An eye on circuit simulation of partial discharge detection system

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Abstract
Partial discharge measurement has received increased attention in recent years across various applications, including insulation condition assessment, fault diagnosis in high-voltage equipment, and the development of advanced monitoring systems. This paper presents recommendations for circuit simulation of partial discharge measurement systems based on electrical methods of detection. It shows that in addition to modeling the detection system itself, simulating the calibration procedure is essential for evaluating measurement accuracy, verifying compliance with standards, and optimizing the performance of individual components. This approach enhances the reliability and efficiency of partial discharge diagnostics during the design stage. Potential directions for future research are considered.

Keywords
calibration procedure, circuit simulation, detection system, partial discharge measurement

1. Introduction

Partial discharges represent a critical degradation mechanism affecting a wide range of electrical equipment across various voltage classes. These localized dielectric breakdowns, which do not completely bridge the insulation between conductors, can initiate and propagate within solid, liquid, or gaseous insulating media. Over time, repeated partial discharge activity leads to insulation erosion, thermal and chemical damage, and ultimately, complete electrical breakdown. From low-voltage electrical machines [1] and medium-voltage switchgear [2] to high-voltage transformers [3] and gas-insulated substations [4], the presence of partial discharges is a key indicator of insulation defects or aging. Therefore, reliable detection, circuit simulation and analysis of partial discharge phenomena are essential for ensuring the operational safety, longevity, and reliability of electrical power systems.

The issues of circuit modeling of partial discharge phenomena have attracted sustained interest from researchers for many years. A significant focus has been placed on the development of capacitive equivalent circuits that simulate the electrical behavior of insulation systems containing defects where partial discharges originate. These models, typically comprising combinations of capacitors, resistors, and controlled switches, allow for the representation of key physical processes such as charge accumulation, breakdown inception, and discharge transients. Among these, the so-called "three-capacitance model" and its modifications [5, 6] have become widely adopted due to their ability to approximate the interaction between the defect site and the surrounding dielectric structure. Such modeling approaches provide a valuable foundation for analyzing discharge dynamics and for designing reliable detection systems [7].

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In recent years, the application of the three-capacitance model in partial discharge research has evolved to address increasingly complex scenarios. While early studies primarily employed this equivalent circuit to represent a single cavity or defect within the insulation system, contemporary research has extended its use to more intricate configurations involving multiple defect sites [8, 9]. This progression reflects a growing recognition of the limitations of simplified models when applied to real-world insulation systems, which often contain several interacting inhomogeneities. As a result, numerous recent publications have proposed modified or expanded circuit models based on the classical three-capacitance framework to simulate the electrical behavior of insulation with multiple defects [10, 11], enabling more accurate analysis of partial discharge interactions and their impact on insulation degradation.

While considerable efforts have traditionally focused on modeling the discharge processes within insulating materials, relatively limited attention has been given to the accurate simulation of detection systems themselves [12, 13], particularly with regard to their sensitivity, frequency response, and interaction with various types of sensors. Given the critical role that detection circuits play in ensuring the reliability and effectiveness of partial discharge diagnostics, their detailed modeling is essential for the advancement of monitoring technologies in high-voltage equipment. Accordingly, the objective of this paper is to examine the specific features of circuit modeling for partial discharge detection systems, with particular emphasis on the calibration procedures required to ensure their accurate operation.

2. General information about partial discharge measurement

Partial discharge is a low-energy ionization phenomenon that occurs within electrical insulation systems. While a single discharge event is typically insufficient to cause immediate damage, the cumulative effect of numerous discharges, often occurring in tens or hundreds during each cycle of a 50 Hz applied voltage (Figure 1), can significantly degrade the insulation over time. Consequently, partial discharges cannot be neglected when evaluating the long-term electrical strength of insulating materials. It is widely recognized that the partial discharge level serves as a key indicator of the long-term electrical strength of insulation, particularly in high-voltage equipment, where the expected service life of insulation typically ranges from 20 to 30 years [14].

