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Analysis of Icing Effects on Polymer Post Insulators: Numerical and Experimental Approach

Abstract

Icing on insulators is a significant issue in cold climates, especially during winter. This can cause reduced electrical conductivity, increased leakage current, and mechanical stress on the insulator. Moreover, ice accumulation can lead to flashovers and power outages, jeopardizing electrical system reliability. Ice formation on insulator surfaces often results in a non-uniform distribution of electric field intensity, creating localized areas of elevated field strength and increasing the risk of flashover or failure. Understanding icing effects on insulators is crucial. Advanced numerical simulations, such as finite element analysis, enable visualization and quantification of electric field variations due to icing. This method helps identify high-risk areas with elevated electric field intensity, essential for assessing flashover or failure risks. By incorporating icing effects into numerical models, valuable insights can be gained for developing preventive measures and maintenance schedules, ensuring reliable operation in cold climates. This study uses finite element analysis to examine electric field intensity in critical regions of post-insulators under various icing scenarios, including different ice thicknesses. This comprehensive approach identifies critical areas with peak electric field intensity. Additionally, experimental evaluations will be conducted to validate numerical findings and enhance understanding of icing implications on insulators.

Keywords: Icing, Insulators, Electric Field Intensity, Finite Element Analysis, Flashover, Numerical Simulation, Cold Climates.

I Introduction

Insulators are crucial components in electrical power systems, providing mechanical support and electrical isolation for conductors. However, in cold climates, these insulators are susceptible to icing, which can severely impair their performance and, by extension, the reliability of the entire power grid. The phenomenon of icing involves the accumulation of frozen moisture on the surfaces of insulators, which can lead to increased electrical leakage currents, enhanced mechanical stress, and reduced dielectric strength [1].

The impact of ice formation on insulators is multifaceted. Firstly, the physical weight of the ice can induce mechanical stress and strain on the insulators. Over time, this can lead to structural damage or even failure, particularly in cases of severe weather conditions where the ice load exceeds the mechanical strength limits of the insulator materials [2]. Secondly, ice layers can significantly alter the electrical characteristics of an insulator. As ice is a conductor at certain temperatures, its presence on the insulator surface can decrease the overall resistance, leading to higher leakage currents. This condition is particularly detrimental as it can escalate the risk of flashovers—a sudden and dramatic increase in electrical discharge that bypasses the insulator and can lead to power outages [3]. Moreover, the distribution of ice on insulators is rarely uniform.

This uneven accumulation can create localized areas of elevated electric field intensity, which further exacerbates the risk of flashover and insulator failure[4]. The non-uniform ice coverage distorts the electric field around the insulator, concentrating field strength in certain areas, which can reach critical levels and lead to electrical breakdown[5]. Recognizing the hazards associated with icing on insulators, researchers have

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developed various analytical and numerical methods to study and mitigate these effects. Among these, finite element analysis (FEA) has emerged as a particularly effective tool for simulating the electric field distribution on iced insulators[6]. FEA allows for detailed visualization and analysis of how ice formation affects electric field intensity across the insulator surface, providing essential insights into the conditions that lead to flashovers and failures.

