Analysis of the Effect of Sea Salt, Volcanic Ash and Black Carbon Contamination on the Insulation Resistance of Porcelain Insulators

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Abstract – **The reliability of porcelain insulators in power systems is strongly influenced by surface conditions, particularly contamination from environmental pollutants. Such contamination can significantly reduce insulation resistance, thereby increasing the risk of leakage currents and flashover. This study aims to analyze the effects of major pollutants—namely sea salt, volcanic ash, and black carbon—on the insulation resistance of porcelain insulators. An experimental approach was employed by testing insulators under clean conditions and comparing the results after artificial contamination with each pollutant under controlled temperature and humidity conditions. Insulation resistance was measured using a megohmmeter, and the data were processed using the arithmetic mean of ten repeated measurements and analyzed descriptively. The results show that the clean condition yielded the highest average insulation resistance of 518 MΩ. Sea salt contamination caused the most significant reduction (210 MΩ), followed by volcanic ash (240 MΩ) and black carbon (280 MΩ). The greater impact of sea salt is attributed to its hygroscopic nature, which forms a conductive electrolyte layer, while volcanic ash contributes through its mineral composition and moisture retention, and black carbon through conductive particle networks. It can be concluded that sea salt has the greatest impact on insulation resistance degradation, followed by volcanic ash and black carbon. Although the measured values remain within acceptable limits for medium-voltage systems, continuous contamination may increase the risk of insulation degradation. Therefore, appropriate maintenance and pollution control strategies are necessary to ensure long-term reliability.**

Keywords: Porcelain Insulator, Insulation Resistance, Pollutant Deposition

I. INTRODUCTION

A reliable power system is essential for modern life. Its reliability depends not only on generation capacity and transmission networks but also on the performance of supporting components, such as insulators. Insulators function to electrically isolate conductors from grounded structures while preventing unwanted current flow. However, their performance is strongly influenced by surface conditions, which are directly affected by environmental exposure. In practice, insulators are often subjected to various pollutants, including volcanic ash, industrial particles, sea salt, and black carbon [1], [2]. The accumulation of these contaminants on the insulator surface can reduce insulation resistance, increase surface conductivity, and, under humid conditions, potentially lead to leakage currents and flashover [3], [4].

Insulation resistance is a key parameter used to evaluate the ability of an insulator to withstand leakage current [5]. A high insulation resistance value indicates effective insulation performance, while a decrease in this value may lead to increased leakage current and potential insulation failure [6]. Environmental pollutants exhibit different physical and chemical characteristics that influence their interaction with insulator surfaces [7]. Sea salt is highly hygroscopic and can form a conductive electrolyte layer under humid conditions [8]. Volcanic ash consists of fine mineral particles that can retain moisture and contribute to surface degradation [9], while industrial dust may contain conductive compounds depending on its chemical composition

[10]. Under humid conditions, these contaminants can form conductive layers that significantly degrade insulation performance [11]. In addition to these contaminants, black carbon is recognized as a fine conductive particle generated from incomplete combustion processes and can contribute to leakage current formation on insulator surfaces [12]. Previous studies have also shown that contamination characteristics significantly influence insulation degradation and flashover risk [13]–[15], while environmental and electrical stresses further affect insulator performance and failure behavior [16]–[18]. Previous studies, such as those conducted by Mulia & Santoso and Hendro et al., have primarily investigated the effects of single pollutants, including sea salt and volcanic ash, on insulator performance. While these studies provide important insights, they do not fully represent actual operating conditions, where insulators are typically exposed to multiple pollutants simultaneously. Moreover, existing studies generally evaluate each pollutant independently, without providing a systematic comparison under identical test conditions. As a result, the relative severity and interaction effects of different pollutants remain insufficiently understood.

Therefore, the novelty of this study lies not only in the use of multiple pollutants but also in the implementation of a controlled and comparative experimental approach that evaluates the effects of sea salt, volcanic ash, and black carbon under the same testing conditions. This approach enables a direct comparison of their impacts and provides a clearer understanding of the relative severity of each pollutant. Accordingly, this study aims to analyze and compare the effects of these major pollutants on the insulation resistance of porcelain insulators. The results are expected to provide a more realistic representation of field conditions and to support the development of more effective maintenance and risk mitigation strategies for power system insulators.

