

Experimental and Numerical Investigation of Surface Flashover Characteristics in Insulated High Voltage Electrode Systems

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ABSTRACT

This study investigates the effectiveness of insulation materials in enhancing the breakdown voltage performance of high-voltage (HV) electrode systems. Bare electrodes and electrodes coated with Teflon and polyolefin were used to conduct the experimental analysis under controlled conditions (DC). Measurement of the breakdown voltage was done through repeated trials, and statistical analyses, including mean and standard deviation, were carried out to determine the consistency of performance. Furthermore, the distribution of electric fields was modeled through a numerical simulation to describe the breakdown behavior. Results indicate that insulated electrodes significantly improve breakdown voltage compared to bare configurations, with polyolefin demonstrating the highest performance. Despite lower variability demonstrated by Teflon, polyolefin attains a high level of dielectric strength with reasonable variability. AC testing further reveals differences in leakage behavior, indicating the influence of alternating stress on surface conduction. These results confirm that the insulation coating can minimize the concentration of the electric fields, thus increasing the reliability of the system. This work provides a viable and efficient methodology toward enhancing HV electrode workability in industrial process applications like EV contactor testing.

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1. INTRODUCTION

A high-voltage (HV) system is the foundation of the modern energy infrastructure. It supports critical sectors such as large-scale energy transmission, manufacturing, electric vehicles (EVs), and renewable energy applications. This reliability is highly dependent on the effectiveness of the insulation used, as a failure of the electrical system could result in catastrophic short circuiting, permanent damage to equipment, and serious safety hazards [1]. In HV applications, the intensity of electric fields near the surface of electrodes is of paramount importance, especially at any geometric irregularity. Several combinations of material properties and environmental conditions (humidity, temperature, sharpness of the electrodes) lead to a higher local electric field, a higher ionization rate, and a higher risk of sparking or surface

flashover [2]. Dielectric coatings are therefore often applied to redistribute the electric potential and prevent the maximum field strength.

The formation of arcs and the electrical breakdown between the electrode gaps are commonly observed in practical industrial applications, especially in EV contactors, during the testing operations. These phenomena are strongly influenced by the geometry of the contacts, operating conditions, and the number of re-switches [3-7]. Partner companies have reported that spark events during high-stress testing could potentially cause machine failures and disrupt surrounding sensitive equipment, as illustrated by the configurations in Figure 1.

Figure 2 shows the HV rod geometry as well as the application insulation tape on the HV rod. Based on Figure 2a,

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the geometry conditions are not assumed to be uniform. Hence, there is a high probability that it can be a source of sparking flash events. Moreover, the conventional method of hand-fitting insulation tapes, as shown in Figure 2b, is insufficient for long-term use and may likely increase the risk of failure. The use of tape can temporarily make the system's appearance look good. However, in prolonged application, it will be subjected to wear and tear and eventually can cause repeated failures. This is the reason why it is important to implement adequate and robust insulation coatings that can handle the pressure of HV without sacrificing the integrity or appearance of the system.

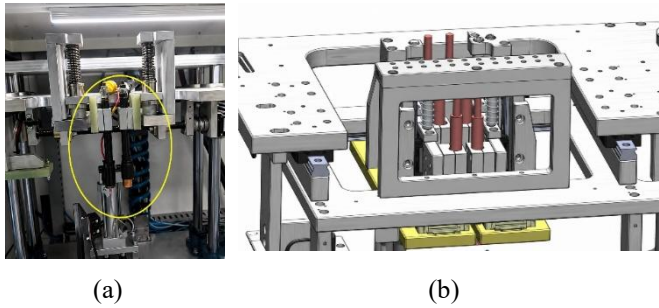


Fig. 1. (a) Real and (b) 3D design of the testing machines.

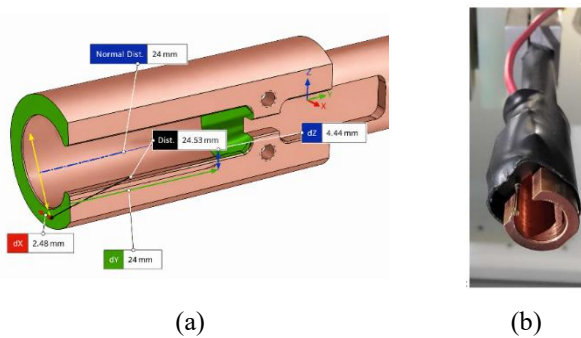


Fig. 2. (a) Rod geometry and (b) insulation tape.

