. In this way, it is possible to predict the technical state of the HV insulation of power cables and other energy facilities that use the voltage and current of industrial frequency. In this context, the expedience of using the high frequency is considered in (Kuchinskii 1979); the concept of implementing the high frequency electrotechnical systems of resonant type is grounded in (Shcherba et al. 2024a); the technique for the determination and study of the operating characteristics of such systems is presented in (Shcherba et al. 2024b).

Conclusion

The paper presents an improved Simulink model of the up-to-date high-voltage polymer insulation of power cables and other energy facilities, provided that partial discharges are initiated in the micro-sized gas voids of the insulation. The model takes into account the voltage at the void, depending on its diameter, as well as the voltages at the inception and extinction of partial discharge. Additionally, it considers the time required for free electron formation in the void, which is a necessary condition for the subsequent partial discharge.

The partial discharges are quantitatively evaluated and studied by their basic characteristics (the number of discharges, total charge in the void, charge of single discharge, average current in the void). The effect of the void diameter, the amplitude, and frequency of applied sinusoidal voltage on these characteristics is analyzed. As shown, when the void diameter *d* increases, the number of discharges in period and the charge of single partial discharge increases too, and the value of the charge grows proportionally with about $d^{1.5–2}$. With the increase in the voltage at the cable, the number of partial discharges within period and other characteristics of the discharges increase. At the rise of applied voltage frequency, the average current of partial discharge increases almost proportionally with this frequency.

The proposed high-voltage generation system offers significant advantages in field applications due to its compact, transformerless design, which enhances portability and ease of deployment in remote or constrained environments. Its tuning flexibility, enabled by frequency adjustment of the resonant circuit, allows for precise voltage control without the need for bulky hardware modifications. This adaptability supports diagnostics across a wide range of insulation conditions and equipment types. The system's lightweight architecture and minimal energy requirements make it suitable for on-site testing where conventional systems are impractical. Overall, the design improves accessibility and efficiency in partial discharge diagnostics for power equipment in real-world operating conditions.

Future research will focus on enhancing the Simulink model by incorporating thermal effects and nonlinear behavior of components to improve simulation accuracy. Experimental validation under diverse environmental and load conditions is planned to verify the model's performance and reliability. Additionally, the integration of real-time data acquisition and adaptive control mechanisms will be explored to enable dynamic tuning and improved diagnostic precision. These developments aim to advance the system's applicability in practical field scenarios and support broader implementation in high-voltage equipment monitoring.

The results concerning the effect of applied voltage frequency on discharge characteristics give a possibility to recalculate the measurement data on discharge level under the action of high-frequency voltage for results on the effect of the voltage at industrial frequency (50 Hz) and in this way to predict the changes in the technical state of the high-voltage insulation of power cables and other energy facilities that use the voltage and current of industrial frequency.

This work was carried out within the project "Development of the theory and methods of the effect of non-sinusoidal voltages and currents and electrothermodynamic processes on the reliability and resource of modern power cable lines" (state registration No. 0123U100693).

The Authors have no conflicts of interest to declare.

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Symulacja komputerowa i zarządzanie wyładowaniami częściowymi w izolacji XLPE kabli wysokiego napięcia

Streszczenie

Celem niniejszego artykułu jest zbadanie wyładowań częściowych (PD) występujących w mikroskopijnych pustkach w izolacji polimerowej kabli wysokiego napięcia, które stanowią kluczowe wczesne wskaźniki wewnętrznych uszkodzeń izolacji i potencjalnych awarii. Dokładna analiza i modelowanie tych zjawisk PD ma zasadnicze znaczenie dla poprawy niezawodności i bezpieczeństwa systemów przesyłu energii elektrycznej. W ramach niniejszych prac badawczych przeprowadzono szczegółową symulację zachowania wyładowań częściowych przy użyciu oprogramowania MATLAB/Simulink, koncentrując się na wpływie wielkości pustki, a także amplitudy i częstotliwości przyłożonego napięcia sinusoidalnego na charakterystykę PD. Model symulacyjny uwzględnia kluczowe parametry fizyczne, aby dokładnie odzwierciedlić środowisko mikropustki i warunki obciążenia elektrycznego. Kluczowe wyniki pokazują, że wraz ze wzrostem średnicy pustej przestrzeni wypełnionej gazem znacznie wzrasta zarówno liczba wyładowań w każdym cyklu napięcia, jak i ładunek przenoszony podczas poszczególnych wyładowań częściowych.

Ponadto wzrost amplitudy przyłożonego napięcia powoduje większą liczbę wyładowań w jednym okresie, co wskazuje na zwiększone naprężenie izolacji. W artykule wskazano również proporcjonalną zależność między częstotliwością napięcia a średnim prądem wyładowań częściowych, gdzie wyższe częstotliwości prowadzą do zwiększonej aktywności wyładowań częściowych. Nowatorskim aspektem tej pracy jest możliwość skorelowania pomiarów wyładowań częściowych uzyskanych w warunkach napięcia o wysokiej częstotliwości z pomiarami wykonanymi przy standardowej częstotliwości przemysłowej 50 Hz. Korelacja ta ułatwia dokładniejszą interpretację i prognozowanie degradacji izolacji oraz pozostałego okresu eksploatacji kabli z izolacją polimerową i innych obiektów energetycznych wysokiego napięcia.

SŁOWA KLUCZOWE: symulacja komputerowa, zarządzanie wyładowaniami częściowymi, kable energetyczne wysokiego napięcia