II. METHOD

This study employed a laboratory-based experimental method to analyze the effect of multiple pollutants on the insulation resistance of porcelain insulators. The experiment was conducted by preparing insulator samples under controlled conditions and subjecting them to different types of contamination, namely sea salt, volcanic ash, and black carbon. Each pollutant was applied separately to ensure consistent comparison of its effect on insulation performance. The research followed a quantitative approach, in which insulation resistance was measured directly using a megohmmeter in accordance with standard testing procedures. To ensure data reliability, each measurement was repeated multiple times and processed using the arithmetic mean. The overall research procedure, including sample preparation, contamination process, measurement, and data analysis, is illustrated in the flowchart presented in Figure 1.

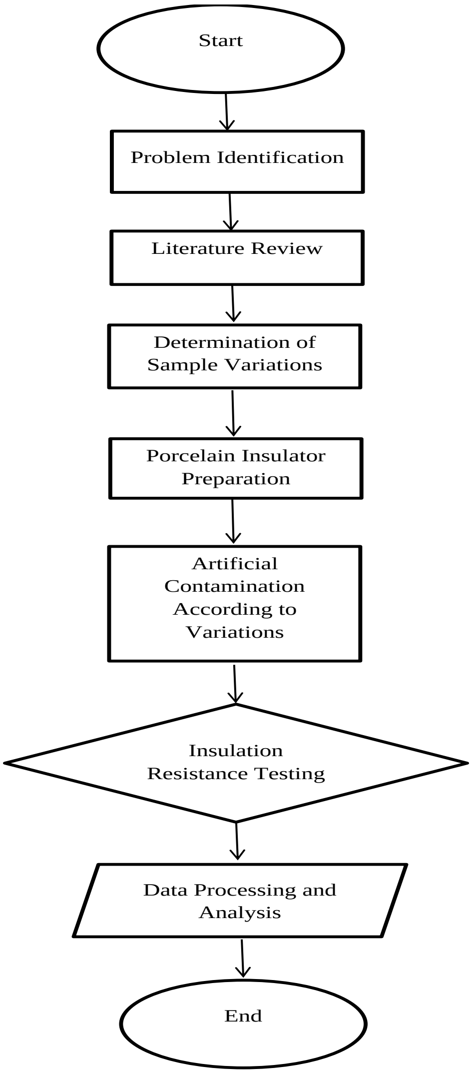

Figure 1. Flowchart

The explanation of the following flowchart is as follows:

1. Start
   The initial stage of commencing the research process as the starting point for all subsequent activities.
2. Problem Identification
   Identifying the core issues that serve as the foundation of the research.
3. Literature Review
   Conducting a literature review to understand theories, previous studies, pollutant characteristics, and insulation resistance testing methods.
4. Determination of Sample Variations
   Defining the variations of samples to be tested.
5. Porcelain Insulator Preparation
   Preparing the porcelain insulators to be used, including initial cleaning to ensure they are free from contamination before pollutant treatment.
6. Artificial Contamination Accroding to Variations

Applying artificial pollutants according to the predetermined variations was conducted using consistent concentrations and application methods to ensure reliable test results. The artificial contamination process was performed under controlled parameters to ensure reproducibility. Sea salt contamination was prepared using a NaCl solution with a concentration of 40 g/L, which was applied uniformly using a spray method until a surface density of approximately 0.5 mg/cm² was achieved. Volcanic ash and black carbon were applied in dry form with a uniform surface distribution of approximately 0.5 mg/cm² on the insulator surface. After contamination, the samples were allowed to dry for 30 minutes under controlled laboratory conditions prior to testing.

7. Insulation Resistance Testing
   Measuring the insulation resistance of each sample using appropriate instruments to evaluate the effect of pollutants on insulator performance.
8. Data Processing and Analysis
   Processing the experimental data and analyzing the differences among pollutant variations, including comparisons with literature and drawing conclusions.
9. End
   Concluding the research process after all data have been collected and analyzed.