Existing studies primarily focus on material characterization under standardized laboratory configurations. Limited studies have investigated practical electrode geometries used in industrial EV contactor testing while simultaneously combining breakdown experiments, leakage-current analysis, Weibull reliability assessment, and FEM electric-field simulation. Among them, the partial discharge (PD) phenomenon in the material and the electric field distribution under different stresses in the material are of particular interest [8-12]. Most of these, however, are separate experimental characterizations or simulation analyses, not a combination of both. Furthermore, the available reports of breakdown performance under repeated testing conditions are often presented with insufficient details, since the event is highly dependent on testing procedures and various factors. As such, a thorough assessment requires detailed statistical analysis, not just a single value [13-15].

As a result, the constraints mentioned above were removed in this study, and both experimental and numerical research on the surface flashover property of insulated electrode systems was conducted. The primary goals are to experimentally verify

the breakdown voltage of bare and polymer-insulated HV electrodes and to conduct a thorough statistical analysis to establish the reliability of the obtained data. Furthermore, physical knowledge of the observed breakdown behaviors is acquired through numerical simulation of the electrical field and potential gradient distributions. Finally, the appropriate insulating material and type for improving system reliability and safety in practical HV system applications are examined.

2. METHODOLOGY

2.1 DC Breakdown Test

Two electrodes were connected to the HV power supply at a fixed distance of 16 mm, as depicted in Figure 3, and the test was conducted under DC-breakdown conditions. Both the HV electrode and crocodile clip were connected to the HV source. The ground point (crocodile plug) was situated 86 mm above the acrylic surface on which the HV electrode was placed. Three different configurations were tested: bare electrode, electrode with Teflon insulation, and electrode with polyolefin insulation. The Teflon and polyolefin insulation layers had thicknesses of 3.0 mm and 0.5 mm, respectively. The insulation dimensions were selected based on practical industrial implementation requirements for EV contactor testing systems. The voltage was slowly raised until failure was induced by a sudden flash of electricity and a large spike in current. Three sets of tests were conducted to obtain reliable data.

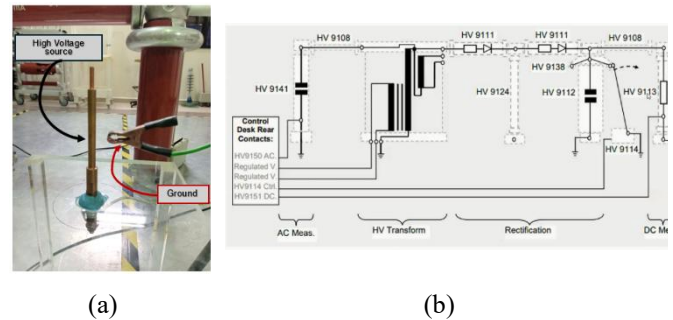


Fig. 3. (a) Laboratory and (b) Schematic diagram of DC breakdown experimental setup.

The standard deviations were used to numerically determine the reliability and repeatability of measurements taken during the experiment. Next, by identifying the distribution of the breakdown voltage values with respect to their mean values, measurement stability under repeated test conditions was evaluated. The standard deviation was obtained using Equation (1).

$$\sigma = \sqrt{\frac{(x-\bar{x})^2}{n-1}} \quad (1)$$

The Weibull model adds to the results of standard deviation analysis by offering a statistical model for the breakdown voltage. Standard deviation analyses measure overall variability, whereas the Weibull distribution shape factor (β) evaluates consistency. Apart from that, the coefficient of variation (CV) provides a normalized measure of data dispersion (see Equation 2), and the 95% confidence interval

provides an estimate of the range within which the true mean breakdown voltage is expected to lie is included in this work.

$$CV = \frac{\sigma}{x} \times 100 \quad (2)$$

It should be noted that, owing to the limited number of replicate breakdown tests ($n = 3$) performed per configuration in this comparative feasibility study, the Weibull shape parameter and associated reliability indices are treated as preliminary trend indicators rather than statistically robust lifetime-reliability estimates; a larger sample size (e.g., $n \geq 10$, consistent with IEC 60243 test guidance) would be required for definitive reliability conclusions.

