SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Semarak International Journal of Material Research

Journal homepage:
https://semarakilmu.my/index.php/sijmr/index
ISSN: 3083-8908

Material Dependent Partial Discharge Behaviour: A Computational Approach for HV System Design

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ARTICLE INFO

Article history:
Received 23 September 2025
Received in revised form 25 October 2025
Accepted 25 October 2025
Available online 28 October 2025

Keywords:
Partial discharge; High-voltage insulation; Electric field simulation; COMSOL Multiphysics; Dielectric permittivity

ABSTRACT

Partial discharge (PD) is an electrical discharge that occurs when a small area of insulation in a high-voltage (HV) environment cannot withstand the electric field and this phenomenon arises from defects such as air voids in the insulation material. This study addresses a gap in the existing literature concerning the comparative PD behaviour across different insulation types under uniform simulation conditions. Utilizing COMSOL Multiphysics, the research effectively simulated electric field distributions and estimate the partial discharge inception voltage (PDIV) for three insulation material including air, mineral oil, and epoxy resin. The result show that air exhibits the lowest PDIV (11.5kV), followed by mineral oil (28kV) and epoxy resin (57kV) confirming that materials with lower permittivity initiate discharge earlier due to higher localized field intensification. These comparative findings highlight the strong influence of dielectric properties on PD initiation and provide a computational foundation to enhance HV insulation design, material selection, and predictive maintenance practices in electric power systems.

1. Introduction

Partial discharge (PD) is a localized dielectric breakdown that occurs within defects such as voids or gas-filled cavities when a high voltage (HV) insulation cannot withstand the applied electric field [1],[2]. Although each PD event releases limited energy, repeated activity accelerates insulation degradation and can lead to complete dielectric failure. Therefore, PD is recognized as both a primary cause of insulation breakdown and an early indicator of defects in HV systems.

Monitoring PD is essential for insulation reliability and predictive maintenance. Despite numerous diagnostic studies [3], [4], few have conducted comparative analyses across different insulation media. Understanding how material properties affect PD inception is crucial for optimizing insulation design and improving HV system performance.

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https://doi.org/10.37934/sijmr.4.1.4148

Earlier investigations have primarily examined single materials. Tai et al. [5] analysed PD inception in PCB-based electrodes, while Aliyu et al. [6], [7] simulated PD behaviour in epoxy resin without extending comparisons to other dielectric types. This study fills that gap by comparing PD characteristics in air, mineral oil, and epoxy resin using a consistent computational approach.

HV insulation maintains electrical and mechanical separation between conductors under high voltage stress. Its performance depends on dielectric strength, permittivity, and conductivity [8]. Imperfections such as voids or impurities locally intensify electric stress, initiating PD. Paschen's Law defines gaseous breakdown as a function of pressure and gap distance, determining the discharge threshold [9]. Layered and composite insulation systems have also been shown to improve electric field uniformity and minimize discharge probability [10]. High-permittivity materials such as epoxy resin distribute electric fields more uniformly, whereas low-permittivity media like air exhibit earlier PD initiation.

Electric field distribution strongly influences PD inception. FEM-based analyses confirm that internal cavities amplify local field intensity [11], [12], while geometric optimization can mitigate discharge risk [13]. Integrating COMSOL Multiphysics and MATLAB allows detailed field visualization and PDIV estimation [14]. Building on previous work [15]–[18], this study investigates how dielectric properties govern PD initiation in various insulation types, offering insights to enhance HV insulation reliability and system safety.

2. Methodology

2.1 Simulation and Research Tools

The simulation was performed using COMSOL Multiphysics 5.5, a finite element analysis (FEA) software. The Electrostatics interface in the AC/DC module was utilized to analyse electric potential and field distribution under static conditions. This method is suitable for estimating the Partial Discharge Inception Voltage (PDIV), as it evaluates the electric field without incorporating transient effects. The study aimed to examine how insulation type, void size, and position influence electric field strength and to estimate PDIV using the breakdown threshold for air, set at 3×10^6 V/m [19].

