

Performance Testing of Breakdown High Voltage Contactor

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Abstract

The aim of this paper is to study the behaviour of a breakdown high voltage (HV) contactor with different insulating materials. The analysis of breakdown voltage and electric field distribution by means of experimental testing and numerical simulation is considered in the study. The purpose is to test the dielectric strength of various insulating materials that is to say acrylic heat shrink rods (Polyolefin), Teflon and uninsulated rods under high voltage stress. The experimental analysis was in a high-voltage laboratory and simulation analysis by using Comsol Multiphysics software. Based on the results, it was found out that the value of the dielectric strength went up sharply with the use of insulation. Precisely, there were low breakdown voltages by bare rods of 23 kV (at 12 mm gap) and 32 kV (at 16 mm gap) whereas the acrylic and Polyolefin insulators had more than 50 kV to break. The same respective distances after being tested, showed a breakdown voltage of 47kV and 49kV with teflon. The simulation results further justified that when you increase the electrode gap it decreases the strength of the electric field, and also full insulation coverage results in widespread field distribution in comparison to partial insulation. This highlights the devastating effect of the insulation material used, how well one insulates, and the spacing between the electrodes of the dielectric behavior. In summary, the reliability and safety of high-voltage contactor systems could be increased greatly by insulating using suitable materials and arrangements.

1. Introduction

High-voltage (HV) systems play a crucial role in contemporary power generation, transmission, and distribution. Within these systems, HV contactors are essential components designed to provide reliable switching and circuit protection under elevated electrical stress conditions. The performance of these contactors is largely determined by their electrical breakdown characteristics, with breakdown voltage serving as a key criterion [1].

Breakdown voltage depends on several factors, including the geometry of the electrode structure, the properties of the insulation material, and the environmental conditions in which the system operates. For instance, studies have shown that electrode configurations, such as the rod-plate design, significantly influence breakdown characteristics by affecting air gap behavior and discharge phenomena like corona discharge. Beyond electrode geometry, the type and density of insulation materials used in HV systems also play a vital role in determining breakdown strength. Furthermore, the interaction between AC breakdown and floating conductors combined with air gaps where parameters such as electrode radius and air gap distance are critical and affects the overall insulation performance [2].

Testing the electrical and dielectric stress of HV components typically involves the use of both bare and insulated rods in various configurations to simulate real-life operating conditions. Bare rods are employed to investigate extreme breakdown conditions and fundamental dielectric properties, while insulated rods help assess insulation failure modes. These testing methodologies have significantly advanced the understanding of electrode and insulation behavior under high voltage stress.

HV contactors are indispensable in modern electrical equipment due to their role in regulating and carrying high currents. However, several challenges remain, particularly regarding insulation performance, breakdown voltage stability, and material durability under HV stress. Acrylic, a commonly used and cost-effective insulator, has demonstrated promising results in some applications. Nonetheless, there is limited information on its relatively poor breakdown voltage and non-ideal long-term properties in HV environments.

Previous research has emphasized the importance of electrode design in enhancing insulation reliability. For example, Researcher [3] highlighted the need to optimize electrode contours to improve insulation performance, especially in vacuum circuit breakers. Similarly, with Researcher [4] discussed spark conditioning procedures for vacuum interrupters, which improve dielectric properties and reduce breakdown incidents, underscoring the need for further studies on material characteristics under HV. Building on these insights, this paper aims to assess the impact of breakdown voltage on different types of insulation materials used in HV contactor applications. Through controlled experimental testing and analysis, the research seeks to identify the causes of insulation failure under elevated voltage conditions.

2. Methodology

Fig. 1 shows a flowchart of the work to be done in this project and would be used as an aid to visualize the workflow that should be completed to attain the project goals to the best of abilities. Flowchart is classified in two phases, which define processes that need to be undertaken to accomplish it. According to stage 1 it deals with experimental work to determine the breakdown voltage of various insulating materials. There are simulations (stage 2) concerning simulation work, the analysis of the electric field and the breakdown voltage with the help of COMSOL Multiphysics software.

