Analysis of partial discharge characteristics in transformer oil insulation media using needle-plane and plane-plane electrode systems

Teuku Khairul Murad[1], Abdul Syakur[2], Iwan Setiawan[1]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang, Indonesia
[2]High Voltage Innovation and Technology Research Laboratory, Faculty of Engineering, Universitas Diponegoro, Semarang, Indonesia

Article Info

Article history:

Received Dec 31, 2024
Revised Jul 3, 2025
Accepted Jul 12, 2025

Keywords:

Insulation
Needle-plane electrode
Partial discharge
Plane-plane electrode
Transformer oil

ABSTRACT

Insulation failure is a common issue in electric power transmission. Insulation is necessary to separate two or more live conductors to prevent electrical arcing or sparking between them. Partial discharge (PD) is a phenomenon that can also occur in high-voltage equipment under pre-breakdown conditions. This PD activity can take place in liquid insulation, such as transformer oil, leading to a decrease in the quality and reliability of the transformer. This study aims to detect PD under various conditions and investigate its characteristics. Although various studies have been conducted on PD in liquid insulation, most of them focus on PD characterization under specific conditions without considering variations in electrode configurations that may influence the PD phenomenon. Therefore, this research is necessary to fill this gap by analyzing PD characteristics using a needle-plane and plane-plane electrode system. This study introduces the use of castor oil as an alternative liquid insulating material. In this study, PD testing will be conducted in a laboratory environment, and it is expected to produce reliable data regarding the capability of liquid insulation to withstand PD. The results obtained indicate that the PD phenomenon occurs more quickly in the needle-plane electrode configuration compared to the plane-plane configuration. PD in the needle-plane electrode occurs at an average voltage of 10.96 kV, while PD in the plane-plane electrode occurs at an average voltage of 12.5 kV.

Corresponding Author:

Abdul Syakur
Department of Electrical Engineering, Faculty of Engineering, Universitas Diponegoro
Professor Soedarto Street No. 13, Semarang, Central Java 50275, Indonesia
Email: gakusei2003@yahoo.com

1. INTRODUCTION

To meet the rapidly growing demand for electricity, high-voltage power systems with higher performance and better stability are needed, making insulation one of the most important aspects in maintaining the safety and performance of high-voltage equipment [1]–[4]. High-voltage equipment includes transformers, generators, high-voltage cables, and others. This equipment typically uses insulation in the form of gas, liquid, and solid materials. Each type of insulation has different properties and capabilities, leading to different implementations [5], this study investigates the partial discharge (PD) phenomenon in solid insulating materials, specifically polyvinyl chloride (PVC), by introducing an artificial cavity in a 0.8 mm thick sheet using a ball-plane electrode system [4], [6]–[8], this study investigates PD activity in ferrofluids based on biodegradable transformer oil with iron oxide nanoparticles [9]. Insulation plays a crucial role in the electrical power system by separating two or more live conductors, serving as a barrier to prevent flashovers or sparks [10]–[13].

A key component in high-voltage generation equipment is the power transformer [14], [15]. Within the power transformer itself, there is an essential component that significantly affects insulation between conductors, namely oil, which acts as a dielectric material or liquid insulation [2], [16]–[19]. Liquid insulation has a higher dielectric capacity compared to gas insulation and has self-healing capabilities if discharge occurs [8], [10], [12], [17], [20]–[22]. However, liquid insulation is not always perfect, so the possibility of PD still exists.

Partial discharge is an electrical discharge event that occurs partially, bridging two electrodes that should otherwise remain unconnected. The causes include defects or aging, such as voids, protrusions, and contaminants. PD events do not instantly cause insulation failure, but continuous PD activity can caused localized overheating, which progressively deteriorates the insulation quality and erodes the dielectric material, possibly leading to total collapse [23]–[26]. Therefore, analyzing PD activity in insulating materials is essential. The PD discussed in this study focuses on PD in liquid insulating material, specifically transformer oil.

Rahman *et al.* [27] This study investigates the effect of irregular-shaped copper (Cu) particles in transformer oil PD characteristics under varying electric field. Rahman and Nirgude [28] This study presents the investigations on PD behavior of irregular-shaped copper particle in oil with pressboard barrier placed in two positions under uniform field with different moisture contents.

