Modeling Leakage Current in Naturally Contaminated Insulators Using Linear Regression for Transmission Line Diagnostics

Original Scientific Paper

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Abstract *– Natural contamination can significantly influence the surface conductivity of high-voltage ceramic insulators and increase the risk of flashover. This study proposes a modeling framework based on multivariate linear regression to characterize leakage current behavior induced by three contamination types: dust, moss, and flashover residues. Experimental data were obtained from controlled laboratory tests with three replications for each contamination type. Total Harmonic Distortion (THD), Equivalent Salt Deposit Density (ESDD), Non-Soluble Deposit Density (NSDD), temperature, and humidity were incorporated as input parameters. THD and NSDD were found to be the dominant predictors for dust-contaminated insulators, with a highly accurate model (prediction error < 1%). For moss contamination, the primary contributing factor was NSDD due to its hygroscopic nature, while THD served as a secondary indicator of electrical distortion. In the case of flashover residues, NSDD exhibited a strong positive contribution to leakage current, while ESDD showed a negative correlation, indicating the non-uniform and degraded nature of post-flashover surfaces. Model validation demonstrated strong agreement with experimental results. Prediction errors were generally below 1%, confirming the robustness of the proposed approach. Among all contamination types, NSDD consistently appeared as the most influential parameter, while THD effectively captured waveform distortion associated with surface degradation. The novel integration of FFT-based harmonic analysis with regression modeling proposed in this study enables a more comprehensive interpretation of electrical and physical interactions on contaminated insulator surfaces. The proposed models provide a practical and cost-effective diagnostic tool for monitoring transmission lines, supporting condition-based maintenance strategies, and enhancing system reliability in tropical regions prone to contamination.*

Keywords: *Leakage current, Linear regression, Total Harmonic Distortion (THD), Equivalent Salt Deposit Density (ESDD), Non-Soluble Deposit Density (NSDD), Flashover, Contamination, Ceramic insulator, Transmission line diagnostics, FFT*

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1. INTRODUCTION

High-voltage insulators play a critical role in power transmission systems. In tropical and humid regions, environmental contamination can accelerate their surface degradation. Several studies have investigated how contamination induces flashover using artificially applied contaminants on insulator surfaces [1-4]. These studies provided valuable insights into flashover mechanisms and the parameters influencing insulation performance. However, in real transmission environments, natural contamination entails high costs, long observation periods, and direct collaboration with utility companies.

In tropical environments, high rainfall, elevated humidity, and airborne pollutants can significantly influence the physical and chemical properties of insulating materials [5][6]. Dust, salt, and biological particles such as moss and fungi can accumulate on insulator surfac-

es and form conductive layers under wet conditions, thereby increasing leakage current (LC) and reducing dielectric strength [7][8]. Such degradation processes can lead to flashovers, particularly in high-humidity regions such as coastal areas, mountainous regions, and fog-prone environments [4][9].

LC reflects surface conductivity and captures the combined effects of environmental factors such as ambient temperature, humidity, pollution, and rainfall [6][7][9]. LC online and continuous monitoring systems, combined with more advanced techniques such as microwave reflectometry applied to dry insulator surfaces, are effective for assessing contaminated insulator performance [8][10]. Previous studies have consistently demonstrated that LC behavior serves as a reliable indicator for evaluating insulator conditions, and various diagnostic techniques and indicators have been proposed to enhance condition assessment [11-16]. However, the high cost of such monitoring systems limits their large-scale deployment in power networks.

In Indonesia, ball-and-socket ceramic suspension insulators are widely used in overhead transmission systems operating at voltage levels of 20 kV, 66 kV, 150 kV, and 500 kV [14]. The 150 kV Payakumbuh–Koto Panjang transmission line, for instance, consists of 140 towers equipped with 11-disc ceramic insulator strings. Based on field data, 63% of the towers are in hilly areas, 20% in rice fields, and 16% in dryland regions. Flashovers more often occur in hilly areas (82%), followed by those in rice fields (16%) and drylands (2%) [17]. Complex terrains accelerate the accumulation of natural contaminants, thereby increasing the risk of leakage currents, partial discharges, and flashover events [18][19]. The transmission lines are subjected to high humidity levels and lightning intensity, reaching 173 days per year [8][10], exacerbating insulator degradation and reducing system reliability.