2.2 AC Leakage Current Measurement

The AC test was carried out to analyze the performance of leakage current under AC stress. Figures 4 and 5 demonstrate the AC leakage current measuring system and the circuit diagram of this research, respectively. The connection between the HV electrode and crocodile clip was fixed in DC tests at the same distance. Voltage was gradually raised during the test while measuring the respective current value with the UT251A high-precision leakage current clamp meter, as illustrated in Figure 6.

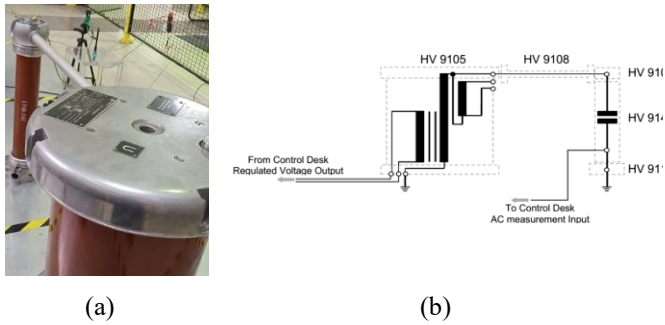


Fig. 4. (a) Laboratory and (b) Schematic diagram of the AC breakdown experimental setup.



Fig. 5. Laboratory leakage current measurement setup.

2.3 Simulation Method

The simulation was modelled in COMSOL Multiphysics software to analyze the electric field and potential distributions under stationary DC conditions. A two-dimensional (2D) geometric model was constructed based on the exact physical dimensions of the HV electrode and grounded crocodile clip used in the experimental setup, maintaining a fixed inter-electrode gap distance of 16 mm, as shown in Figure 6. Given

the symmetrical geometry of the electrode system, the numerical model was formulated using a 2D axisymmetric model class, allowing the 3D potential field to be accurately represented by its cross-sectional domain.

The computational domain was bounded by a 250mm X 400mm outer air enclosure ($\epsilon_r = 1$) representing free-space insulation conditions. Electrostatic physics governed the domain, solving Laplace's equation for scalar electric potential as given in Equation (3):

$$\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = 0 \quad (3)$$

Where ϵ_0 is the vacuum permittivity and ϵ_r is the relative permittivity of the respective domain material. A continuous DC potential ($V_{applied}$) corresponding to the experimental breakdown values was assigned to the copper HV electrode, while the crocodile clip was set to ground boundary conditions ($V = 0$).

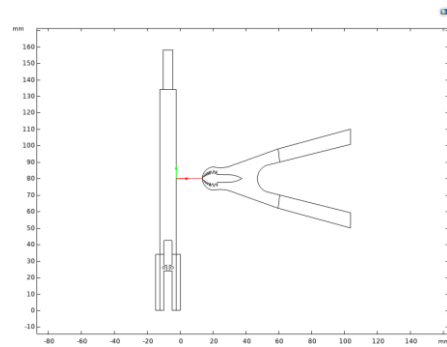


Fig. 6. Two-dimensional geometric model of the experimental setup used for Finite Element Method (FEM) software.

The dielectric properties and physical dimensions of the insulation coatings applied to the electrode surface are summarized in Table 1. The domain was discretized using a physics-controlled free triangular mesh, with local refinement applied along the electrode interfaces and insulation air-gaps to capture steep electric field gradients. The complete discretized mesh consisted of approximately 18,500 domain elements, ensuring numerical convergence and independent solution stability.

Table 1. Insulation thickness and permittivity.

Insulation type	Thickness (mm)	Relative permittivity (ϵ_r)
Teflon	3.0	2.1
Polyolefin	0.5	2.5

3. RESULTS AND DISCUSSION

3.1 DC Breakdown Performance

The breakdown voltage performance of bare and insulated HV electrodes was evaluated under controlled DC conditions. As summarized in Table 2, the application of insulation materials yielded a significant improvement in dielectric strength.

Table 2. Breakdown voltage values for bare and different insulated electrodes.

