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Cost-Benefit Analysis of Nano Coating on Ceramic Insulators on Leakage Current Characteristics

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ABSTRACT

Ceramic insulator components have high popularity because the majority of electrical distribution systems in Indonesia use ceramic insulators. Ceramic insulators have advantages in mechanical strength, but the nature of the surface material makes it easy to absorb water, which can accelerate aging and increase leakage current when used in high-pollution areas. This research will test the effect of salt and fly ash contaminants on the leakage current characteristics of ceramic insulators. Furthermore, it will be tested the effect of nano coating on the leakage current characteristics of ceramic insulators. Tests were conducted to analyze the leakage current characteristics on the insulator surface due to the influence of contaminants by varying the ESDD and NSDD values of contaminants with light, medium, heavy, and very heavy categories on the ceramic insulator surface. The results show that the higher the NSDD level and ESDD level of salt and fly ash contaminants, will increase the leakage current value. The test results of nano-coated ceramic insulators prove that they can reduce the value of leakage current. In testing ceramic insulators coated with nano coating materials contaminated with salt with a very heavy pollutant category, it is proven that the leakage current value is reduced by 23.5%. Testing ceramic insulators coated with nano coating materials contaminated with fly ash with a very heavy pollutant category proved that the leakage current value was reduced by 23.7%. Benefit-cost analysis is used to assess whether the nano-coating project on ceramic insulators is feasible or not feasible. The results of the analysis show that the Benefit Cost Ratio (BCR) value is obtained from the total present value benefit divided by the total present value cost, so that the result is 1< or more than one. The nano-coating project on ceramic insulators from the BCR parameter is feasible to implement.

INTRODUCTION

Electrical insulators play a crucial role in ensuring safety and efficiency in power transmission and distribution systems (Pansini, 2020; Borghei & Ghassemi, 2021). Their primary function is to separate high-voltage conductors, preventing uncontrolled electrical currents that could lead to short circuits or system failures (Gockenbach, E. 2021; Muniappan, 2021). Common materials used for electrical insulators include polymers, porcelain, and glass (Küchler, 2018; Haque et al., 2021). However, the performance and reliability of these materials are continuously challenged by environmental stressors such as pollution, humidity, salt contamination, and UV radiation. These stressors can accelerate the degradation of the insulator's surface, reducing its dielectric strength and increasing the risk of leakage currents and flashovers (Asif et al., 2024).

Pollutants accumulating on insulator surfaces originating from industrial emissions, vehicle exhaust, sea salt in coastal regions, and other sources create a conductive path for leakage currents (He et al., 2022; Nawab et al., 2023). This phenomenon, often exacerbated by the “dry band” effect, leads to surface discharges and insulation breakdown (Ilhan, 2018; Kumar & Maheswari, 2024). Research by Zhou et al. (2024) highlights that variations in electric field distribution due to pollution can accelerate material aging, further degrading insulator performance. Furthermore, the accumulation of contaminants can lead to permanent damage in power systems, increasing maintenance costs and reducing overall system reliability (Rahman et al., 2023; Ethiraj & Samuel, 2024).

To mitigate these challenges, various strategies have been developed, including the periodic cleaning of insulators, the selection of insulator types adapted to local environmental conditions, and the application of surface coatings that enhance hydrophobicity (Yang et al., 2018; Sun et al., 2024). Among these, the use of nano coatings has emerged as a promising innovation. Nano coatings, typically applied in thin layers at the nanometer scale, offer enhanced surface properties such as increased water repellency, self-cleaning behavior, and resistance to chemical corrosion. These characteristics can significantly reduce leakage current and extend the lifespan of ceramic insulators (Fernando & Gubanski, 2020; Li et al., 2022).

Several studies have explored the use of hydrophobic coatings and nano-materials for improving insulator performance. For example, research by Xuan et al. (2025) demonstrated that nano-SiO_2 coatings could improve the water repellency and reduce surface leakage under polluted conditions. However, this study was limited to laboratory-scale experiments under controlled contamination and did not address long-term performance in field conditions. Similarly, Osman et al. (2021); Chapa (2024) evaluated nano-alumina coatings on polymer insulators but focused on thermal degradation resistance rather than electrical performance. Furthermore, Bouiti et al. (2024) tested nano-hybrid coatings for glass insulators but did not include economic evaluations related to coating application or maintenance reduction.