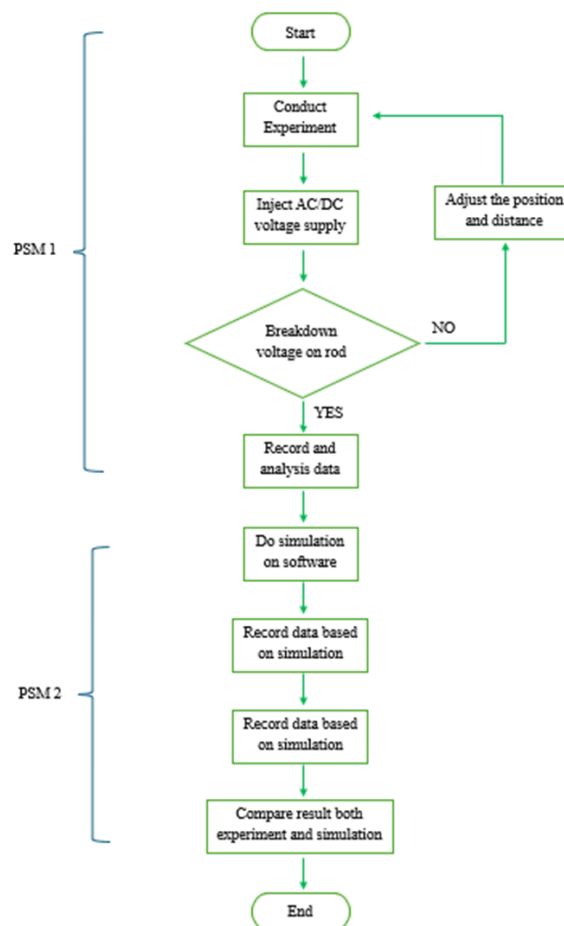


Fig.1 Flowchart of the project for Performance Testing of Breakdown High Voltage Contactor

2.1 Experimental Setup

In this section, the method has been conducted by using the HV laboratory to measure the breakdown voltage on each material properties of insulation with different gap distance between copper rod and grounded probe. Fig. 2 shows the setup of experimental works before examining the dielectric strength of acrylics, uninsulated rod, Teflon and heat shrink.

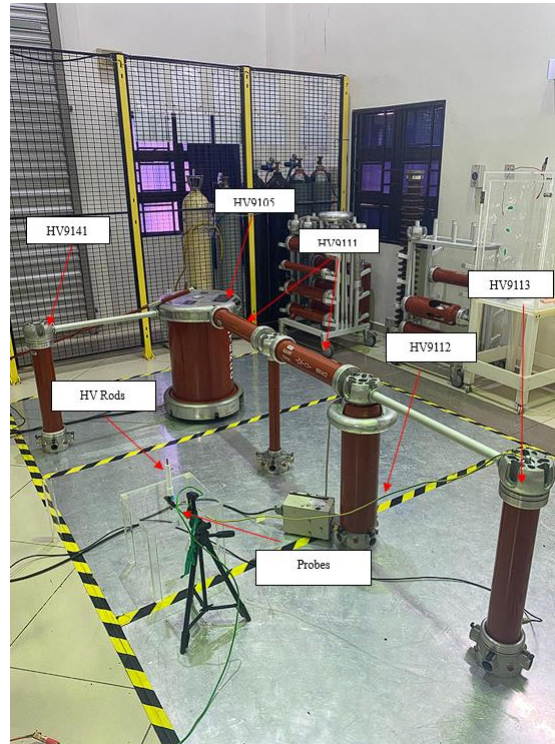
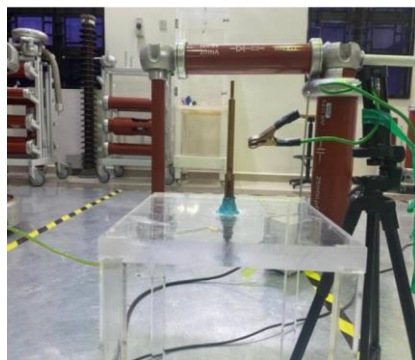


Fig. 2 Experiment Setup of shown High Voltage

2.2 Materials of Insulator

In this experiment, a rod without insulator and rod with three different types of insulators been injected with voltage to measure the breakdown voltage. Fig. 3 shows each material of insulators set up around the rod copper. Acrylics, Polyolefin, and Teflon were chosen as insulation materials in this paper with the properties of chosen insulation material are tabulated in Table 1.