Insulation types	Bare	Teflon	Polyolefin
Reading 1	31.9 kV	50.6 kV	58.5 kV

Reading 2	31.2 kV	50.4 kV	55.8 kV
Reading 3	31.1 kV	50.1 kV	57.3 kV
Average	31.4 kV	50.4 kV	57.2 kV

The bare electrode exhibits the lowest breakdown voltage because of its susceptibility to the effects of the electric field, which causes an elevated concentration of the electric field at the edges of the electrode. Conversely, electrodes coated with Teflon and polyolefin demonstrate significantly higher dielectric breakdown capabilities. Among all the examined materials, yields the highest breakdown voltage, followed by Teflon [16]. It should be explicitly noted that the Teflon (3.0 mm) and polyolefin (0.5 mm) layers were not thickness-matched, as both were selected based on their as-supplied, practical industrial specifications for EV contactor insulation rather than for idealized comparative testing. Despite being substantially thinner, polyolefin achieved the highest breakdown strength. This outcome demonstrates that insulation efficacy is not solely governed by physical thickness but is strongly driven by dielectric properties and electric field redistribution characteristics. The application of the dielectric coating redistributes the electric field lines in accordance with dielectric field-grading principles in high-voltage insulation systems, thereby dampening peak electric field intensities, suppressing localized ionization, and ultimately enhancing breakdown strength [17, 18].

3.2 Weibull Statistical Analysis

The objective of this work is a comparative industrial feasibility study rather than statistical lifetime modelling. Therefore, repeated measurements were conducted to establish repeatability while FEM simulation was used to validate the observed trends. To assess the dependability and predictability of the insulating materials, the Weibull distribution of breakdown was evaluated [19-21]. Figure 7 displays the Weibull distribution of breakdown voltage for each kind of electrode.

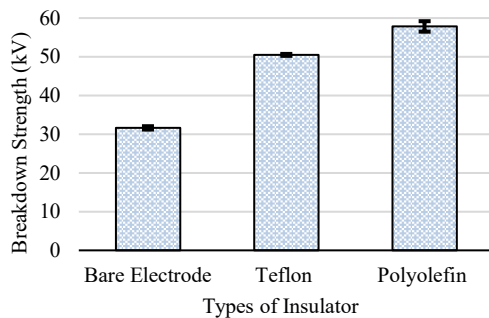


Fig. 7. Comparison of DC breakdown strength of bare and different insulated electrodes.

Table 3 presents the parameters of the Weibull distribution. The findings indicate a strong discrepancy between dielectric strength and consistency. While polyolefin has the highest typical strength, it has a smaller β , resulting in higher unpredictability in breakdown behavior. At the same time, however, Teflon has a higher value of β than polyolefin, which implies a higher stability and safety of the breakdown voltage, although its characteristic strength is lower than that of polyolefin.

Table 3. DC breakdown parameters comparing bare and different insulated electrodes.

Types of Insulators	α (kV)	β
Bare Electrode	31.632	61.62 $\pm$ 0.435
Teflon	50.548	93.10 $\pm$ 0.252
Polyolefin	57.836	40.78 $\pm$ 1.350

3.3 Reliability Analysis

To further evaluate the reliability and repeatability of the measured breakdown voltages, additional statistical parameters were analysed beyond the Weibull distribution. [21]. While the Weibull shape parameter provides information regarding the consistency of breakdown behaviours, the standard deviation, coefficient of variation (CV), and 95% confidence interval offer complementary measures of data dispersion and statistical confidence. The coefficient of variation normalizes the variability relative to the mean breakdown voltage, allowing a direct comparison between insulation materials with different voltage levels. Meanwhile, the confidence interval provides an estimate of the range within which the true mean breakdown voltage is expected to lie at a 95% confidence level. The reliability analysis results for the bare, Teflon-insulated, and polyolefin-insulated electrodes are summarized in Table 4.

The results indicate that Teflon exhibited the lowest coefficient of variation and the highest Weibull shape parameter, indicating excellent consistency and repeatability under repeated breakdown testing. In contrast, polyolefin recorded the highest average breakdown voltage but also exhibited a higher coefficient of variation, suggesting slightly greater variability in its breakdown performance. Nevertheless, the variability remains relatively small compared to the significant increase in dielectric strength achieved by the polyolefin insulation. The 95% confidence intervals further support these observations, where Teflon demonstrated the narrowest interval, indicating a high degree of confidence in the measured mean value. Overall, the reliability analysis confirms that Teflon provides superior consistency, whereas polyolefin offers the highest breakdown performance with acceptable variability.

Table 4. Reliability analysis of breakdown voltage for different insulation materials.