These gaps highlight the need for comprehensive studies that not only assess the electrical improvements brought by nano-coating but also consider the economic implications of their application. Cost-Benefit Analysis (CBA) serves as a valuable tool in this regard, enabling decision-makers to compare the projected benefits, such as reduced power loss and extended service life, against the costs of nano-coating application and maintenance. CBA also promotes a transparent and systematic approach to evaluating technological interventions, even when some variables are difficult to quantify (Edwards & Lawrence, 2021).

This study aims to investigate the impact of nano-coating application on ceramic insulators, specifically focusing on leakage current characteristics under both uncontaminated and polluted conditions. It further conducts a cost-benefit analysis using assumed cost parameters and power loss estimates sourced from previous research. By integrating technical performance assessment with economic feasibility analysis, this study seeks to provide a more holistic understanding of nano-coating potential for improving the reliability of overhead power distribution systems.

METHODS

The research methodology consists of several stages, starting with the alignment of concepts based on IEC 60815 standards, contaminant types, nano coating, and AC voltage generation systems. This phase uses data from previous studies found in national journals, international conferences, and related books. The next step involves collecting data regarding the IEC 60815 standard, the types of contaminants (salt and fly ash), and specifications for ceramic insulators, including the ESDD and NSDD values of the contaminants and testing methods for leakage current in AC voltage systems.

Following this, laboratory testing is conducted to measure leakage current on ceramic insulators both before and after nano coating application, under varying contaminant conditions (Saleem et al., 2025). The data is then processed to compare leakage currents across different conditions (contaminated and non-contaminated). The analysis phase interprets the processed data to examine the characteristics of leakage current in ceramic insulators and evaluate the impact of nano-coating. Finally, conclusions and recommendations are drawn based on the findings, and the feasibility of nano-coating application is assessed through a cost-benefit analysis.

RESULTS AND DISCUSSION

Leakage Current Testing of Ceramic Insulators Without Contaminants

Based on a meticulous analysis of the influence of nano-coating deposition on the leakage current characteristics of ceramic insulators, as derived from comprehensive laboratory evaluations, a comparative assessment was conducted. The experiment scrutinized leakage current behavior under pristine conditions and in the presence of saline and fly ash contaminants, both prior to and subsequent to the application of nano-coating. The contaminant variations were systematically classified according to the Equivalent Salt Deposit Density (ESDD) and Nonsoluble Deposit Density (NSDD), reflecting the insulator's pollution severity.

The leakage current assessment on uncoated ceramic insulators was executed across five voltage levels (20 kV, 22 kV, 24 kV, 26 kV, and 30 kV), with each test iterated five times to ensure statistical robustness. The insulators were subjected to three distinct conditions: uncontaminated, salt-polluted, and fly ash-polluted. The resulting leakage current values were meticulously analyzed and juxtaposed to elucidate the impact of contaminants on insulator performance. Ultimately, the findings from the uncontaminated insulator trials served as a benchmark for evaluating the extent of contamination-induced alterations in leakage current behavior.

