The Effect of Aluminum Wire Winding Patterns on Partial Discharge Occurrence in 24 kV Insulator Strings

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Received: 14 January 2025 | Revised: 6 February 2025, 10 February 2025, and 17 February 2025 | Accepted: 21 February 2025

 DOI: https://doi.org/10.48084/etasr.10223

ABSTRACT

This study investigates Partial Discharge (PD) on aluminum wire insulators for 24 kV transmission lines. Using the IEC 60270 charge measurement, PD was evaluated on line post 57-2, line post 57-3, and pin post 56/57-2 insulators. A metallic pipe modeled the transmission line, with aluminum wire wound in straight and curved patterns as per Thailand's PEA standards. A test voltage of 10–25 kV was applied, and the Phase Resolved Partial Discharge (PRPD) analysis identified corona discharge as the primary PD type. The results showed increased PD magnitude and frequency at higher voltages, peaking at 90° and 270° phase angles. In addition, the pin post insulator and straight winding produced the highest PD. This study highlights the impact of wire winding patterns on PD, an often-overlooked factor. The simple, cost-effective evaluation method provides insights for optimizing insulation, maintenance, and real-time monitoring in high-voltage systems, benefiting applications such as cable spacers and lightning arresters.

Keywords-discharge; insulator; corona discharge; phase-resolved analysis; aluminum wire

I. INTRODUCTION

The demand for electricity is growing rapidly in both the industrial and residential sectors, prompting the continuous expansion of power distribution systems. As a result, the development of stable and reliable electrical systems is critical to ensuring uninterrupted and safe power delivery. These systems must operate with minimal disruption, necessitating the integration of advanced technologies, such as data communication systems and Supervisory Control and Data Acquisition (SCADA) [1]. These technologies greatly enhance the ability to monitor equipment conditions in real-time and facilitate rapid response to emergencies [2]. In addition, regular maintenance and inspection of electrical equipment are crucial to improving system stability. The power transmission and distribution system consist of various components, including generators, transformers, insulators, circuit breakers, and lightning arresters, with insulators being the most prevalent in the distribution network. Insulators serve to isolate conductors from grounded structures and to withstand mechanical stresses, such as those caused by conductor weight and wind pressure. Their role is vital in ensuring both the safety and stability of the electrical system. Damage to insulators can lead to power disruptions, widespread outages, and pose significant risks to public safety and property. As such, insulator damage represents a critical issue that warrants attention. Preventing damage to electrical insulators includes using insulators that comply with standards [3] and performing regular inspections and maintenance during operation. The condition of insulators should be assessed through a combination of measurement tools and visual inspection [4-8] to identify potential problems, such as cracks, fractures, or material degradation. In the event of damage, prompt replacement is necessary. These preventive measures ensure the efficient operation of electrical systems, enhance safety, prolong equipment lifespan, and reduce costs associated with insulator replacement.

PD is a major cause of insulator failure [9-11], influenced by factors, such as weather conditions, insulator type, surface pollution, conductor wiring patterns, material degradation, and improper use. If not monitored and mitigated, PD can cause significant damage. Therefore, this research aims to investigate the PD phenomenon in insulators, focusing on the effects of voltage levels, wiring configurations, and insulator types. The study utilizes charge measurement techniques based on relevant standards to collect accurate and valuable data for preventing and mitigating PD problems in power distribution systems. The results of this research will increase the effectiveness of insulator inspection and maintenance, reduce the likelihood of damage, and improve the long-term reliability of power distribution systems.

II. THEORIES AND RELATED WORKS

A. Partial Discharge and Related Works

PD occurs when electrical stress within an insulation material exceeds its local withstand capacity without causing complete breakdown. It typically occurs in voids, cracks, or impurities within the insulation and serves as a key indicator of degradation [12]. Over time, PD can deteriorate insulation materials, reducing equipment performance and potentially leading to system failure [13]. Commonly affected equipment includes transformers, high-voltage cables, and insulators. PD is classified into three types: corona discharge, which occurs at conductor edges and leads to insulation degradation; surface discharge, which forms on insulation surfaces under high stress, especially in moist or contaminated areas; and internal discharge, which occurs within voids in solid insulation, causing hidden damage.