To better understand insulator degradation under such conditions, leakage current and test voltage measurements were conducted on ceramic insulators with 2–5 years in service. The measured data were analyzed using the Fast Fourier Transform (FFT) to identify harmonic patterns in leakage current signals that reflect the insulator surface conditions [4][11][12].

Despite extensive research on leakage current and contamination effects, there remains a significant gap in developing accurate analytical models based on naturally contaminated insulators under real tropical conditions. Most existing studies rely on controlled laboratory environments with artificial pollutants, which may not fully represent actual field conditions.

Given these limitations, this study proposes a combined analytical approach integrating FFT and linear regression modeling for comprehensive leakage current characterization. The FFT method is used to extract harmonic spectra associated with contamination-induced distortions, while regression analysis quantifies the relationships between LC, Total Harmonic Distortion (THD), Equivalent Salt Deposit Density (ESDD), Non-Soluble Deposit Density (NSDD), temperature, and humidity. By combining spectral and statistical approaches, this study develops predictive models that effectively represent the behavior of naturally contaminated ceramic insulators.

This study provides empirical data on leakage current characteristics from naturally contaminated 150 kV ceramic insulators in a tropical transmission environment. Regression-based predictive models developed for various contamination types (dust, moss, and flashover residues) have been validated using laboratory measurements. This study also demonstrates the complementary roles of FFT-based harmonic analysis and regression modeling in transmission line diagnostics. These contributions are expected to support predictive maintenance strategies and reduce contamination-induced flashover risks in high-voltage transmission systems.

2. METHODOLOGY

2.1. DATA ACQUISITION

LC data were obtained from ceramic insulators exposed to dust, moss, and flashover residues. totaling 9 disc-type insulators—three for each category. Although the sample size is relatively small, this study is intended as a preliminary investigation to understand the effects of various types of contamination.

Each experimental setup consisted of a high-voltage AC source (10–30 kV) and precision current sensors to ensure accurate measurement of leakage current waveforms. The data were recorded at high resolution with multiple replications to improve reliability and capture variations caused by environmental parameters, such as temperature and humidity.

In real operating conditions, insulator contamination may occur due to the accumulation of dust particles, mud deposits, or biological growth on the insulator surface. Representative examples of such contamination are illustrated in Fig. 1.

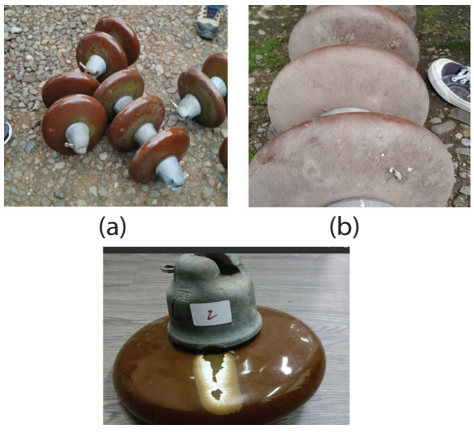


Fig. 1. Ceramic insulators under natural contamination of (**a**) moss contamination; (**b**) dust contamination (**c**) Insulators with Flashover Marks

A laboratory-scale high-voltage test was conducted to evaluate the dielectric strength of insulators in relation to leakage current under controlled conditions of constant temperature and humidity, as depicted in Fig. 2.