Although many studies have been conducted on PD in liquid insulation, most previous research has focused on PD characterization under specific conditions without considering variations in electrode configurations that may influence PD inception and development. Additionally, prior studies have predominantly used electrode systems with larger gap distances (25 and 50 mm) [23], whereas research on PD in transformer oil with a smaller electrode gap (2.5 mm). Therefore, this study aims to fill this research gap by observing and measuring PD in transformer oil using more varied electrode configurations and a smaller gap, to gain a deeper understanding of the mechanisms of PD inception and development in liquid insulation.

Korobeynikov *et al.* [20] This study shows that PD in liquids can develop in various forms, including gas discharge within bubbles and impact ionization in the liquid under extreme electric fields. This study also highlights the importance of initial electrons in PD inception and the influence of X-rays in lowering the PD inception voltage.

Pasternak and Rozga [4] conducted laboratory-scale research on an oil-wedge type electrode system, focusing on the comparison of partial discharge inception voltage (PDIV) when immersed in liquid dielectric. Pattanadech *et al.* [23] studied PD in liquid insulation media using plane electrodes with gap distances of 25 and 50 mm. Pan *et al.* [16] this study shows that the presence of metallic particles in moving transformer oil affects the characteristics of PD and breakdown voltage. Experimental results indicate that an increase in oil flow velocity raises the PDIV, while the magnitude and frequency of PD decrease.

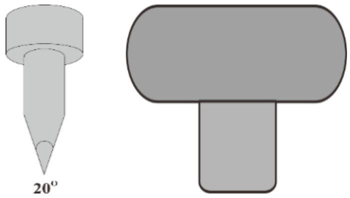
This study uses a new approach in analyzing the characteristics of PD using two different electrode configurations (needle-plane and plane-plane) on transformer oil based on castor oil. The novelty of this research lies in the use of castor oil as an alternative liquid insulating material, with PD detection performed through the observation and measurement of charge pulses using needle-plane and plane-plane electrode systems with a 2.5 mm gap under varying AC voltages. This study also highlights the sensitivity of PD detection and the discharge initiation time as indicators of oil degradation.

2. METHOD

2.1. Electrode and sample

The electrodes used in this measurement are needle electrodes and plane electrodes made of copper. The tip of the needle is sharpened until it is sharp like a pencil, with a sharp angle of 20°. The plate is cylindrical, with a diameter of 4.5 cm and a thickness of 1 cm. The shape of the needle and plane electrodes used is shown in Figures 1(a) and 1(b).

The sample used is a new liquid insulating material in the form transformer oil based on castor oil, and the gap distance between the electrodes is 2.5 mm, as shown in Figures 2(a) and 2(b). The castor oil used has a breakdown voltage of more than 30 kV, a viscosity of 200–300 cSt, a tan delta value of less than 0.02, and a water content of 500 ppm, as shown in Table 1. The test voltage ranges from 0 to 20 kV AC with a frequency of 50 Hz. The test is carried out at room temperature (25 °C) with controlled humidity. The PD signal is captured using a capacitor coupling sensor and amplified before being analyzed. Partial discharge signal data is analyzed using a time domain approach using the partial discharge phase-resolved (PRPD) method, which maps the characteristics of the discharge pattern to the AC voltage phase angle to identify the type of PD.



(a) (b)

Figure 1. The electrodes for measurement (a) needle and (b) plane electrodes

(a) (b)

Figure 2. The sample for a new liquid insulating material (a) castor oil test sample and (b) needle-plane electrodes

Table 1. Physical and chemical specifications of castor oil

Parameter	Typical value
Appearance	Pale yellow to golden yellow
Kinematic viscosity at 40 °C	200-300 cSt (mm²/s)
AC breakdown voltage	> 30 kV
Water content	< 500 ppm
Dielectric dissipation factor (tan δ)	< 0.02

2.2. Experimental set up

The stages of the experiment are shown in Figure 3. Measurements are conducted using AC input with a frequency of 50 Hz connected to the needle-plane and plane-plane electrodes. The transformer oil sample being tested will exhibit PD, which will then be detected by the RC detector, functioning as an integrator. The R and C components in the RC detector are used to adjust the sensitivity of the PD detector.