Material	Bare	Teflon	Polyolefin
Mean Breakdown Voltage (kV)	31.4	50.4	57.2
Std. Dev (kV)	0.44	0.25	1.35
CV (%)	1.39	0.50	2.36
Weibull β	61.62	93.10	40.78
95% Confidence Interval (kV)	30.32 – 32.48	49.74 – 50.99	53.84 – 60.56

It is important to acknowledge that the Weibull and reliability parameters reported in Tables 3 and 4 were derived from only three breakdown measurements per configuration. While consistent with the exploratory, comparative nature of this feasibility study and supplemented by FEM simulation to corroborate the observed field-related trends. This sample size is below that typically recommended for robust Weibull parameter estimation. Consequently, the β values, standard deviations, and 95% confidence intervals should be interpreted as indicative of relative trends among the three configurations

rather than as definitive reliability metrics. Expanding the dataset in future work will allow more statistically robust reliability conclusions to be drawn.

3.4 AC Leakage Current (LC) Analysis

AC stress tests were performed to determine the fabricated sample's impact on surface conduction. Specifically, the analysis was carried out to estimate the dielectric properties of insulating materials under AC electric stress conditions. The current-voltage waveform are shown in Figure 8, while the experimental data are shown in Table 5. According to the findings, it can be concluded that the dielectric properties of the HV rod were significantly improved due to the insulating material, in agreement with [1].

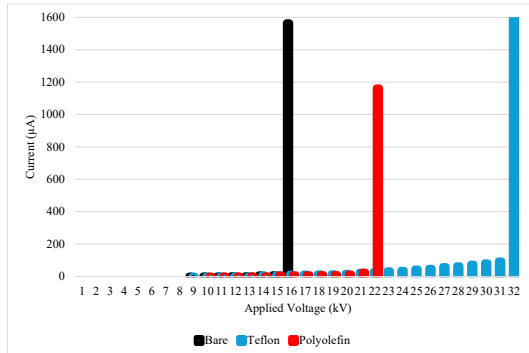


Fig. 8. Leakage current characteristics of bare, Teflon, and polyolefin-insulated electrodes under AC voltage.

Table 5. Measured leakage current values as a function of applied voltage for bare and insulated HV electrodes.

Applied Voltage (kV)	Current (μA)		
	Bare	Teflon	Polyolefin
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	1	1	0
10	2	2	1
11	2	2	2
12	3	3	2
13	3	3	3
14	9	9	3
15	10	10	9
16	1565	13	10
17		14	10
18		15	11
19		16	11
20		19	13
21		25	26
22		29	1163
23		34	
24		37	
25		45	
26		50	
27		60	
28		65	
29		75	
30		83	
31		95	
32		1595	

The recorded increase in LC after the application of 9 kV is attributed to an increase in surface conductivity and ionization reactions under higher electric field strength [2]. An

audible hissing sound, tentatively associated with discharge activity along the electrode/insulation surface, was first perceived at approximately 15 kV for both the bare and Teflon samples, whereas for polyolefin this audible activity was delayed to approximately 18 kV, where the current was 11 μA.

Figure 9 depicts an LC waveform under alternating current voltage stress that was used to study the pre-breakdown condition. As seen from Figure 9, the waveforms progressed from conducting to pre-breakdown, leading to distortions. The appearance of the distortions and instabilities indicates that a process of discharge and ionization is taking place, which eventually leads to breakdown voltage [22]. Identification of such waveform characteristics forms the basis for studying leakage currents and their effect on insulation [18].

The distortion observed in the LC waveform when the material was subjected to AC stresses, as shown in Figure 9, can be explained by the effect that the alternating electric field has on the surface states present in the polymeric insulator. The alternating nature of stress in the form of AC differs from that in DC, as the polarities alternate at every half cycle. Therefore, the state of the surface trap states is greatly influenced by this change in polarities. When subjected to high electric fields, both electrons and ions are driven into the polymer surface (Teflon or polyolefin) and are trapped in highly energetic states in the gap energy states. The reversing of polarities causes charges to accumulate at certain spots, creating a space-charge field that opposes or aids the applied field [23].

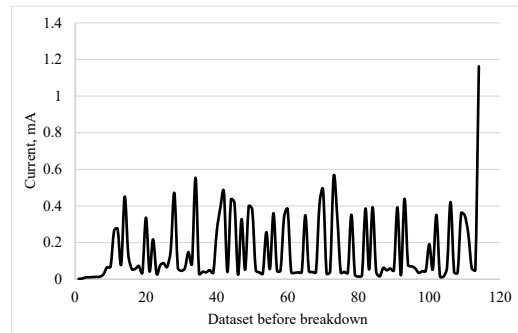


Fig. 9. LC pre-breakdown waveform under AC stress.