(a)



(b)



Fig. 3 Type of insulator (a) uninsulated rod (b) acrylics (c) teflon (d) Polyolefin

Table 1 Properties of insulation materials

Property	Bare rod	Acrylic	Polyolefin	Teflon (PTFE)
Dielectric strength (kV/mm)	Variable	> 150	20 – 30	60 – 250
Thermal Stability	Moderate	Up to 80	Up to 125	-200 to +260
Moisture Resistance	Limited	Moderate	Good	Excellent

2.3 Simulation Works

COMSOL Multiphysics was used to simulate work and perform the analysis of electric field distribution and breakdown voltage estimation. There were two primary conditions under study, varying gap distances between the copper rod and the grounded probe, and different insulation coverage on the copper rod (partial and full insulation coverage). The real configuration was mimicked by a two-dimensional axisymmetric replica in which the copper rod was given high voltage and probe grounded.

In the former case, a change in gap between the rod and probe was used to check how distance influences the strength of the electric field and electrode strength. Under the second condition, the simulation test involved partially and fully coated rods to understand the effect of the insulation coverage on field concentration.

Electric field was calculated by using Electrostatics interface and meshing was fine in the regions where it is of critical importance [5]. Analysis was executed based on the electric field distribution and the comparison of those results with that of dielectric strength of air to observe the chances of any possible break points. Fig. 4 shows the simulation part under these two conditions.

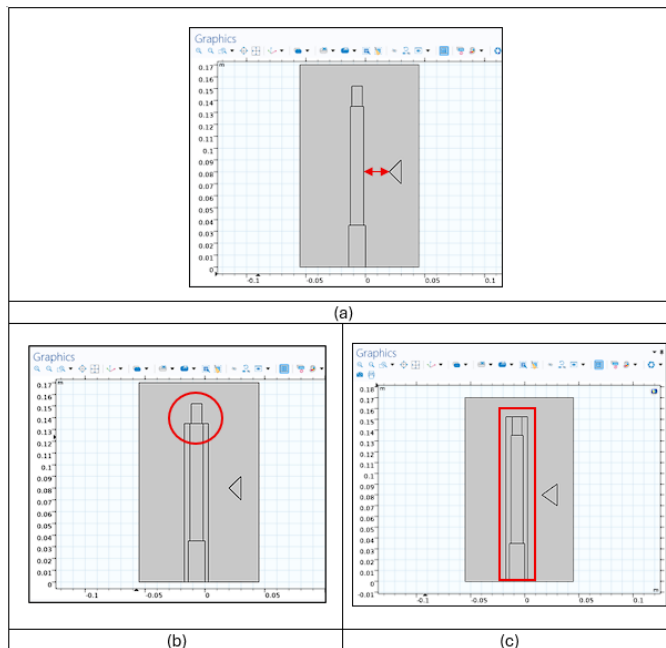


Fig. 4 Software modelling under two conditions (a) different gap between copper rod and grounded probe (b) partial coating (c) full coating

2.4 Simulation Parameters

To examine the voltage and electric field distribution on the insulator at varied distance and partial and full insulation around rods, the relative permittivity of each material required. This project needs insulation properties to observe the breakdown voltage and electric fields. The relative permittivity of a material describes the material's ability to respond to an electric field. Relative permittivity or relative dielectric constant is the ratio between the electrical permittivity of a material and the electrical permittivity in a vacuum. According to None Suwarno [6] the higher the relative permittivity value, the greater the material's ability to reduce the electric field. Fig. 5 shows the section that needs to define the material of insulation

