The Influence of Iron Particle Contamination on the Breakdown Characteristics of Circulating Mineral Oil under DC Voltage

Daniar Fahmi
Sepuluh Nopember Institute of Technology, Indonesia
daniarfahmi@ee.its.ac.id (corresponding author)

Muhammad Fadlan Akbar
Sepuluh Nopember Institute of Technology, Indonesia
5022201171@student.its.ac.id

I Made Yulistya Negara
Sepuluh Nopember Institute of Technology, Indonesia
yulistya@ee.its.ac.id

Dimas Anton Asfani
Sepuluh Nopember Institute of Technology, Indonesia
anton@ee.its.ac.id

I Gusti Ngurah Satriyadi Hernanda
Sepuluh Nopember Institute of Technology, Indonesia
didit@ee.its.ac.id

Received: 31 July 2024 | Revised: 28 August 2024 and 9 September 2024 | Accepted: 12 September 2024

ABSTRACT

The presence of metallic particles can lead to the degradation of transformer oil due to the intensification of the electric fields near the conductive components. The primary objective of this research was to investigate the impact of iron impurities on the electrical properties of Mineral Oil (MO), particularly under conditions of continuous flow. Five distinct samples with varying levels of contaminants were carefully prepared for analysis. A specialized chamber was designed to replicate the circulation conditions of oil within an operating transformer. The focus of the investigation was on the breakdown characteristics under DC voltages. The results indicated that higher concentrations of iron impurities were associated with a reduction in breakdown voltage although the circulation of oil exhibited a beneficial effect. To validate these findings, Finite Element Method (FEM)-based simulations were conducted. The analysis of the electric field distribution revealed that iron impurities amplified the electric field intensity, while circulation served to mitigate this effect. Furthermore, the simulations tracking the trajectory of iron particles demonstrated that circulation hindered the particles from reaching the electrodes, thereby diminishing discharge events and lowering the risk of dielectric failure. In conclusion, the circulation of MO enhanced its breakdown voltage, although the presence of iron contamination could still pose a risk under DC voltage conditions.

Keywords-dielectric properties; breakdown voltage; electric field distribution; iron particle movement; circulating mineral oil

I. INTRODUCTION

Oil is a standard liquid insulator employed in power transformers, serving both as a coolant and possessing a relatively high dielectric strength [1-3]. MO, derived from petroleum through distillation, is the most widely used material for this purpose [4]. An additional advantage of utilizing MO is its low content of compounds that can enhance oxidation resistance and gas absorption capabilities [5].

Across the various stages of transformer production, installation, operation, and maintenance, the insulating oil may become contaminated with iron particles, adversely affecting the insulation properties and contributing to approximately 5-10% of transformer failures [6-10]. Increased flow velocities in transformer oil lead to a reduction in the frequency of Partial Discharges (PD), subsequently enhancing the breakdown voltage of the insulating oil [11]. Authors in [12] studied the influence of temperature on the partial discharge and breakdown behavior of the moving transformer oil contaminated with metallic particles. It was observed that the breakdown voltage increases with rising temperatures due to the reduction in viscosity of the transformer oil, which alters the forces on the particles and subsequently decreases their collision frequency with the electrodes.

Prior studies have investigated the impact of contaminants on breakdown voltage and their motion properties, but the interplay between the electric field in the circulating oil and the contaminant movement remains unexplored. This study aims to address this research gap by specifically examining the impacts of incorporating iron particles into the circulating MO, as evaluated through the measured electric field distribution within the test samples.

II. EXPERIMENTAL SETUPS

The experiment featured the design of a transformer oil circulation system to examine the DC breakdown behavior under diverse flow velocities, as depicted in Figure 1. The system incorporated an oil pump to circulate the transformer oil, while a flow meter was utilized to measure the oil flow velocity at the inlet. To generate a consistent electric field, two parallel-plate electrodes fabricated from steel [13] were situated 10 mm apart within a plexiglass oil channel. Each electrode possessed a diameter of 50 mm and a thickness of 10 mm