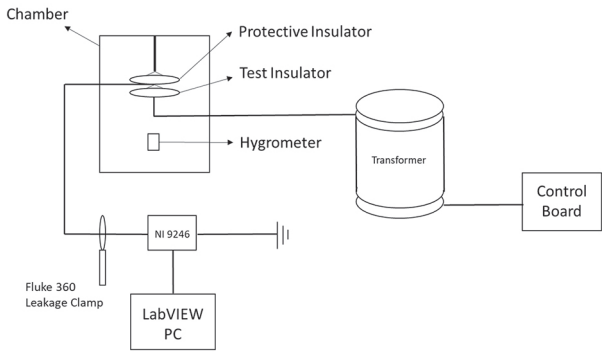


Fig. 2. Leakage Current Measurement Procedure Series

2.2. FFT ANALYSIS

The recorded LC waveforms were processed using FFT to extract spectral features. Two main spectral parameters, namely the dominant frequency component and the harmonic magnitude, were considered. These features provided information about the energy distribution of the leakage current signal and its distortion characteristics under different contamination conditions.

2.3. REGRESSION MODEL DEVELOPMENT

To quantify the relationship between LC and the influencing factors, a multivariate linear regression model was developed using SPSS (Statistical Package for the Social Sciences). The general form of the regression equation is expressed as

$$Y = \beta_0 + \beta_1 X_{THD} + \beta_2 X_{Temp} + \beta_3 X_{Hum} + \beta_4 X_{ESDD} + \beta_5 X_{NSDD} \quad (1)$$

Where

- Y: predicted leakage current (mA),
- β_0: regression intercept, representing the baseline LC when all predictors are zero,
- β_1: regression coefficient of THD,
- β_2: regression coefficient of temperature (°C),
- β_3: regression coefficient of relative humidity (%),
- β_4: regression coefficient of Equivalent Salt Deposit Density (ESDD, mg/cm^2), and
- β_5: regression coefficient of Non-Soluble Deposit Density (NSDD, mg/cm^2).

2.4. MODEL VALIDATION AND STATISTICAL TESTS

The regression models were evaluated using three statistical criteria:

1. Coefficient of Determination (R^2)

R^2 quantifies the proportion of variance in leakage current explained by the predictors. A value close to 1 indicates high predictive accuracy, while lower values suggest that other factors influence the LC behavior.

2. Statistical Significance (p-value)

Hypothesis testing was performed using the t-test (for individual coefficients) and F-test (for the overall model). A p-value < 0.05 indicates statistical significance at the 95% confidence level. Variables with p-values > 0.05 were considered statistically insignificant and subject to exclusion from the final model.

3. Multicollinearity Check (Variance Inflation Factor, VIF)

VIF values were calculated to detect multicollinearity among predictors. A VIF > 10 indicates strong interdependence among variables, which could destabilize the regression. In such cases, redundant predictors were excluded or transformed to improve robustness.

2.5. SPSS WORKFLOW

The regression analysis was executed in SPSS following these steps:

1. Data Import – Experimental measurements and FFT-derived parameters were prepared in CSV/Excel format and imported into SPSS.
2. Variable Definition – Dependent variable: leakage current (Y); independent variables: FFT dominant frequency, harmonic magnitude, ESDD, NSDD, temperature, and humidity.
3. Regression Execution – Analyze → Regression → Linear was used to define the regression model. The "Enter" method was applied to include all predictors simultaneously.
4. Result Interpretation – R^2 values were examined for model accuracy, regression coefficients (β) were analyzed to assess predictor contributions, p-values were used to test significance, and VIF values were reviewed to detect multicollinearity.

2.6. DATA DESCRIPTION

Experimental data were obtained from laboratory measurements of leakage current in high-voltage ceramic insulators subjected to three types of natural contamination (dust, moss, and flashover residues). Each experiment was repeated three times to ensure data reliability under controlled environmental conditions. The measured parameters included leakage current (mA), Total Harmonic Distortion (THD, %), temperature (°C), relative humidity (%), Equivalent Salt Deposit Density (ESDD, mg/cm^2), and Non-Soluble Deposit Density (NSDD, mg/cm^2).

2.6.1. Dust Contamination

Table 2.1 presents the dataset for insulators contaminated with dust. The Test Voltage (V) ranged from 10,578 V to 30,616 V with corresponding THD values between 13.3% and 25.3%. The environmental conditions were relatively stable, with temperature varying from 30.6°C to 33.8°C and relative humidity ranging from 69.3% to 74.8%. The ESDD values were within a narrow range of 0.525–0.639 mg/cm², while NSDD values varied from 0.0622 to 0.0977 mg/cm².