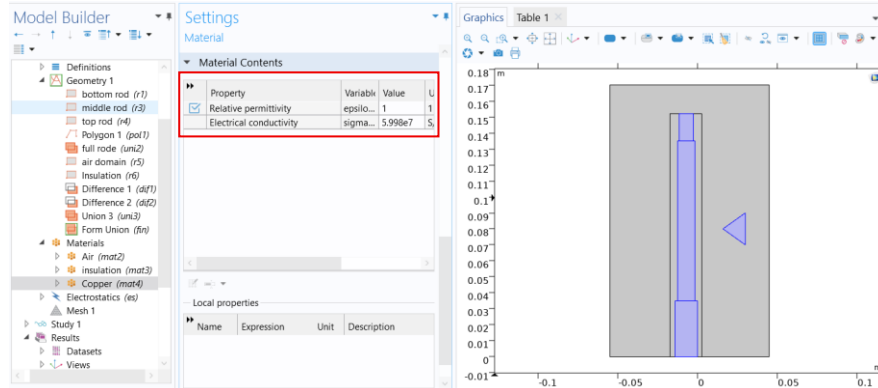


Fig. 5 Section of Relative Permittivity

Table 2 shows the relative permittivity values of each material, which need to be added in the simulation to define the properties of each material.

Table 2 Value relative permittivity of material properties

Type of Insulation	Relative Permittivity Value
Without Insulator	1
Acrylics	3.3
Teflon	2.39
Polyolefin	4

3. Results and Discussion

3.1 Experimental Result

In this section, four types of insulators underwent examinations in the laboratory. Every material will be injected with DC voltage with different distances, partial and full coating on rod to get the data. The rods without insulation, acrylics, heat shrinks, and Teflon will be tested in this experiment to analyze the breakdown voltage. Table 3 displays the recorded maximum breakdown voltage of each material. The breakdown voltage will be recorded when injecting the DC supply to fifty kilovolts.

Table 3 Data of injected DC voltage before breakdown.

Type of Insulator	Gap Distance 12mm	Gap Distance 16mm
Without Insulator	23kV	32kV
Acrylics	>50kV	>50kV
Teflon	47kV	49kV
Polyolefin	>50kV	>50kV

The breakdown voltage was tested using bare copper rod and the same rod which had been covered with the diverse forms of insulating materials including acrylic, Teflon, and Polyolefin. The tests were done with two gap distances, 12mm and 16mm. The effects on the dielectric strength were evident through the findings that indicated that type of insulation matters. The rod recorded the lowest breakdown voltages of 23 kV at 12 mm and 32 kV at 16mm indicating that it is easier to break without any insulators in place. On the contrary, the breakpoint voltages of rods coated with acrylic, Teflon and Polyolefin. were much higher. Acrylic and Polyolefin. values were above 50 kV at both distances whereas Teflon values recorded 47 and 49 kV at 12 and 16 respectively.

These results are in the predicted range of performance with respect to the dielectric characteristics of the materials. The increased breakdown voltage of acrylic and Polyolefin is probably because their insulation capability and thickness were stronger and could break down only when the test limit was surpassed. The slightly reduced values of Teflon could be possibly resulted due to differences in thickness or surface quality. It also assisted in the electric field distribution process that was made more homogeneous and therefore less stressful and raised the breakdown voltage. Overall, the experiment demonstrates that the selection of an appropriate insulation variety is essential to enhance integrity and safety on HV systems.

3.2 Simulation Result

A simulation of four different materials of insulation was performed, each material will analyze the electric fields distribution. Fig. 6 shows the electric field distribution on COMSOL Multiphysics software.