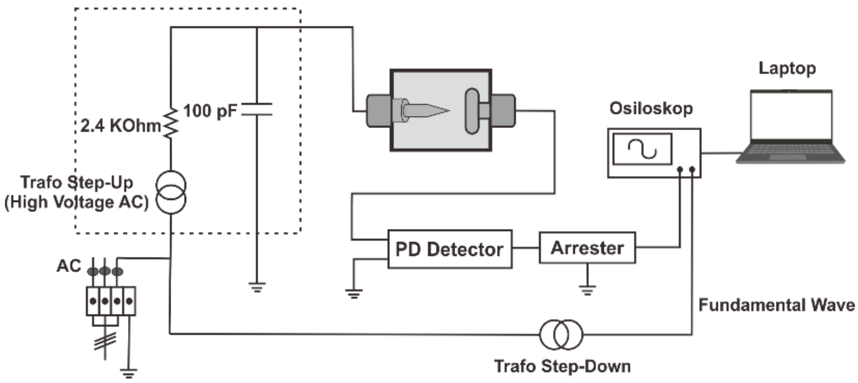


Figure 3. Needle-plane electrode PD measurement system

The arrester connects the RC detector to the oscilloscope via channel 1, which shows the partial discharge phenomenon on the oscilloscope, while channel 2 is used to obtain the sinusoidal waveform. The oscilloscope records the PD and sends the data to a computer device via a flash drive for further analysis. During the testing process, the electrodes used were needle-plane and plane-plane configurations, with the sample consisting of transformer oil based on castor oil. The initial test was carried out to obtain the PD inception voltage. The PD inception voltage (Vin) was determined by gradually increasing the voltage until PD phenomena occurred for the first time. This step was repeated three times to obtain the average PD inception voltage. The PD phenomena occurring during the measurement were observed using an oscilloscope.

After the average PD inception voltage was determined, the voltage was set at a constant level below the average PD inception voltage or before the occurrence of the PD phenomenon. The sample was then left for a period until PD occurred, and the inception time was recorded. This delay is referred to as the PD inception time (Tin), as PD does not occur immediately but requires a certain delay time before appearing for the first time. This procedure was also repeated three times, similar to the PD inception voltage (Vin), to obtain the average PD inception time (Tin).

After the average initial PD voltage and initial time were determined, measurements were carried out for voltage variations on each test electrode. This was done by increasing the voltage by 10% above the average initial PD voltage that had been obtained. During the test using the needle-plane electrode, the needle was connected to a high-voltage alternating current, while in the test using the plane-plane electrode, the plane was also connected to a high-voltage alternating current. Each voltage variation was measured for 1 hour. During the measurements, both the needle-plane and plane-plane electrodes were immersed in a tank containing transformer oil based on jatropha oil to prevent surface charge discharge into the air. The PD occurring in the sample was detected by an RC detector that functions as an integrator. The PD detector used had a measurement bandwidth of 50 to 800 kHz, with a minimum sensitivity of 1 pC. This range allows the detection of PD pulses typically found in liquid insulation systems.

3. RESULTS AND DISCUSSION

3.1. PD inception voltage (Vin)

The inception voltage (Vin) is obtained by gradually increasing the voltage until the first observable PD phenomenon occurs. This process will be repeated three times for both the needle-plane and plane-plane electrodes. The three measured inception voltage (Vin) values will be combined to obtain the average inception voltage (Vin). The measured inception voltage (Vin) for the transformer oil sample is shown in Table 2.

Table 2 shows that in the first trial for the needle-plane electrode, the initial voltage was recorded at 11 kV, while in the second trial, the initial voltage was 10.9 kV, and in the third trial, it was 11 kV. Based on these three initial voltage values, the average PD inception voltage (Vin) for the needle-plane electrode is calculated to be 10.96 kV.

For the plane-plane electrode, the initial voltage recorded in the first trial was 12.5 kV, in the second trial it was 12.4 kV, and in the third trial, it was 12.5 kV. From these three initial voltage values, the average PD inception voltage (Vin) for the plane-plane electrode is determined to be 12.5 kV. The average inception voltage (Vin) for the needle-plane electrode tends to occur more quickly because the electric charge is concentrated at the sharp tip of the needle, influencing the onset of the PD phenomenon.