Table 1. Instruments Used in the Research

No	Equipment	Description
1	Insulator Resistance Tester	1 unit
2	Digital Thermo-Hygrometer	1 unit
3	Digital Weighing Scale	1 unit
4	Spray Bottle	1 unit
5	Stopwatch	1 unit

Table 1 lists the instruments and equipment used in this study. An insulation resistance tester (megohmmeter) was used to measure the insulation resistance of the porcelain insulators. A digital thermo-hygrometer was employed to monitor temperature and humidity conditions during testing. A digital weighing scale was used to ensure accurate pollutant mass, while a spray bottle was utilized to apply moisture evenly on the insulator surface. A stopwatch was used to maintain consistent measurement duration.

Artificial contamination was applied to simulate environmental exposure using three types of pollutants: sea salt (NaCl), volcanic ash, and black carbon. Each pollutant was applied separately to the insulator surface to allow a consistent comparison of their individual effects. For sea salt contamination, a saline solution was prepared by dissolving 40 g of NaCl in 1 liter of distilled water (4% concentration). The solution was uniformly sprayed onto the surface of the porcelain insulator using a spray bottle until a thin and even layer was formed.For volcanic ash contamination, fine ash particles were first sieved to obtain a uniform particle size. The ash was then applied evenly to the insulator surface with an approximate surface density of 0.5 mg/cm². For black carbon contamination, fine carbon particles were distributed uniformly on the insulator surface with a similar surface density of 0.5 mg/cm². After the application of each pollutant, the insulator was left under controlled environmental conditions to allow stabilization before measurement. Each test was conducted independently to avoid cross-contamination between different pollutants.

Insulation resistance measurements were carried out using a megohmmeter. A constant test voltage was applied, and the insulation resistance value was recorded in megaohms (MΩ). Each measurement was repeated ten times to ensure data reliability, and the final value was calculated using the arithmetic mean of all measurements. Insulation resistance measurements were carried out using a megohmmeter. A constant test voltage was applied, and the insulation resistance value was recorded in megaohms (MΩ). Each measurement was repeated ten times to ensure data reliability, and the final value was calculated using the arithmetic mean of all measurements.

III. RESULTS AND DISCUSSION

This study aims to analyze the effect of environmental pollutants on the insulation resistance of porcelain insulators. The testing was conducted by comparing insulation resistance values under clean and contaminated conditions. Each condition was tested ten times using an insulation resistance tester with a test voltage of 1000 V DC to ensure data accuracy and reliability. During the testing process, environmental parameters such as temperature and humidity were maintained within a controlled range to ensure valid comparison. The characteristics of the porcelain insulator used in this study are presented in Table 2.

Table 2. Characteristics of the Tested Porcelain Insulator

Parameter	Description
Type of Insulator	Pin-Type Porcelain Insulator
Nominal Voltage	20 kV
Insulator Length	25 cm
Shed Diameter	15 cm
Weight	3.5 kg
Material	Porcelain with protective glaze
Color	Brown
Year of Installation	2015
Service Duration	10 years
Physical Condition	No visible cracks; minor surface contamination observed
Operating Environment	Outdoor environement

Table 2 presents the characteristics of the porcelain insulator used in this study. The insulator is a pin-type unit with an operating age of approximately 10 years. Although no visible cracks are observed, minor surface contamination such as dust deposits is present due to environmental exposure. The combined effects of service age and outdoor exposure make this insulator representative of actual field conditions. The insulation resistance measurement results under clean conditions are presented in Table 3.

Table 3. Insulation Resistance Measurement Results of Clean

Test Number	Insulation Resistance (MΩ)	Temperature (°C)	Humidity (%)
1	520	28	70
2	515	28	70
3	518	28	70
4	523	29	70
5	519	28	71
6	522	28	70
7	516	28	71
8	521	29	70
9	517	28	71
10	520	28	70

Table 3 presents the insulation resistance results under clean conditions, with values ranging from 515 to 523 MΩ and an average of approximately 518 MΩ. The relatively small variation indicates stable measurement conditions and confirms that the insulator maintains good dielectric performance in the absence of surface contamination. From a physical perspective, the high insulation resistance is attributed to the absence of conductive pathways on the insulator surface. The protective glaze layer of the porcelain prevents moisture penetration and limits surface conduction, thereby minimizing leakage current. Although minor fluctuations are observed, these are primarily influenced by slight variations in temperature (28–29 °C) and humidity (70–71%), which may affect surface moisture adsorption. However, under clean conditions, such environmental variations do not significantly alter the insulation behavior. These results serve as a baseline reference for evaluating the degradation caused by different pollutants. Any significant reduction observed under contaminated conditions can therefore be directly associated with the formation of conductive layers and changes in surface properties due to pollutant interaction. Table 4 presents the insulation resistance results under sea salt contamination, showing a significant decrease compared to the clean condition
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Table 4. Insulation Resistance Measurement Results of Sea Salt-Contaminated Insulator