A 3D model was developed to represent the PD setup, consisting of two parallel copper electrodes and a dielectric medium that varied by material—air, mineral oil, or epoxy resin. A high voltage was applied to the top electrode, while the bottom electrode was grounded. Field evaluation points were placed at the void centre to monitor electric field intensity. A parametric sweep was conducted to observe variations in field strength across voltage increments for each insulation medium.

The model geometry included two copper electrodes (20 mm × 20 mm × 1 mm) positioned at (0,0,0) and (0,0,11). Between them, a glass block (20 mm × 20 mm × 10 mm) served as a container. The insulation layer was modelled as an 18 mm × 18 mm × 8 mm block for mineral oil and an 18 mm × 18 mm × 1 mm layer for air, located at (1,1,2). This adjustment ensured the electric field reached the PDIV threshold for air, which does not concentrate the field naturally. For epoxy resin, a cylindrical dielectric (radius 1 mm, height 0.5 mm) was placed at (10,10,8), while a spherical air void (radius 1 mm for oil, 0.2 mm for solid) was embedded at (6,6,8) and (10,10,6.2), respectively. A point evaluation was set at the sphere's centre for consistent monitoring of field enhancement.

This configuration allowed consistent comparison of field concentration and PD inception behaviour across insulation types, providing a realistic simulation of HV conditions. Figure 1 illustrates the geometry for each insulation material.

Table 1
Table of the Geometry Details

Components	Shape	Dimensions(mm) (Length x Width x Diameter)	Position(X,Y,Z) in mm
Ground Electrode	Block	20 x 20 x 1	(0,0,0)
Top Electrode	Block	20 x 20 x 1	(0,0,11)
Glass	Block	20 x 20 x 10	(0,0,1)
Layer in Glass as Insulation (Air and Oil)	Block (Oil) Block (Air)	18 x 18 x 8 18 x 18 x1	(1,1,2)
Insulation (Solid)	Cylindrical	1 (radius), 0.5 (height)	(10,10,6)
Sphere (air void for oil and solid)	Sphere	1 (radius) for oil 0.2 (radius) for solid	(6,6,8) for oil (10,10,6.2) for solid
Evaluation Point	Coordinate	None	Centre of sphere