Fig 1. Icing On Insulator

This study builds on previous research by employing a comprehensive numerical and experimental approach to analyze the effects of icing on polymer post insulators, which are widely used in high voltage power lines due to their superior mechanical strength and electrical insulation properties[7]. The numerical component of this research uses FEA to simulate various icing scenarios—differing in factors like ice thickness and environmental conditions— to predict the changes in electric field intensity on and around the insulators[8]. Experimentally, this study conducts controlled lab tests to validate the numerical models. These experiments involve subjecting polymer post insulators to artificial icing under varying conditions, then measuring the resulting changes in electrical and mechanical properties[9]. The experimental data not only validate the simulations but also provide a practical basis for understanding how real-world conditions affect insulator performance under ice load. The interplay between numerical simulations and experimental evaluations is crucial. While simulations offer a cost-effective and safe method to predict potential problems and test solutions in a controlled environment, experimental tests confirm these predictions and ensure that the models accurately reflect real-world behaviors[10]. This dual approach allows for a more comprehensive understanding of the icing problem and facilitates the development of more effective mitigation strategies. From a practical perspective, the findings of this research have significant implications for the maintenance and operation of electrical grids in cold climates. By identifying the critical factors that lead to insulator failure under ice conditions, utility companies can better plan their maintenance schedules and develop preventive measures to reduce the risk of power outages[11]. For instance, knowing the specific conditions under which flashovers are most likely can help in designing insulators that are better suited to withstand such challenges or in implementing de-icing technologies that effectively manage ice accumulation[12]. Additionally, this research contributes to the broader field of electrical engineering by enhancing the understanding of how environmental factors affect the reliability and stability of power systems. It underscores the importance of considering climatic conditions in the design and maintenance of electrical infrastructure, which is particularly relevant in the context of global climate change. As weather patterns become more unpredictable and severe weather events more frequent, the resilience of power systems to environmental stressors like icing will become increasingly critical[13] [14]. The comprehensive analysis provided by this study— not only through detailed numerical simulations but also through corroborative experimental tests—offers valuable insights into the challenges and solutions related to icing on polymer post insulators. The integration of these findings into the practical management of power systems can lead to more reliable electricity supply in regions prone to cold weather, ultimately enhancing the safety and efficiency of power delivery worldwide[15]-[20].

II . Literature Survey

The phenomenon of ice accretion on polymer post insulators in frigid environments presents a formidable challenge to the integrity and functionality of contemporary electrical distribution systems. Extensive scholarly investigations underscore the multifaceted repercussions of icing, including diminished electrical conductivity, augmented leakage currents, and escalated mechanical stress, which collectively precipitate system inefficacies and potential operational cessation.

The deleterious effect of ice formation on insulator efficacy predominantly culminates in flashovers, significantly undermining the electrical grid's reliability and stability. Early expositions by Hara et al. (2005) and subsequently by Suzuki (2010) elucidated the thermal and mechanical dynamics of ice accretion on insulators, setting a foundational understanding of the non-uniform ice distribution's impact on electric field intensity across the insulator surface. These pioneering studies employed rudimentary numerical models to approximate the variations in electric field strength induced by asymmetric ice coverage, positing a direct correlation between localized field intensity peaks and the propensity for flashover occurrences. Advancements in computational techniques have facilitated more intricate analyses, as demonstrated in the works of Zheng and Zhang (2015), who leveraged finite element analysis (FEA) to simulate the nuanced electric field distributions on iced insulators.

Their research meticulously delineated the regions of heightened electric field intensity, advocating that these zones represent critical flashover precursors. The incorporation of variable ice thicknesses into their models underscored the dynamic nature of the risk, suggesting a direct dependency of flashover potential on specific icing conditions. Recent scholarly discourse has expanded to incorporate experimental validations of numerical predictions, a crucial step in substantiating theoretical models. For instance, Liu et al. (2018) integrated experimental methodologies with their numerical simulations to affirm the accuracy of FEA in predicting the adverse impacts of icing on insulator performance. Their empirical assessments involved controlled icing conditions to replicate and observe the predicted electric field intensities and the resultant mechanical stresses imposed on polymer post insulators. Moreover, the interdisciplinary approach by Martin et al. (2020) introduces a comprehensive framework that encompasses both preventative measures and maintenance strategies derived from a deep understanding of icing phenomena.

