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RESEARCH ARTICLE

Development of an Industrial Partial Discharge Calibrator and Its Performance Tests

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ABSTRACT In industrial electromechanical manufacturing, ensuring the accuracy of electrical partial discharge measurements is crucial for the reliability and efficiency of electrical power systems. The cornerstone of such precision is a well-designed partial discharge calibrator that strictly aligns with the IEC 60270 standard parameters, including apparent charge, rise time, and pulse repetition frequency. This research delineates the systematic development and subsequent performance evaluations of an innovative industrial partial discharge calibrator. The calibrator uniquely integrates advanced functionality while maintaining cost efficiency, offering an alternative to the current partial discharge calibrator market. Its design allows for a broad spectrum of pulse frequency adjustments, making it adaptable to various apparent charge bandwidths and highlighting its adaptability for high-voltage applications. Building upon the foundational understanding of partial discharge as characterized by standards such as IEC 60270, the study underscores the calibrator's capacity to elevate the standards of partial discharge measurements within high-voltage equipment.

INDEX TERMS High voltage, high voltage test techniques, partial discharge, partial discharge calibrator, partial discharge measurements.

I. INTRODUCTION

Across various literature, one can find multiple definitions about partial discharge. However, one of the most universally acknowledged and frequently referenced definitions is provided by IEC 60270 [1]. In this standard, partial discharge is characterized as "a localized electrical discharge that only partially bridges the insulation between the conductors and which can or cannot occur adjacent to a conductor." This definition underscores the inherent nature and behavior of partial discharges within insulating mediums [2].

"Partial discharge" (PD) represents a limited electrical fault in an insulator that does not lead to a complete breakdown between elements such as phase and earth. Conversely, "full discharge" means a direct electrical fault between different phases or between a phase and the earth. Such significant faults typically cause safety mechanisms to disconnect the circuit.

Monitoring PD is essential to detect and address insulation weaknesses before they become costly failures. It is, therefore, crucial in assessing the health of insulation systems in electrical power equipment. Electrical PDs due to insulation problems can cause partial damage to the dielectric insulation over time and, for example, may destroy the entire line.

For this reason, measuring the PDs in the insulating materials is necessary. Nevertheless, disruptions can lead to power outages in critical areas like hospitals or residential zones. Moreover, industries with continuous production processes, including petrochemical, cement, and semiconductor fabrication, can suffer significant financial losses due to brief power failures, potentially halting operations for extended periods. Additionally, insulation failures might damage neighboring components, amplifying repair costs. For instance, failures in major utility generators or transformers can entail repairs costing millions and lengthy plant shutdowns, leading to substantial production losses.

When studies on the evolution of PD measurement instrumentation are reviewed in the literature, three periods can be defined depending on the technological developments [3]:

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- Techniques employing Radio Interference Voltage (RIV)
- Utilization of analog detection methods capable of monitoring frequencies up to 1 MHz, visualized through oscilloscope displays
- Implementation of digital detection with subsequent computer-based analysis and measurement, suitable for processing frequencies in the GHz range

The *RIV method*, originating as a measure for corona interference from transmission lines, identifies disturbances to analog radio and TV receptions. The RIV methodology utilizes an antenna or a coupling capacitor as sensors. Signals were gauged using specialized radio receivers (radio noise meters), typically around the 1 MHz frequency range. The primary indicator was the "quasi peak" level of noise from PD activities. These noise meters began with custom constructions by researchers and later evolved into commercial instruments. Beyond their initial application, RIV methods transitioned to inspecting oil-paper-insulated power cables and oil-filled power transformers. It became an industry standard, influencing designs and quality assessments [4], [5], [6].

The progression of PD measurement techniques entered a second phase wherein *analog electronics* were utilized to capture and display PD pulses on an oscilloscope, aligning these pulses with the prevailing 50 or 60 Hz AC cycle. This approach, functioning within the time domain, contrasts the frequency-domain orientation of the initial RIV/EMI testing [7], [8], [9], [10].

Several technical shifts have marked recent evolutions in PD measurement. The initial transition moved away from analog electronics and oscilloscope visualization towards the utilization of *digital electronics*. These digital systems, backed by the proliferation of advanced analog-to-digital converters (ADCs), not only stored but also displayed PD data more efficiently. As a result, measurements started encompassing higher frequencies, even extending into the ultrahigh-frequency (UHF) spectrum. This era also saw a heightened focus on data processing. Whether through real-time digital logic devices or subsequent computer software analyses, the intent was clear: to distinguish PD from other potential disturbances and to accurately identify the root causes of any detected PD [11], [12], [13], [14].

Alongside these advancements in digital hardware, there has been a parallel evolution in noise suppression methodologies and signal processing techniques, both critical for accurate PD measurements. This has enabled PD testing to be more effectively applied to high-voltage equipment installed within power systems and industrial infrastructures. Such evaluations are crucial for two primary reasons: firstly, they provide insights into the possible degradation of the high-voltage insulation system, and secondly, they aid in predicting the imminent risks of system failures. As a result, the insights derived from these evaluations have become instrumental in informing the necessary maintenance protocols and ensuring that operational equipment meets the required safety and performance benchmarks [15].

Detection methodologies for Partial Discharge (PD) fall into two primary categories: conventional and unconventional. Traditional techniques, which are electrical, comply with the IEC-60270 standard, serving as the benchmark for PD measurement. Conversely, unconventional methods capture high-frequency PD signals via alternative approaches, including acoustic detection, optical monitoring, Ultra High Frequency (UHF) analysis, and the use of High-Frequency Current Transformers (HFCT), expanding the scope of PD detection beyond the limitations of standard electrical methods [16], [17]. Where appropriate techniques are used, it is also possible to observe the effects of the discharge in the test sample later. In general, these methods are not used to measure partial discharge quantities' magnitude but primarily for the detecting and localizing discharges. These approaches utilize various methodologies to identify and locate discharge events, enabling partial discharge to be detected beyond conventional electrical measurements [18].