Table 1. PD inception voltage (Vin)

Experiment	Needle-plane electrode	Plane electrodes
PD inception voltage 1	11 kV	12.5 kV
PD inception voltage 2	10.9 kV	12.4 kV
PD inception voltage 3	11 kV	12.5 kV
Average inception voltage	10.96 kV	12.5 kV

3.2. PD inception time (Tin)

After obtaining the average inception voltage (Vin), the voltage will then be set slightly below the inception voltage (Vin) or just before the occurrence of the PD phenomenon. This experiment is conducted three times for both the needle-plane and plane-plane electrodes, with the voltage reduced by 0.3 kV for each trial. This step aims to identify the inception time (Tin), as the PD phenomenon does not occur immediately but requires a short delay before appearing. The measured inception time (Tin) for the transformer oil sample is shown in Table 3.

Table 3 shows that the average PD inception time (Tin) for both the needle-plane and plane-plane electrodes tends to be directly proportional to the applied voltage. For the needle-plane electrode, when the applied voltage is 10.6 kV, the time required for PD to occur is 1 minute and 13 seconds. When the applied voltage is 10.3 kV, the time until PD occurs increases to 5 minutes and 32 seconds. At an even lower applied voltage of 10 kV, the time until the PD phenomenon occurs extends to 11 minutes and 7 seconds. For the plane-plane electrode, when the applied voltage is 12.2 kV, the time required for PD to occur is 2 minutes and 3 seconds. When the applied voltage is reduced to 11.9 kV, PD occurs after 7 minutes and 46 seconds. At an applied voltage of 11.6 kV, the time until the PD phenomenon occurs reaches 17 minutes and 21 seconds. Thus, it can be seen that the lower the applied voltage, the longer it takes for the PD phenomenon to occur. This is because the electric field formed at lower voltages is not strong enough to trigger the ionization process within the liquid insulation sample, which in this case is transformer oil. However, it is important to note that this relationship between voltage drop and PD onset time is not universal, but rather depends on the characteristics of the electrode type, oil, and other experimental conditions. In this case, the voltage drops results in a weaker electric field, thus increasing the time required to trigger ionization and PD onset.

Table 2. PD inception time (Tin)

Voltage (kV)		Inception time (minutes)	
Needle-plane electrode	Plane electrodes	Needle-plane electrode	Plane electrodes
10.6	12.2	1:13	2:03
10.3	11.9	5:32	7:46
10	11.6	11:07	17:21

3.3. Comparison of PD testing configurations using castor oil

Table 4 summarizes the comparison between needle–plane and plane–plane electrode configurations, highlighting key parameters such as electric field distribution, PDIV, phase-resolved PD behavior, and their respective advantages and limitations. Furthermore, the study acknowledges the relevance of investigating biodegradable insulating oils to evaluate their effectiveness in mitigating PD activity compared to conventional transformer oils.

Table 3. Comparison of PD testing configurations using castor oil

Electrode configuration	Electric field	PDIV	PD phase distribution	Advantages	Limitations
Needle–plane	Non-uniform (focused)	Lower (more sensitive)	60°–150° & 240°–330°, dominated by corona discharge	Early PD detection, simulates localized surface defects	Does not fully represent uniform field conditions in transformers
Plane–plane	Uniform	Higher	More symmetrical PD distribution	Closer to actual field distribution in power transformers	Less sensitive to early-stage or micro-discharge phenomena

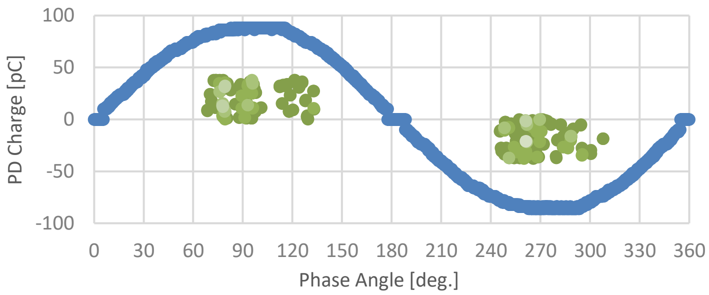
3.4. Partial discharge characteristics

The inception voltage (Vin) obtained will then be increased by approximately 10% above the inception value, after which it will be held constant for 1-hour. The PD phenomenon will subsequently be measured during this 1-hour period to determine the characteristics and magnitude of the PD occurring in the transformer oil. The needle-plane configuration simulates a focused electric field, while the plane-plane represents a uniform field distribution commonly found in transformers, so both were chosen to represent real-world conditions. The plane-plane configuration is used to simulate a uniform field. Both configurations provide insight into how PD can occur under a variety of real-world transformer operating conditions.