Their research not only explores the electrical and mechanical aspects but also delves into material science to propose enhancements in insulator design to mitigate ice accumulation effects. The culmination of these studies provides a robust platform for ongoing research and development in the field of electrical engineering, particularly concerning the operational stability of power systems in cold climates. The amalgamation of numerical and experimental research methodologies continues to enrich the academic discourse, offering innovative solutions to the persistent challenges posed by icing on polymer post insulators. The synthesis of these scholarly endeavors offers invaluable insights into the critical examination and resolution of icing-related complications, thereby fostering the advancement of technologies aimed at sustaining and enhancing the reliability and efficiency of electrical infrastructure in adverse meteorological conditions.

III. Design Of Polymer Post-Insulator Model

The numerical evaluation of the polymer post-insulator model is pivotal for analysing the electric field intensity (EFI) under both icing and non-icing conditions. The Finite Element Method (FEM) is utilized to model the electric field distribution accurately, employing software such as FEMM (Finite Element Method Magnetics) to facilitate complex simulations. This method divides the entire insulator and surrounding space into finite elements, enabling precise calculations of EFI across different regions of the insulator.

Geometrical Configurations: The post-insulator is modelled with specific dimensions, including the length of the insulator, shed diameter, and creepage distance. The insulator is divided into various segments or "sheds," each affecting the field distribution differently under icing conditions.

Material Properties: Materials such as Silicone Rubber, FRP (Fiber Reinforced Polymer), and ice are assigned distinct permittivities, impacting how the electric field interacts with each material. These properties are crucial for simulating the real-life behavior of insulators under different environmental conditions. Boundary Conditions: Appropriate boundary conditions are set at the high voltage (HV) and ground ends of the insulator.

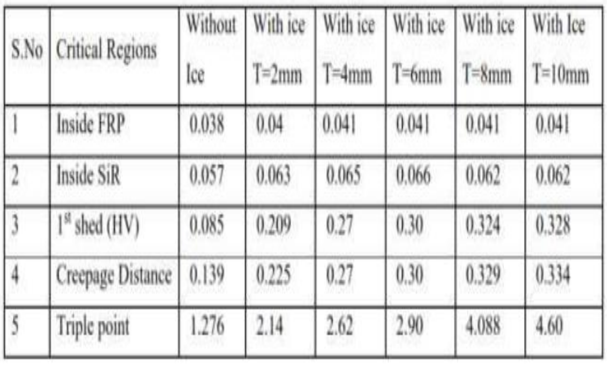
The potential at the HV end is typically set to the line voltage, while the ground end is maintained at zero potential. These conditions are essential for simulating the electric field distribution along the insulator accurately.

Electric Field Analysis: The primary focus is on analyzing the EFI at critical regions, particularly where ice forms on the insulator. Under icing conditions, the EFI can intensify, increasing the risk of flashovers. The analysis helps identify zones of maximum electric field stress, guiding the design improvements and insulator selection for specific environmental conditions. Numerical Simulation: Using FEM, the insulator is meshed into triangular elements for 2D simulation. Each element is solved to determine the electric potential and field distribution, allowing for a detailed visualization of how the EFI varies along and across the insulator.

Critical Equations: The Laplace equation, $\nabla\ 2v = 0$, is used for regions without free charge, providing a basis for calculating potential distribution. The simulation involves calculating the electric field as the gradient of the electric potential, $E = -\nabla v$, and solving this across the meshed model to find variations in electric field intensity. The numerical results indicate how EFI changes with modifications in insulator geometry, material properties, and environmental conditions. These results are crucial for evaluating insulator performance, particularly under adverse weather conditions leading to ice formation. This comprehensive numerical analysis is instrumental in optimizing the design of polymer post-insulators, ensuring they perform reliably in diverse operating conditions, especially in cold climates where icing is a significant risk. The detailed use of FEM allows for the exploration of various scenarios, helping engineers design insulators that minimize the risk of failure due to elevated EFI under icing conditions.