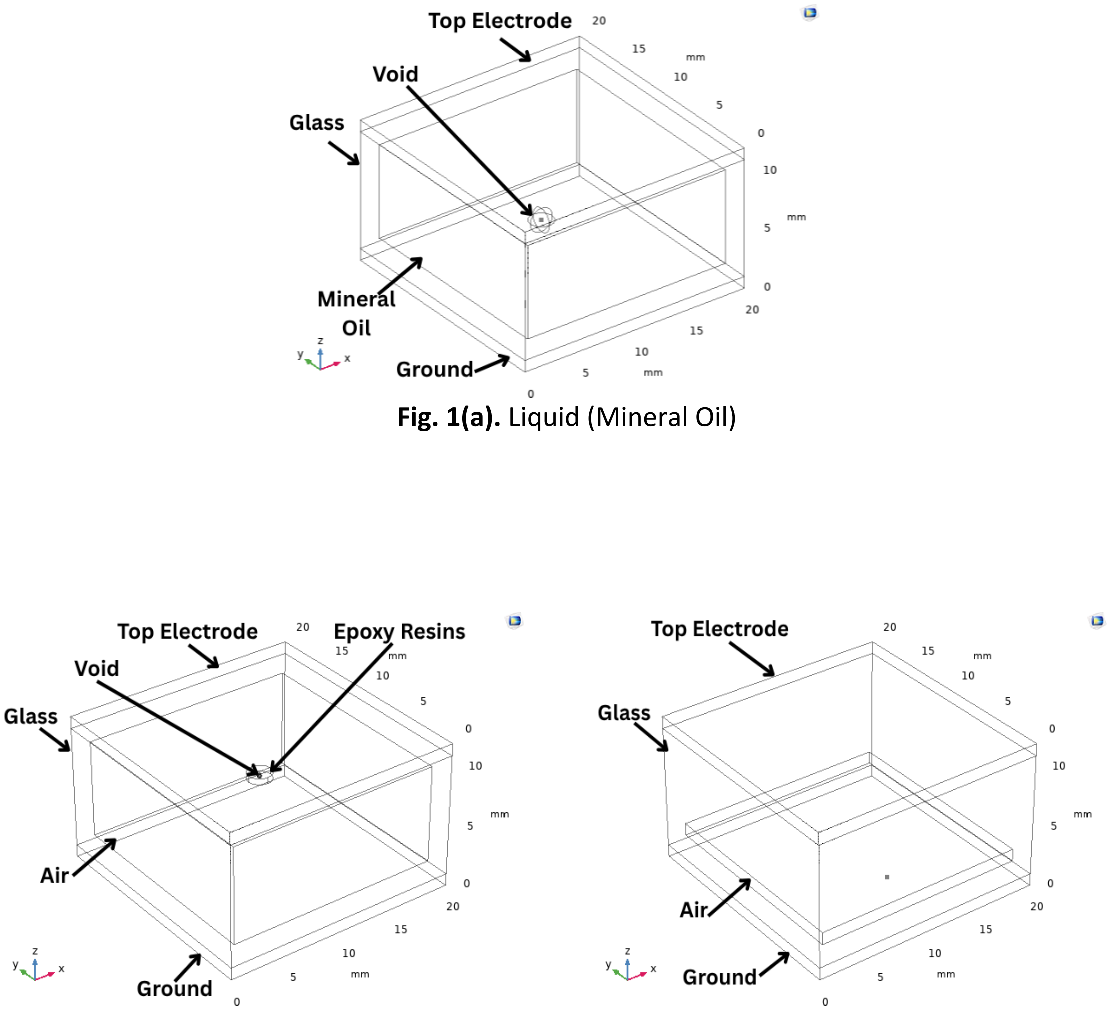

Fig. 1(a). Liquid (Mineral Oil)

Fig. 1(b). Solid (Epoxy Resin)

Fig. 1(c). Air

Fig. 1. Geometry details

2.2 Model Setup: Materials, meshing and Study Parameters

Elements are important to accurately compute the electric field distribution and assess the PDIV across different insulation materials. Based on the Table 3, it shows the table of material properties that utilised in the simulation, in which different materials have different relative permittivity and electric conductivity. In this simulation, each geometry component was assigned with their materials properties either through built in or custom defined material from COMSOL.

The simulation employed a physics-controlled meshing approach, with the element size set to finer to ensure precise electric field resolution, especially around the air void. This mesh setting in Figure 2 balances computational efficiency with the detail needed for field concentration analysis. The stationary study type is selected, as the simulation focuses on the static electric field distribution. Besides that, a parametric sweep is implemented to examine the effect of the increasing voltage. This enables consistent tracking of the electric field intensity at each voltage level to estimate the PDIV threshold. The use of fine mesh refinement and incremental voltage steps improves the reliability of the results from the simulation.

Table 2
Material Properties

Material	Relative Permittivity (εr)	Electric Conductivity (S/m)
Mineral Oil	2.2	1e-12
Epoxy Resin	3.2	1e-14
Air	1	0
Copper (Top Electrode)	1	5.998e7
Glass	4.2	1e-14