Test Number	Insulation Resistance (MΩ)	Temperature (°C)	Humidity (%)
1	210	28	72
2	215	28	72
3	208	29	73
4	212	29	72
5	214	28	73
6	209	28	72
7	209	28	72
8	213	29	72
9	210	29	73
10	214	28	72

Table 4 presents the insulation resistance results under sea salt contamination, showing a significant decrease compared to the clean condition. The average insulation resistance drops to approximately 210 MΩ from 518 MΩ, indicating a substantial degradation in insulating performance. This reduction is primarily attributed to the hygroscopic nature of sodium chloride (NaCl), which absorbs moisture and forms a conductive electrolyte layer on the insulator surface. At the microscopic level, the dissolution of NaCl produces mobile ions (Na^+ and Cl^-), significantly increasing ionic conductivity. This process enhances surface conduction and facilitates leakage current formation. Compared to other pollutants, sea salt exhibits the most pronounced effect due to its ability to rapidly form a highly conductive medium under humid conditions. These findings are consistent with previous studies, which identify salt contamination as a dominant factor in insulator degradation, particularly in coastal environments. Consequently, this condition increases the risk of flashover, especially under high humidity and operating voltage stress. The insulation resistance results under volcanic dust contamination are presented in Table 5.

Table 5. Insulation Resistance Measurement Results of Insulators Contaminated with Volcanic Dust

Test Number	Insulation Resistance (MΩ)	Temperature (°C)	Humidity (%)
1	245	28	72
2	238	28	72
3	242	28	71
4	236	28	70
5	240	28	71
6	243	29	70
7	239	28	70
8	242	29	71
9	241	28	70
10	240	28	71

Table 5 presents the insulation resistance results under volcanic dust contamination, showing a noticeable reduction compared to the clean condition. The average value is approximately 241 MΩ, which is higher than that of sea salt contamination (210 MΩ) but still significantly lower than the clean condition (518 MΩ). This reduction is associated with the mineral composition of volcanic dust, which contains silica (SiO_2) and various metal oxides. Under humid conditions, these particles can retain moisture and form a semi-conductive layer on the insulator surface. At the microscopic level, the interaction between mineral particles and absorbed water facilitates partial ionic conduction, thereby increasing surface conductivity and promoting leakage current formation. In addition, the abrasive nature of volcanic dust can gradually degrade the protective glaze layer, increasing surface roughness and enhancing pollutant accumulation. Compared to sea salt, volcanic dust exhibits a less significant effect due to its lower hygroscopicity; however, its combined chemical and mechanical interactions still contribute substantially to insulation degradation, particularly in volcanic or ash-prone environments. Following the evaluation of sea salt and volcanic dust contamination, the effect of black carbon on insulation resistance is analyzed to represent urban and industrial pollution conditions. The corresponding measurement results are presented in Table 6.

Table 6. Insulation Resistance Measurement Results of Porcelain Insulators with Black Carbon Contamination

Test Number	Insulation Resistance (MΩ)	Temperature (°C)	Humidity (%)
1	282	28	70
2	276	28	70
3	279	28	71
4	283	28	70
5	283	28	70
6	283	29	71
7	281	28	70
8	277	29	71
9	283	29	70
10	280	28	70

Table 6 presents the insulation resistance results under black carbon contamination, showing a reduction compared to the clean condition. The average insulation resistance is approximately 281 MΩ, which is lower than the clean condition (518 MΩ) but higher than both sea salt (210 MΩ) and volcanic dust (241 MΩ). This reduction is associated with the intrinsic electrical conductivity of black carbon, which consists of fine carbonaceous particles with a high specific surface area. At the microscopic level, these particles can form interconnected conductive networks on the insulator surface, enabling leakage current flow. However, due to its relatively hydrophobic nature, black carbon does not readily absorb moisture, limiting the formation of a continuous conductive layer. As a result, its impact is less significant compared to sea salt, which relies on strong hygroscopic and ionic conduction mechanisms. Nevertheless, the fine particle size of black carbon promotes strong adhesion to the insulator surface, and in the presence of moisture, partial conductive paths may still form. Over time, this accumulation can contribute to gradual insulation degradation, particularly in urban and industrial environments with high pollution levels.