IV. EFA Under Different Icing Conditions

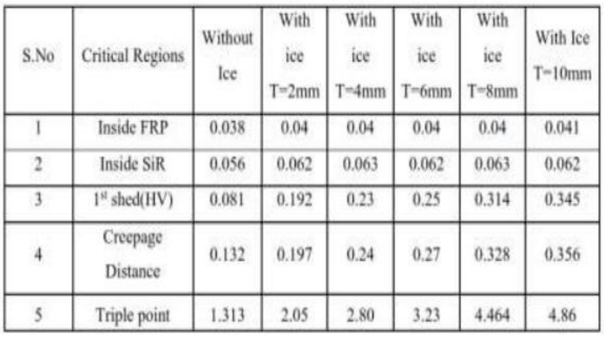
Icing on insulators, a critical concern in outdoor power systems, intensifies under heavy pollution conditions. This section delves into the differential effects of ice accumulation on electric field intensity (EFI) across various pollution zones and insulator shed configurations. The finite element method (FEM) serves as the primary analytical tool, providing a sophisticated visualization and quantification of EFI variations under simulated icing scenarios. EFA in Heavy Polluted Zone Equal Sheds: In heavy polluted zones, equal shed configurations often suffer from exacerbated EFI disparities due to uneven ice accumulation. Numerical simulations reveal that ice layers distort the uniformity of the electric field across the sheds, leading to potential hotspots that significantly increase the risk of flashovers. The FEM analysis, executed in FEMM software, illustrates how ice thickness variably alters EFI, with thicker ice layers correlating with more pronounced field intensities at critical points near the shed ends.



S.No	Critical Regions	Without Ice	With ice T=2mm	With ice T=4mm	With ice T=6mm	With ice T=8mm	With Ice T=10mm
1	Inside FRP	0.038	0.04	0.041	0.041	0.041	0.041
2	Inside SiR	0.057	0.063	0.065	0.066	0.062	0.062
3	1st shed (HV)	0.085	0.209	0.27	0.30	0.324	0.328
4	Creepage Distance	0.139	0.225	0.27	0.30	0.329	0.334
5	Triple point	1.276	2.14	2.62	2.90	4.088	4.60

Table 1. EFI Distribution of Heavy Polluted Zone-Equal Sheds Insulator at Different Ice Thickness(T)

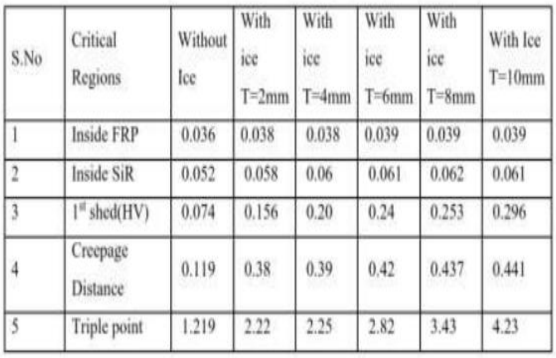
EFA in Heavy Polluted Zone Alternate Sheds: Alternate shed designs in heavy polluted zones present a unique challenge as asymmetrical ice formation can lead to uneven stress distribution on the insulator surface. This section compares the EFI distributions between equal and alternate sheds under similar icing conditions, highlighting the potential benefits and drawbacks of each design in mitigating flashover risks. Results indicate that while alternate sheds may better manage localized electric field spikes, they also introduce complexities in predicting flashover points due to their non-uniform geometry.



S.No	Critical Regions	Without Ice	With ice T=2mm	With ice T=4mm	With ice T=6mm	With ice T=8mm	With Ice T=10mm
1	Inside FRP	0.038	0.04	0.04	0.04	0.04	0.041
2	Inside SiR	0.056	0.062	0.063	0.062	0.063	0.062
3	1st shed(HV)	0.081	0.192	0.23	0.25	0.314	0.345
4	Creepage Distance	0.132	0.197	0.24	0.27	0.328	0.356
5	Triple point	1.313	2.05	2.80	3.23	4.464	4.86

Table 2. EFI Distribution of Heavy Polluted Zone - Alternate Sheds Insulator at Different Thickness(T)