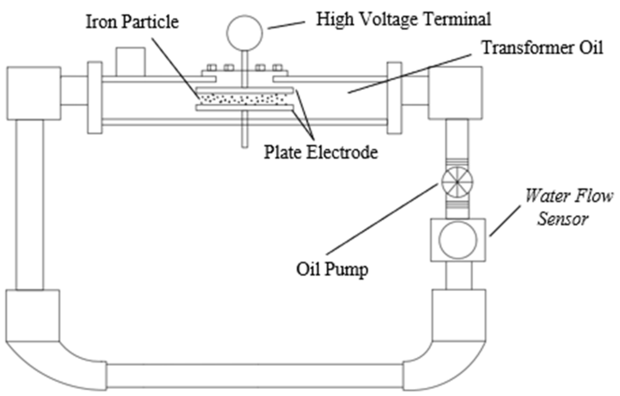


Fig. 1. Transformer oil circulation chamber.

The study used Shell Diala S4 ZX-1 MO. Prior to each test, the oil underwent filtration and degassing to meet the experimental requirements before being introduced into the circulation system [14-16]. Metallic particles in power transformers typically range from 5 to 200 µm in diameter, with particles exceeding 100 µm posing a greater risk to the insulation [17, 18]. To simulate contamination scenarios, 100 µm iron particles were introduced into the oil at concentrations ranging from 0 to 0.3 g/l. Additionally, the oil flow velocity was maintained at 0.0 (static) and 0.30 m/s (circulating), as speeds exceeding 0.50 m/s in large power transformers can lead to flow electrification [19-21]. The variations in the test samples are detailed in Table I.

TABLE I. TEST SAMPLE VARIATIONS

Sample	Oil Volume (ml)	Iron Particle Mass (mg)	Iron Particle Concentration (g/l)	Circulation Velocity (m/s)
MO	360	0	0.00	0.0 (Static) 0.3 (Circulating)
MO/Fe^{-1}		25	0.07	
MO/Fe^{-2}		50	0.15	
MO/Fe^{-3}		75	0.22	
MO/Fe^{-4}		100	0.30	

III. EXPERIMENTAL RESULTS

The voltage required to initiate electrical conductivity in an insulating material, thereby allowing current flow, is known as the Breakdown Voltage (BDV). This phenomenon is characterized by the formation of a spark or a sudden increase in the current between two electrodes. To determine the BDV, a DC voltage was progressively increased and applied to the electrodes until the dielectric strength of the nanofluid was surpassed by the electrical stress induced by the elevated voltage. The BDV measurements were validated through twenty trials for each sample.

This study utilizes the Weibull probability approach to assess the forecasted breakdown probability in MO samples. The Weibull probability method is frequently employed to evaluate system reliability and is particularly prominent in the analysis of life test data, which indicate the probability of a component functioning as intended for a specified time period during a given test [22, 23]. Figure 2 depicts the Weibull probability plot representing the breakdown voltage for each test sample. The Weibull distribution of BDV values for the tested samples is characterized by cumulative probabilities of 1, 10, and 50%. The DC-BDV at an 1% cumulative probability denotes the minimum value indicative of the insulating liquid's reliability. Some researchers have chosen to utilize the DC-BDV corresponding to a 10% risk level instead of the 1% threshold. Conversely, the 50% DC-BDV represents the average value.

The findings presented in Table II indicate that the introduction of the circulating motion led to an increase in the dielectric BDV of the MO samples. Specifically, the BDV of the pure MO increased by 42%, while the BDVs of the MO with iron particle contamination, MO/Fe-1, MO/Fe-2, MO/Fe-3, and MO/Fe-4, increased by 51, 55, 46, and 66%, respectively, under circulating conditions. Conversely, the inclusion of iron particles resulted in a decrease in the dielectric BDV of the MO. The BDV of the MO/Fe-1 sample decreased by 15% under static conditions and 10% under circulating conditions. Similarly, the BDVs of the MO/Fe-2, MO/Fe-3, and MO/Fe-4 samples decreased by 22 and 14%, 29 and 21%, and 35 and 26%, respectively, for static and circulating conditions.