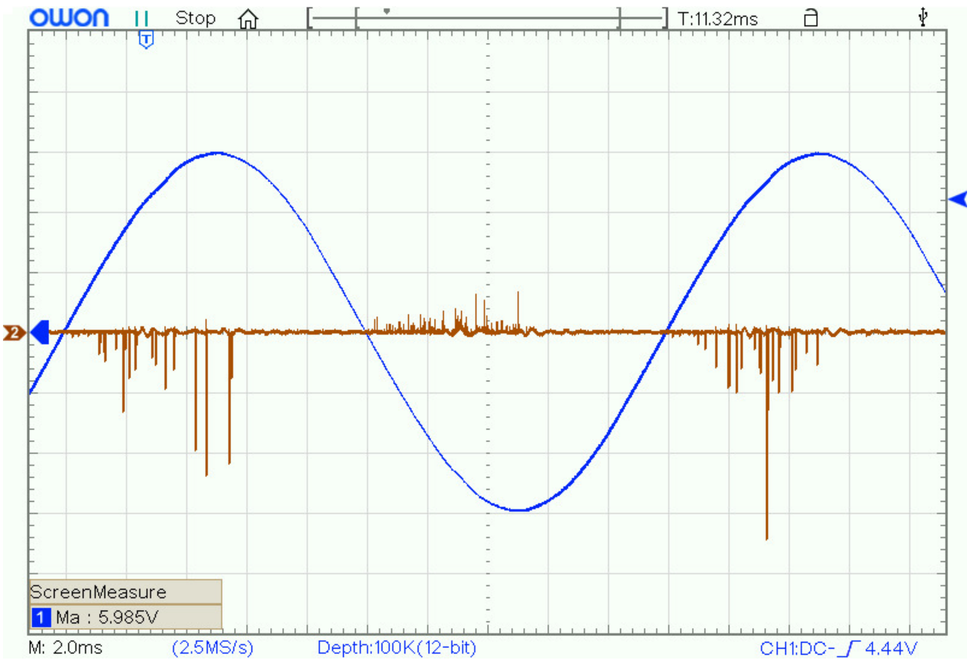

Figure 1: Typical oscillogram of partial discharges under sinusoidal applied voltage

Research on partial discharges, initiated in the 1960s, has led to the development of standardized guidelines, such as the International Standard IEC 60270:2000 High-voltage Test Techniques – Partial

Discharge Measurements, which defines the procedures for electrical measurement of partial discharge characteristics. This standard specifies several equivalent circuit configurations for conducting such measurements, ensuring consistency and reliability in diagnostic practices.

Each measurement circuit typically comprises the following components: a source of adjustable high voltage, usually implemented as a test transformer; the test object; a coupling capacitor that provides a path for partial discharge current pulses; a measuring element; and a measuring device connected in parallel with the measuring element. In most cases, a filter or protective resistor is connected between the high-voltage source and the remainder of the circuit to reduce external electromagnetic interference or limit transient currents. The general view of laboratory partial discharge detection system is shown in Figure 2.

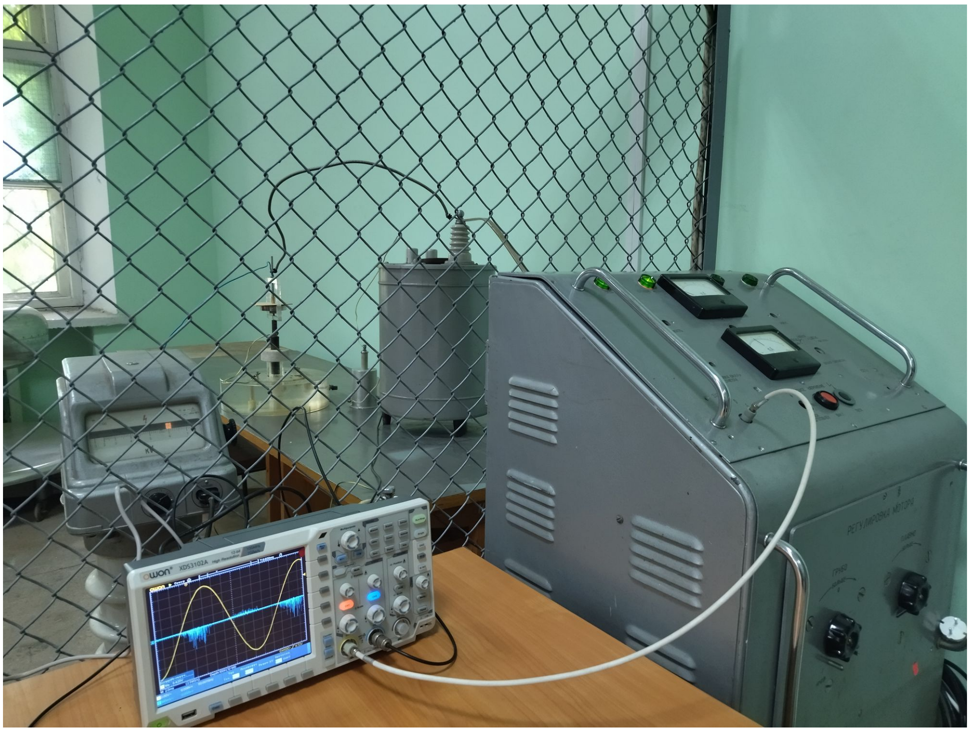

Figure 2: Photograph of a partial discharge detection system with an oscilloscope and voltage regulator in the foreground