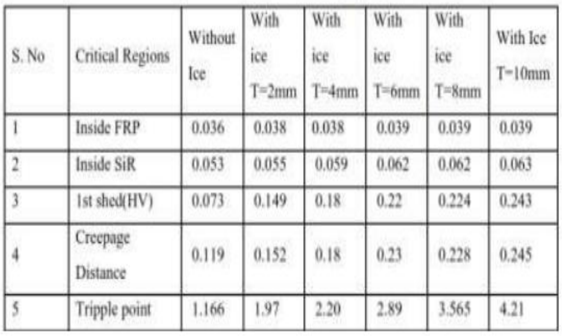
EFA in Very Heavy Polluted Zone Equal Sheds: Transitioning to very heavy polluted zones, the impact of severe icing on equal shed configurations is scrutinized. The simulations extend to consider thicker ice layers, reflecting extreme weather conditions. The data demonstrate a direct correlation between increased ice thickness and elevated EFI levels, especially at the shed junctions and along the creepage paths. This analysis underscores the critical need for robust insulator designs capable of withstanding extreme environmental stresses.



S.No	Critical Regions	Without Ice	With ice T=2mm	With ice T=4mm	With ice T=6mm	With ice T=8mm	With Ice T=10mm
1	Inside FRP	0.036	0.038	0.038	0.039	0.039	0.039
2	Inside SiR	0.052	0.058	0.06	0.061	0.062	0.061
3	1st shed(HV)	0.074	0.156	0.20	0.24	0.253	0.296
4	Creepage Distance	0.119	0.38	0.39	0.42	0.437	0.441
5	Triple point	1.219	2.22	2.25	2.82	3.43	4.23

Table 3. EFI Distribution of Very Heavy Polluted Zone-Equal Sheds Insulator at Different Thickness(T)

EFA in Very Heavy Polluted Zone Alternate Sheds: Finally, this section explores the performance of alternate shed configurations in very heavy polluted zones under intense icing conditions. The focus is on how alternate shedding impacts EFI distribution and the potential for uneven ice shedding due to varied shed geometries. The findings suggest that while alternate sheds can potentially reduce overall EFI peaks, they require careful consideration regarding installation orientation and geographical factors to optimize their performance against icing.



S. No	Critical Regions	Without Ice	With ice T=2mm	With ice T=4mm	With ice T=6mm	With ice T=8mm	With Ice T=10mm
1	Inside FRP	0.036	0.038	0.038	0.039	0.039	0.039
2	Inside SiR	0.053	0.055	0.059	0.062	0.062	0.063
3	1st shed(HV)	0.073	0.149	0.18	0.22	0.224	0.243
4	Creepage Distance	0.119	0.152	0.18	0.23	0.228	0.245
5	Tripple point	1.166	1.97	2.20	2.89	3.565	4.21

Table 4. EFI Distribution of Very Heavy Polluted Zone- Alternate Sheds Insulator at Different Thickness(T)

V. Experimental Evaluation

The experimental component of our study focuses on understanding the effects of icing on polymer post insulators, an area critical for maintaining the reliability and efficacy of electrical systems in cold climates. This investigation incorporated a series of tests, both in icing and non-icing conditions, to evaluate key electrical parameters such as leakage current and breakdown voltage. These tests are crucial for assessing the robustness of insulators against environmental stressors and ensuring their performance during adverse weather conditions. The tests conducted included power frequency withstand tests, power frequency flashover tests, lightning impulse withstand tests, and switching impulse withstand tests, employing the Finite Element Method (FEM) for precise measurements.