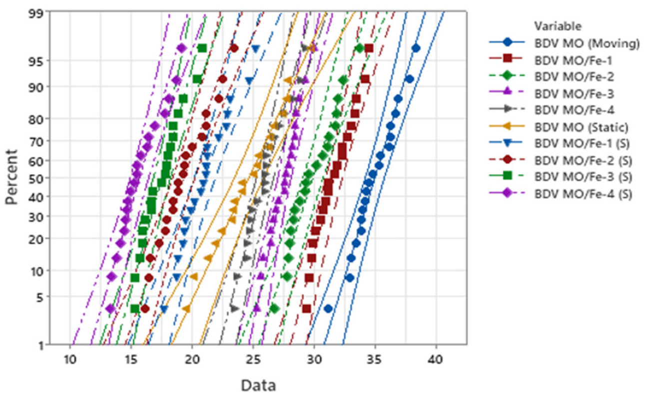


Fig. 2. Weibull probability plot of breakdown voltage of test sample.

The results demonstrate a progressive decline in the BDV as the concentration of iron particles increases. This can be attributed to the elevated conductivity of the test medium resulting from the presence of iron particles (1.04×10^7 S/m), which enables a more facile passage of the electric current through the medium.

TABLE II. DC-BDV RESULTS OF TEST SAMPLES

Sample	Weibull Probability (%)	Static DC-BDV (kV)	Circulating DC-BDV (kV)
MO	1	16.58	28.86
	10	20.79	32.22
	50	24.92	35.19
MO/Fe^{-1}	1	14.39	26.26
	10	17.84	29.22
	50	21.18	31.83
MO/Fe^{-2}	1	12.76	23.39
	10	16.13	26.91
	50	19.47	30.12
MO/Fe^{-3}	1	12.14	23.30
	10	14.93	26.65
	50	17.63	27.71
MO/Fe^{-4}	1	10.07	20.23
	10	12.92	23.32
	50	15.97	26.14

The results further suggest that incorporating circulation into the system improved the dielectric strength across all examined samples. The circulation mechanism reduced the time required for metallic particles to traverse the oil channel, thereby decreasing the duration of contact and impact between the upper and lower electrode plates. This subsequently diminished the probability of discharge events caused by a charge transfer between the particle and the plate.

IV. SIMULATION RESULTS

A. *Electric Field Distribution*

The main objective of this study is to provide a more thorough examination of the relationship between the concentration of iron impurities and the BDV in MO. The simulations utilized a FEM-based software, and accurate material parameters for MO, electrodes, and iron particles, which were essential for determining the electric field distribution [24]. The design of the electric field distribution simulation is illustrated in Figure 3.

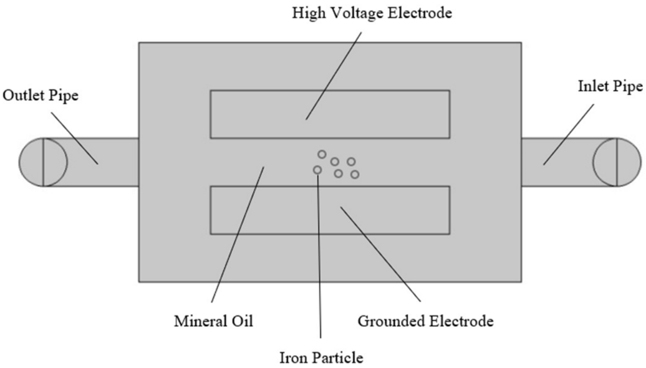


Fig. 3. Simulation design model.

The foundational principles of a model design are heavily dependent on the governing equations and boundary conditions, which specify how physical processes are simulated within defined geometric constraints and under particular conditions. In this study, the governing equations are formulated as:

$$-\nabla \cdot V = E \quad (1)$$

In the field of electrostatics, the relationship between the electric field (E) and the electric potential (V) is described by an equation that assumes stationary charges and the absence of time-varying magnetic fields. The electric field is mathematically correlated with the gradient of the electric potential, where the negative sign indicates that the electric field E is directed towards regions of decreasing electric potential V. Fundamentally, the flow of the electric field lines occurs from areas of higher potential (positive charges) to lower potential areas (negative charges or regions where the potential decreases along the gradient). The creeping flow module is used to simulate the fluid flow at velocities below 1 m/s, which is particularly appropriate for materials in which viscosity is a more significant factor than inertia.

$$\rho(\boldsymbol{\nabla} \cdot u) = 0 \quad (2)$$

This is especially pertinent for substances like MO, which are classified as incompressible fluids. In such fluids, the density (ρ) remains constant, and the volume of the oil entering a chamber at a specific velocity (u) equals the volume of the oil exiting the chamber.