Several studies have explored the characteristics and detection methods of PD in high-voltage insulation systems. Authors in [14] investigated the behavior of PD in gas, liquid, and solid insulation, emphasizing the role of electric field enhancement at interfaces and the impact of different dielectric materials on discharge characteristics. Authors in [15] examined the occurrence of PD in 10 kV covered conductors around transmission tower heads, identifying key contributing factors, involving surface contamination, moisture, and mechanical defects. Their study highlighted how these factors influence the discharge pulse characteristics, leading to insulation degradation and potential system failures. Furthermore, authors in [16] analyzed the effect of insulator and metal binding wire configurations on PD activity in distribution networks, demonstrating how different structural setups alter the electric field distribution and the likelihood of discharge inception. These findings underscore the importance of effective insulation monitoring and maintenance strategies to prevent insulation failures and ensure the reliability of high-voltage electrical systems.

B. Partial Discharge Measurement Circuit

The PD measurement circuit consists of three primary subsystems:

- The coupling device serves as the interface between the measurement system and the test object, facilitating the transfer of signals from the test material to the measuring equipment.
- The signal transmission system consists of signal measurement cables or fiber optic cables used to transmit high-frequency pulse signals between different components within the system.
- The measuring instrument functions to detect and record the signals generated by the PD, including analysis and processing of the data obtained from the tests.

PD measurements according to IEC 60270 [17] are based on detecting high-frequency pulse currents i(t) generated in the test material. These currents circulate between the coupling capacitor (Ck) and the test object (Ca). The pulse current is detected at the input impedance (Zmi), as illustrated in Figure 1. The components involved in the measurement system are:

- U: High-voltage supply
- Ck: Coupling capacitor
- CC: Connecting cable
- Z: Filter
- CD: Coupling device
- MI: Measuring instrument
- Ca: Test object
- Zmi: Input impedance of the measuring system

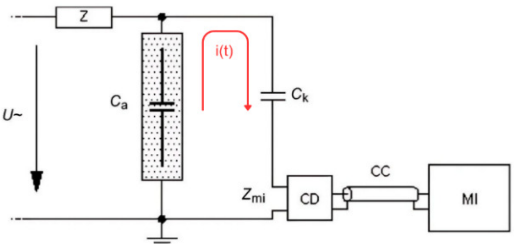
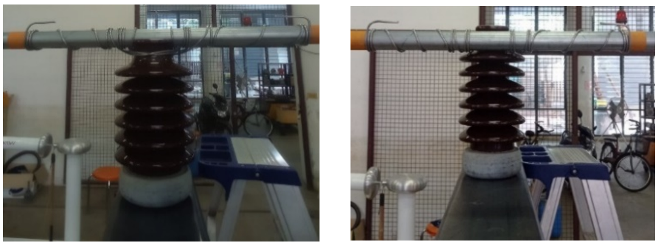


Fig. 1. PD measurement circuit.

III. METHODOLOGY

This research focuses on the studying the occurrence of PD in areas where aluminum wire is wound around a conductor attached to an insulator. The goal is to analyze the impact of the winding pattern and the type of insulator on the PD. Two types of insulators were used: line post insulators and pin post insulators installed at the center of a C-shaped steel base with a width of 6 inches and a thickness of 2.3 mm. Aluminum wire was then wound around a metal conductor pipe with a diameter of 1.25 inches, following the standard installation pattern of the Provincial Electricity Authority (PEA) [18] in Thailand, in both straight and curved patterns, as shown in Figure 2. In addition, a grading ring was installed at both ends of the conductor pipe. The insulator was connected to a PD measurement circuit consisting of a high-voltage power supply, a coupling capacitor, the system's input impedance (Tettex: AKV 9310), and a PD detector (Haefely: DDX 9121b) [19]. The discharge detector was connected to a computer via fiber optic cables. The complete experimental setup is depicted in Figure 3.