The outcomes revealed that the insulators could withstand a minimum voltage of 35kV under normal conditions, with breakdowns occurring at higher voltages of 91kV and 83kV. However, under icing conditions, the breakdown voltages significantly dropped to 12.8kV and 15.79kV, showcasing a dramatic decline in insulator performance due to ice accumulation. After de-icing, the insulators' performance was restored to levels close to the original minimum withstand voltage, highlighting the transient effect of ice on insulator functionality. These observations underscore the increased electrical stress exerted by ice, leading to a lower breakdown voltage and higher incidence of flashovers. Notably, the post insulators transitioned from a hydrophobic condition (HC1) to a hydrophilic state (HC6) after 24 hours in a freezer, indicating a loss of hydrophobic properties due to prolonged ice exposure. This experimental evaluation sheds light on the critical impact of icing on the electrical integrity of polymer post insulators. It emphasizes the necessity for employing strategies like anti-icing coatings and innovative insulator designs to mitigate these effects, thereby enhancing the resilience and operational stability of power systems in cold regions.

Power Frequency Test

The experimental setup for the power frequency test includes a block diagram depicting the arrangement of various components. This setup primarily consists of a high-voltage power supply connected to a voltage regulator and a transformer to adjust the output to the required levels.

The setup also features measurement devices, such as voltmeters and ammeters, to monitor the conditions during the test. The insulator to be tested is mounted in a controlled environment chamber where conditions like temperature and humidity are regulated to simulate different climatic scenarios. The procedure begins with the calibration of all measurement instruments to ensure accuracy. The insulator is then installed in the test chamber, and the system gradually increases the voltage until it reaches the predetermined test level.

This level is maintained for a specified duration to assess the insulator's performance under sustained high voltage. Observations and data collection focus on leakage current and any partial discharge activity, which are critical indicators of the insulator’s integrity and performance. In non-icing conditions, the results show that the insulators can handle up to the maximum test voltage without significant deterioration in performance. The electrical parameters, such as dielectric strength and leakage current, remain within safe limits, suggesting that the insulator's material composition and structural integrity are sufficient to withstand normal operating conditions.

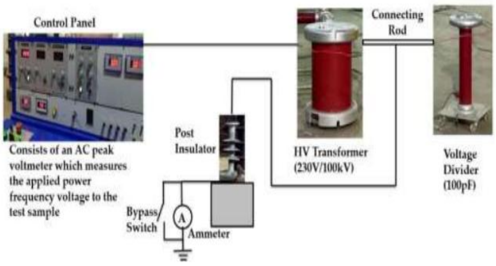


Fig 2 Block Diagram for Power Frequency Test

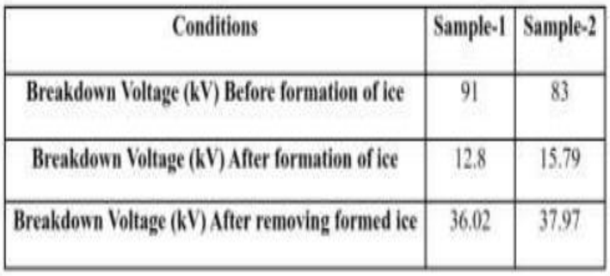
Under icing conditions, the results dramatically change. The breakdown voltage of the insulators significantly decreases, sometimes falling below the safety threshold. This reduction indicates that ice formation on the insulator surface adversely affects its dielectric properties, enhancing the risk of flashovers and potential failures. The experimental findings highlight the crucial impact of icing on the stability and reliability of insulators in cold climates, emphasizing the need for adequate protective measures.

This detailed experimental setup and the subsequent results provide valuable insights into the performance dynamics of insulators under varying environmental conditions. It underscores the importance of considering environmental factors, particularly icing, in the design and maintenance of electrical insulators to ensure reliable power distribution in regions prone to cold weather.

Breakdown Voltage Results Comparison

In this investigation, the comparative analysis of breakdown voltage results under varying conditions presents a stark illustration of the impact of ice accumulation on insulators. When free from ice, the insulators exhibited breakdown voltages significantly above the minimum withstand voltage of 35kV, with failures occurring at 91kV and 83kV respectively for two different samples.