The study utilized the fluctuation in particle count to analyze the variations in the concentration of the test sample. This was determined through the principles of density and by comparing the total contamination volume to the volume of a single iron particle. The variance in particle count is portrayed in Table IV. The applied voltage was 10 kV, which was based on the minimum BDV findings documented in Table II.

The data presented in Table IV exhibit the electric field distribution patterns across all test samples. As the concentration of iron particle impurities increased, the observed electric field magnitude correspondingly escalated. Conversely, the introduction of the circulation motion within the samples resulted in a reduced electric field distribution value for each tested sample.

TABLE III. PARTICLE COUNT VARIATIONS

Sample	Iron Density (g/cm^3)	Iron Particle Mass (mg)	N-particle
MO	7.87	0	0
MO/Fe-1		25	6000
MO/Fe-2		50	12000
MO/Fe-3		75	18000
MO/Fe-4		100	24000

The presence of conductive iron powder particles in MO is associated with an enhanced electric field strength. This is facilitated by an ionization process that generates free electrons and positive ions through charge induction and polarization within the iron powder. Subsequently, the migration of these particles within the electric field establishes a conductive pathway between the electrodes. Therefore, it can be concluded that an increase in both the concentration of iron powder and the electric field strength within the MO correlates with an increase in the oil's conductivity, while simultaneously resulting in a decrease in its dielectric strength.

TABLE IV. ELECTRIC FIELD DISTRIBUTION RESULTS OF TEST SAMPLES

Sample	Electric Field -Static Sample (kV/mm)	Electric Field – Circulating Sample (kV/mm)
MO	1.40	1.00
MO/Fe-1	1.54	1.09
MO/Fe-2	1.55	1.18
MO/Fe-3	1.64	1.19
MO/Fe-4	1.73	1.22

The diminished electric field strength observed in the circulating MO sample is attributed to the redistribution of accumulated charges throughout the oil's volume. Under static conditions, charges generated through ionization tend to accumulate, leading to localized increases in the electric field intensity and accelerating the failure of the test sample. In contrast, the circulation motion facilitates the dispersion of charge concentration, thereby reducing the electric field intensity within the test material. This dynamic process stands in opposition to the static conditions, as the circulation can effectively mitigate the failure process in the test sample.

B. Particle Trajectory

A particle trajectory simulation was conducted to investigate the influence of particle movement on the breakdown characteristics of MO, with a particular focus on the micro-discharge phenomenon caused by polarity differences. The simulation employed the Lagrangian coordinate system to track the trajectory of iron particles and analyze their motion vectors in accordance with Newton's Second Law of Motion:

$$\frac{4}{3}\pi r^3\rho_p\frac{du_p}{dt} = F_D + F_e + F_g + F_{other} \quad (3)$$

where:

$$F_D = \frac{1}{2}C_d\pi r_p^2\rho_l(u_l - u_p)|u_l - u_p| \quad (4)$$

$$F_e = kqE \quad (5)$$

$$F_g = \frac{4}{3}\pi r_p^3 g(\rho_p - \rho_l) \quad (6)$$

where C_d is the resistance coefficient, r_p is the radius of the iron particles, ρ_l is the density of the circulating oil, u_l is the velocity of the circulating oil, u_p is the velocity of the iron particles, and ρ_p is the density of iron particles. The charge obtained by the iron particles is denoted with q, E is the electric field in the test medium, and k is the electrostatic coefficient.

When the charged particles are positioned far from the electrode surface, the parameter k receives the value of 1, and when they come into contact with the electrode, k is 0.832. Furthermore, the horizontal motion of the iron particles is represented by the parameter F_D, while their vertical motion is depicted by the F_e parameter. The gravitational force is denoted as F_g, and F_{other} represents other forces considered to have negligible effects, such as inertia, buoyancy, and Saffman forces. Additional experimental conditions include a test media speed of 0.3 m/s, an iron particle diameter of 100 μm, and a voltage of 10 kVDC.