(a) (b)

Fig. 2. Winding of round aluminum wire: (a) straight pattern, and (b) curved pattern.

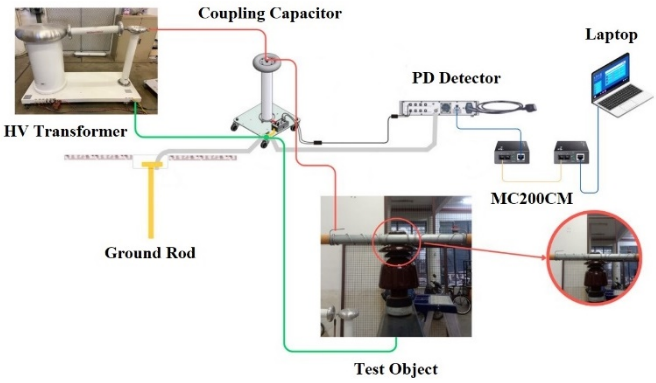
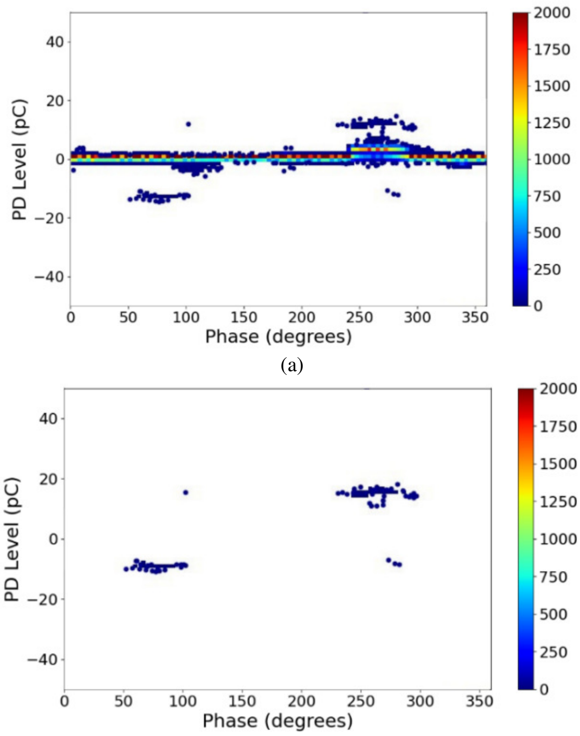


Fig. 3. Experimental setup for PD measurement.

TABLE I. DETAILS OF EXPERIMENTAL SETUPS

Experimental set	Type of insulator	Wire winding method
1	Line post 57-2	Straight
2	Line post 57-2	Curved
3	Line post 57-3	Straight
4	Line post 57-3	Curved
5	Pin post 56/57-2	Straight
6	Pin post 56/57-2	Curved

The PD measurements in this research were divided into 6 experimental sets based on the winding pattern and insulator type, as portrayed in Table I. The starting test voltage was 10 kV, increasing to 12.7 kV, 16 kV, 20 kV, and 25 kV, corresponding to 80%-200% of the normal operating voltage. Each voltage level was applied for 20 seconds, and data were recorded 10 times per experimental set. The experimental results are presented in the form of PRPD analysis, which is a method of analyzing PD occurrences by comparing the position of the discharge within one cycle using a sine wave. The horizontal axis represents the phase angle of the PD, whereas the vertical axis represents the magnitude of the PD. However, the experimental data contain noise that distorts the information. Therefore, a filtering process is needed to eliminate the noise and identify the actual PD signals. This process begins by calculating the maximum charge magnitude at each phase angle from the collected data. The average charge for each trial is then calculated, and these averages are used to compute the Standard Deviation (SD). A threshold, calculated as the average of all trials plus two times the SD, is applied to remove the noise, as displayed in Figure 4.