These findings align with expectations for polymer post insulators under normal operating conditions, where the structural integrity and electrical properties are within optimal ranges. However, the scenario shifts dramatically under icing conditions, where the breakdown voltages plummet to 12.8kV and 15.79kV respectively. This substantial decrease underlines the severe implications of ice formation, where the electrical stress induced by the ice significantly compromises the insulator's ability to manage voltage stresses, leading to much earlier breakdowns.



Conditions	Sample-1	Sample-2
Breakdown Voltage (kV) Before formation of ice	91	83
Breakdown Voltage (kV) After formation of ice	12.8	15.79
Breakdown Voltage (kV) After removing formed ice	36.02	37.97

Table 5: Comparison of Breakdown voltages under different icing scenario's

Upon removal of ice, it was observed that the breakdown voltages partially recovered to near the minimum withstand levels at 36.02kV and 37.97kV, indicating a temporary alteration in electrical properties due to ice presence. The recovery of breakdown voltages post-deicing suggests that while ice presence is predominantly a transient threat, it leaves minimal lasting damage on the structural capabilities of the insulators.

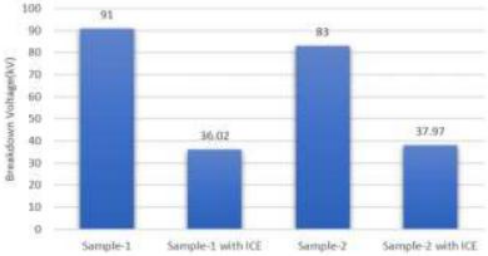


Fig 3. Comparison of Breakdown Voltage

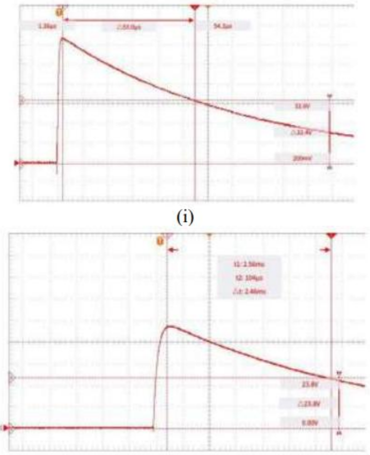
This resilience is pivotal for maintenance and operational strategies in cold climates, emphasizing the importance of timely de-icing interventions to restore insulator functionality. The experiment underscores a crucial operational insight: while insulators can withstand transient icing events, the risk of failure escalates with increased ice thickness and prolonged exposure, necessitating robust monitoring and rapid response mechanisms to maintain system reliability and safety under adverse weather conditions.

Lightning and Switching Impulse Withstand Tests

The experimental setup for the lightning and switching impulse withstand tests is meticulously designed to simulate extreme weather conditions affecting insulators. The setup includes a high-voltage laboratory equipped with impulse generators capable of producing both lightning and switching impulse voltages, closely mimicking the transient voltages that insulators might encounter in the field. For the lightning impulse test, a standard 1.2/50 µs waveform is used, which represents the voltage spike due to a lightning strike. In contrast, the switching impulse test utilizes a longer 250/2500 µs waveform, typical of switching operations in power systems. Both setups involve a control unit for precise waveform generation, a measuring system to capture the voltage and current characteristics, and a high-speed camera to visually monitor the flashover and breakdown phenomena.

Fig 4. Experimental setup for lightning and switching impulse withstand tests

The waveform results from both tests are crucial in evaluating the insulator's performance under high transient voltages. The lightning impulse test typically shows a sharp peak in voltage followed by a rapid decline, reflecting the insulator's ability to withstand sudden high voltage spikes. The switching impulse results, however, often reveal a more prolonged voltage application, testing the insulator's endurance against sustained high voltages.