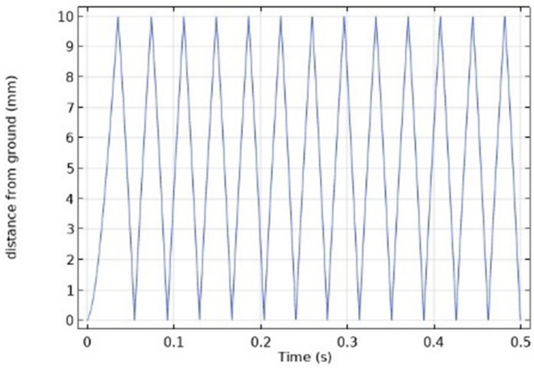
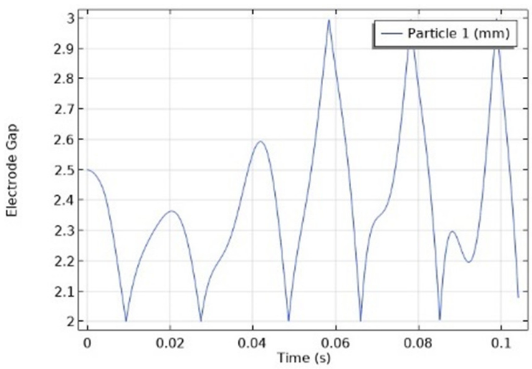


Fig. 4. Static iron particle trajectory.



(b)

Fig. 5. Circulating iron particle trajectory.

Figures 4 and 5 display the behavior of the iron particles under the influence of a DC voltage. In Figure 4, the particles exhibit a tendency to traverse between the electrodes due to the orientation of the constant electric field generated by the DC voltage. This results in the particles being continuously attracted to the energized electrode while discharging towards the grounded electrode. Conversely, Figure 5 presents the trajectory of the iron particles in a circulating environment. Here, the particles are inclined to gravitate towards the grounded electrode due to gravitational forces. Upon contact, the particles acquire a charge. The movement of the particles along the y-axis is influenced by the counteracting forces of the electric field and gravity. Additionally, the net horizontal force generated by the circulation of oil impedes the velocity at which the iron particles approach the electrodes. The circulating motion also indicates that the oscillatory behavior of the particles, driven by both the oil circulation and gravitational forces, contributes to a deceleration in the formation of bridging or vertical conductive pathways among the iron particles.

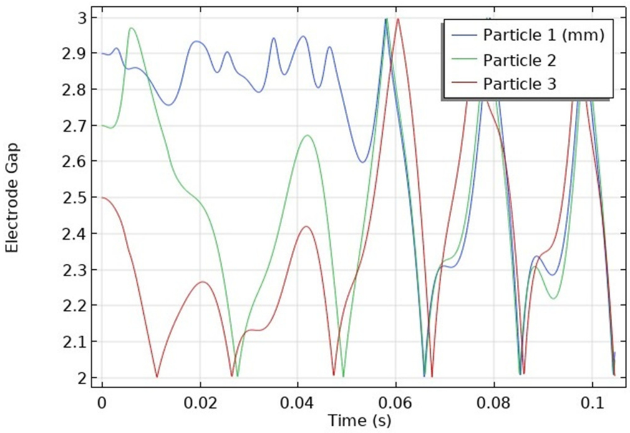


Fig. 6. Three iron particles trajectories in circulating condition.