The emphasis on measurement precision has concurrently grown, heightening the standards for the exactitude of PD calibrators, a vital component of measurement systems. Because the integrity of measurement outcomes is profoundly contingent upon calibrating the PD measurement apparatus. Calibration seeks to validate the system's proficiency in accurately measuring designated PD magnitudes, a cornerstone for ensuring the fidelity of diagnostic assessments. This calibration procedure is pivotal for experimental configurations, as it underpins the measurement's accuracy and reproducibility, aligning with established standards and contributing to the broader discourse on PD measurement methodologies. Such meticulous calibration underscores the critical role of precision in the empirical investigation of electrical insulation systems, facilitating a more profound understanding of PD phenomena [19]. Charges are conventionally calibrated between 10 pC and 10 nC, which is based on industry standards and practical considerations, including the typical PD values observed in equipment and the capabilities of measurement devices. This range balances sensitivity and practical applicability, ensuring accuracy across common PD scenarios. However, with advancements in insulating materials, particularly in high-voltage cable systems, calibrations down to a few pC have become essential [20], [21]. The fidelity of PD measurement techniques is intrinsically tied to the precision of the charge produced by the calibration apparatus. As for the PD sources, there may be solid, liquid, or gas voids and cavities within dielectrics between electrodes. Numerous studies have been carried out on PD, especially within air gaps. These publications aim to deepen the understanding of the PD concept by thoroughly explaining its phenomena [22], [23], [24].

There are many standards, theoretical, and experimental studies on PDs, one of the most critical factors affecting the lifetime of dielectric insulation. While decades of research and numerous field reports have investigated the aging and failure of electrical insulation materials, some areas still need to be explored. In particular, a better understanding of the complex relationship between aging mechanisms and tangible quantities such as space charge, PDs, and conduction current will enable us to improve the durability and performance of electrical insulating elements, leading to longer lifetimes of insulating materials [25]. In addition, the PD measurement system's response rate is deeply influenced by the interaction between the PD interfacing network and the object under test, along with the related high-voltage setup. Given this interplay, calibrating the entire testing circuit, including the high-voltage setup, becomes essential for accurate PD assessments. Hence, the PD calibrator is a pivotal tool in upholding the integrity of high-voltage evaluations [26].

This study introduces a partial discharge (PD) calibrator design that diverges from conventional models, such as the Tettex 9520 and Robinson Miniature Discharge 753US-1PD, which rely on simple low-voltage impulse or sawtooth waveform generators with internal power sources and galvanic separation [27], [28]. This laboratory-designed calibrator leverages a pulse generator in series with parallel-connected capacitors, enabling adjustable charge levels through manual switches. Including a timer circuit and a precise series RC configuration ensures rapid pulse rise and fall times, fulfilling stringent measurement criteria. This design simplifies the complexity typically associated with electrical PD calibrators, offering a cost-effective and stable measurement solution.

The contributions of this study and its significance are summarized below:

- The designed PD calibrator combines advanced functionality and cost efficiency through an innovative design that utilizes economically priced components, offering significant advantages in terms of adaptability and affordability across various applications, and demonstrating considerable cost savings compared to existing alternatives.
- The calibrator design meets the parameters set by the IEC 60270 standard. It also allows for various pulse frequency adjustments, making it suitable for reliable and precise high-voltage testing in different industrial applications. This versatility is an essential cost-effective contribution to literature as it fulfills the need for specialized PD measurement solutions in different industries.
- The performance evaluations to demonstrate the accuracy and reliability of the PD calibrator not only verify the effectiveness of the developed calibrator but also contribute to the body of knowledge by providing empirical data on its operation under different variations.
- Finally, by addressing the cost and adaptability issues of existing PD calibrators, it offers a new solution that could significantly fill a market gap.

II. MATERIALS AND METHODS

Within solid insulating structures, some gaps or voids are typically present. Often, these voids may be filled with ambient air, byproducts emitted during the creation of the solid dielectric, or another type of gas if the system is submerged in a gaseous insulator. Generally, these gaps in the nanometer dimension pose minimal risk to the insulation's integrity. However, as these spaces expand to the micrometer scale, as seen in power cable insulations, or even larger scales observed in components like stator windings or GIS insulators, they can become areas prone to PDs, which could culminate in a system breakdown.

PDs are pulses that form due to overvoltage across a cavity, with their magnitude being proportional to the *n*th power of the overvoltage. The magnitude reduces with increased cavity space and moisture content. Figure 1 shows the electrical equivalent circuit of a dielectric with cavities, the most common sources of PDs.

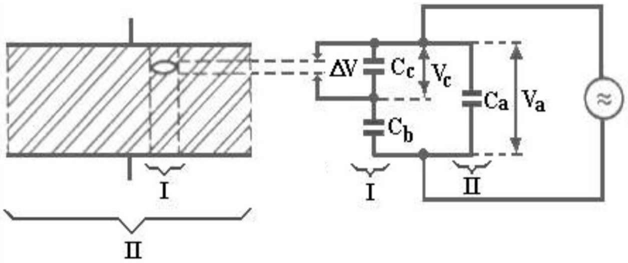


FIGURE 1. Electrical equivalent circuit of a dielectric insulation with a cavity.

Due to different theories about the formation of PDs, there are different methods in the literature to measure PDs. The most used PD measurement circuit with a coupling capacitor is illustrated in Figure 2 [29], [30], [31].

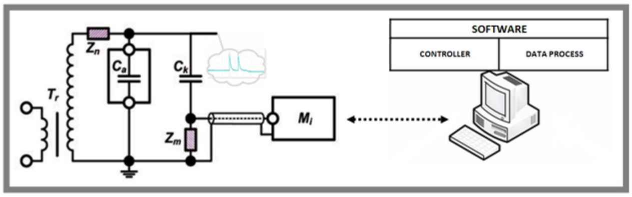


FIGURE 2. The circuit of partial discharge measurement system.