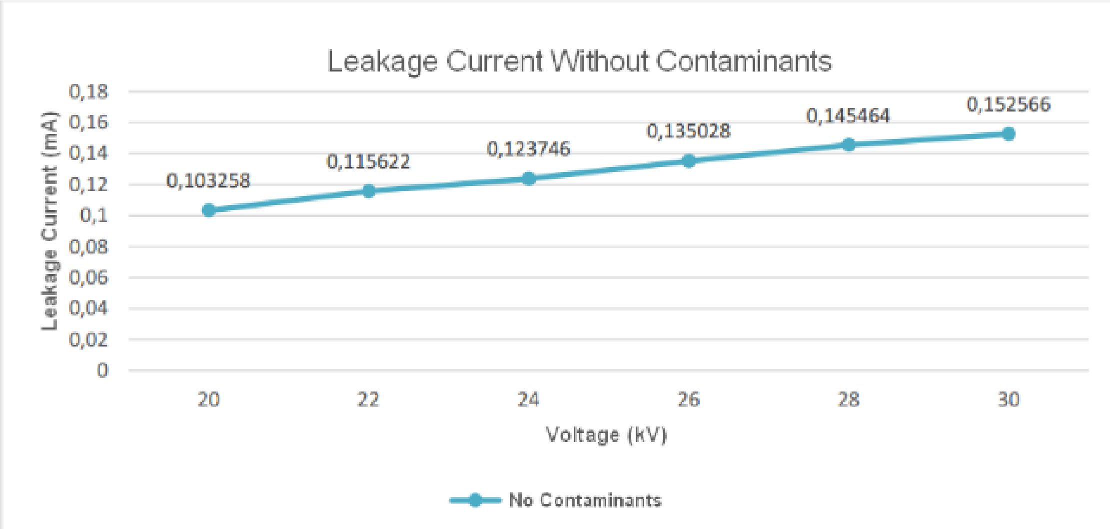

Figure 1. Test Results of the Effect of Voltage Changes on the Leakage Current of the Isolator

Based on the test results, the measured leakage current increased with voltage levels: 0.103 mA at 20 kV, 0.115 mA at 22 kV, 0.123 mA at 24 kV, 0.134 mA at 26 kV, 0.145 mA at 28 kV, and 0.152 mA at 30 kV. This indicates a direct correlation between voltage magnitude and leakage current.

Leakage Current Testing Results of Salt Contaminant Ceramic Insulators

In this test, the ceramic insulator with salt contamination was examined in a dry condition. The applied voltage variations were 22 kV, 24 kV, 26 kV, 28 kV, and 30 kV. Salt contamination was categorized by pollution levels: light, moderate, heavy, and very heavy, with ESDD values of 0.0522 mg/cm² (Light), 0.1039 mg/cm² (Moderate), 0.2337 mg/cm² (Heavy), and 0.5197 mg/cm² (Very Heavy).