Different micro-discharge events and the release of stored charges were found to be linked to both the spikes and peaks in the LC signal. Surface flashover or insulation failure was preceded by the distortion of the ohmic conductivity to non-linearity. When compared to the bare electrode, the polyolefin exhibited a delay in the commencement of these distortions, indicating that it either contains fewer surface traps or requires a higher injection energy, which is consistent with its superior current-limiting behavior.

It was also observed that audible hissing sounds were present at higher voltage levels; while such sounds are commonly associated with discharge activity, this interpretation remains qualitative in the absence of dedicated PD instrumentation and is reported here as an observational finding rather than a confirmed PD measurement. This phenomenon happened at a lower voltage for the bare electrode and was delayed for the insulated ones, especially polyolefin. The surface conduction and charge accumulation effects were also increased by the continuous polarity switching under AC conditions. The results showed that the insulation materials not

only had a positive effect on the breakdown voltage but also affected the LC and discharge characteristics under alternating stress. The observations are further corroborated by electric field simulation results showing less electric field concentration and better stress distribution in the insulated configurations.

3.5 Simulation Results

Electric field and electric potential distributions for bare, Teflon, and polyolefin configurations are illustrated in Figure 10. The electric field distribution clearly demonstrated that for the bare electrode, it was highly concentrated in the vicinity of the electrode edges, with dense electric field lines signifying high electric stresses in this region. A steep voltage distribution was found, consistent with the presence of localized field enhancement. These properties led to early ionization and

reduced breakdown voltage. The electric field distribution was more uniform when it was used with the insulation [24]. Teflon insulation smoothed field lines to reduce maximum field intensity, whereas polyolefin achieved an even greater peak field reduction and more uniform surface distribution.

The voltage distribution for the insulated electrodes exhibited a more gradual potential gradient, which corresponds to reduced electric stress concentration at the electrode. This was more noticeable in the polyolefin configuration. Insulation changed the permittivity interface, resulting in electric field line redistribution and a reduction of peak field intensity [25]. This retards ionization and contributes to the improvement of the breakdown performance.