The circuit of the electrical PD measurement system is composed of a high voltage transformer, a coupling capacitor, a measurement lead with four terminals, a measuring instrument, and the PD calibrator. The component Z_n primarily acts as a high series inductance that ensures transient PD currents are directed through the coupling capacitor rather than the transformer, enhancing measurement sensitivity. In many setups, the inherent self-inductance of the transformer is sufficient for this purpose. However, if additional inductance is needed to prevent PD currents from affecting the transformer, supplementary series elements may be introduced to augment the low-pass filtering effect and further improve the system's performance. The PD calibrator's output is connected directly to the terminals of the device under test and its reference potential is connected to ground. Then, pulses with calibrated apparent charges are applied to the coupling capacitor [8], [30], [31]. Any PDs appearing across the coupling capacitor under high-frequency charge are measured by a PD meter to verify the apparent charge calibration. In partial discharge (PD) measurement systems, calibration involves accurately adjusting the system to measure PD events within high-voltage equipment. The verification coefficient of the measuring system is defined as the $k - factor$, obtained by dividing the pulse of known charge (Q_{Cal}) by the voltage provided by the peak detector (V_{Cal}) that is a calibration constant selected to compensate for the short-duration current pulses generated by a charge q_0. This factor is crucial for ensuring that the measurement system accurately reflects the charge magnitude of PD events by accounting for the system's response to these rapid pulses. The $k - factor$ adjustment is essential for accurately quantifying PD regarding apparent charge, enabling reliable insulation assessment. [3] The PD measuring system must meet the parameter values specified in IEC-60270 for the applied pulses of the PD calibrator. The apparent charge value measured by the PD meter depends on the capacity value and the measuring circuit [27], [32], [33].

Direct measurement of PD occurring within insulation flaws is not feasible. Instead, an associated electrical parameter, known as the apparent charge, is utilized to characterize the PD activity. This apparent charge represents the quantity of charge that, when swiftly applied across the terminals of the Device Under Test (DUT) in a designated testing setup, would replicate the same measurement indicator of the actual PD current pulse. A high voltage is applied to the DUT to assess the PD, leading to the measurement of the apparent charge following a PD occurrence [34]. The scale factor of the measurement system, which is the proportion of the actual input to the displayed reading, is calibrated within the entire testing circuit. This is crucial because the response of the measurement system is contingent upon the configuration of the testing circuit [35].

In the test procedure, the PD apparent charge value is calculated by comparing PD pulses defined in the PD detector with calibrated PD signals. The PD pulses applied from the calibrator should also be periodically measured and checked. According to IEC 60270 standard, pulse parameter values applied from the PD calibrator should be as indicated in Table 1.

The construction of the PD calibrator is carried out following the guidelines established by prior simulation models, with its design rooted in the values derived from these simulations. Furthermore, choosing resistors, inductors, and capacitors compatible with integrated circuits is essential to guarantee the calibrator's effective operation [36], [37], [38].

TABLE 1. Uncertainty values for PD calibrator according to the IEC 60270 standard.

Parameters	Uncertainty Values
Apparent Charge (q_0)	$\pm$ 5% or $\leq$ 1 pC
Rise Time (t_r)	$\pm$ 10% ($\leq$ 60 ns)
Repetition Rate (N)	$\pm$ 1%

The calibrator is configured with a pulse generator aligned in series with an array of parallel-connected capacitors, allowing various charge levels to be achieved by operating push-button switches alternating between these capacitors. The pulses are generated using an IC 566 timer circuit, channeling the output into a series RC circuit. This RC configuration is instrumental in attaining the targeted pulse rise time (less than $60ns$), fall time, and pulse duration (less than $5\mu s$) [1]. A configuration of capacitors arranged in parallel, integrated with push button switches, facilitated the generation of outputs at variable charge levels. These outputs are quantified across the measuring resistor, R_m. Components, including the battery, IC 566 timer, series RC circuit, the parallel capacitors with their switches, and the measuring resistor, are assembled on an electronic board and soldered to establish the calibrator. The final output is then gauged across R_m [38].

The circuit of the electrical PD calibrator usually has complicated structures. In this study, the design of the PD calibrator capable of taking stable measurements is realized using simple circuit elements. The simple schematic of the PD calibrator circuit performed in this study is given in Figure 3 [28], [39].

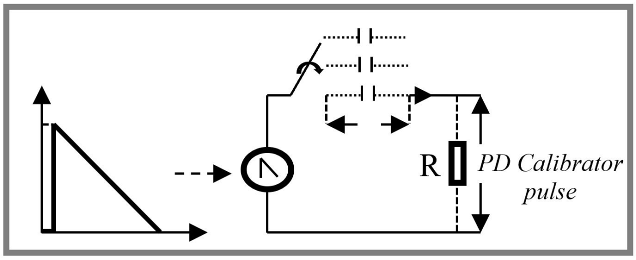


FIGURE 3. Schematic of PD calibrator circuit.

The apparent load (q) values applied from the PD calibrator are dependent upon the unit step voltage (V') and the series connected capacitors (C_0). In this study, different apparent charge values are obtained by changing the values of series-connected capacitors while the unit step voltage is kept constant. The expression of the apparent charge values applied from the PD calibrator is given below:

$$q = C_0 * V'. \quad (1)$$

The pulse form shown in Figure 4 is generated for single-sided pulse generation applied from the PD calibrator. In addressing the challenge of simulating realistic PD waveforms, the study elaborates on using sawtooth pulse forms for single-sided pulse generation by a PD calibrator. Recognizing that ideal step voltage is theoretically unattainable in practice.

The methodology in this study hinges on ensuring rapid voltage transitions—specifically from ($0.1U_0$) to ($0.9U_0$) is shorter than *60 nanoseconds*, and it may be possible to produce the identical amount of charges as in the ideal case by the standards. When generating single polarity step voltages, it is necessary to ensure that the step voltage should return smoothly to the initial state in $T_S = 10 - 50\mu s$. Otherwise, PD pulses in undesirable charges may be encountered [1], [40].