The trajectory outcomes depicted in Figure 6 were influenced by the introduction of iron particle contaminants. Specifically, the inclusion of iron particles led to an increase in the number of contacts within the test medium. This phenomenon may have contributed to an elevated electric field within the system, thereby increasing the probability of electrical breakdown. Figures 7 and 8 illustrate the trajectory of the iron particles in relation to the electrode diameter in x-axis, and to the electrode gap in y-axis. As shown in Figure 7, under static conditions with a test duration of 0.1 seconds, the maximum distance travelled by particles within the voltage region was 12 mm. The electric field strength in this static scenario was 5.68 kV/mm. Conversely, Figure 8 portrays a static scenario, where the maximum distance for particle movement through the voltage area was 15 mm over a slightly longer duration of 0.101 seconds, accompanied by a lower electric field strength of 5.5 kV/mm. The implementation of the circulation flow is crucial for mitigating the formation of weak points within the oil, which could potentially lead to failure. In this experimental setup, iron particles act as weak points due to their conductive properties, thereby enhancing the conductivity of the test sample, as indicated by the increased value of the distributed electric field, which may trigger discharge-to-breakdown phenomena. Nevertheless, the circulation flow facilitates the rapid traversal of conductive iron particles through regions of intense electric fields, hence complicating the discharge process between the iron particles and the electrodes. As a result, the movement induced by oil circulation contributes to inhibiting the progression of the discharge towards failure, leading to an elevation of the breakdown voltage of the test sample.

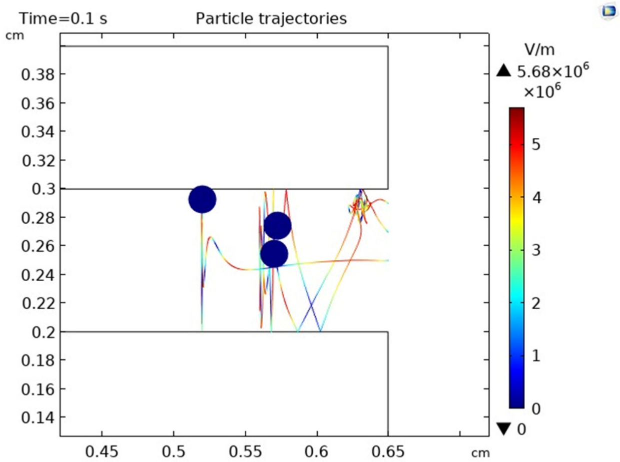


Fig. 7. Static particle tracetorry position.

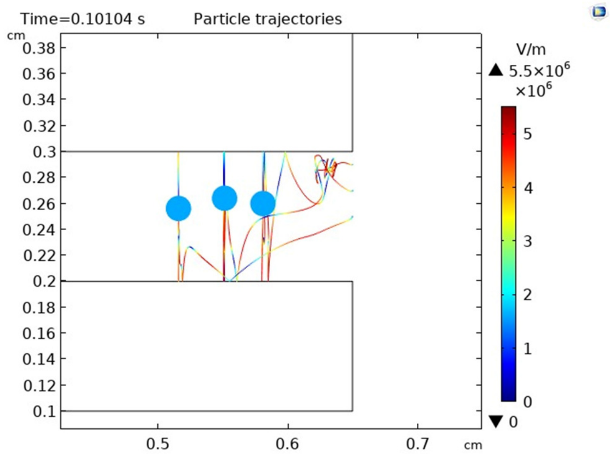


Fig. 8. Circulating particle tracetorry position.

V. CONCLUSIONS

This study investigated the impact of iron particle contaminants on the DC Breakdown Voltage (DC-BDV) of circulating Mineral Oil (MO) through experiments and simulations. The results demonstrate a clear correlation between the level of iron particle contamination and the electric field distribution within the MO. As the concentration of iron particles increases, the electric field distribution value correspondingly rises. This heightened electric field intensifies the discharge activity, primarily due to the increased frequency and severity of collisions between the iron particles and the electrodes. These collisions disrupt the stability of the electric field, leading to a decrease in the observed breakdown voltage during the experimental trials. Ultimately, the presence of iron particles serves as a catalyst for electrical discharges, compromising the insulating properties of the MO.

In contrast, incorporating a circulation system into the experimental setup was found to have a beneficial impact on the electric field distribution. The circulation system disrupts the collision dynamics between the iron particles and the electrodes, creating an oscillatory effect that reduces the likelihood of prolonged collisions. Additionally, the circulation system decreases the duration that iron particles remain within the high-voltage region, further mitigating the potential for electrical breakdown. Consequently, the recorded breakdown voltage during the experiments increased, demonstrating that the circulation system plays a crucial role in enhancing the electrical performance of the mineral oil by minimizing the detrimental effects of particle contamination. The DC voltage characteristics on the particle path involve iron particles consistently colliding with the voltage electrode and the ground due to the constant voltage and the electric field of the DC voltage.