Table 2.1. Input data structure for multivariate regression of dust-contaminated insulators

Test Voltage (V)	THD (%)	Temperature (°C)	Humidity (%)	ESDD mg/cm²	NSDD mg/cm²
10,578	13.3	33.8	69.3	0.546	0.0622
20,551	18.5	30.6	74.8	0.639	0.0977
30,616	25.3	31.1	74.1	0.525	0.0795

These results indicate that, even under stable soluble contamination (ESDD), non-soluble deposits (NSDD) influence leakage current behavior. This is consistent with the physical mechanism described earlier, where surface particles increase roughness and local conductivity.

Statistical analysis shows that the coefficient of variation (CV) for temperature and humidity is below 10%, which confirms stable test conditions. ESDD also shows low variability. In contrast, leakage current and THD vary more, indicating their sensitivity to surface conditions. Despite the limited dataset (n = 3), the data show consistent trends without significant outliers. Therefore, the dataset is considered reliable and representative.

2.6.2. Moss Contamination

Table 2.2. presents the dataset for insulators contaminated with moss. The Test Voltage (V) ranged from 10,578 V to 30,569 V while Total Harmonic Distortion (THD) varied between 18.26% and 38%. The environmental conditions showed temperatures between 28.2°C and 31.8°C and relative humidity levels ranging from 57.8% to 76.1%. The ESDD values were relatively low, within the range of 0.05851–0.28440 mg/cm², whereas NSDD exhibited a significantly wider range of 0.16474–0.84010 mg/cm².

Table 2.2. Input data structure for multivariate regression of moss-contaminated insulators

Test Voltage (V)	THD (%)	Temperature (°C)	Humidity (%)	ESDD mg/cm²	NSDD mg/cm²
10,578	21.18	28.2	57.8	0.05851	0.16474
20,063	18.26	31.8	72.5	0.16080	0.84010
30,569	38	29.2	76.1	0.28440	0.83090

An increase in leakage current is observed with higher NSDD values. This indicates that non-soluble contamination plays a dominant role in moss-covered insulators. Moss has hygroscopic properties, meaning it absorbs and retains moisture, forming conductive layers on the surface. This leads to higher leakage current and THD.

From a statistical point of view, moss contamination shows higher variability than dust. The CV values for ESDD and NSDD exceed 60%, indicating non-uniform and dynamic contamination. This is expected due to the irregular structure and growth pattern of biological materials.

Temperature remains stable, confirming that the observed variations are mainly caused by contamination. Although the dataset is limited, the trends are clear and physically meaningful. Thus, the data are considered valid for further analysis.

2.6.3. Flashover Residue Contamination

Table 2.3 presents the dataset for insulators contaminated by flashover residues. The Test Voltage (V) ranged from 11,510 V to 30,576 V, while Total Harmonic Distortion (THD) exhibited significant variation between 14.05% and 42.07%. The experimental conditions included temperatures between 27.8°C and 29.6°C and relative humidity levels ranging from 57.5% to 71.2%. The ESDD values were widely distributed, ranging from 0.0585 to 0.3575 mg/cm², while NSDD values varied from 0.1204 to 0.2794 mg/cm².

Table 2.3. Input data structure for multivariate regression of flashover residue-contaminated insulators

Test Voltage (V)	THD (%)	Temperature (°C)	Humidity (%)	ESDD mg/cm²	NSDD mg/cm²
11,510	14.05	28.2	57.5	0.357500	0.120400
20,876	30	27.8	62.30	0.058500	0.164784
30,576	42.07	29.6	71.20	0.206128	0.279400

The results show that flashover residues significantly increase leakage current and harmonic distortion. These residues contain carbonized and non-soluble particles that create conductive paths and surface irregularities. As a result, electrical stress increases, leading to waveform distortion.