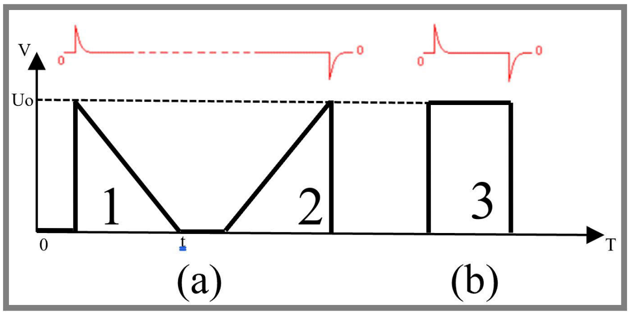


FIGURE 4. Voltage impulses regarding (a) single and (b) double step voltages.

Calibration pulses are generated by applying U_0 step voltage to the test object over one of the selected series capacitors, $C_0, C_1, C_2 \ldots$ of which capacity values are known. Herein, the measurement system measures the voltage across the test object. As the capacitor C_0 charges with voltage U_0, the charges q_0 pass through the system. The calibration of the PD measurement system is adjusted by selecting the $k - factor$ due to the short time current pulses caused by the charge of q_0.

Firstly, negative saw-tooth pulses are generated in the PD calibrator. Afterward, a negative saw-tooth pulse is produced at the desired rate using the LM566 oscillator chip and necessary circuit elements such as resistance, capacitor, and transistor. At this point, shorter rise time is the most important feature in generating the negative saw-tooth pulses. Because a shorter rise time of negative saw-tooth pulse ensures the formation of the PD signal smoother, negative saw-tooth pulse generation will produce a positive PD pulse and avoid the formation of negative PD. Figure 5 shows the LM566 circuit diagram. The microchips used in the circuit are selected according to the low-frequency values.

The capacitors $C_0, C_1, C_2 \ldots$ used in generating the calibration pulses should have the features of low noise, stability, and capability of using high-frequency signals. Figure 6 shows the adjustable capacitors used in this study. This study uses six adjustable capacitors for the PD calibrator, and the desired 6-different charge ratings are obtained with the adjusted capacity values. If the chosen capacity value changes over time, the desired charge level can be obtained again by setting the capacity value of adjustable capacitors. At the output of the PD Calibrator, calibration pulses can be generated at $5 - 20 - 50 - 100 - 200 - 500pC$ values. The magnitude of the calibration pulses at the output can be set with the help of an adjustable switch.

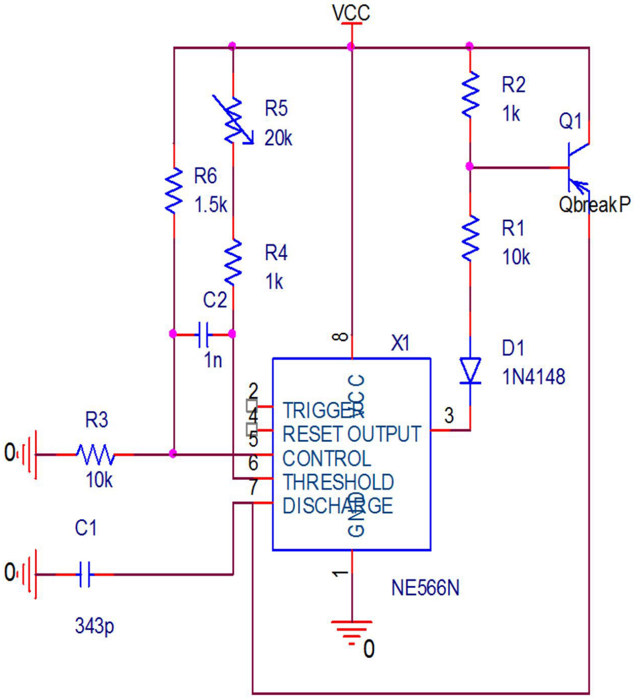


FIGURE 5. Negative saw-tooth pulse generator circuit.

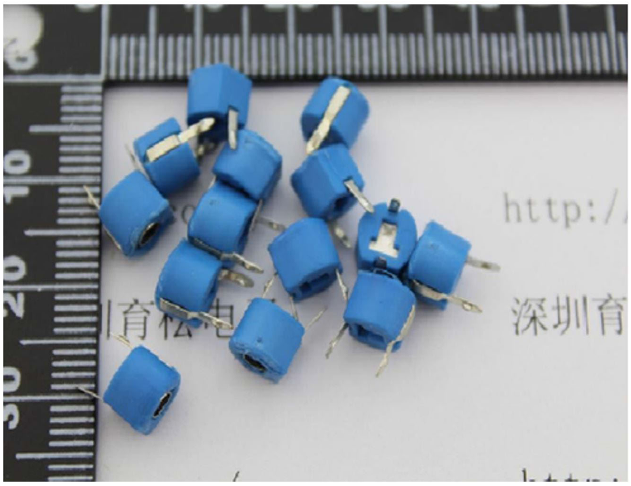


FIGURE 6. Adjustable capacitors used in the production of PD pulses.

Two $9V$ batteries are used in the PD calibrator supply circuit, and the voltage is kept constant with a $12V$ zener diode. Thus, desired PD charge values at constant voltage are generated using different capacitors. In case of a total voltage level lower than $12V$ at the supply circuit, the battery level is controlled by a designed LED-based low battery level control circuit. Accordingly, when the battery level falls below 12V, the LED flashes and warns the user, as detailed in Figure 7.