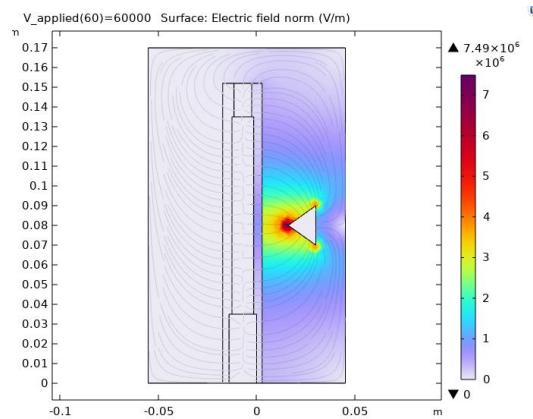


Fig. 6 Electric Field Distribution

3.2.1 Electric Fields (Varies Distance Between Rod Copper and Grounded Probe)

The electric field between a copper rod, set at a high voltage and a grounded probe was measured at both 12 mm and 16 mm separation. The distance between the electrodes affects electric field strength because $E=V/d$. That is why the electric field tends to decrease as the distance between objects increases. The simulation showed that at the same voltage, there was a stronger electric field at 12 mm than at 16 mm gap. As the distance between electrodes decreased, the electric field increased and when the gap increased, the field reduced. This study backs up the theory and demonstrates that well-managed spacing is key to lowering the threat of dielectric breakdown in the insulation design of high-voltage systems. Fig. 7,8,9,10 and 11 show the results for four materials with 12mm and 16mm gap distance.

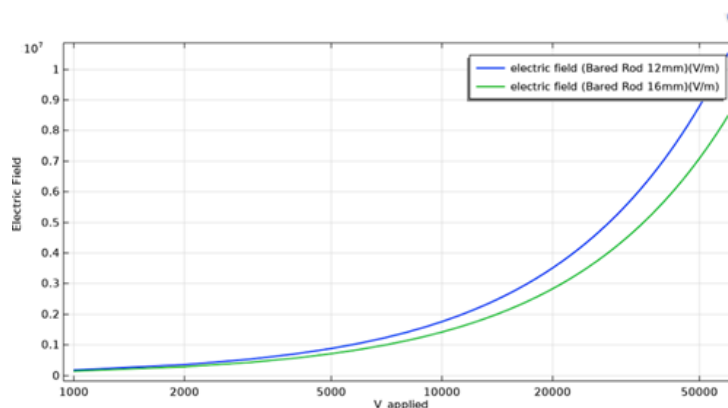


Fig. 7 Electric field vs voltage applied for bared rods performance.

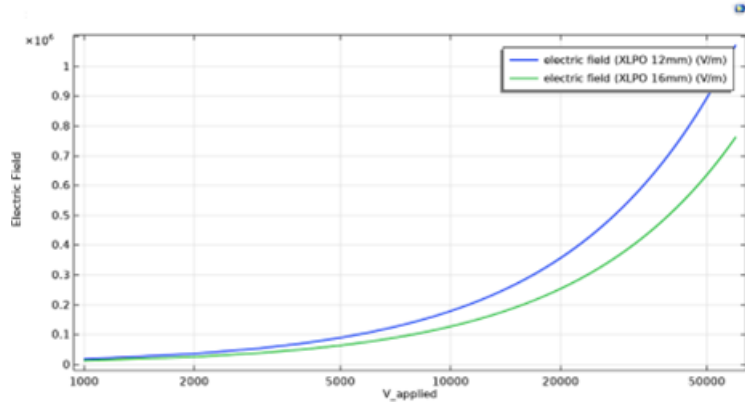


Fig. 8 Electric field vs voltage applied for polyolefin insulation performance.