(a)

(b)

Fig. 4. Example of some discharge measurement results: (a) before noise removal, and (b) after noise removal.

IV. EXPERIMENTAL RESULTS

This section presents an analysis of the experimental results related to the occurrence of PD, considering the PD initiation conditions and its characteristics and behavior. The data used in the analysis consist of three main components: the phase angle at which the PD occurs, the magnitude of the discharge, and the frequency of its occurrence. These data points are analyzed to identify the factors that influence PD initiation.

A. Comparison of the Effects of Voltage

From the experimental results at various voltage levels, it was found that a higher density of some discharges is observed near the phase angles corresponding to the peaks of the sine wave, particularly at phase angles around 90° and 270°, which correspond to the maximum voltage levels for both positive and negative polarities, as shown in Figure 5. When the voltage reaches 20 kV, the distribution and magnitude of some discharges become more noticeable and tend to increase with the voltage level. The increased intensity of these discharges at higher voltages makes the discharge points more clearly identifiable according to the phase angles.

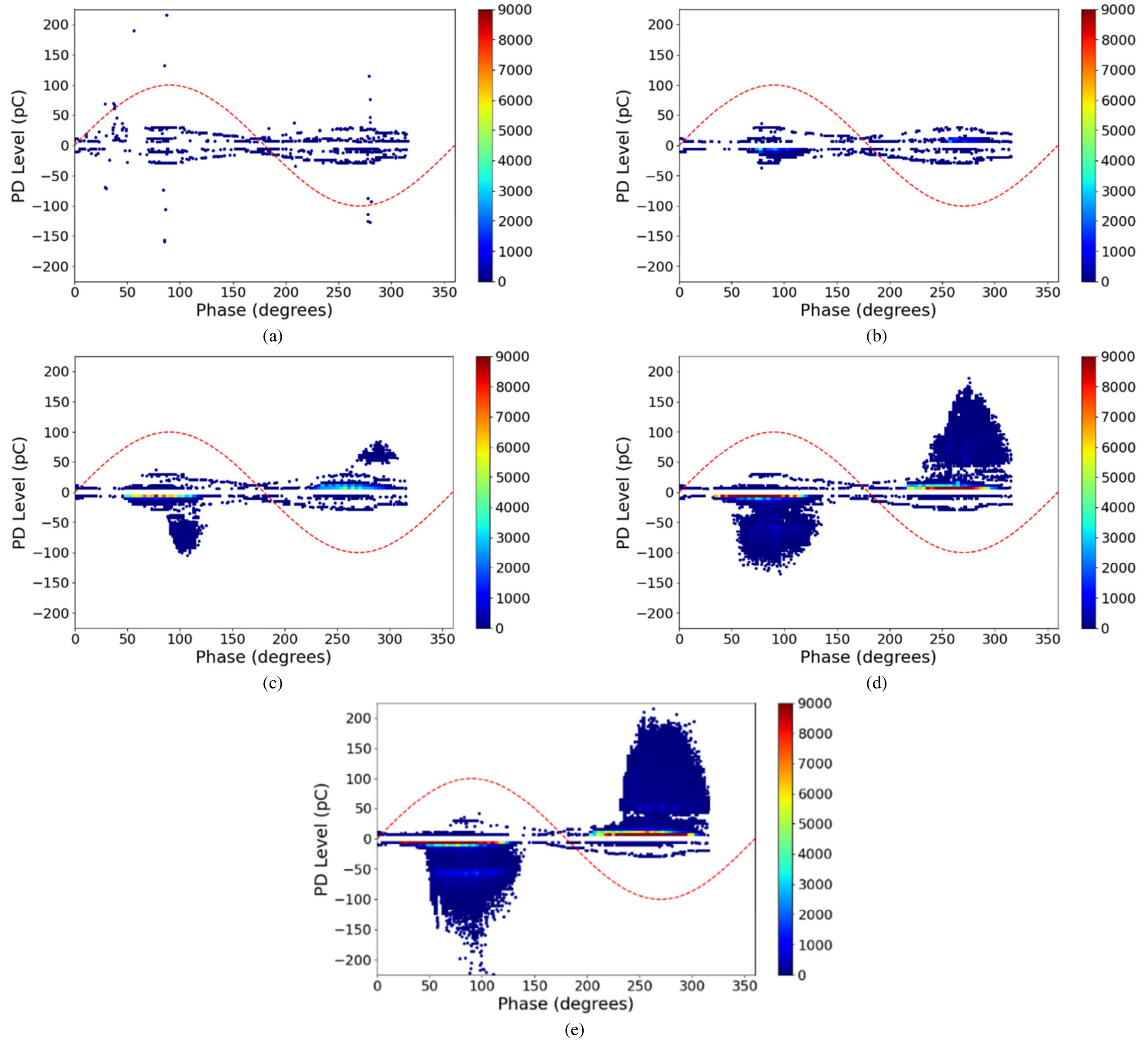


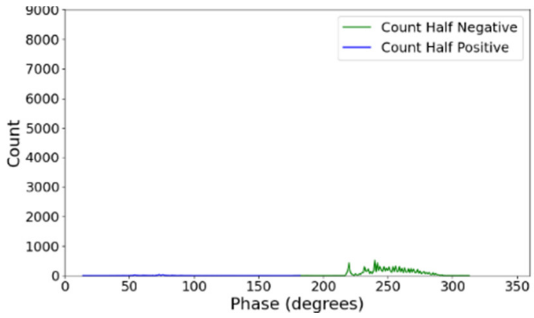
Fig. 5. PD at various test voltages:(a) 10 kV, (b) 12 kV, (c) 16 kV, (d) 20 kV, and (e) 25 kV.

B. Comparison of the Effects of Different Insulator Types

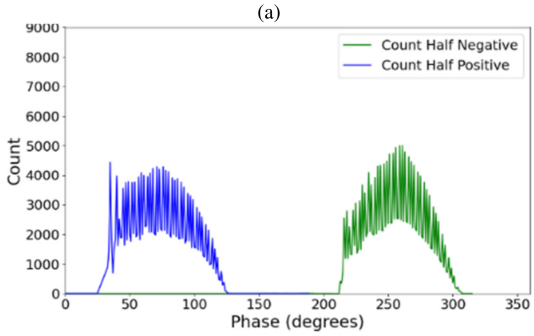