The proper cabling process is one of the most essential considerations in PD calibrator design. If cabling is not done

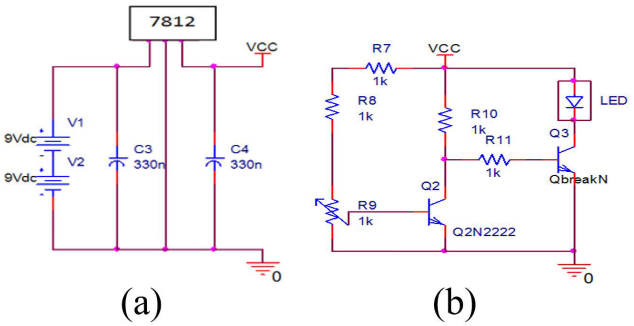


FIGURE 7. Supply circuit (a) and battery indicator circuit (b).

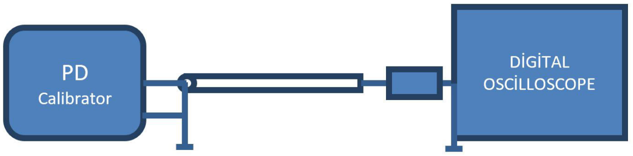


FIGURE 8. PD calibrator analysis (second method).

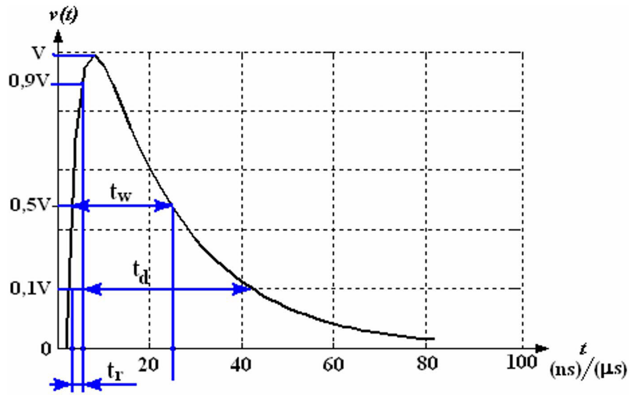


FIGURE 9. Graphical representation of the partial discharge signal.

correctly, possible leakage capacity in the system may be created. These resulting leakage capacities may affect the PD's output power, which may cause the reference PD signal to be distorted at the calibrator output. Hence, all connections must be accomplished using shielded cables to avoid the creation of leakage capacitors in the system. The structure of the tap changing switch (adjustable switch) used for adjusting the PD calibrator output power may also affect the PD value. It is necessary to connect the PD capacitors with the shortest path to the taps of the switch in order to avoid capacity creation between switch taps.

The fundamental components used in the industrial PD calibrator design are a saw-tooth pulse generator, capacitors, and the supply unit. As a saw-tooth generator, the LM566 integration chip produces pulses, the rise time of which is in the range of nanoseconds. The generated saw-tooth pulse signals are transferred to the capacitors using a particular cabling method. Adjustable capacitors can change capacity values between $1pF$ and $100pF$. Applied saw-tooth pulse signals are sent to the relevant capacitors using a tap-changing switch, and the output signal is taken via the BNC connector.

FIGURE 10. The industrial partial discharge calibrator (TÜBİTAK UME).

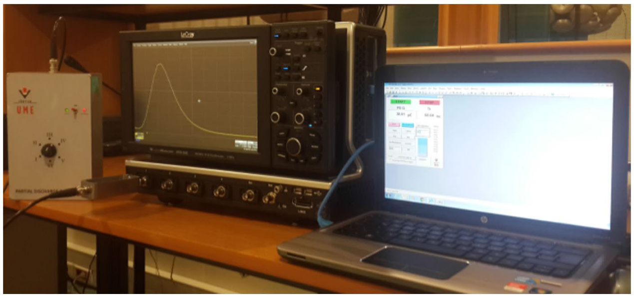


FIGURE 11. PD calibrator analysis by reference PD measurement system.