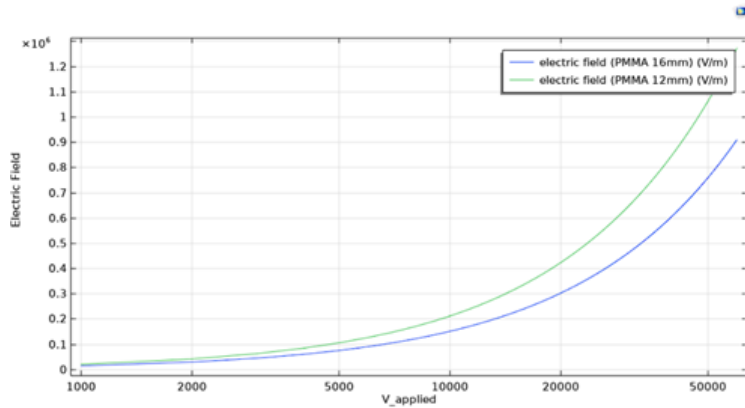


Fig.9 Electric field vs voltage applied for acrylics insulation performance

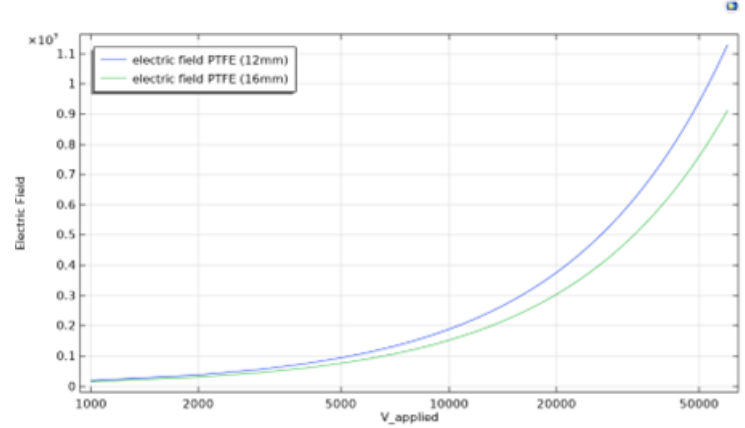


Fig.10 Electric Field vs Voltage Applied for Teflon Insulation Performance

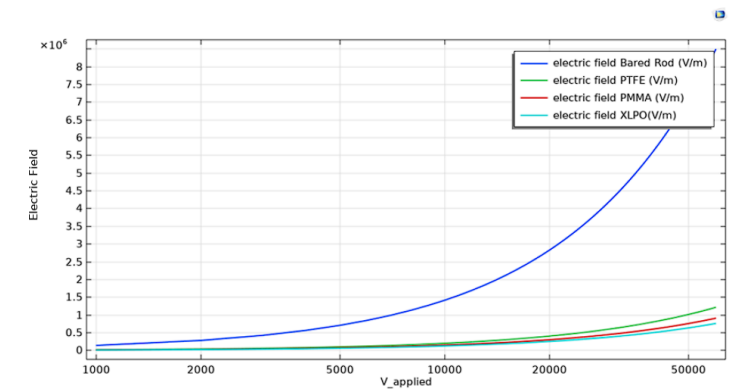


Fig.11 Electric field vs voltage applied performance for overall insulation

The result in COMSOL Multiphysics software in Fig. 7,8,9,10 and 11 shows the electric field between a copper rod and grounded probe is affected by the gap distance. When the gap is small, the electric field strength increases because the potential difference is concentrated in narrow space and lead to breakdown voltage. Conversely, when the gap is increases, the electric field strength weakens as the field line spread out surrounding the rod copper. As result we can describe that gap distance is inversely proportional with electric field. With the help of the insulation, it might take longer for the insulation to be used before a breakdown happens. Based on the result it successfully proved the previous research which mentioned about the gap distance between two electrodes is going to affect the breakdown voltage level because changes of electric field [7].

3.2.2 Electric Fields (Partial and Full Coating)

Insulating a high-voltage conductor can change the amount of electric field present and can also change the breakdown voltage of the system. With a full insulation coating, the electric field spread steadily, and its strength drops at all points of the wire. The uniform field limits stress on specific areas of the dielectric and greatly enhances the system's breakdown voltage by keeping out air gaps and surface discharges that most often cause dielectric failure. However, when the conductor is only partially insulated, sections at the ends are still visible since the area where the conductor, insulator, and air connect (the triple point) creates a strong electric field. Electric field peaks cause places where some discharges begin, and the breakdown of electrical materials starts. So, partial insulation in a system usually results in a lower breakdown voltage when compared to a system that is fully insulated. Fig. 12 shows the partial and full coating.