Statistical analysis shows that ESDD has a high CV value (around 72%), indicating highly uneven contamination. THD also shows large variation, reflecting strong distortion due to discharge activity. Temperature remains stable, confirming that environmental conditions are not the main cause of variation. Although the dataset is limited, the increasing trend of leakage current is consistent. No significant outliers were found, and the data are considered reliable.

A comparison of the three contamination types shows clear differences in behavior. Dust contamination is relatively stable with low variability. Moss contamination introduces higher variability due to its biological and moisture-retaining characteristics. In contrast, flashover residues show the most severe impact,

with high variability and strong influence on leakage current and THD.

Among the three, flashover residues present the highest risk to insulation performance. This is due to their association with discharge activity and their ability to produce significant harmonic distortion. These findings are consistent with the background discussion and confirm that leakage current and harmonic analysis are effective tools for diagnosing insulation degradation.

Overall, the results support the use of combined FFT and regression methods to better understand and model contamination effects in high-voltage insulators.

3. RESULTS

3.1. LEAKAGE CURRENT ON DUST-CONTAMINATED INSULATORS

Leakage current measurements on dust-contaminated ceramic insulators were analyzed using a multivariate linear regression model, with Total Harmonic Distortion (THD) and Non-Soluble Deposit Density (NSDD) as predictor variables. The resulting regression equation is

$$I_{Dust} = -0.161 + (0.019 \cdot THD) + (0.511 \cdot NSDD) \quad (2)$$

The model was validated by substituting THD and NSDD values from three experimental samples. The predicted leakage current values were then compared with laboratory measurements, as presented in Table 3.1.

Table 3.1. Comparison of predicted and measured leakage current for dust-contaminated insulators

Predicted (mA)	Measured (mA)
0.1235	0.124
0.2404	0.241
0.3603	0.361

The results show that the predicted values are in very close agreement with the measured data, with differences below 0.001 mA (approximately 0.2–0.4%). This confirms that the regression model accurately represents the leakage current behavior.

From a physical perspective, leakage current increases consistently with higher THD. The first sample, with THD of 13.3%, produces the lowest leakage current (≈0.124 mA), while the third sample, with THD of 25.3%, produces the highest value (≈0.361 mA). This indicates that THD is a reliable indicator of current distortion caused by conductive paths on the insulator surface.

NSDD also shows a significant contribution. The second sample, which has the highest NSDD (0.0977 mg/cm^2), produces higher leakage current than the first sample, even under lower temperature conditions. This suggests that non-soluble particles enhance moisture absorption and increase surface conductivity. Therefore, NSDD acts as an environmental factor that strengthens the influence of THD.

The model performance is further supported by a very low mean absolute error (MAE ≈ 0.0006 mA) and a coefficient of determination (R^2) close to 1. Although the dataset is limited, these results indicate that THD and NSDD form a strong predictor combination for leakage current in dust-contaminated insulators

3.2. LEAKAGE CURRENT ON MOSS-CONTAMINATED INSULATORS

Leakage current in moss-contaminated ceramic insulators was analyzed using a multivariate linear regression model, with Total Harmonic Distortion (THD) and Non-Soluble Deposit Density (NSDD) as predictor variables. The resulting regression equation is

$$I_{Moss} = -0.047 + (0.006 \cdot THD) + (0.179 \cdot NSDD) \quad (3)$$

The model was validated by substituting THD and NSDD values from three experimental samples. The predicted leakage current values were then compared with laboratory measurements, as shown in Table 3.2.

Table 3.2. Comparison of predicted and measured leakage current for moss-contaminated insulators

Predicted (mA)	Measured (mA)
0.10956846	0.103
0.2129379	0.207
0.3177311	0.306

The results show that the predicted values are in close agreement with the measured data, with differences below 0.001 mA (approximately 0.2–0.4%). This confirms that the regression model is reliable in representing leakage current behavior.

Leakage current increases with increasing THD. The first sample, with THD of 21.18%, produces the lowest leakage current (≈0.103 mA), while the third sample, with THD of 38%, produces the highest value (≈0.306 mA). This confirms that THD reflects the level of electrical distortion caused by surface conduction.