To provide a clearer comparison of insulation resistance under different conditions, a visual representation is presented in Figure 2.

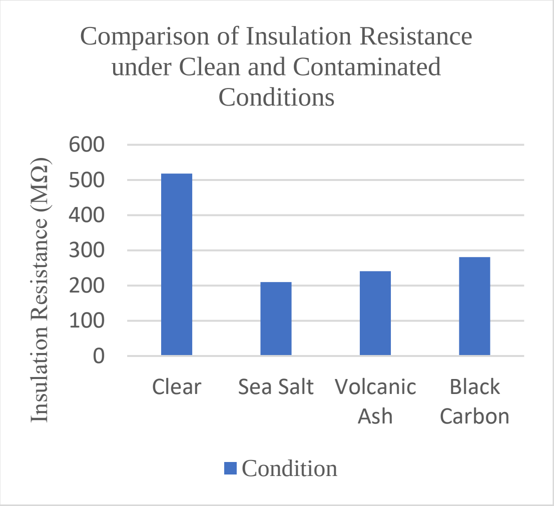

Figure 2. Comparison of Insulation Resistance under Clean and Contaminated Conditions

Figure 2 clearly illustrates the significant reduction in insulation resistance due to contamination, with sea salt exhibiting the most pronounced effect. Overall, the results demonstrate that each pollutant reduces insulation resistance through different physical and chemical mechanisms. Sea salt causes the most significant degradation due to its hygroscopic behavior and strong ionic conduction, followed by volcanic dust with its combined moisture retention and abrasive effects, and finally black carbon, which contributes through surface conductivity and particle accumulation. A clear distinction is observed between clean and contaminated conditions, where all pollutants lead to a substantial decrease in insulation resistance. The clean condition (518 MΩ) serves as a baseline, while contaminated conditions show reductions of up to more than 50%. In comparison with commonly accepted practices for medium-voltage systems (e.g., 20 kV), the measured values remain above typical minimum insulation resistance thresholds. However, the observed decreasing trend indicates a potential risk under prolonged exposure, especially in high-humidity environments where conductive layers are more likely to form. From a practical perspective, these findings suggest that insulators in coastal areas require more frequent cleaning due to the dominant effect of salt contamination. In contrast, insulators in volcanic regions and urban-industrial environments require periodic inspection to prevent long-term degradation caused by particle accumulation and surface damage.

IV. CONCLUSION

Based on the test results, it can be concluded that the cleanliness of porcelain insulator surfaces significantly affects insulation resistance. Clean conditions provide the highest insulation resistance, while contamination leads to performance degradation with different mechanisms depending on the pollutant type. Sea salt contamination has the most significant impact due to its hygroscopic nature, forming a conductive electrolyte layer on the insulator surface. Volcanic dust reduces performance through abrasive properties and conductive mineral content, whereas black carbon forms conductive pathways with comparatively lower influence. The overall order of impact is sea salt, volcanic dust, and black carbon. These findings confirm that environmental conditions strongly determine insulator performance and reliability. From a practical utility perspective, maintenance strategies should be adapted to the dominant pollution characteristics of each geographic zone. Coastal areas require shorter inspection and washing intervals due to continuous salt deposition, while volcanic regions should apply condition-responsive cleaning, particularly after ash eruption events. Industrial or urban areas with carbon-based pollution can adopt moderate but regularly scheduled maintenance intervals supported by periodic monitoring of insulation resistance. In addition, utility companies are encouraged to implement a zonal-based maintenance scheduling system combined with condition-based maintenance (CBM) to optimize cleaning cycles. This approach ensures that maintenance frequency is aligned with actual environmental stress levels, thereby reducing contamination accumulation, minimizing flashover risk, and improving the long-term reliability of power distribution systems.

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