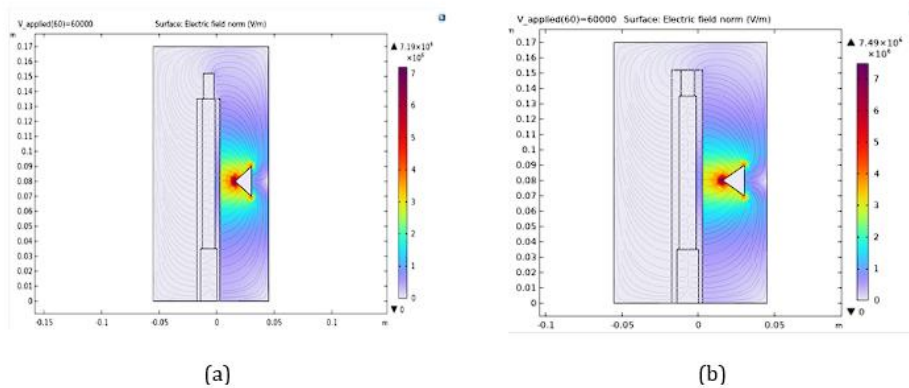


Fig. 12 Partial and full coating on rod (a) partial coating (b) full coating

Fig. 13 presents the graph showing the electric field results for both partial and full coating, illustrating their electric stress performance.

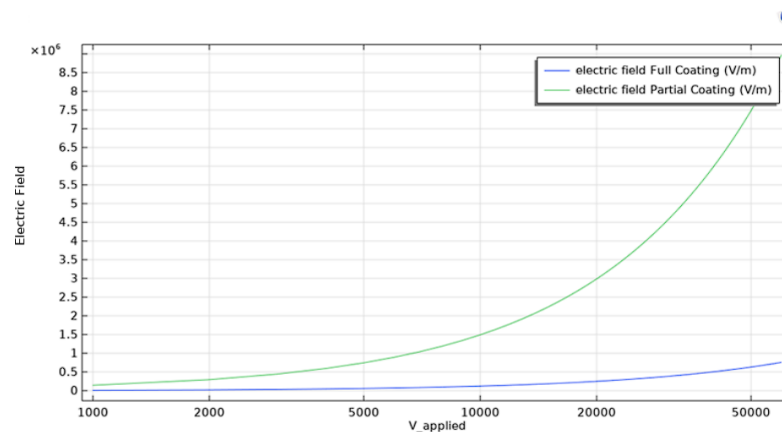


Fig.13 Result electric field vs voltage applied for partial and full coating

The result in Fig.13 shows the electric field around conductor significantly affected with the designing of coating. With the full coating, the electric field distributed around the surface of conductor and preventing the electric field to concentrating on the specific point which may lead to electrical breakdown. In contrast, partial coating has exposed part of rod which may lead to electric field to concentrating at the exposed part and the

electric field gets uneven with higher fields where the insulation is missing, this can result in high field strength areas that can lead to dielectric breakdown when the field strength increased beyond the voltage withstand ability of the insulation. Thus, when considering distribution and capability to withstand high voltages, full insulation gives better results rather than partial coating.

4. Conclusion

In conclusion, the project titled "Performance Testing of Breakdown High Voltage Contactor" successfully achieved all its objectives. The first objective, which was to analyze the dielectric strength of different insulation materials during breakdown voltage, was fulfilled through experimental work conducted in the High Voltage Laboratory. The data collected during the experiment distinguished the dielectric strength of each material. The second objective, to compare the breakdown voltage and electric field strength at varying distances between a copper rod and the ground probe, under partial and full coating, was addressed through simulation. The results from the simulation showed the comparison between these two factors and how they affect both the electric field and the breakdown voltage. In conclusion, the research successfully met all its objectives and established a clear relationship between displacement distance, insulation coating, and insulation material in influencing breakdown voltage and electric field behavior.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception, design, data analysis and manuscript preparation:** Muhammad Akram Hamdan; **manuscript verification:** Nordiana Azlin Othman. All authors reviewed the results and approved the final version of the manuscript.*

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