Each type of insulator shows a distinct difference in PD behavior, both in terms of size and frequency of occurrence. Some PDs are distributed over various phase angle ranges but exhibit a high density around phase angles of 90° and 270°, corresponding to the points where the voltage peaks, as illustrated in Figure 6. From the analysis of the PD distribution presented in Figure 7, it was found that the insulator type 56/57-2 has the widest data distribution, indicating irregular and highly fluctuating discharge occurrences. In contrast, the line post insulators have a narrower data distribution, but have values that are more distant from the main cluster (outliers), indicating occasional severe discharges. When comparing insulator types line post 57-2 and 57-3, it was found that insulator 57-2 has a wider data distribution, reflecting greater variability in the severity and magnitude of the PDs. In contrast, insulator 57-3 has a narrower discharge distribution, indicating more consistent and stable PD behavior.

C. Comparison of the Effects of Different Wire Winding Patterns

The effect of different winding patterns, as portrayed in Figure 8, clearly influences the distribution and magnitude of PDs. The straight winding pattern results in a higher density and frequency of PDs compared to the curved winding pattern, both during the positive and negative half-cycles. This suggests that the straight winding pattern results in more frequent and severe PDs. Figure 9 shows that most of the discharges occur during the negative half-cycle, indicating that the discharges are concentrated in the positive half of the sine waveform. When comparing the distribution of discharge magnitudes between the two winding patterns, both winding patterns exhibit similar variations in discharge size. However, the straight winding pattern demonstrates a greater degree of abnormal distribution, reflecting inconsistency and occasional intense discharges.