Partial discharges must not occur within the regulated high-voltage source or the coupling capacitor, as this would compromise measurement accuracy. The measuring element is typically implemented as either a resistor or an inductor, depending on the desired frequency response and measurement characteristics. The measurement of partial discharge current pulses requires the implementation of high-pass filters capable of suppressing the power frequency (50 Hz) component by at least 80 dB. The use of modern oscilloscopes with amplification levels up to 60 dB enables high sensitivity in the measuring circuit, typically allowing detection thresholds in the range of a few picocoulombs (pC) per division.

It should be noted that the measurement of partial discharges in insulating materials is a technically complex process. An even greater challenge lies in establishing clear criteria for assessing their impact on insulation condition. The lack of specific, universally accepted regulatory documentation that defines precise thresholds for insulation health reflects the complexity and multifaceted nature of this issue. Existing standards in various countries, including IEC 60270 and related national regulations, often provide general guidelines for partial discharge measurement but rarely include definitive recommendations regarding acceptable partial discharge levels for specific types of electrical insulating materials. In this regard, the practical approach to insulation assessment in many cases relies on monitoring the trends of partial discharge activity over time.

Practical experience in measuring partial discharges demonstrates that both the number of pulses and their amplitudes vary between the positive and negative half-cycles of the applied voltage (refer to Figure 1). Moreover, the pulse count is not constant across successive voltage periods, exhibiting stochastic behavior. As a result, it is generally necessary to record partial discharge activity for at least one second to obtain a representative sample. These temporal and polarity-dependent characteristics of partial discharges present significant challenges for accurate reproduction in circuit-level simulations.

3. Circuit simulation of a partial discharge detection procedure

When modeling a partial discharge measurement system (Figure 3), it is essential to incorporate the key components that make up the system, with particular emphasis on those elements that directly influence the signal displayed on the oscilloscope screen. Foremost among these is the high-pass filter, which plays a critical role in shaping the measurable signal by suppressing low-frequency components and allowing partial discharge pulses to pass through.

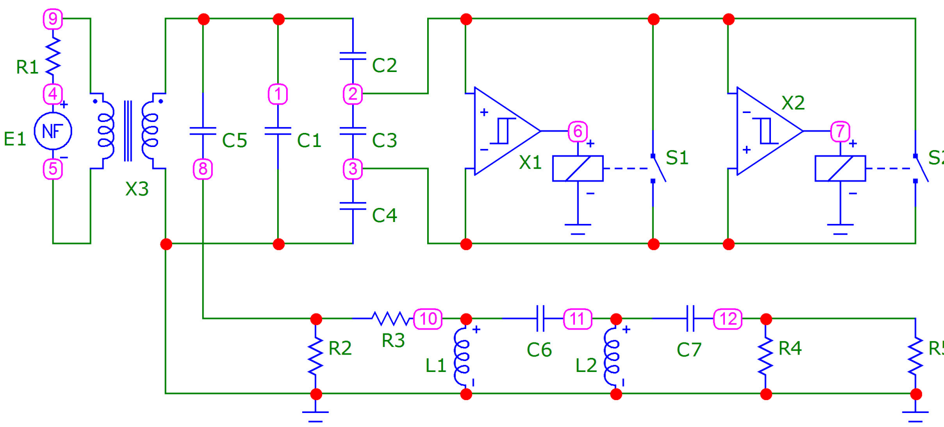

Figure 3: Simulation of a partial discharge detection system with a series connection of a coupling capacitor with a measuring element

In Figure 3: E_1 – source of alternating current (AC) test voltage; R_1 – internal resistance of the high-voltage source (10 Ohm); C_1 – capacitance of the undamaged part of insulation in the test object (500 pF); C_2 – capacitance of the undamaged part of the insulation above the air cavity in the dielectric (0.006 pF); C_3 – capacitance of the air cavity in the insulation (0.004 pF); C_4 – capacitance of the undamaged part of the insulation beneath the air cavity in the dielectric (0.006 pF); C_5 – coupling capacitor (50 pF); R_2 – measuring element (500 Ohm); R_3 = 500 Ohm, R_4 = 500 Ohm, L_1 = 104 mH, L_2 = 43 mH, C_6 = 172 nF, C_7 = 415 nF – elements of high-pass filter; R_5 – measuring device (500 Ohm); X_1, X_2 – voltage comparators with hysteresis; S_1, S_2 – voltage-controlled switches; X_3 – step-up transformer. The voltage comparator X_1, in combination with the voltage-controlled switch S_1, is used to simulate electrical breakdown events occurring during the positive half-cycle of the applied sinusoidal voltage. Similarly, the comparator X_2, together with switch S_2, is employed to model partial discharge activity during the negative half-cycle. This configuration enables the representation of polarity-dependent discharge behavior within the simulated insulation system [7]. The modeling was performed in the Micro-Cap circuit simulator, which has become free since 2019 [15].