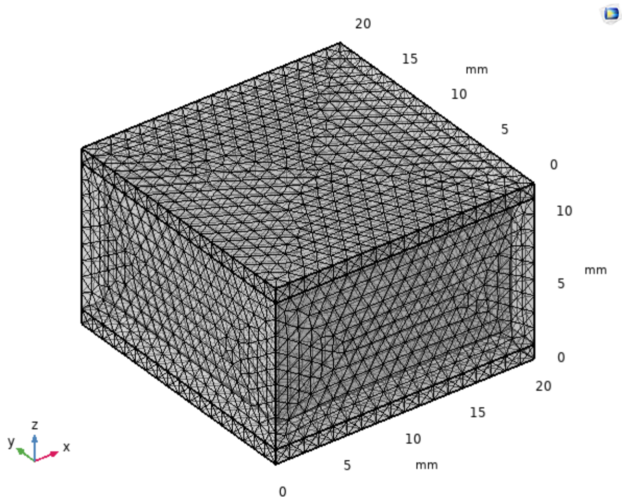

Fig. 2. Mesh Geometry

3. Results

3.1 The Simulation Result for Liquid Insulation

The simulation of partial discharge (PD) in mineral oil demonstrated a proportional relationship between the applied voltage and the electric field intensity. At 2 kV, the electric field magnitude was approximately 2.17×10^5 V/m, increasing to 8.68×10^5 V/m at 8 kV. The Partial Discharge Inception Voltage (PDIV) occurred at an applied voltage of 28 kV, corresponding to an electric field of 3.0 MV/m, the breakdown strength of air within the embedded void. As illustrated in Figure 3, this threshold indicated by the red dashed line signifies the critical voltage level at which PD initiates, providing essential insight for high-voltage insulation design and reliability assessment.

Additionally, the electric field image illustrates in Figure 4 shows that the air void exhibits a higher concentration of electric stress than the surrounding mineral oil. The central circular zone highlighted in green represents regions where the electric field intensity peaks, confirming that microscopic voids can lead to PD initiation. This shows that mineral oil provides moderate insulation performance and compared with air but remaining less resistant than solid materials. Its intermediate permittivity explains its balanced dielectric response, making it suitable for HV applications where both cooling and dielectric protection are required.

3.2 The Simulation Result for Solid Insulation

The epoxy resin simulation showed a direct proportionality between applied voltage and electric field intensity. At 2 kV, the electric field was 1.06×10^5 V/m and increased to 1.06×10^6 V/m at 20 kV. The Partial Discharge Inception Voltage (PDIV) occurred at an applied voltage of 57 kV, corresponding to an electric field of 3.0 MV/m, marking the onset of discharge within the embedded air void. Although epoxy resin has a higher dielectric strength, PD initiates in the air void, which cannot sustain the elevated electric field. The graph (Figure 5) shows a linear increase in electric field intensity with voltage, with the PDIV threshold highlighted at 57 kV by the red dashed line.

The field distribution plot (Figure 6) indicates a strong concentration around the void, with red-to-yellow regions denoting high field intensity and blue-to-green regions representing lower stress areas, confirming that localized voids are critical initiation sites for PD, even in high permittivity epoxy resin. Hence, the result highlights that epoxy resin exhibits more resistant as it reducing the probability of early PD activity compared with liquid and air insulations. Consequently, epoxy-based insulation remains a preferred choice for dry-type transformers, bushings and cable joints that demand reliability in HV systems.