(a)



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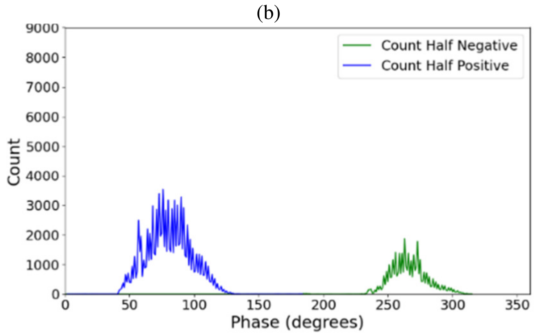


(c)

Fig. 6. The PD on each type of insulator at a voltage of 20 kV: (a) line post 57-2, (b) line post 57-2, and (c) pin post 56/57-2.

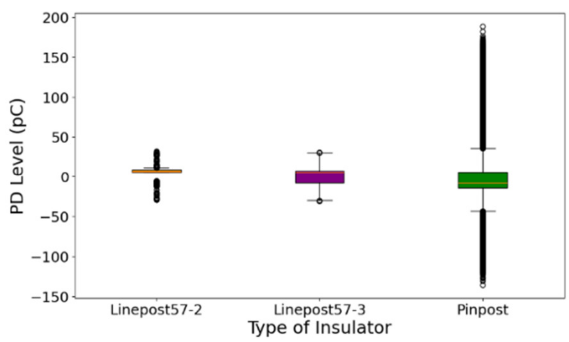
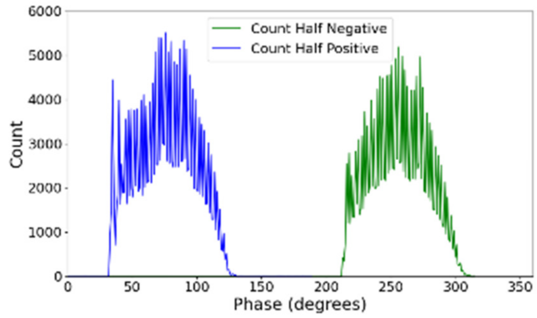
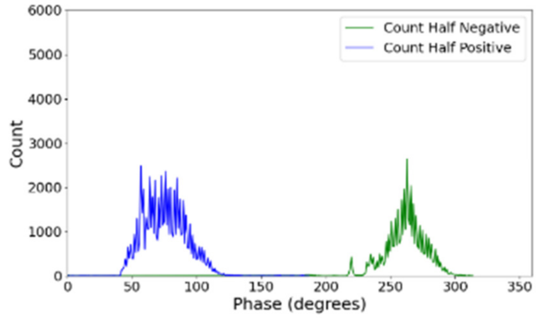


Fig. 7. The distribution of PD according to the type of insulator at a voltage of 20 kV.



(a)



(b)

Fig. 8. The PD in the form of different winding configurations at a voltage of 20 kV: (a) straight pattern and (b) curved pattern.

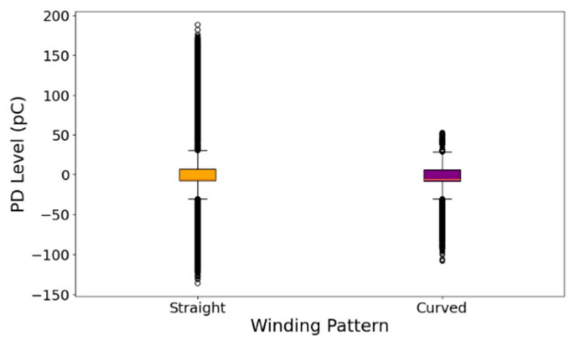


Fig. 9. The distribution of PD according to the wire winding pattern at a voltage of 20 kV.