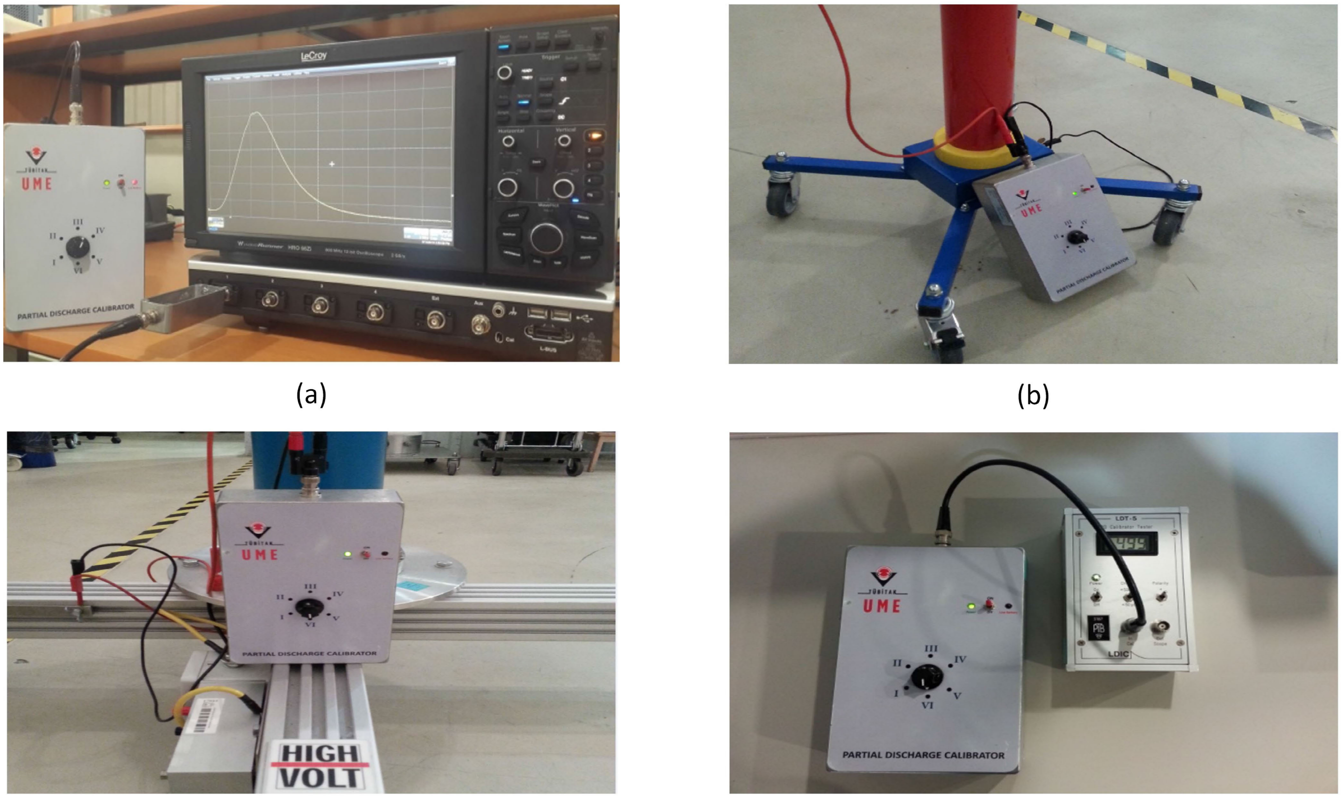
III. RESULTS AND DISCUSSION

A. PD CALIBRATOR ANALYSIS

According to the IEC 60270 standard, two different methods exist for analyzing PD calibrators. The first method compares the PD calibrator to be analyzed with a standard PD on a PD measurement system. The second method transfers the applied PD calibrator pulse to the oscilloscope over resistance, and the applied signals are analyzed afterward [1].

The first method described above is more expensive and more complex because it requires a PD calibrator, PD detector, and PD measurement device. In the second method, only an oscilloscope and software capable of calculating pulse parameter values are sufficient. In this study, analyses are performed based on the above-mentioned second method.

As shown in Figure 8, the output of the PD calibrator is applied to the oscilloscope over a resistor with the shortest BNC connector cable. Resistor modules designed for the PD



(a) (b)

(c) (d)

FIGURE 12. (a) Measurements made with the reference PD measurement system, (b) The OMICRON PD measurement system, (c) The LDS-6 PD measurement system, (d) The LDT-5 PD measurement system.

TABLE 2. Analysis of industrial PD calibrator on reference PD measurement system.

Applied value (pC)	Measured value (pC)	Rise time (ns)
5	5.1	15.1
20	19.8	20.2
50	49.9	30.1
100	100.0	40.5
200	200.0	42.5
500	501.5	50.2

measurement system are $50\Omega - 100\Omega - 200\Omega$. Selecting 200Ω as specified in the IEC 60270 standard is appropriate to analyze the impulse signal at nominal values [25], [32].

The apparent charge (Q), the PD calibrator's characteristic value, is calculated based on the pulse integration method, which uses known and stable etalon resistance. The following equation defines the mathematical expression for voltage integration, and software is used for the method of integration calculation. Using this method, the average of the rise and delay times, as well as the apparent charge, is calculated in PDCAL format. Afterward, the standard deviation values are determined, and the voltage across the resistor is analyzed with the help of a digital oscilloscope.

$$q = \int i(t)dt = 1/R_m \int U_m(t)dt. \qquad (2)$$

where $i(t)$ is the current pulse produced by the calibrator, and $U_m(t)$ is the voltage drop measured by the oscilloscope.

The graph of the PD signal is given in the Figure 9 [39]. The rise time of the impulse voltage, which is measured by an oscilloscope over 50Ω resistance (R_i) is defined as the time that corresponds to points between the peak voltage values of 10% and 90% in the front period of the pulse. As for the time delay (t_d) of the pulse, it is defined as the time between 10% value in the front period of the pulse and 10% value in the damping period [1].

The results of the reference PD measurement system developed at TÜBİTAK UME, whose design is shown in Figure 10, are given in Table 2 under 1 kHz repetition frequency.

The parameters, i.e., apparent charge (q_0), rise time (t_r), and repetition frequency (N) values of the pulses applied from the PD calibrator are calculated. Figure 11 shows PD calibrator analysis with reference PD measurement system.

The uncertainty factors for the PD calibrator are presented in Table 3. Uncertainty values of calibrated systems do not include long-term stability and long-term error. Declared expanded measurement uncertainty results from multiplying the standard measurement uncertainty by $k = 2$, which ensures the 95% reliability level based on a normal distribution. Standard measurement uncertainty is specified by GUM and EA-4/02 documents [41].

TABLE 3. Uncertainty source values affecting PD calibrator.

Uncertainty source	Uncertainty type	Uncertainty value (%)
Standard deviation	A	1.5
Oscilloscope uncertainty	B	0.05
R_m resistance uncertainty	B	0.3
General uncertainty for reference measurement system	B	0.7
Total uncertainty	A+B	1.8

B. COMPARISON OF PD CALIBRATOR WITH MEASUREMENT SYSTEMS

The developed PD calibrator is compared with four different PD measurement devices as in Table 4. Comparisons of the PD calibrator with different devices are shown in Figure 12. In the comparison in Table 4, one reference PD measurement system, two coupling capacitor test methods with a PD detector, and an electronically designed PD measurement device are used. It is clear from the comparison result that the developed calibrator is compatible with all systems.

TABLE 4. Calibration results of PD calibrator.

Applied value (pC)	UME measurement value (pC)	Omicron measurement value (pC)	LDS-6 measurement value (pC)	LDT-5 measurement value (pC)
5	5.1	5.2	5.2	5.1
20	19.8	19.9	19.9	19.8
50	49.9	49.9	50.1	49.9
100	100.0	100.1	100.0	100.0
200	200.0	200.0	200.0	200.0
500	501.5	501.2	501.0	499.0

IV. CONCLUSION

Developing an industrial PD calibrator that complies with the IEC 60270 standard has been successfully achieved. The primary objective was to create a PD calibrator capable of calibrating PD measurement systems while meeting the industry's stringent accuracy and reliability requirements.