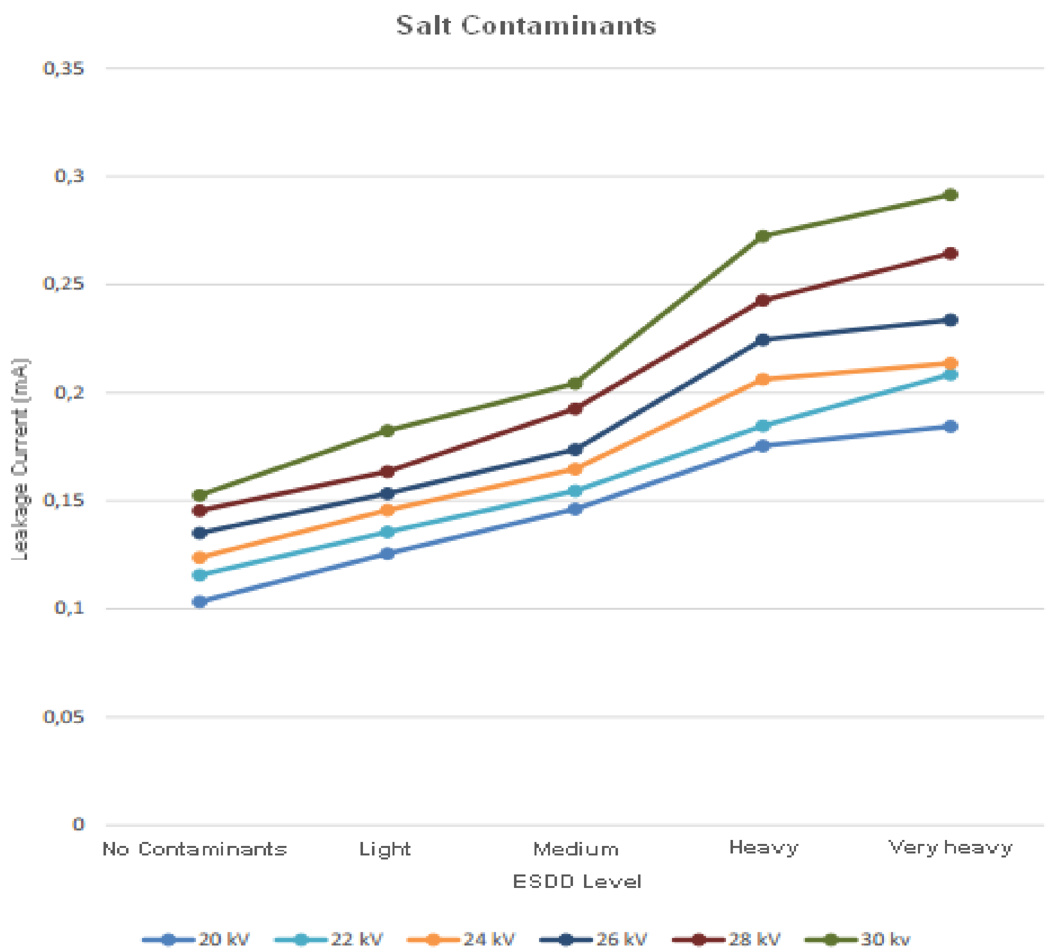

Figure 2. Effect of Salt Contaminant ESDD on Insulator Leakage Current

The test results indicate that leakage current increases due to the conductive nature of salt contamination on the ceramic insulator surface. The measured leakage current ranged from a minimum of 0.125508 mA to a maximum of 0.291478 mA. The ESDD levels, light, moderate, heavy, and very heavy, directly influenced the recorded leakage current values.

In general, there is a tendency that an increase in voltage from 22 kV to 30 kV results in an increase in leakage current in a linear manner for each ESDD category. However, there are some fluctuations at certain points that do not follow a linear pattern completely. For example, at the voltage level of 26 kV and medium ESDD, the value of the leakage current has increased disproportionately compared to the difference between 24 kV to 26 kV or 26 kV to 28 kV. These fluctuations can be caused by several factors:

1. Measurement Inconsistency – Technical factors such as the sensitivity of the measuring instrument or external interference (noise) can cause small deviations in current readings.
2. Variations in Surface Conditions – Even if the insulator is in dry conditions, differences in the distribution of salt contaminants in the micro can lead to local differences in conductivity.
3. Transient Effect – At some voltage points, leakage current can be affected by transient effects due to partial ionization or uneven distribution of surface charges. It is important to note that the leakage current is affected not only by the magnitude of the voltage and the degree of contamination, but also by the dynamic nature of the charge distribution and changes in the characteristics of the insulator surface during the test.

By understanding the causes of these anomalies, this analysis becomes more comprehensive and illustrates the complexity of insulator operational conditions in the field. It also confirms the importance of surface treatments such as nano coatings in stabilizing the electrical characteristics of insulators, especially in environments with high levels of pollution (de Santoz & Bobi, 2021).

Leakage Current Testing Results of Fly Ash Contaminant Ceramic Insulators

In this test, the ceramic insulator with fly ash contamination was examined in a dried condition. The applied voltage variations were 22 kV, 24 kV, 26 kV, 28 kV, and 30 kV. Fly ash contamination was categorized by pollution levels: light, moderate, heavy, and very heavy, with NSDD values of 0.0598 mg/cm² (Light), 0.1975 mg/cm² (Moderate), 0.5717 mg/cm² (Heavy), and 1.2993 mg/cm² (Very Heavy).