REFERENCES

[1] V. Shewale, A. A. Kapse, S. D. Barahate, S. P. Jadhav, and S. J. Suryawanshi, "An Experimental Study on the Performance Enhancement of a Heat Pump System using Nanofluids," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12518–12523, Feb. 2024, https://doi.org/10.48084/etasr.6571.

[2] I. M. Yulistya Negara, D. Fahmi, D. A. Asfani, I. G. N. S. Hernanda, M. Wahyudi, and M. N. Ibrahim, "Effect of Floating Metallic Particles in Pre-Breakdown and Breakdown Characteristics of Oil Transformer under DC Voltage," *Energies*, vol. 14, no. 12, Jun. 2021, Art. no. 3669, https://doi.org/10.3390/en14123669.

[3] M. Danikas and R. Sarathi, "Alternative Fluids – with a Particular Emphasis on Vegetable Oils – as Replacements of Transformer Oil: A Concise Review," *Engineering, Technology & Applied Science Research*, vol. 10, no. 6, pp. 6570–6577, Dec. 2020, https://doi.org/10.48084/etasr.3943.

[4] A. Reffas, A. Beroual, and H. Moulai, "Comparison of breakdown voltage of vegetable olive with mineral oil, natural and synthetic ester liquids under DC voltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 27, no. 5, pp. 1691–1697, Oct. 2020, https://doi.org/10.1109/TDEI.2020.008308.

[5] D. Fahmi, H. A. Illias, H. Mokhlis, and I. M. Yulistya Negara, "Effect of Static Floating Particle Shapes on Partial Discharge Characteristics in Mineral Oil," in *Proceedings of International Conference on the Properties and Applications of Dielectric Materials*, Johor Bahru, Malaysia, 2021, pp. 147–150, https://doi.org/10.1109/ICPADM49635.2021.9494002.

[6] M. Dan, J. Hao, R. Liao, L. Cheng, J. Zhang, and F. Li, "Accumulation Behaviors of Different Particles and Effects on the Breakdown Properties of Mineral Oil under DC Voltage," *Energies*, vol. 12, no. 12, Jun. 2019, Art. no. 2301, https://doi.org/10.3390/en12122301.

[7] L. Gautam, A. J. Amalanathan, R. Sarathi, U. M. Rao, and I. Fofana, "Effect of Magnetic Field on Partial Discharge Initiated by Metallic Particle in Thermally Aged Natural Esters Under AC and Harmonic Voltages," *IEEE Access*, vol. 10, pp. 101198–101206, 2022, https://doi.org/10.1109/ACCESS.2022.3208353.

[8] M. Danikas, R. Sarathi, and S. Morsalin, "A Short Review of Some of the Factors Affecting the Breakdown Strength of Insulating Oil for Power Transformers," *Engineering, Technology & Applied Science Research*, vol. 10, no. 3, pp. 5742–5747, Jun. 2020, https://doi.org/10.48084/etasr.3554.

[9] Y. Lu, P. Wu, F. Tao, X. Li, and L. Zhou, "Iron particle effect on the breakdown strength of insulating oil at AC and DC voltages," in *Proceedings of IEEE Electrical Insulation Conference*, Baltimore, MD, USA, 2017, pp. 495–498, https://doi.org/10.1109/EIC.2017.8004621.

[10] S. Tenbohlen, J. Jagers, and F. Vahidi, "Standardized survey of transformer reliability: On behalf of CIGRE WG A2.37," in *Proceedings of International Symposium on Electrical Insulating Materials*, Toyohashi, Japan, 2017, pp. 593–596, https://doi.org/10.23919/ISEIM.2017.8166559.

[11] X. Luo, J. Tang, C. Pan, and Y. Zhang, "Contribution of free iron particles to PD characteristics in flowing transformer oil at DC voltages," *IET Generation, Transmission & Distribution*, vol. 14, no. 2, pp. 294–300, Jan. 2019, https://doi.org/10.1049/iet-gtd.2019.1227.