The designed PD calibrator demonstrated exceptional performance during various tests, showcasing its suitability for calibrating PD measurement systems across various applications. Notably, the proposed PD calibrator exhibited impressive precision, applying PD pulses with an uncertainty level of approximately 1.8% across charge values of $5\ pC$, $20\ pC$, $50\ pC$, $100\ pC$, $200\ pC$, and $500pC$. This remarkable level of accuracy ensures the trustworthiness of PD measurements in high-voltage establishments.

Furthermore, the versatility of the PD calibrator is a significant advantage, as it can accommodate a wide range of pulse charges. This adaptability positions the calibrator to meet the diverse PD calibrator requirements of various high-voltage manufacturers within the industry. From a forward-looking perspective, future work will focus on designing industrial PD calibrators capable of applying even smaller apparent charges, particularly below $5pC$. These developments aim to address the evolving needs of the industry and further enhance the accuracy and reliability of PD measurements.

The PD calibrator's successful development and testing represent a significant advancement in high-voltage testing. The achieved level of precision, compatibility with industry standards, and cost-effectiveness make it a valuable tool for ensuring accurate PD measurements and enhancing the overall quality of electrical equipment in industrial applications.

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REFERENCES

[1] *High-Voltage Test Techniques—Partial Discharge Meas.*, document IEC 60270, 3rd ed., 2000.

[2] R. M. S. de Oliveira, R. F. Zampolo, L. D. S. Alcantara, G. G. Girotto, F. H. R. Lopes, N. M. Lopes, F. S. Brasil, J. A. S. Nascimento, and V. Dmitriev, "Analysis of ozone production reaction rate and partial discharge power in a dielectric-barrier acrylic chamber with 60 Hz high-voltage electrodes: CFD and experimental investigations," *Energies*, vol. 16, no. 19, p. 6947, Oct. 2023, doi: 10.3390/en16196947.

[3] G. C. Stone, A. Cavallini, G. Behrmann, and C. A. Serafino, *Practical Partial Discharge Measurement on Electrical Equipment* (IEEE Press Series on Power and Energy Systems). Hoboken, NJ, USA: Wiley, 2023.

[4] J. R. Meador, R. B. Kaufman, and H. H. Brustle, "Transformer corona testing," *IEEE Trans. Power App. Syst.*, vol. PAS-85, no. 8, pp. 893–900, Aug. 1966, doi: 10.1109/TPAS.1966.291630.

[5] J. S. Johnson and M. Warren, "Detection of slot discharges in high-voltage stator windings during operation," *Trans. Amer. Inst. Electr. Eng.*, vol. 70, no. 2, pp. 1998–2000, Jul. 1951, doi: 10.1109/T-AIEE.1951.5060664.

[6] J. E. Timperley, "Incipient fault identification through neutral RF monitoring of large rotating machines," *IEEE Power Eng. Rev.*, vol. PER-3, no. 3, p. 37, Mar. 1983, doi: 10.1109/MPER.1983.5519239.

[7] E. Lemke, S. Berlijn, E. Gulski, M. Muhr, E. Pultrum, and T. Strehl, *Guide for Electrical Partial Discharge Measurements in Compliance to IEC 60270*, document CIGRE WG D1.33 of Technical Brochure, ELECTRA No. 241, Dec. 2008, pp. 61–67.

[8] W. Hauschild and E. Lemke, *High Voltage Test and Measuring Techniques*, 2nd ed. Cham, Switzerland: Springer, 2019.

[9] G. Mole, *Design and Performance of a Portable AC Discharge Detector*, document ERA Report V/T 115, 1952.

[10] F. H. Kreuger, *Discharge Detection in High Voltage Equipment: A Heywood Book*. Amsterdam, The Netherlands: American Elsevier Publishing Company, 1965.

[11] R. Bartnikas and J. H. E. Levi, "A simple pulse-height analyzer for partial-discharge-rate measurements," *IEEE Trans. Instrum. Meas.*, vol. IM-18, no. 4, pp. 341–345, Dec. 1969, doi: 10.1109/TIM.1969.4313834.

[12] B. H. Ward, "Digital techniques for partial discharge measurements," *IEEE Trans. Power Del.*, vol. 7, no. 2, pp. 469–479, Apr. 1992, doi: 10.1109/61.127039.

[13] T. Okamoto and T. Tanaka, "Novel partial discharge measurement computer-aided measuremnet systems," *IEEE Trans. Electr. Insul.*, vol. EI-21, no. 6, pp. 1015–1019, Dec. 1986, doi: 10.1109/TEI.1986.349017.

[14] E. Gulski and F. H. Kreuger, "Computer-aided analysis of discharge patterns," *J. Phys. D, Appl. Phys.*, vol. 23, no. 12, pp. 1569–1575, Dec. 1990, doi: 10.1088/0022-3727/23/12/013.

[15] *High Voltage Test Techniques—Measurement of Partial Discharges by Electromagnetic and Acoustic Methods*, document IEC TS 62478, 2016.

[16] A. H. Alshalawi and F. S. Al-Ismail, "Partial discharge detection based on ultrasound using optimized deep learning approach," *IEEE Access*, vol. 12, pp. 5151–5162, 2024, doi: 10.1109/ACCESS.2024.3350555.

[17] L. G. P. K. Chaganti, M. H. Ahmad, M. A. M. Piah, M. Y. M. Noor, and A. I. Azmi, "Fiber optic acoustic sensor based on SMS structure with thin polymer diaphragm for partial discharge detection," *IEEE Access*, vol. 8, pp. 188044–188055, 2020, doi: 10.1109/ACCESS.2020.3031578.

[18] S. Bang, H.-W. Lee, and B.-W. Lee, "Comparison of AC and DC partial discharge by monitoring of vacuum degree in a distribution class vacuum interrupter," *IEEE Access*, vol. 10, pp. 36254–36267, 2022, doi: 10.1109/ACCESS.2022.3163448.