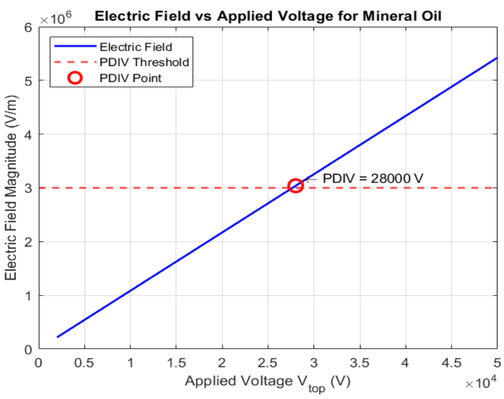

Fig. 3. Graph of Electric Field vs Applied Voltage for Mineral Oil

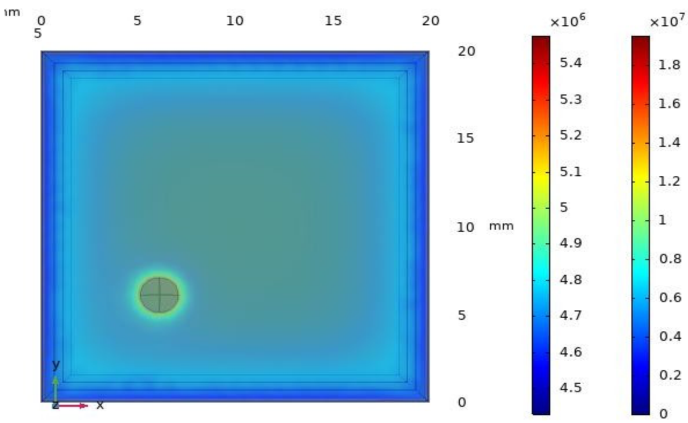

Fig. 4. Electric Field Distribution in Mineral Oil

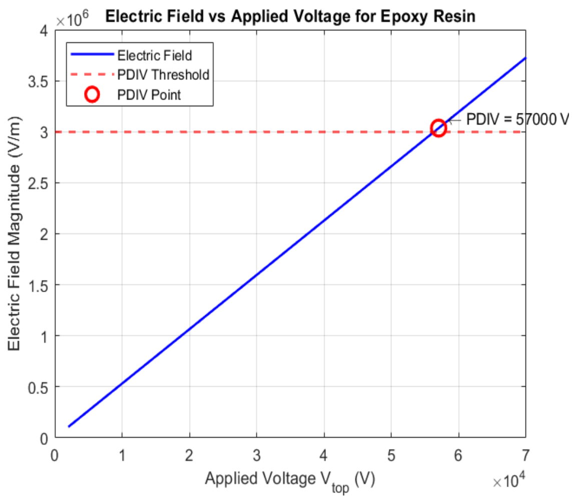

Fig. 5. Graph of Electric Field vs Applied Voltage for Epoxy Resin

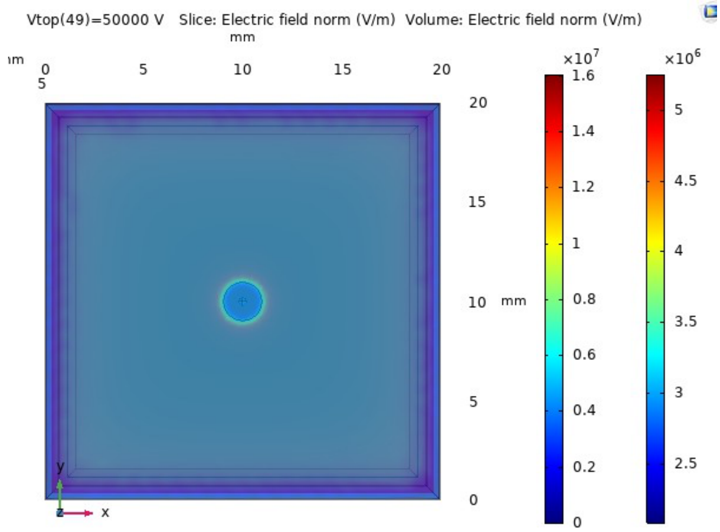

Fig. 6. Electric Field Distribution in Epoxy Resin

3.3 The Simulation Result for Air Insulation

The simulation of air insulation revealed a proportional increase in electric field intensity with applied voltage, ranging from 5.31×10^5 V/m at 2 kV to 3.98×10^6 V/m at 15 kV. The Partial Discharge Inception Voltage (PDIV) occurred at 11.5 kV, where the electric field reached 3.05 MV/m, slightly exceeding the air breakdown threshold of 3.0 MV/m. This confirms the onset of ionization and validates the simulation's accuracy.

The plot (Figure 7) shows a linear relationship between applied voltage and field intensity, with the PDIV point clearly marked at 11.5 kV. The field distribution (Figure 8) indicates a uniform electric field across the air medium, with blue-to-light-green regions representing low stress levels. Unlike oil and epoxy resin, air—being homogeneous and low in permittivity—exhibits minimal field localization, resulting in earlier PD initiation. This behaviour underscores that material with lower permittivity manifests lower PDIV. Although air's dielectric weakness limits its application in HV systems, its predictable discharge pattern makes it valuable for validating PD simulation and diagnostic models in research and testing environments.