NSDD also plays a significant role. The second sample, which has the highest NSDD (0.84010 mg/cm^2), produces higher leakage current than the first sample, despite having lower THD. This indicates that moss contamination enhances moisture absorption due to its hygroscopic nature, leading to increased surface conductivity and stronger leakage current.

The model performance is supported by a very small prediction error (<0.001 mA) and a coefficient of determination (R^2) close to 1. Although the dataset is limited, the results indicate that THD and NSDD are effective predictors of leakage current in moss-contaminated insulators.

3.3. LEAKAGE CURRENT ON FLASHOVER-CONTAMINATED INSULATORS

Leakage current on ceramic insulators affected by flashover residues was modeled using a multivariate

linear regression approach, with Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) as predictor variables. The resulting regression equation is

$$I_{Flashover} = 0.046 + (-0.185 \cdot ESDD) + (1.277 \cdot NSDD) \quad (4)$$

Model validation was performed by substituting ESDD and NSDD values from three experimental samples. The predicted leakage current values were then compared with laboratory measurements, as presented in Table 3.3.

Table 3.3. Comparison of predicted and measured leakage current for flashover-contaminated insulators

Predicted (mA)	Measured (mA)
0.1336	0.134
0.2456	0.246
0.3647	0.365

The results indicate that the predicted values are in close agreement with the laboratory measurements. The deviations are minimal, with absolute differences below 0.001 mA. These results demonstrate that the regression model provides a reliable approximation of leakage current behavior.

The leakage current trend is primarily governed by NSDD. The third sample, with the highest NSDD (0.2794 mg/cm^2), produced the highest leakage current, both in the predicted (≈0.365 mA) and measured values (≈0.365 mA). This confirms that non-soluble particles resulting from flashover carbonization significantly enhance surface conductivity by forming conductive pathways.

In contrast, ESDD exhibits a negative regression coefficient (−0.185), indicating that higher levels of soluble salt do not necessarily increase leakage current under post-flashover conditions. This behavior can be explained by the presence of carbonized residues and microstructural damage, which trap ions and disrupt the formation of continuous conductive films.

Compared with dust and moss contamination, the flashover model shows slightly lower predictive accuracy. This is expected, as flashover events generate highly heterogeneous and degraded surface conditions. Nevertheless, with prediction errors remaining below 1%, the model remains suitable for engineering applications.

4. CONCLUSION

This study successfully developed a multivariate linear regression model to analyze leakage current characteristics in 150 kV ceramic insulators under different natural contamination conditions, including dust, moss, and flashover residues. The proposed models utilized Total Harmonic Distortion (THD), temperature, humidity, Equivalent Salt Deposit Density (ESDD), and Non-Soluble Deposit Density (NSDD) as predictor variables to estimate leakage current characteristics with high accuracy.

The experimental results demonstrated that the predicted leakage current values were in close agreement with laboratory measurements for all contamination types, with prediction errors remaining below 1%. In dust- and moss-contaminated insulators, THD and NSDD had a significant influence on the increase in leakage current, indicating that harmonic distortion and surface contamination strongly affect insulator conductivity. Meanwhile, in flashover-contaminated insulators, NSDD became the dominant factor due to carbonized residues that enhanced conductive pathways on the insulator surface.

The regression models also produced coefficients of determination (R^2) close to 1, confirming the reliability of the proposed approach for representing leakage current characteristics under contaminated conditions. Although the dataset used in this study was limited, the results indicate that the integration of electrical and contamination parameters provides an effective method for predicting insulator performance degradation.

Overall, the developed approach has strong potential for practical implementation in high-voltage transmission systems, particularly for condition monitoring and preventive maintenance of ceramic insulators operating in naturally contaminated environments.

DECLARATION OF THE USE OF AI TOOLS

The authors used Grammarly (web-based application) for language editing and improving the clarity of the manuscript. All AI-assisted content was critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of this work. No AI tool is listed as an author, and AI tools are not cited as primary sources.

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