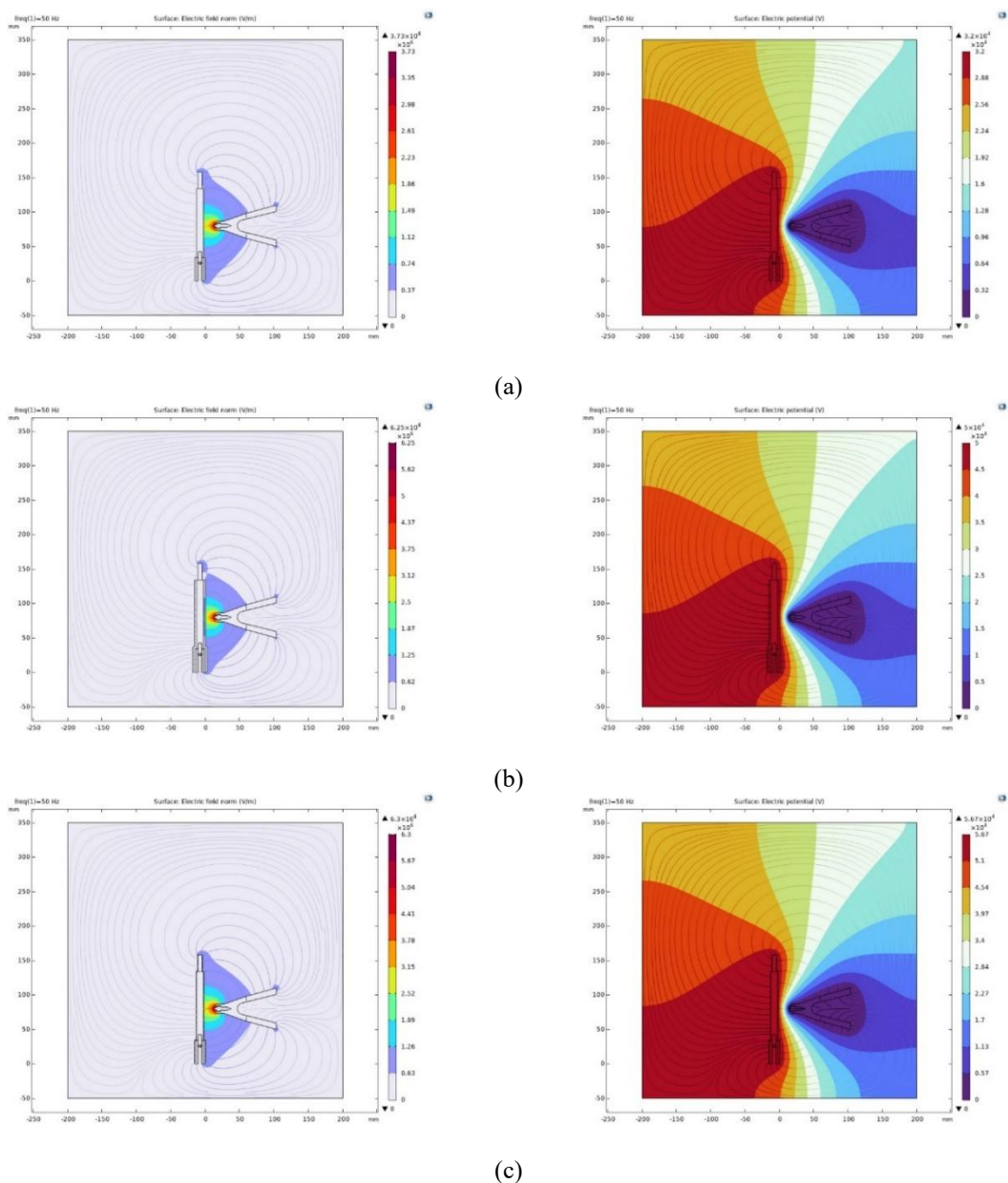


Fig. 10. The distribution of electric field (left) and electric potential (right) for bare, Teflon, and polyolefin configurations using finite element software.

Figure 11 shows the comparative analysis of breakdown voltage for both the bare and different insulated electrodes. The bare and insulated situations revealed a noticeable difference in the voltage distribution across the electrode gap. The voltage gradient for this bare electrode was quite non-uniform, with a large potential drop in the vicinity of the electrode surface. This means a high electric field concentration was present in a localized area, which may lead to early breakdown [26]. The voltage distribution around the electrode surface, on the other hand, was more gradual and uniform for the Teflon- and polyolefin-insulated electrodes [27]. As a result of the insulation layer, the electric potential was substantially redistributed, thereby dampening sharp voltage gradients and having a limiting effect on the creation of stress points in the insulation.

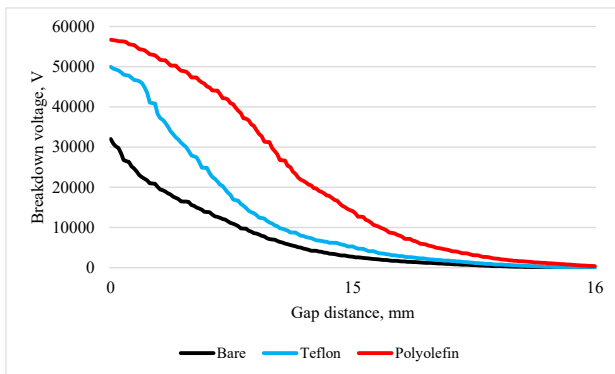


Fig. 11. Comparison of breakdown voltage for bare, Teflon-insulated, and polyolefin-insulated electrodes.

The electric field distribution also validates the effect of insulation on the breakdown performance. Thus, comparative analysis of electric field strength for bare and different insulated electrodes is illustrated in Figure 12. It was noted that for the bare electrode, a large amount of electric field concentration was found around the edge of the electrodes and around the gap region. This high field intensity is attributed to the lack of insulation in such a place and the interaction of the discontinuity in the geometry with the electric field, which results in the field being enhanced locally, and hence a greater chance of surface flashover. The electric field distribution, however, was smoother when Teflon insulation was applied, and the peak electric field intensity had been noticeably reduced. The electric field was redistributed and prevented from stress concentration due to the effect of the dielectric layer [24]. This is the reason for better uniformity of the breakdown characteristics in the experimental results [25]. Conversely, the decrease in peak electric field intensity with respect to the bare electrode was more significant for the polyolefin insulation. Field lines were more evenly distributed across the insulation surface, which shows that the field enhancement effects have been mitigated effectively. The decrease in the maximum electric field strength directly contributes to the increase in breakdown voltage that has been experimentally observed. Directly, this reduction in the peak electric field intensity mirrors the higher measured breakdown voltages with polyolefin.