A characteristic feature of partial discharge detection systems used for high-voltage electrical insulation is that the coupling device (or signal sensor) detects not only short-duration pulse signals generated by partial discharges, but also sinusoidal components of the test voltage at the power frequency (Figure 4).

Including the high-pass filter in the simulation model allows verification, at the system design stage, that the filter effectively suppresses the low-frequency component of the test voltage while allowing partial discharge pulses, whose spectral content lies in the high-frequency range, to pass through (Figure 5).

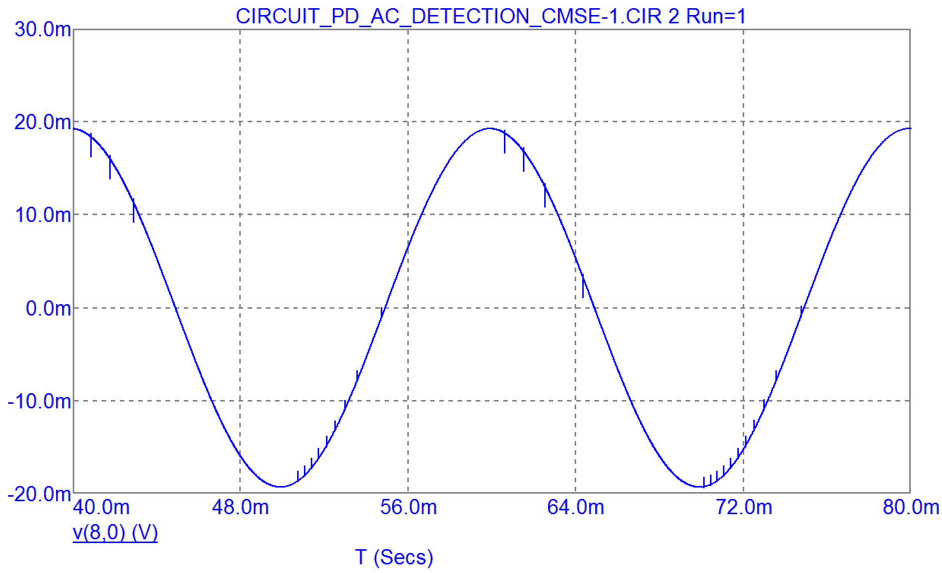

Figure 4: Voltage signal on a measuring element

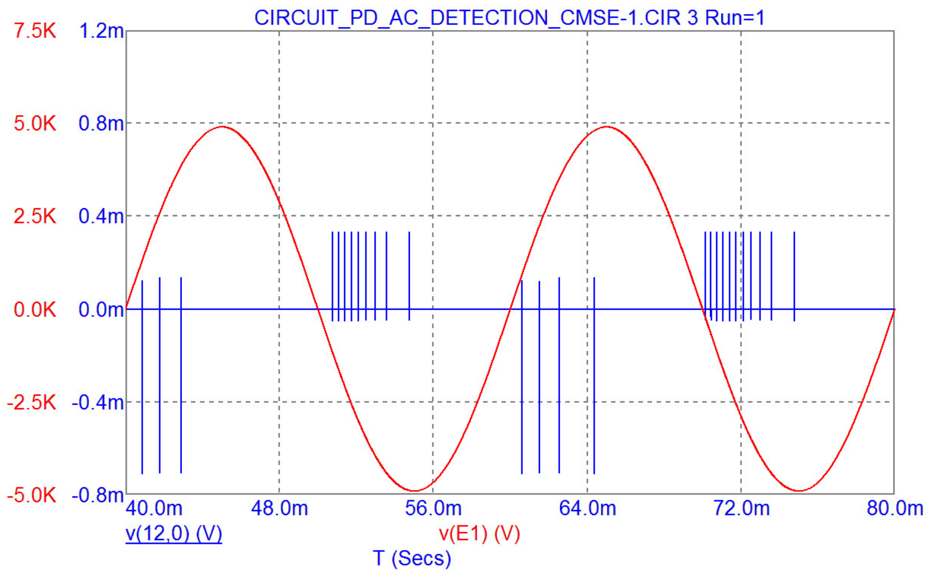

Figure 5: Voltage signal on a measuring device

In addition to the partial discharge pulses, Figure 5 also displays the applied voltage waveform, enabling a comparison of the timing of partial discharge events relative to the phase angle of the voltage at the output of the high-voltage transformer.