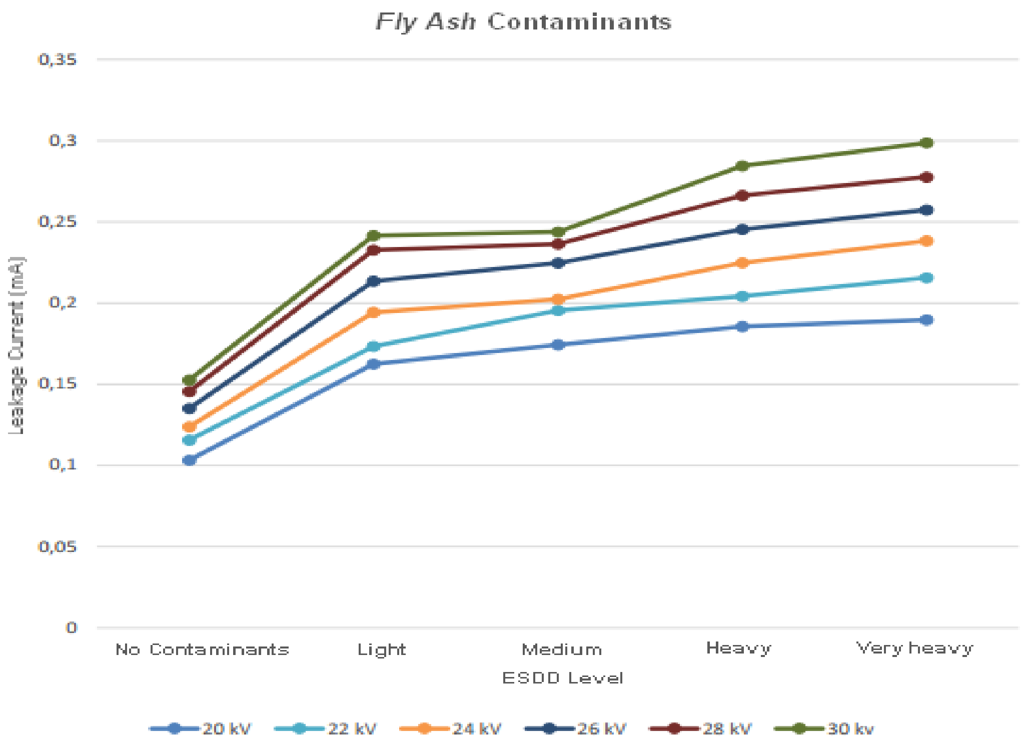

Figure 3. Effect of NSDD of Fly Ash Contaminants on Leakage Current of Insulators Ceramic

The test results indicate that leakage current increases due to the conductive nature of fly ash contamination on the ceramic insulator surface. The NSDD levels, light, moderate, heavy, and very heavy, directly influenced the recorded leakage current values. The measured leakage current ranged from a minimum of 0.162396 mA to a maximum of 0.298646 mA.

Comparison of Leakage Current Testing Without Contaminants with Salt Contaminant, Fly Ash

The ceramic insulator in an uncontaminated condition will be compared and analyzed against insulators contaminated with salt and fly ash to assess their impact on leakage current. The applied voltage levels are 20 kV, 22 kV, 24 kV, 26 kV, 28 kV, and 30 kV. For comparison, the highest contamination level (very heavy) of salt and fly ash is used.

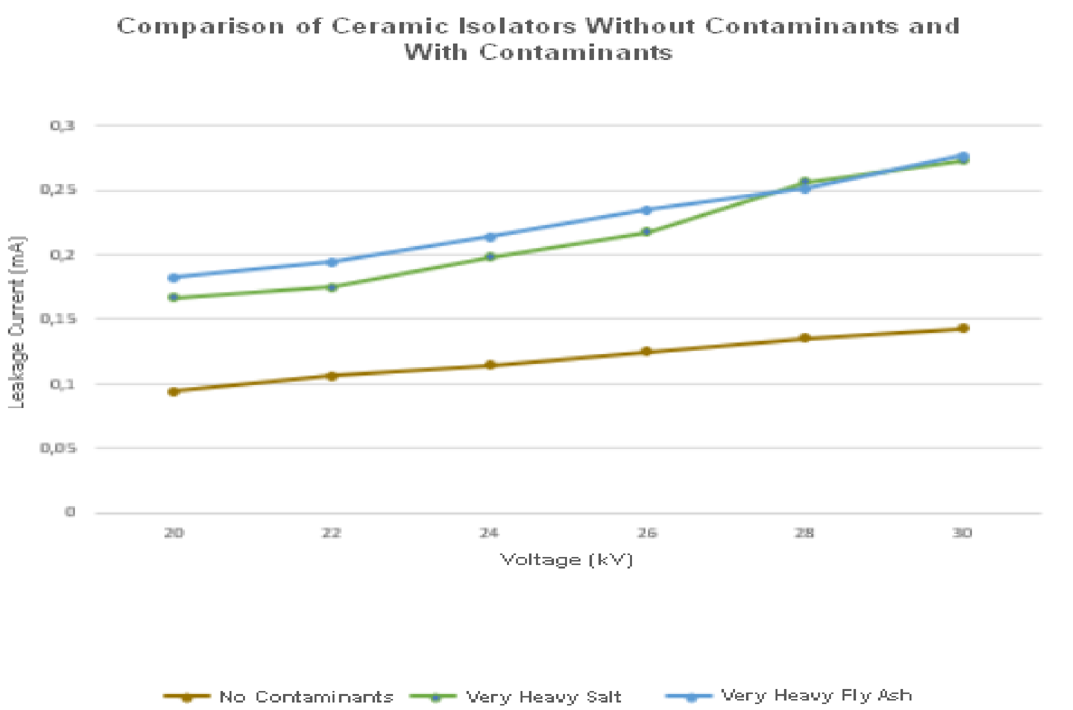

Figure 4. Comparison of Leakage Current of Ceramic Insulators Without Contaminants and With Contaminants