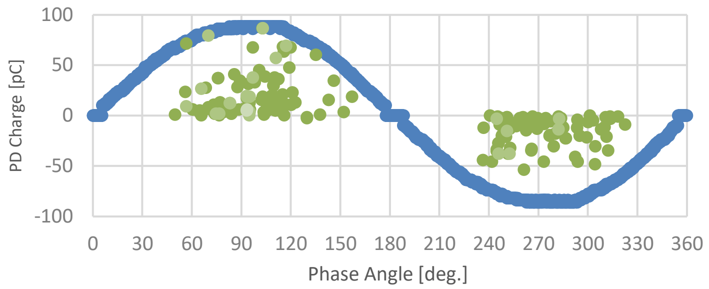
The PD inception voltage (Vin) values that are close at high electric fields can be caused by differences in field distribution and dominant electrode surface effects in the needle-plane configuration. This is because the roughness of the electrode surface and the geometry of the test can affect the local electric field intensity. From the PD inception voltage (Vin) measurements on the needle-plane electrode type, a value of 10.96 kV was obtained, so the voltage will be increased to 12 kV and 13 kV. For the PD inception voltage (Vin) measurements on the plane-plane electrode type, a value of 12.5 kV was obtained, so the voltage will be raised to 13.5 kV and 14.5 kV. The PD phenomenon will then be detected by the RC detector and displayed on the oscilloscope used during the measurement. The resulting PD graphs can be seen in Figures 4 and 5.

3.4.1. Needle-plane electrode

Figure 4 illustrates the PD magnitude pattern during one hour of transformer oil aging using a needle-plane electrode. At 12 kV, showing that PD mostly occurs at angles between 60° to 150° for the positive cycle and 240° to 330° for the negative cycle, with a maximum discharge magnitude of ±37.8 pC, as shown in Figure 4(a). Meanwhile, at 13 kV, PD is mostly observed at angles between 30° to 180° for the positive cycle and 210° to 330° for the negative cycle, with a maximum discharge magnitude of ±86.6 pC, as shown in Figure 4(b).



(a)

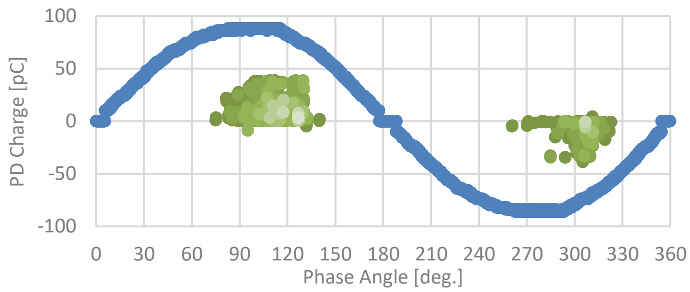


(b)

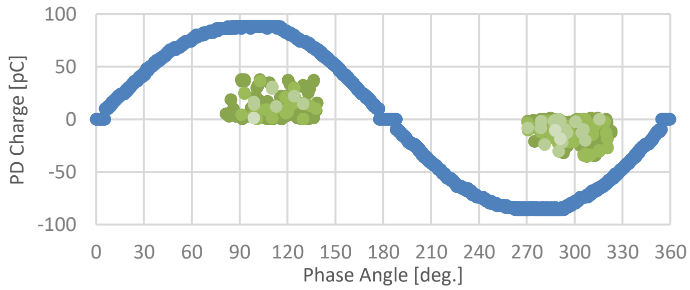
Figure 4. The PD values over a 1-hour period for the needle-plane electrode with applied voltages are as follows (a) at 12 kV and (b) at 13 kV

3.4.2. Plane-plane electrode

Figure 5 illustrates the plane-plane electrode with an applied voltage of 13.5 kV, where PD occurs at angles between 60° to 150° for the positive cycle and 240° to 330° for the negative cycle, with a maximum discharge magnitude of ±35.4 pC, as shown in Figure 5(a). At 14.5 kV, PD is observed at angles between 60° to 150° for the positive cycle and 270° to 330° for the negative cycle, with a maximum discharge magnitude of ±37.8 pC, as shown in Figure 5(a).