In the proposed model, the partial discharge inception voltage (PDIV) is represented by the upper threshold of the input voltage at which the state of voltage comparators X_1 and X_2 changes. Similarly, the partial discharge extinction voltage (PDEV) corresponds to the lower threshold of the input voltage at which the comparators revert to their initial state. This approach allows for the simulation of hysteresis behavior typically observed in partial discharge phenomena.

To reproduce the polarity effect, the values of PDIV and PDEV must differ for the positive and negative half-cycles of the applied voltage, respectively. For example, to obtain the partial discharge pattern shown in Figure 5, the values $PDIV = 1000\ V$ and $PDEV = 1550\ V$ were used for comparator X_1, and $PDIV = 950\ V$ and $PDEV = 1150\ V$ were used for comparator X_2, respectively.

Another important aspect is the selection of the electrical resistance values of switches S_1 and S_2 in their closed and open states within the circuit shown in Figure 3, as these parameters directly influence the accuracy of simulating the processes associated with the initiation and extinction of partial discharges. It is sufficient to assume that the resistance of the switches in the open state is 1×10^{20} Ohm, and in the closed state it is 1×10^{6} Ohm.

4. Circuit simulation of a detection system calibration procedure

To ensure the accuracy of the relationship between the measured apparent charge of a partial discharge and the actual charge occurring within the test object, the measurement circuits used for partial discharge detection must undergo a calibration procedure. This calibration is carried out to determine the scale factor k, which unambiguously establishes the relationship between the apparent charge magnitude and the response of the measuring system to its occurrence.

Calibration of a partial discharge measurement system should be performed with the entire circuit fully assembled and configured in its operational state. This approach ensures that all components influencing the system's response – such as coupling capacitors, connecting elements, high-frequency filters, and measuring devices – are included in the calibration process. Only under these conditions can the calibration coefficient reliably reflect the actual transfer characteristics of the assembled system. Consequently, when developing circuit models for partial discharge measurement systems, it is also advisable to simulate the complete configuration. Modeling the entire circuit allows for a more accurate evaluation of system performance, including sensitivity, frequency response, and signal distortion effects, thereby enhancing the reliability of the simulated calibration and overall diagnostics. The model of calibration circuit is shown in Figure 6.

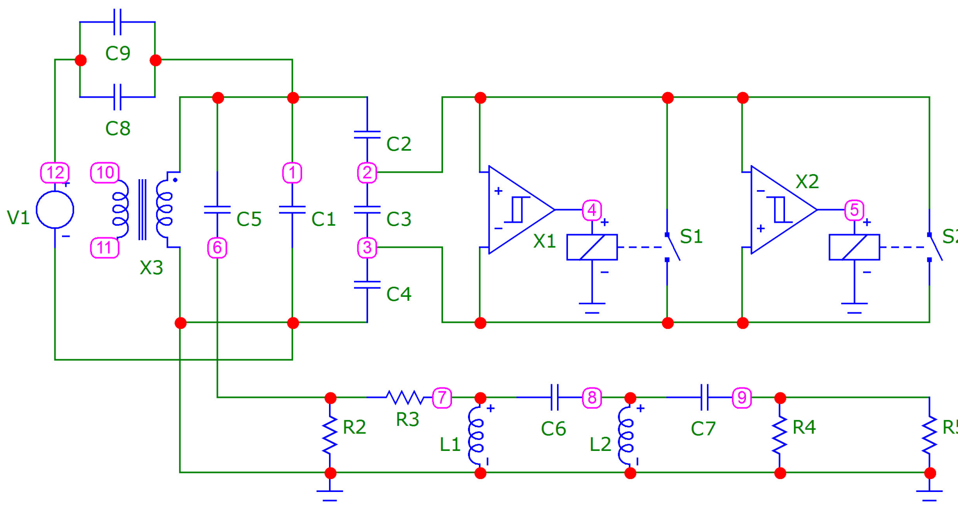

Figure 6: Simulation of a calibration circuit with a series connection of a coupling capacitor with a measuring element

In Figure 6: V_1 – rectangular pulse generator; C_8 – calibration capacitor (10 pF); C_9 – parasitic capacitance (1 pF). Other element designations are identical to Figure 3.