The test results indicate that each contaminant significantly contributes to the increase in leakage current. The leakage current of contaminated insulators is consistently higher than that of uncontaminated ones. Among the tested conditions, the highest leakage current is observed with fly ash contamination, followed by salt contamination, while the lowest occurs in the uncontaminated insulator.

Comparison of Leakage Current Test Results on Ceramic Insulators Salt Contaminants Without Nano Coating with Ceramic Insulators Nano Coated

Ceramic insulators contaminated with salt will be compared and analyzed before and after nano-coating to assess its impact on leakage current. The applied voltage levels are 20 kV, 22 kV, 24 kV, 26 kV, 28 kV, and 30 kV. Salt contamination is classified into four pollution levels: light (0.0522 mg/cm²), moderate (0.1039 mg/cm²), heavy (0.2337 mg/cm²), and very heavy (0.5197 mg/cm²) based on ESDD values.

Figure 5. Comparison of Leakage Current of Salt Contaminant Ceramic Insulators Before Nano Coating with After Nano Coating

Based on the conducted tests, the comparison results show that the leakage current of ceramic insulators contaminated with salt increases with voltage, both with and without the nano-coating layer, in accordance with Ohm's law. It can be observed that the ceramic insulator with the nano-coating layer experiences a reduction in leakage current in the very heavy contamination category at a test voltage of 30 kV, with a decrease of 23.7% compared to the leakage current before the nano-coating was applied.

Comparison of Leakage Current Testing Results on Fly Ash Contaminant Ceramic Insulators Without Nano Coating with Nano Coating Coated Ceramic Insulators

Ceramic insulators contaminated with fly ash will be compared and analyzed before and after nano-coating to assess its impact on leakage current. The applied voltage levels are 20 kV, 22 kV, 24 kV, 26 kV, 28 kV, and 30 kV. Fly ash contamination is categorized by pollution levels: light (0.0598 mg/cm²), moderate (0.1975 mg/cm²), heavy (0.5717 mg/cm²), and very heavy (1.2993 mg/cm²) based on NSDD values.