(a)



(b)

Figure 5. The PD values over a 1-hour period for the plane-plane electrode with applied voltages are as follows (a) at 13.5 kV and (b) at 14.5 kV

For the needle-plane configuration is most likely due to the field buildup effect in that part of the voltage cycle. Although classical theory states that the discharge occurs at the beginning and end of the half cycle, the discharge in castor oil shows a delay due to the dielectric properties of the oil and the jump mechanism that is restrained by the viscosity of the oil. Additionally, it can be observed that PD charges occur more quickly in the needle-plane electrode compared to the plane-plane electrode. This difference is likely influenced by the type of electrode used, as the sharp needle electrode facilitates the concentration of electrical charge at a single point. The applied voltage also affects the PD magnitude, where an increase in voltage strengthens the electric field around the sample. This increase in the electric field accelerates the ionization process, resulting in a larger PD magnitude. However, at higher voltages, PD tends to occur at almost all angles.

4. CONCLUSION

The measurement and analysis of PD characteristics in transformer oil samples (castor oil type) using needle-plane and plane-plane electrode systems have been conducted. The results show that PD charges occur more quickly in the needle-plane electrode configuration compared to the plane-plane configuration. This difference is influenced by the type of electrode used, as the sharp needle electrode facilitates the concentration of electric charges at a single point. In the needle-plane electrode system, the average initial PD voltage (Vin) was found to be 10.96 kV, while for the plane-plane electrode system, the average initial PD voltage (Vin) was 12.5 kV.

Under varying voltage conditions, the PD magnitude patterns during one hour of transformer oil aging using needle-plane electrodes at 12 kV showed that PD mostly occurred at angles between 60° to 150° in the positive cycle and 240° to 330° in the negative cycle. Meanwhile, at 13 kV, PD was mostly observed at angles between 30° to 180° in the positive cycle and 210° to 330° in the negative cycle. In contrast, the PD magnitude pattern during one hour of transformer oil aging using plane-plane electrodes at an applied voltage of 13.5 kV showed that PD occurred at angles between 60° to 150° in the positive cycle and 240° to 330° in the negative cycle. At 14.5 kV, PD was observed at angles between 60° to 150° in the positive cycle and 270° to 330° in the negative cycle. These values indicate that the average initial PD voltage (Vin) for the needle-plane electrode is generally lower than that for the plane-plane electrode, suggesting that PD phenomena in the needle-plane system occur more rapidly. Moreover, the average initial time (Tin) is directly proportional to the applied voltage. This indicates that a lower applied voltage results in a weaker electric field, which increases the time required to trigger ionization and initiate PD. Furthermore, the magnitude of the applied voltage affects the PD charge and the number of PD activities at certain phase angles.

ACKNOWLEDGEMENTS

Author would like to thank their supervising lecturer for their invaluable assistance throughout the research process. They also extend their gratitude to the Department of Electrical Engineering, University of Diponegoro, for providing research facilities. Additionally, the authors wish to express their appreciation to all parties who have contributed to this research.

REFERENCES

[1] F. Liu, Y. Wang, and X. Zhu, "Design and management of high voltage power systems and insulation materials," *Energies*, vol. 15, no. 13, p. 4620, Jun. 2022, doi: 10.3390/en15134620.

[2] H. Besharatifard, S. Hasanzadeh, E. Heydarian-Forushani, H. H. Alhelou, and P. Siano, "Detection and analysis of partial discharges in oil-immersed power transformers using low-cost acoustic sensors," *Applied Sciences*, vol. 12, no. 6, p. 3010, Mar. 2022, doi: 10.3390/app12063010.

[3] K. N. Koutras, S. N. Tegopoulos, V. P. Charalampakos, A. Kyritsis, I. F. Gonos, and E. C. Pyrgioti, "Breakdown performance and partial discharge development in transformer oil-based metal carbide nanofluids," *Nanomaterials*, vol. 12, no. 2, p. 269, Jan. 2022, doi: 10.3390/nano12020269.

[4] B. Pasternak and P. Rozga, "Influence of dielectric liquid type on partial-discharge inception voltage in oil-wedge-type insulating system under AC stress," *Energies*, vol. 16, no. 2, p. 1005, Jan. 2023, doi: 10.3390/en16021005.