V. CONCLUSION

This study investigates the occurrence of Partial Discharge (PD) on insulators used in the installation of 24 kV electrical transmission lines. The study uses three different types of insulators and two configurations of aluminum wire winding: a straight-wound configuration and a curved-wound configuration. The tests were conducted at voltage levels ranging from 10 kV to 25 kV, and the measurements were performed in accordance with the IEC 60270 standard, which is commonly used to detect and analyze PD in electrical equipment. The experimental results were analyzed using the Phase Resolved Partial Discharge (PRPD) method, which allows a detailed observation of the PD characteristics over time, considering both amplitude and phase information. The analysis revealed that the PDs exhibited characteristics, like corona discharges, with both the size and frequency of the discharges increasing with the applied voltage. Notably, the PD occurrences were particularly pronounced at certain phase angles of 90° and 270°. These findings highlight the critical influence of wire configuration and phase angle on the intensity of PD activity. Furthermore, the study underscores the importance of employing robust insulation designs to mitigate potential risks in high-voltage applications.

Among the insulators tested, the pin post insulator 56/57-2 exhibited the highest occurrence of PDs. Additionally, the wire winding configuration was found to have a significant effect on the PD behavior. Specifically, the straight wire configuration resulted in a greater dispersion of PDs with larger discharge sizes compared to the curved wire configuration, which resulted in a more localized discharge pattern with smaller sizes. The findings of this research highlight the important role that both insulator type and winding configuration play in the occurrence and characteristics of PDs in electrical transmission systems. These findings stress the importance of addressing these factors to reduce the risk of PDs and prevent insulation damage and system failures. Understanding these variables will help operators and engineers reduce PD risks, ensuring a more reliable and efficient operation of high-voltage systems.

This study introduces a novel perspective by examining the impact of wire winding patterns on PD occurrence, an aspect often overlooked in previous research, which focuses primarily on insulator properties. The evaluation method is simple, cost-effective, and easily adaptable to on-site applications. These findings provide a foundation for future research on PD patterns at operating voltage levels, optimizing winding configurations and insulator types, and developing real-time monitoring systems for field testing. The results can also be applied to similar equipment, such as cable spacers and lightning arresters, while considering real-world factors, like conductor types, environmental conditions, and mechanical forces. These insights help improve insulation reliability, optimize maintenance strategies, and enhance high-voltage system performance.

REFERENCES

[1] W. Sikorski, K. Walczak, W. Gil, and C. Szymczak, "On-Line Partial Discharge Monitoring System for Power Transformers Based on the Simultaneous Detection of High Frequency, Ultra-High Frequency, and Acoustic Emission Signals," *Energies*, vol. 13, no. 12, Jun. 2020, Art. no. 3271, https://doi.org/10.3390/en13123271.

[2] M. Ghassemi, "Accelerated insulation aging due to fast, repetitive voltages: A review identifying challenges and future research needs," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 26, no. 5, pp. 1558–1568, Oct. 2019, https://doi.org/10.1109/TDEI.2019.008176.

[3] O. E. Gouda, M. M. F. Darwish, K. Mahmoud, M. Lehtonen, and T. M. Elkhodragy, "Pollution Severity Monitoring of High Voltage Transmission Line Insulators Using Wireless Device Based on Leakage Current Bursts," *IEEE Access*, vol. 10, pp. 53713–53723, 2022, https://doi.org/10.1109/ACCESS.2022.3175515.

[4] C. He, L. Jiang, and L. Jiang, "Seismic Failure Risk Assessment of Post Electrical Equipment on Supporting Structures," *IEEE Transactions on Power Delivery*, vol. 38, no. 4, pp. 2757–2766, Aug. 2023, https://doi.org/10.1109/TPWRD.2023.3257305.

[5] S. Kaziz *et al.*, "Radiometric Partial Discharge Detection: A Review," *Energies*, vol. 16, no. 4, Feb. 2023, Art. no. 1978, https://doi.org/10.3390/en16041978.