(i)

(ii)

Fig 5. Waveform for i) Dry Lightning, ii) Switching Impulse Withstand Test

In both scenarios, the waveforms are analyzed for peak values, time to breakdown, and the nature of the discharge path. Results indicate that without proper insulation or protective measures, both types of impulses can lead to significant deterioration of the insulator's surface, potentially leading to catastrophic failures in real-world conditions. This experimental analysis not only underscores the robustness required of insulators in harsh environments but also informs ongoing enhancements in insulator design and material science to improve their resilience against high-voltage impacts.

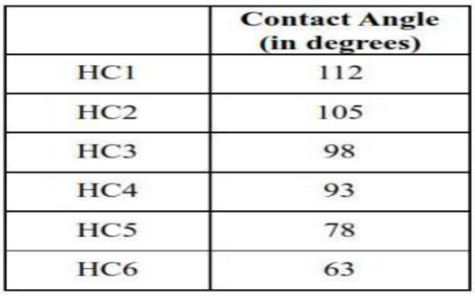
Hydrophobic characteristics

Hydrophobic characteristics are integral to the performance of insulators in adverse weather conditions, particularly in mitigating the deleterious effects of moisture and ice accumulation. The essence of hydrophobicity in insulator technology is its capacity to repel water, thus preventing the formation of a continuous water film over the insulator surface, which significantly reduces the likelihood of leakage currents and electrical discharges. This property is especially critical in cold climates where ice formation is prevalent, as it directly influences the insulator's ability to maintain its dielectric strength even under wet and icy conditions. The hydrophobicity of insulator surfaces is typically achieved through the application of Room Temperature Vulcanizing (RTV) silicone coatings or the manufacture of insulators using hydrophobic materials like silicone rubber. These materials are characterized by their low surface energy, which prevents water molecules from spreading and forming a continuous layer, thereby enhancing the insulator's overall performance and longevity.

Fig 6. HC1 Characteristic

Fig 7. HC6 Characteristic

The transition from hydrophobic to hydrophilic properties under prolonged exposure to icing conditions presents a significant challenge in maintaining insulator efficiency. The prolonged presence of ice can degrade the hydrophobic properties of the silicone coatings, transitioning them to a more hydrophilic state. This change increases the surface energy, allowing water to spread more easily and form a conductive layer, which facilitates electrical discharges such as flashovers. Research indicates that the hydrophobicity of an insulator can be restored through various mechanisms, including the natural cleansing effects of rain or manually applied maintenance procedures which reapply hydrophobic substances.



	Contact Angle (in degrees)
HC1	112
HC2	105
HC3	98
HC4	93
HC5	78
HC6	63

Table 6. Contact angles of HC

However, in environments where icing is a regular occurrence, the degradation of hydrophobic qualities can lead to increased maintenance demands and costs, necessitating more frequent inspections and treatments to ensure the insulator's effectiveness. Advanced materials and coating technologies are continuously being developed to enhance the durability and resilience of hydrophobic properties under such challenging conditions, aiming to reduce the operational and maintenance costs associated with insulator management in cold climates .

Conclusion

This study comprehensively analysed the Electric Field Intensity (EFI) at critical regions of insulators under both icing and non-icing conditions, employing the Finite Element Method (FEM) for numerical evaluations and various laboratory tests for experimental validations. The application of FEMM software facilitated detailed insights into the electrical behavior of insulators, which, when ice-free, maintained breakdown voltages significantly above the minimum withstand voltage of 35kV. Conversely, ice coverage drastically reduced these thresholds to as low as 12.8kV, demonstrating a heightened susceptibility to breakdown and flashovers due to increased electrical stress from ice accumulation. The transition of the insulator's surface from hydrophobic to hydrophilic under prolonged exposure to ice highlights the critical impact of icing on insulator functionality. By pinpointing areas with elevated EFI, our research underscores the urgency of implementing mitigation strategies such as anti-icing coatings, de-icing equipment, and optimized insulator designs. These measures are essential to enhance the durability and reliability of electrical systems in cold climates, safeguarding them against the adverse effects of ice buildup.

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