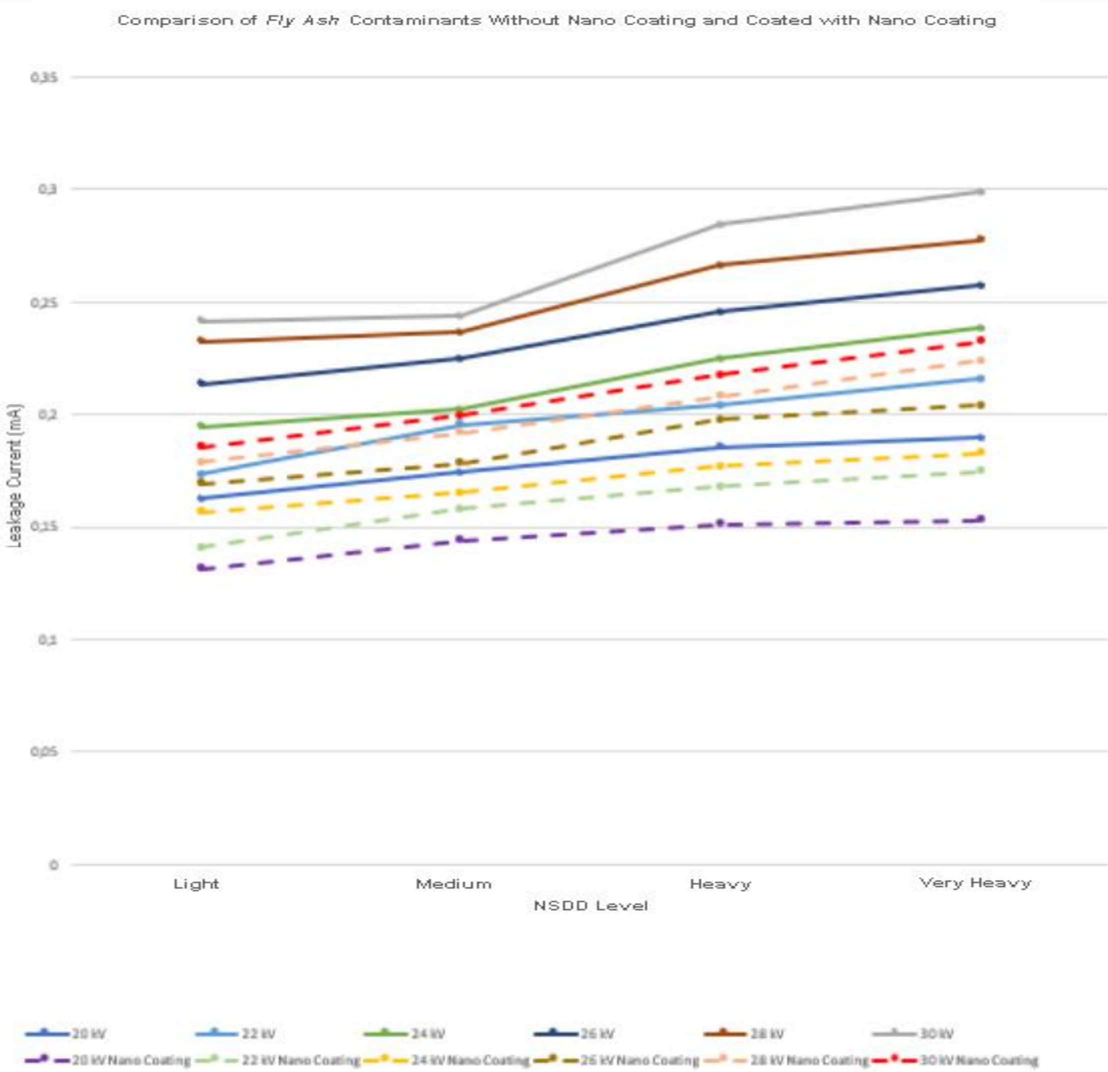

Figure 6. Comparison of Leakage Current of Fly Ash Contaminant Ceramic Insulators Before Nano Coating with After Nano Coating

Based on the tests conducted, the comparison results show that the leakage current of ceramic insulators contaminated with salt increases with voltage, both with and without the nano-coating layer, in accordance with Ohm's law. It can be observed that the ceramic insulator with the nano-coating layer experiences a 23.5% reduction in leakage current in the heavy contamination category at a test voltage of 30 kV, compared to the leakage current before the nano-coating was applied.

Comparison of Leakage Current Test Results on Ceramic Insulators Without Nano Coating with Nano Coating