It is generally recommended to include both the calibration capacitor and parasitic capacitances when modeling partial discharge measurement systems. The calibration capacitor defines the reference charge injection during the calibration procedure, directly influencing the accuracy of the calibration coefficient. Parasitic capacitances, inherent in the measurement setup and test object, affect the signal shape, amplitude, and frequency response of the detection system. Neglecting these elements can lead to significant discrepancies between the modeled and actual system behavior, reducing the reliability of simulation results and impairing the validity of subsequent diagnostics. Therefore, comprehensive modeling should account for all relevant capacitances to ensure realistic representation and precise interpretation of partial discharge phenomena. The simulated signals are shown in Figure 7.

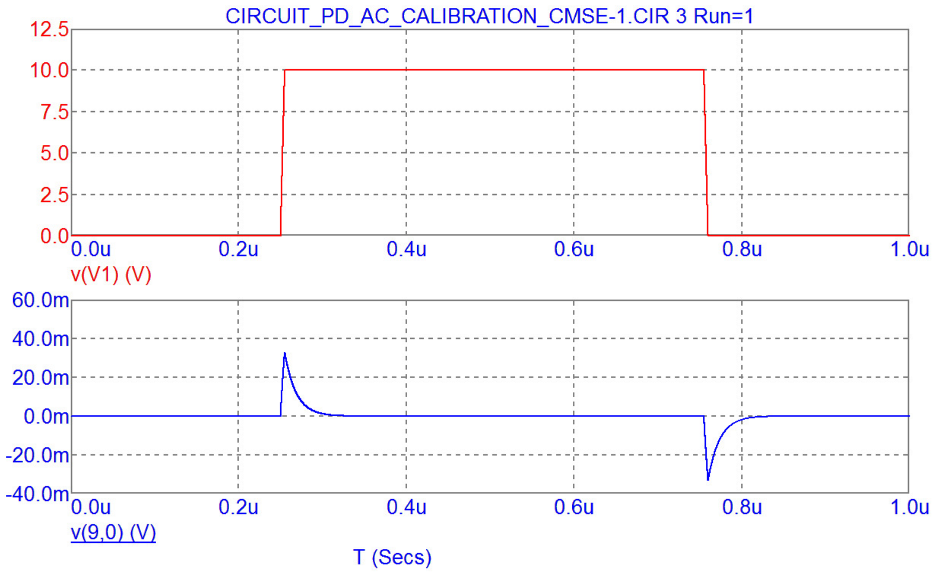

Figure 7: Calibration pulse (top) and response of the measuring system (bottom)

In Figure 7, $v(V_1)$ represents a virtual waveform of a calibration pulse with an amplitude of 10 V and a rise time of 5 ns, which meets the requirements of IEC 60270:2000; $v(9,0)$ shows the response of the measuring system to the calibration pulse, as observed on the screen of the virtual oscilloscope. Knowing the amplitude of the calibration voltage pulse (10 V) and sum of calibration and parasitic capacitances (11pF) , one can, as a first approximation, estimate the charge (C) injected into the measuring system:

$$Q = 10 \cdot 500 \times 10^{-12} = 5 \times 10^{-9}. \tag{1}$$

Based on the graph in Figure 7, the response of the measuring system to the injected charge is determined to be 33 mV. Using this value and expression (1), the calibration coefficient (C/V) can be calculated as follows:

$$k = \frac{5 \times 10^{-9}}{33 \times 10^{-3}} = 1.515 \times 10^{-7}. \tag{2}$$

With the calibration coefficient known, and the voltage values of the partial discharge pulses determined from the graph in Figure 5, the apparent charge of the partial discharges can be estimated. Since the polarity effect is accounted for in the model, the calculations must be performed separately for partial discharge pulses of positive and negative polarity.

According to the graph in Figure 5, the amplitude of the partial discharge pulses occurring in the insulation during the positive half-cycles of the applied voltage is 0.708 mV. Using calibration coefficient (2), the corresponding apparent charge (C) is calculated as follows:

$$Q_+ = 0.708 \times 10^{-3} \cdot 5 \times 10^{-9} = 1.073 \times 10^{-10}. \tag{3}$$

In turn, according to Figure 5, the amplitude of the partial discharge pulses occurring in the insulation during the negative half-cycles of the applied voltage is 0.332 mV. By multiplying this value by the calibration coefficient (2), the corresponding apparent charge (C) is obtained as follows:

$$Q_- = 0.332 \times 10^{-3} \cdot 5 \times 10^{-9} = 5.03 \times 10^{-11}. \tag{4}$$

When analyzing the intensity of partial discharges, it is often more convenient to use non-SI units of measurement. After converting expressions (3) and (4) to picocoulombs, the corresponding apparent charge values are 2.36 pC and 1.107 pC, respectively. Simulating the calibration process of the measurement system enables verification that these calculated apparent charge values align closely with those obtained during actual electrical insulation tests.