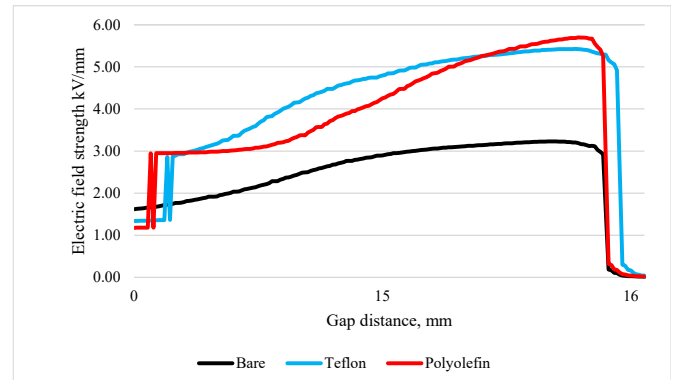


Fig. 12. Comparison of maximum electric field strength obtained from FEM simulation for bare, Teflon-insulated, and polyolefin-insulated electrodes.

3.6 Integrated Discussion and Practical Implications

Both Teflon and polyolefin enhance the electric field distribution; however, they have differing effects. The field distribution was uniform, matching the high Weibull shape parameter, which means that the breakdown of the material is consistent. In contrast, the peak electric field intensity of polyolefin was lower, and this was reflected in the higher breakdown voltage. The results of the simulation were found to be in good agreement with the experimental results. The decrease in the electric field concentration in the insulated electrodes can be correlated with the rise of the breakdown voltage in the DC test result. Moreover, the smooth field distribution diminishes the risk of localized ionization and thereby improves the insulation performance.

The results show that the concentration of the electric field on the electrode surface is a strong factor affecting surface flashover. Insertion of the insulation layers alters the electric field, which leads to less surface stress and a longer delay in the beginning of discharge. This is especially relevant to HV applications, where surface insulation is a major concern in the reliability of the system. This means that Teflon has greater reliability and consistency, while polyolefin is a better insulator due to its ability to reduce electric field stress more effectively.

According to the simulation results, the electric field concentration was reduced with the insulated electrodes compared with the bare electrode. Polyolefin exhibited the lowest electric field strength of all the materials examined. This value is in line with the experimental results, which showed that polyolefin exhibited the highest breakdown voltage, thus proving the insulation effectiveness in terms of improving the dielectric results.

The results of this study have direct implications for HV applications, such as EV contactor testing and insulation design. With suitable insulation materials, the electric field stress can be reduced, and the likelihood of premature breakdown can be drastically decreased, making a huge impact on system reliability. Polyolefin was found to be the best choice for breakdown performance, and Teflon for consistency and stability. Hence, reliable values should be taken into account in the choice of insulation material along with performance.

4. CONCLUSION

This work investigates the insulation effect on HV electrodes under both DC and AC conditions in a comprehensive experimental and computational way. The results show that insulation materials play a significant role in improving the breakdown voltage due to the reduction of electric field concentration and the increase of the voltage distribution uniformity. Polyolefin records the largest breakdown strength among the tested configurations, which is due to its ability to reduce the peak electric field intensity, as supported by the simulation analysis. Teflon, on the other hand, presents better consistency in breakdown behavior within the tested sample, evidenced by the higher value of the Weibull shape parameter and the low standard deviation; this trend tentatively indicates greater stability and predictability but should be confirmed with a larger sample size in future work. These results indicate a compromise between peak insulation and reliability.

The AC leakage current analysis also demonstrates the effect of insulation materials on surface conduction and discharge characteristics under AC stress. Polyolefin exhibits better leakage current control and delay in discharge activity, and Teflon exhibits a stable electrical response. On the whole, it is found that the good agreement between the experimental measurement, statistical analysis, and simulation results verifies that the insulation coatings can significantly improve the reliability of HV systems. The results are useful and can serve as a reference for the design and optimization of insulation systems for practical applications, e.g., in the operation of EV contactors or HV equipment. Finally, future works should concentrate on (i) the use of thickness-matched insulation samples to isolate material and thickness effects, (ii) expansion of the breakdown-test dataset to strengthen the statistical robustness of the Weibull/reliability analysis, and (iii) dedicated partial discharge (PD) measurement techniques (e.g., IEC 60270-compliant PD detection) to confirm the nature of the observed audible discharge activity.

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