[19] M. Krbal, L. Pelikan, J. Stepanek, J. Orsagova, and I. Kolcunova, "A physical calibrator for partial discharge meters," *Energies*, vol. 12, no. 11, p. 2057, May 2019, doi: 10.3390/en12112057.

[20] G. Crotti, S. DEmilio, P. A. Giorgi, and O. Sarcco, "System for calibration of partial discharge calibrators," in *Proc. 9th Int. Symp. High Voltage Eng.*, Graz, Austria, Sep. 1995, p. 4511.

[21] J. Havunen and J. Hällström, "Application of charge-sensitive preamplifier for the calibration of partial discharge calibrators below 1 pC," *IEEE Trans. Instrum. Meas.*, vol. 68, no. 6, pp. 2034–2040, Jun. 2019, doi: 10.1109/TIM.2019.2895437.

[22] C. M. Escurra, A. R. Mor, and P. Vaessen, "IEC 60270 calibration uncertainty in gas-insulated substations," in *Proc. IEEE Elect. Insul. Conf. (EIC)*, Quebec City, QC, Canada, Jun. 2023, pp. 1–4, doi: 10.1109/EIC55835.2023.10177354.

[23] R. Procházka and J. Hlavácek, "Validation of partial discharge calibrators for small charge rates," in *Proc. 23rd Int. Scientific Conf. Electr. Power Eng. (EPE)*, May 2023, pp. 1–4.

[24] C. M. Escurra and A. R. Mor, "Balanced magnetic antenna for partial discharge measurements in gas-insulated substations," in *Proc. 9th Int. Conf. Condition Monitor. Diagnosis (CMD)*, Kitakyushu, Japan, Nov. 2022, pp. 509–512, doi: 10.23919/CMD54214.2022.9991698.

[25] H. N. Afrouzi, A. Hassan, D. Tay Ye Chee, K. Mehranzamir, Z. A. Malek, S. V. Mashak, and J. Ahmed, "In-depth exploration of partial discharge modelling methods within insulations," *Cleaner Eng. Technol.*, vol. 6, Feb. 2022, Art. no. 100390, doi: 10.1016/j.clet.2021.100390.

[26] R. Prochazka, K. Draxler, J. Hlavacek, and V. Kvasnicka, "Verification of partial discharge calibrators," in *Proc. Int. Conf. Appl. Electron.*, Pilsen, Czech Republic, Sep. 2013, pp. 1–3.

[27] O. Gunnarsson, A. Bergman, and K.-E. Rydler, "A method for calibration of partial discharge calibrators," *IEEE Trans. Instrum. Meas.*, vol. 48, no. 2, pp. 453–456, Apr. 1999, doi: 10.1109/19.769625.

[28] X. Ma, C. Zhou, and I. J. Kemp, "Interpretation of wavelet analysis and its application in partial discharge detection," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 3, pp. 446–457, Jun. 2002, doi: 10.1109/TDEI.2002.1007709.

[29] M. Sack and A. J. Schwab, "Design of a digital partial discharge measurement system," in *Proc. 6th Int. Conf. Optim. Electr. Electron. Equipments*, vol. 1, May 1998, pp. 167–170.

[30] K. Schon and H. D. Valentini, "Programmable impulse charge generator for calibrating PD instruments," in *Proc. 10th Int. Symp. High Voltage Eng.*, Montreal, QC, Canada, Aug. 1997, pp. 33–36.

[31] G. C. Stone, "Partial discharge diagnostics and electrical equipment insulation condition assessment," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 12, no. 5, pp. 891–904, Oct. 2005, doi: 10.1109/TDEI.2005.1522184.

[32] A. Merev, I. Karaman, S. Dedeoglu, and M. Arifoviç, "Performance of reference partial discharge measurement system," in *Proc. Conf. Precis. Electromagn. Meas. (CPEM)*, Paris, France, Jul. 2018, pp. 1–2.

[33] P. Osvath, E. Carminati, and A. Gandelli, "A contribution on the traceability of partial discharge measurements," *IEEE Trans. Electr. Insul.*, vol. 27, no. 1, pp. 130–134, Feb. 1992, doi: 10.1109/14.123448.

[34] O. Gunnarsson, *Calibration PD-Calibrators*, document SP Report 1998:01, SP Swedish Nat. Testing and Res. Inst., Boras, Stockholm, Sweden, 1998.

[35] G. Mole, "Basic characteristics of corona detector calibrators," *IEEE Trans. Power App. Syst.*, vol. PAS-89, no. 2, pp. 198–204, Feb. 1970, doi: 10.1109/TPAS.1970.292752.

[36] K. Schon and W. Lucas, *Intercomparison of Impulse Charge Measurements*, document FP4-SMT Specific Research and Technological Development Program in the Field of Standards, Measurements and Testing, Braunschweig, Germany, 1998.

[37] A. Gupta and S. Ray, "Modeling of calibration circuit for partial discharge measurement," M.S. thesis, B.Tech. Dept. Elect. Eng., Nat. Inst. Technol., Rourkela, Odisha, India, May 2013.

[38] R. Gobbo, "Influence quantities in the calibration of PD calibrators contribution to the uncertainty estimate," in *Proc. 11th Int. Symp. High-Voltage Eng.*, Aug. 1999, Art. no. 272275.

[39] M. Fidan and H. Ismailoglu, "A novel partial discharge calibrator design via dual microcontroller and high speed DAC," in *Proc. ELECO 5th Int. Conf. Elect. Electron. Eng.*, Bursa, Turkey, Dec. 2007, pp. 1–4.

[40] Y. Asiri, "Neural network-based detection of partial discharge in HV motors," M.S. thesis, Dept. Elect. Eng., King Fahd Univ. Petroleum Minerals, Dhahran, Saudi Arabia, 2010.

[41] *Expression of the Uncertainty in Measurement in Calibration*, document EAL Task Force, EA 4/02, 1999.

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