[6] Q. Zhang, C. Li, S. Zheng, H. Yin, Y. Kan, and J. Xiong, "Remote detecting and locating partial discharge in bushings by using wideband RF antenna array," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 6, pp. 3575–3583, Dec. 2016, https://doi.org/10.1109/TDEI.2016.005747.

[7] Y. Xu, J. Cheng, W. Liu, and W. Gao, "Evaluation of the UHF method based on the investigation of a partial discharge case in post insulators," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 6, pp. 3669–3676, Dec. 2017, https://doi.org/10.1109/TDEI.2017.006779.

[8] S. Panigrahy and S. Karmakar, "Real-Time Condition Monitoring of Transmission Line Insulators Using the YOLO Object Detection Model With a UAV," *IEEE Transactions on Instrumentation and Measurement*, vol. 73, pp. 1–9, 2024, https://doi.org/10.1109/TIM.2024.3381693.

[9] L. Yang, J. Fan, Y. Liu, E. Li, J. Peng, and Z. Liang, "A Review on State-of-the-Art Power Line Inspection Techniques," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 12, pp. 9350–9365, Dec. 2020, https://doi.org/10.1109/TIM.2020.3031194.

[10] R. Fechet, A. I. Petrariu, and A. Graur, "Partial Discharge and Internet of Things: A Switchgear Cell Maintenance Application Using Microclimate Sensors," *Sensors*, vol. 21, no. 24, Dec. 2021, Art. no. 8372, https://doi.org/10.3390/s21248372.

[11] T. Shahsavarian *et al.*, "A Review of Knowledge-Based Defect Identification via PRPD Patterns in High Voltage Apparatus," *IEEE Access*, vol. 9, pp. 77705–77728, 2021, https://doi.org/10.1109/ACCESS.2021.3082858.

[12] T. Ye, B. Kai, X. Nianwen, S. Lei, Z. Lijun, and L. Hui, "Study on the Influence of 10kV Insulator and Metal Binding Wire Form on Partial Discharge in Distribution Network," in *2022 China International Conference on Electricity Distribution*, Changsha, China, 2022, pp. 483–488, https://doi.org/10.1109/CICED56215.2022.9928832.

[13] R. Szilágyi, P. Molinié, M. J. Kirkpatrick, E. Odic, G. Galli, and P. Dessante, "Role of Temperature in Partial Discharge Inception Voltage at Triple Junctions," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 6, pp. 2809–2818, Dec. 2023, https://doi.org/10.1109/TDEI.2023.3315686.

[14] H. Suwarno, "Partial Discharge in High Voltage Insulating Materials," *International Journal on Electrical Engineering and Informatics*, vol. 8, no. 1, pp. 147–163, Mar. 2016, https://doi.org/10.15676/ijeei.2016.8.1.11.

[15] L. Zhou, Y. Tian, W. Chen, S. Huang, and T. Wen, "Characteristics of Partial Discharge on 10 kV Covered Conductor Around Tower Head," *IEEE Access*, vol. 10, pp. 98140–98152, 2022, https://doi.org/10.1109/ACCESS.2022.3206374.

[16] T. Ye, B. Kai, X. Nianwen, S. Lei, Z. Lijun, and L. Hui, "Study on the Influence of 10kV Insulator and Metal Binding Wire Form on Partial Discharge in Distribution Network," in *2022 China International Conference on Electricity Distribution*, Changsha, China, 2022, pp. 483–488, https://doi.org/10.1109/CICED56215.2022.9928832.

[17] *High-voltage test techniques - partial discharge measurements*, IEC 60270, 2000.

[18] "Provincial Electricity Authority (PEA)." https://www.pea.co.th/en.

[19] *Operating Instructions DDX 9121b Partial Discharge Detector, Haefely Test AG,* (2014). Accessed: Feb. 25, 2025. [Online]. Available: https://hubbellcdn.com/ohwassets/HCI/Haefely_Hiptronics/Product-Documents/Measuring_Instruments-Partial-Discharge/DDX9121b/MA_DDX9121b_V7.3.pdf.

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