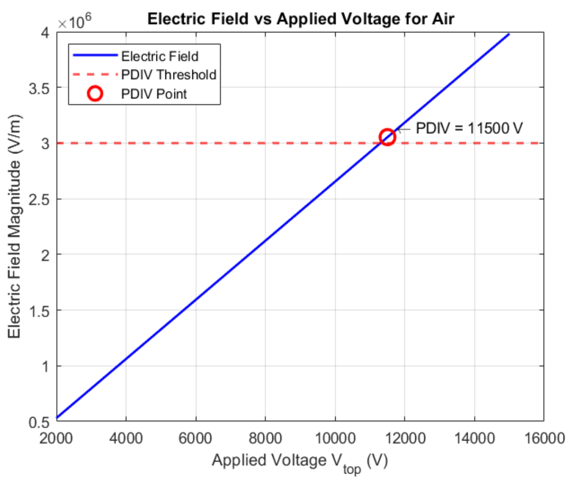

Fig. 7. Graph of Electric Field vs Applied Voltage for Mineral Oil

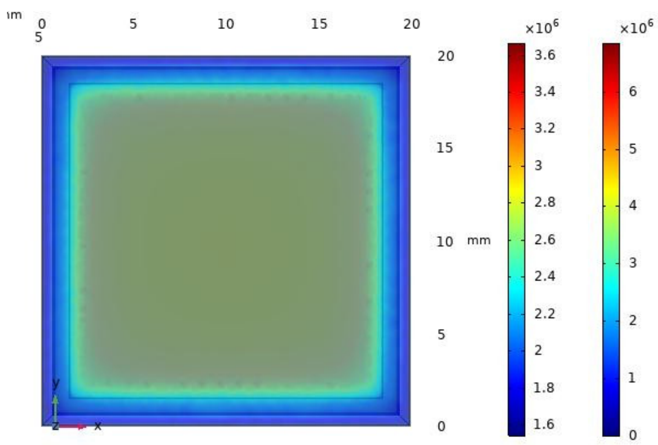

Fig. 8. Electric Field Distribution in Air

3.4 Comparison of Partial Discharge Analysis

The simulation compared air, mineral oil, and epoxy resin to evaluate their Partial Discharge Inception Voltage (PDIV) and electric field behaviour. The results, summarized in Table 3, show that epoxy resin recorded the highest PDIV at 57 kV due to its high permittivity and strong dielectric strength, followed by mineral oil at 28 kV, and air at 11.5 kV, which exhibited the earliest discharge due to its low permittivity. This pattern demonstrates a material-dependent relationship between permittivity and discharge initiation. Air exhibited steep field gradients and concentrated stress near the electrodes, indicating early discharge onset. Epoxy resin displayed a uniform and layered field distribution with gradual intensity transitions, reflecting superior dielectric performance. Mineral oil demonstrated intermediate behaviour, with moderate field localization around void regions.

The computational comparisons are essential for material selection and insulation modelling in high voltage (HV) design. Overall, the comparative analysis contributes to enhancing the predictive maintenance by linking dielectric properties to discharge tendency and enable early detection of insulation degradation. These findings thus provide a useful computational foundation for improving insulation reliability and advancing PD diagnostic accuracy in simulation-based studies.

Table 3
Material Properties

Materials	Partial Discharge Inception Voltage (PDIV)
Mineral Oil	28kV ±2 kV
Epoxy Resin	57kV ±2 kV
Air	11.5kV±2 kV

4. Conclusions

In conclusion, this study explored the partial discharge (PD) behaviour in high voltage (HV) insulation systems, with a focus on three categories of insulation materials including liquid, solid and air. The main objective, which involved simulating PD behaviour in various insulation materials, was successfully achieved using COMSOL Multiphysics. The simulation enabled for an in-depth analysis of the electric field distribution and partial discharge inception voltage (PDIV) for each material under high voltage stress. The results revealed that material permittivity strongly influences PD onset, with air exhibiting lowest PDIV, liquid providing moderate resistance, and solid demonstrating the highest dielectric strength. These results highlight the pivotal role of material selection in HV system design, as insulation with higher permittivity effectively delays discharge initiation. The outcomes also provide a valuable computational foundation for improving insulation modelling and reliability assessment. Future work should extend these simulation trends through experimental studies to deepen and expand insights in HV systems under operational conditions.

Acknowledgement
This research was partially funded by the Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis.

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