[12] C. Pan, J. Tang, Y. Zhang, X. Luo, and X. Li, "Variation of Discharge Characteristics With Temperature in Moving Transformer Oil Contaminated by Metallic Particles," *IEEE Access*, vol. 6, pp. 40050–40058, 2018, https://doi.org/10.1109/ACCESS.2018.2856580.

[13] IEC 60156, Insulating liquids – Determination of the breakdown voltage at power frequency – Test method, 3rd ed. Geneva, Switzerland: International Electrotechnical Commission, 2018.

[14] G. Zhang, W. Yan, X. Zhang, X. Liu, and Y. Huang, "Simulation Study on the Motion Characteristics and Influencing Factors of Fiber Impurity Particles in Oil Flow in a Typical Distributed Electric Field," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 5, pp. 2033–2042, Oct. 2023, https://doi.org/10.1109/TDEI.2023.3281541.

[15] H. Subekti, I. M. Y. Negara, D. A. Asfani, and D. Fahmi, "Effect Of Cellulose Impurities On Breakdown Voltage Characteristic In Semiconductive Nanofluid," in *Proceedings of International Seminar on Intelligent Technology and Its Applications*, Surabaya, Indonesia, 2023, pp. 780–785, https://doi.org/10.1109/ISITIA59021.2023.10220990.

[16] I. G. N. Satriyadi Hernanda, A. C. Mulyana, D. A. Asfani, I. M. Y. Negara, and D. Fahmi, "Application of health index method for transformer condition assessment," in *Proceedings of TENCON 2014 - 2014 IEEE Region 10 Conference*, Bangkok, Thailand, Jan. 2015, https://doi.org/10.1109/TENCON.2014.7022433.

[17] Z. Wang, X. Wang, Z. D. Wang, and J. Noakhes, "Motion of conductive particles and the effect on AC breakdown strengths of esters," in *Proceedings of IEEE International Conference on In Dielectric Liquids*, Trondheim, Norway, 2011, pp. 1–4, https://doi.org/10.1109/ICDL.2011.6015453.

[18] W. Cai, C. Zhang, M. J. Zhang, and J. Tang, "Discharge characteristics and mechanism of conductive metal particles in function of the oil flow under AC voltages | IEEE Journals & Magazine | IEEE Xplore," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 1, pp. 268–278, Feb. 2017, https://doi.org/10.1109/TDEI.2016.005901.

[19] P. Wang, N. Zhang, J. Xu, J. Zhang, and B. He, "Charging Characteristics of Micrometer-Sized Metal Particles and Their Effects on Partial Discharge of Insulating Oil in Flowing," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 3, pp. 1145–1153, Jun. 2023, https://doi.org/10.1109/TDEI.2022.3233008.

[20] C. Pan, J. Tang, Y. Zhang, X. Luo, and X. Li, "Variation of Discharge Characteristics With Temperature in Moving Transformer Oil Contaminated by Metallic Particles," *IEEE Access*, vol. 6, pp. 40050–40058, 2018, https://doi.org/10.1109/ACCESS.2018.2856580.

[21] 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, https://doi.org/10.1109/TDEI.2018.007182.

[22] F. D. A. García, F. R. A. Parente, G. Fraidenraich, and J. C. S. S. Filho, "Light Exact Expressions for the Sum of Weibull Random Variables," *IEEE Wireless Communications Letters*, vol. 10, no. 11, pp. 2445–2449, Nov. 2021, https://doi.org/10.1109/LWC.2021.3102877.

[23] K. Koutras, V. Charalampakos, G. Peppas, I. Naxakis, and E. Pyrgioti, "Investigation of the Effect of Semi-conducting and Insulating Nanoparticles' Concentration on the Breakdown Voltage of Dielectric Nanofluids," in *Proceeding of IEEE 21st International Conference on Dielectric Liquids*, Sevilla, Spain, 2022, pp. 1–4, https://doi.org/10.1109/ICDL49583.2022.9830931.

[24] Y.-Y. Wang, Y.-L. Li, C. Wei, J. Zhang, and X. Li, "Copper Particle Effect on the Breakdown Strength of Insulating Oil at Combined AC and DC Voltage," *Journal of Electrical Engineering and Technology*, vol. 12, no. 2, pp. 865–873, Mar. 2017, https://doi.org/10.5370/JEET.2017.12.2.865.