It should be noted that in practice, the response of the measuring system to the injected charge largely depends on how small the insulation capacitance of the test object is (Figure 8) and how thoroughly the inductive connections are taken into account in the entire circuit, while the latter is a rather complex task.

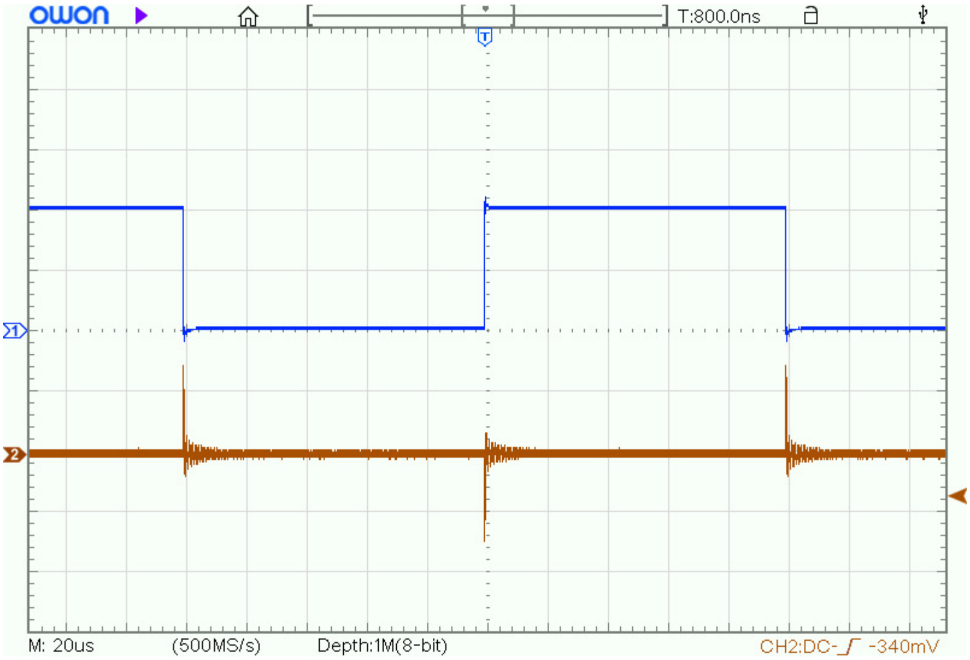

Figure 8: Calibration pulse (top) and response of the measuring system (bottom) for a test object with a capacitance of about 5 pF

In general, simulating the calibration procedure allows researchers to evaluate how accurately the detection system measures partial discharge signals under various controlled conditions. This helps verify whether the system meets the required sensitivity and frequency response. By simulating the calibration process, one can identify potential nonlinearities, frequency-dependent losses, or signal distortion in the measurement chain – before building hardware. Calibration procedures are often defined by standards such as IEC 60270:2000. Simulating the process helps ensure the system's design and response comply with those standards. It helps in tuning components (e.g., coupling capacitors, measuring impedance, filtering stages) by showing how they behave during calibration with known input signals. Running simulations of calibration procedures can reduce the need for repeated physical tests and adjustments during development, saving time and resources.

5. Conclusions

Circuit simulation is a vital tool for investigating electrical discharge phenomena in the insulation of various types of electrical equipment. One of the fundamental challenges faced by researchers is assessing how closely the results of numerical modeling correspond to the actual behavior of the physical process – in other words, how well simulation results reflect the outcomes of physical experiments. However, conducting such experiments is not always feasible, particularly at the design stage of new equipment.

This study proposes that, in addition to modeling the partial discharge detection system, the calibration circuit of the developed measurement system should also be simulated. This can be viewed as a form of inverse modeling, which makes it possible to evaluate how closely the computed values of apparent charge approximate expected values for a given test object, as reported in technical standards or scientific literature. In the three-capacitance equivalent circuit of a dielectric containing a gas-filled void, the key capacitive parameters and the inception and extinction voltages of partial discharges are typically not known with high precision and are introduced with some degree of uncertainty. In this context, the integration of a validation criterion through simulation tools becomes particularly relevant and beneficial.

This work presents a circuit-level simulation of partial discharges occurring in insulation that includes a defect in the form of a gaseous cavity, with consideration of the polarity effect of the applied voltage. The results demonstrate that the simulated apparent charge values, 2.36 pC and 1.107 pC, obtained through the modeled calibration circuit are reasonably consistent with values typically observed in testing solid insulation systems, including those monitored in power cable insulation.