[5] N. Ra and U. Khayam, "Partial discharge measurement of 4 types of electrodes configuration in air insulation using high frequency current transformer sensor," in *Proceedings - Joint International Conference on Electric Vehicular Technology and Industrial, Mechanical, Electrical and Chemical Engineering, ICEVT 2015 and IMECE 2015*, 2016, pp. 100–105, doi: 10.1109/ICEVTIMECE.2015.7496667.

[6] A. Syakur, Y. Z. Arief, Z. A. Malek, and H. Ahmad, "An experimental study on partial discharge characteristics of polyvinyl chloride (PVC) under AC - DC voltages," in *PECon 2008 - 2008 IEEE 2nd International Power and Energy Conference*, 2008, pp. 1687–1690, doi: 10.1109/PECON.2008.4762750.

[7] O. Faruqe, A. Hoang, P. C. Saha, A. Koh, and C. Park, "Preventing partial discharge in liquid metal polymer composites under steep voltage pulses," *Composites Part B: Engineering*, vol. 272, p. 111206, Mar. 2024, doi: 10.1016/j.compositesb.2024.111206.

[8] J. H. Park, N. Kim, and J. I. Lee, "The effect of insulation on boil-off gas in liquid air storage tank," *Energy*, vol. 291, p. 130265, Mar. 2024, doi: 10.1016/j.energy.2024.130265.

[9] J. Kurimský, M. Rajňák, K. Paulovičová, and M. Šárpataky, "Electric partial discharges in biodegradable oil-based ferrofluids: A study on effects of magnetic field and nanoparticle concentration," *Heliyon*, vol. 10, no. 7, p. e29259, Apr. 2024, doi: 10.1016/j.heliyon.2024.e29259.

[10] A. Rajab *et al.*, "Partial discharge phase distribution of palm oil as insulating liquid," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 9, no. 1, pp. 151–160, 2011, doi: 10.12928/telkomnika.v9i1.683.

[11] H. N. Afrouzi *et al.*, "In-depth exploration of partial discharge modelling methods within insulations," *Cleaner Engineering and Technology*, vol. 6, p. 100390, Feb. 2022, doi: 10.1016/j.clet.2021.100390.

[12] Y. Sha, Y. Zhou, J. Li, and J. Wang, "Partial discharge characteristics in oil-paper insulation under combined AC-DC voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 21, no. 4, pp. 1529–1539, Aug. 2014, doi: 10.1109/TDEI.2014.004273.

[13] C. Pan, J. Tang, G. Chen, Y. Zhang, and X. Luo, "Review about PD and breakdown induced by conductive particles in an insulating liquid," *High Voltage*, vol. 5, no. 3, pp. 287–297, Jun. 2020, doi: 10.1049/hve.2019.0166.

[14] R. J. Liao, L. J. Yang, J. Li, and S. Grzybowski, "Aging condition assessment of transformer oil-paper insulation model based on partial discharge analysis," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 1, pp. 303–311, 2011, doi: 10.1109/TDEI.2011.5704522.

[15] M. Pompili, C. Mazzetti, and R. Bartnikas, "Partial discharge pulse sequence patterns and cavity development times in transformer oils under ac conditions," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 12, no. 2, pp. 395–403, 2005, doi: 10.1109/TDEI.2005.1430407.

[16] C. Pan, J. Tang, X. Tao, Y. Zhang, and S. Ma, "Partial discharge and breakdown characteristics of moving transformer oil contaminated by metallic particles," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 5, pp. 1774–1784, Oct. 2018, doi: 10.1109/TDEI.2018.007182.

[17] L. M. Salvatierra *et al.*, "Self-healing during electrical treeing: A feature of the two-phase liquid-solid nature of silicone gels," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 2, pp. 757–767, Apr. 2016, doi: 10.1109/TDEI.2015.004813.

[18] C. Zhang, Y. Li, S. Yang, and R. Li, "Study on development characteristics of partial discharge in oil-pressboard insulation under constant DC voltage," *Energies*, vol. 16, no. 10, p. 3970, May 2023, doi: 10.3390/en16103970.

[19] W. Chang *et al.*, "Study on partial discharge characteristics of oil-immersed paper in wrinkled state under alternating current and direct current compound voltage," *Journal of Physics: Conference Series*, vol. 2030, no. 1, p. 012020, Sep. 2021, doi: 10.1088/1742-6596/2030/1/012020.