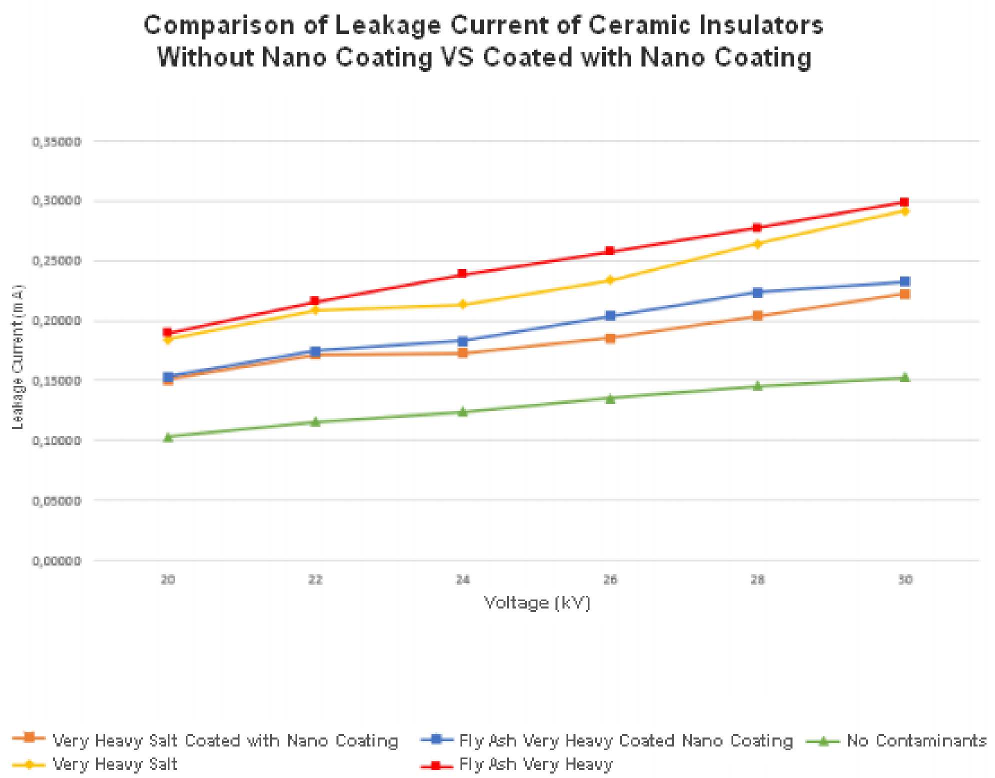

Figure 7. Comparison of Leakage Current of Ceramic Insulators Before Coating Nano Coating with After Nano Coating

Based on the tests conducted, the comparison results show that the leakage current of ceramic insulators, both with and without the nano-coating layer, increases with voltage, in accordance with Ohm's law. It can be observed that the ceramic insulator with the nano-coating layer experiences a 23.7% reduction in leakage current in the very heavy salt contamination category at a test voltage of 30 kV, compared to the leakage current before the nano-coating was applied. Additionally, a 23.5% reduction in leakage current is observed in the heavy fly ash contamination category at a test voltage of 30 kV, compared to the leakage current before nano-coating.

Cost-Benefit Analysis of Nano Coating on Ceramic Insulators

Cost-Benefit Analysis (CBA) is a method used to assess a project or investment by comparing the costs incurred with the expected benefits (Mishan, 2020; Luminita, 2022). The first step in the CBA for nano-coating on ceramic insulators is identifying the costs and benefits. The costs include the initial coating application, maintenance costs, and extended economic lifespan of the insulator. The benefits include savings in maintenance costs, reduced replacement costs, and operational cost savings. In this analysis, cash flows are calculated based on annual maintenance and replacement costs, with a discount rate of 8% over a 6-year period.

The comparison of Net Present Value (NPV) between scenarios with and without nano-coating showed that the total NPV for the uncoated insulator is 1,323,052, while for the nano-coated insulator, it is 1,095,779. The Benefit-Cost Ratio (BCR) for the project is calculated as 1.171, which indicates that the nano-coating project is economically feasible and should be implemented based on this analysis.

Conclusion

The experimental analysis on ceramic insulators, coated with nano-coating, definitively demonstrates a marked reduction in leakage current, with the fly ash-contaminated, nano-coated insulator exhibiting a 23.7% decline in leakage current relative to the untreated counterpart. The assessment varied the ESDD and NSDD levels of contaminants on the insulator's surface, with ESDD values ranging from 0.0522 mg/cm² (Light) to 0.5197 mg/cm² (Very Heavy), and NSDD values from 0.0598 mg/cm² (Light) to 1.2993 mg/cm² (Very Heavy). At a voltage of 30 kV, the leakage current for the pristine insulator was 0.152566 mA, whereas the salt-contaminated insulator at an ESDD of 0.0522 mg/cm² exhibited 0.182396 mA, and the fly ash-laden insulator at 0.0598 mg/cm² recorded 0.241492 mA. These findings underscore that elevated ESDD and NSDD levels in both salt and fly ash contaminants precipitate a commensurate rise in leakage current. Additionally, the ESDD of salt and the NSDD of fly ash play a pivotal role in augmenting leakage current, with higher contaminant concentrations contributing to elevated leakage. Ultimately, the calculated Benefit-Cost Ratio (BCR) of 1.171 affirms the project's viability for the application of nano-coating on ceramic insulators.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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