The subsequent phase of the research involves refining the parameters of the partial discharge detection system by incorporating a more comprehensive representation of parasitic capacitive and inductive elements that may be inherently present in the circuit.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

References

[1] A. Mbaye, F. Grigorescu, T. Lebey, B. Ai, Existence of partial discharges in low-voltage induction machines supplied by PWM drives, IEEE Transactions on Dielectrics and Electrical Insulation 3 (1996) 554–560. doi:10.1109/94.536735.

[2] S. Kingkham, K. Smerpitak, W. Inwanna, S. Jeenmuang, T. Buranaaudsawakul, N. Pattanadech, Partial discharge characteristics of MV Switchgear using TEV and HFCT sensors, in: 2024 IEEE 14th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), 2024, pp. 105–108. doi:10.1109/ICPADM61663.2024.10750736.

[3] S. Dhara, C. Koley, S. Chakravorti, Monitoring of partial discharge inside high-voltage power transformer using UHF sensors, in: 2024 IEEE 7th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), 2024, pp. 97–101. doi:10.1109/CATCON60527.2024.10831919.

[4] C. M. Escurra, A. R. Mor, Partial discharge charge estimation in gas-insulated substations using electric and magnetic antennas, in: 2022 IEEE 4th International Conference on Dielectrics (ICD), 2022, pp. 25–28. doi:10.1109/ICD53806.2022.9863499.

[5] Z. Achillides, E. Kyriakides, M. G. Danikas, Partial discharge modeling: An advanced capacitive model of void, IEEE Transactions on Dielectrics and Electrical Insulation 26 (2019) 1805–1813. doi:10.1109/TDEI.2019.008163.

[6] S. Iwata, R. Kitani, Phase-resolved partial discharge analysis of different types of electrode systems using machine learning classification, Electrical Engineering 103 (2021) 3189–3199. URL: https://doi.org/10.1007/s00202-021-01306-5. doi:10.1007/s00202-021-01306-5.

[7] Y. Trotsenko, V. Brzhezitsky, O. Protsenko, V. Chumack, Y. Haran, Experimental study and modeling of partial discharge detection system, Technology audit and production reserves 4 (2018) 17–22. URL: https://journals.uran.ua/tarp/article/view/139942. doi:10.15587/2312-8372.2018.139942.

[8] J. Deng, M. Wang, Y. Zhou, Z. Zhou, Y. Zhang, L. Zhang, X. Liu, Partial discharge characteristics of uniform gap in oil-impregnated paper insulation under switching impulse voltage, IEEE Transactions on Dielectrics and Electrical Insulation 23 (2016) 3584–3592. doi:10.1109/TDEI.2016.005508.

[9] Y. Trotsenko, V. Brzhezitsky, O. Protsenko, V. Mykhailenko, Application of three-capacitance models for simulation of partial discharges in solid dielectric containing several cavities, in: 2019

IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON), 2019, pp. 279–282. doi:10.1109/UKRCON.2019.8879931.

[10] M. Hlongwane, R. K. Links, C. Nyamupangedengu, Characterising double cavity partial discharges, in: 2021 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa (SAUPEC/RobMech/PRASA), 2021, pp. 1–6. doi:10.1109/SAUPEC/RobMech/PRASA52254.2021.9377013.

[11] M. Thekiso, C. Nyamupangedengu, I. K. Kyere, Measured and simulated PD characteristics of closely coupled air cavities in polymeric insulation, in: 2024 IEEE PES/IAS PowerAfrica, 2024, pp. 1–5. doi:10.1109/PowerAfrica61624.2024.10759317.

[12] S. D. M. S. Gunawardana, A. A. T. Kanchana, P. M. Wijesingha, H. A. P. B. Perera, R. Samarasinghe, J. Lucas, A Matlab Simulink model for a partial discharge measuring system, in: Electrical Engineering Conference, 2015, pp. 29–34. URL: http://dl.lib.uom.lk/handle/123/20383.

[13] D. Verginadis, A. Karlis, M. G. Danikas, J. A. Antonino-Daviu, Investigation of factors affecting partial discharges on epoxy resin: Simulation, experiments, and reference on electrical machines, Energies 14 (2021). URL: https://www.mdpi.com/1996-1073/14/20/6621. doi:10.3390/en14206621.

[14] C. Homagk, K. Mossner, T. Leibfried, Investigation on degradation of power transformer solid insulation material, in: 2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2008, pp. 75–78. doi:10.1109/CEIDP.2008.4772830.

[15] Archive of Micro-Cap website, 2025. URL: https://web.archive.org/web/20230214034930/http://www.spectrum-soft.com/index.shtm.