[20] S. M. Korobeynikov *et al.*, "Study of partial discharges in liquids," *Journal of Electrostatics*, vol. 103, p. 103412, Jan. 2020, doi: 10.1016/j.elstat.2019.103412.

[21] Q. Xie, S. Cheng, F. Lü, and Y. Li, "Location of partial discharge in transformer oil using circular array of ultrasonic sensors," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, no. 5, pp. 1683–1690, 2013, doi: 10.1109/TDEI.2013.6633698.

[22] M. Jaroszewski and K. Rakowiecki, "Partial discharge inception voltage in transformer natural ester liquid — Effect of the measurement method in the presence of moisture," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 4, pp. 2477–2482, 2017, doi: 10.1109/TDEI.2017.005917.

[23] N. Pattanadech, A. A. Kemma, T. F. Sipahutar, F. Pratomosiwi, and M. Muhr, "The possibility of using a needle plane electrode for partial discharge inception voltage measurement," *Annual Report - Conference on Electrical Insulation and Dielectric Phenomena, CEIDP*, pp. 1258–1261, 2013, doi: 10.1109/CEIDP.2013.6748212.

[24] C. Li, T. Shahsavarian, M. A. Baferani, K. Davis, Y. Cao, and D. Zhang, "Understanding DC partial discharge: recent progress, challenges, and outlooks," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 3, pp. 894–909, 2022, doi: 10.17775/CSEEJPES.2021.04740.

[25] A. Bhure, E. G. Strangas, J. Agapiou, and R. M. Lesperance, "Partial discharge detection in medium voltage stators using an antenna," in *Proceedings of the 2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, SDEMPED 2017*, 2017, vol. 2017-Janua, pp. 480–485, doi: 10.1109/DEMPED.2017.8062398.

[26] L. Calcara, M. Pompili, and F. Muzi, "Standard evolution of partial discharge detection in dielectric liquids," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 1, pp. 2–6, Feb. 2017, doi: 10.1109/TDEI.2016.006499.

[27] M. F. Rahman, P. Nirgude, and N. R. Burjupati, "Effect of irregular-shaped Cu particles on transformer oil PD characteristics under varying electrode configurations," *IET Science, Measurement & Technology*, vol. 13, no. 2, pp. 201–211, Mar. 2019, doi: 10.1049/iet-smt.2018.5181.

[28] M. F. Rahman and P. Nirgude, "Partial discharge behaviour due to irregular-shaped copper particles in transformer oil with a different moisture content of pressboard barrier under uniform field," *IET Generation, Transmission & Distribution*, vol. 13, no. 24, pp. 5550–5560, Dec. 2019, doi: 10.1049/iet-gtd.2019.0382.

BIOGRAPHIES OF AUTHORS

Teuku Khairul Murad is a master student at Electrical Engineering Department at Diponegoro University, Semarang, Indonesia. Received his S.T in electrical engineering from Institut Teknologi PLN Jakarta in 2021. He can be contacted at email: khairulmurad38@gmail.com.

Abdul Syakur is a senior lecturer at Electrical Engineering Department at Diponegoro University, Semarang, Indonesia. He received his B.Eng., M.Eng. and Ph.D. degrees in electrical engineering from Universitas Diponegoro, Institut Teknologi Bandung and Universitas Gadjah Mada, in 1997, 2002 and 2015, respectively. He has been an associate professor in Universitas Diponegoro, Semarang, Indonesia since 2007. He is currently the head of High-Voltage Innovation and Technology (Hi-VIT) research laboratory also member of IEEE since 2011 until now. His research interests include high-voltage generation, high-voltage insulation technology, electrical tracking in insulator materials, partial discharge, lightning phenomenon, and its protection system. He can be contacted at: gakusei2003@yahoo.com.

Iwan Setiawan is a professor at electrical engineering at Diponegoro University, Semarang, Indonesia. received the B.Eng. and M.Eng degrees from the Engineering Faculty of Gadjah Mada University, Indonesia in 1998 and 2003, respectively. In 2016 he received Doctor degree from the Electrical Engineering Department of Institut Teknologi Sepuluh Nopember, Indonesia. In 2025, he was awarded the title of Professor by the Faculty of Engineering, Diponegoro University, Semarang, Indonesia. His research interest includes power electronics, control design for renewable energy power generation. He can be contacted at email: iwansetiawan@lecturer.undip.ac.id.