Contamination Assessment of 150-kV Ceramic Insulators Based on ESDD and NSDD Using a Mamdani Fuzzy Logic Approach

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Abstract

The reliability of high-voltage transmission systems is significantly affected by contamination on ceramic insulators, which reduces dielectric strength and increases flashover risk. This study proposes a Mamdani Fuzzy Logic approach to assess contamination severity on 150-kV ceramic insulators along the Koto Panjang–Payakumbuh transmission line. The 86-km transmission line consists of 248 towers, with approximately 82% of flashover incidents occurring in hilly areas. The fuzzy inference system was developed in MATLAB using the Equivalent Salt Deposit Density (ESDD) as the primary input parameter to estimate flashover voltage. Experimental results indicate that increasing ESDD decreases flashover voltage from 346.8 kV at 160.8 mg/cm² to 341.2 kV at 284.4 mg/cm², demonstrating that higher contamination severity increases flashover susceptibility. The proposed model achieved a prediction accuracy of 94%, while the agreement between calculated and experimental results reached 83%. These findings demonstrate that the Mamdani Fuzzy Logic model provides an effective and reliable tool for contamination assessment and supports condition-based maintenance of high-voltage transmission insulators.

Keywords: *Ceramic insulators; Contamination assessment; Mamdani fuzzy logic; Flashover voltage; Condition-based maintenance.*

1. Introduction

The reliability of high-voltage transmission systems depends significantly on the insulation performance of transmission line insulators[1][2][3]. Ceramic insulators are widely employed in 150-kV transmission networks because of their excellent mechanical strength, electrical insulation capability, and long service life[4]. However, prolonged exposure to environmental conditions such as high temperature, humidity, airborne dust, and biological contaminants can deteriorate the insulation surface, leading to increased surface conductivity and reduced dielectric strength. These conditions promote leakage current and eventually increase the probability of flashover, thereby compromising the continuity and reliability of power delivery [5][6].

The 150-kV Koto Panjang–Payakumbuh transmission line in Indonesia is particularly vulnerable to contamination-induced insulation failures because it traverses mountainous terrain characterized by high humidity and frequent lightning activity[7][8][9]. The transmission line extends approximately 86 km and consists of 248 transmission towers equipped with porcelain suspension insulators. Field observations indicate that approximately 82% of flashover incidents occur in hilly areas, while only 16% occur in agricultural regions and 2% in open areas. Several towers, including Towers 10, 17, 43, 48, 50, and 59, experience repeated flashover events with more than one trip-out annually. These failures reduce transmission reliability and increase maintenance costs [10][9][11].

Previous studies have demonstrated that contamination severity can be evaluated using the Equivalent Salt Deposit Density (ESDD) recommended by IEC 815, which classifies contamination levels from light to very heavy according to salt deposit density [12][13][14]**.** Numerous investigations have also reported that increasing contamination decreases flashover voltage and accelerates insulation degradation [5]. Other researchers have employed artificial intelligence techniques, including Artificial Neural Networks, Support Vector Machines, and fuzzy inference systems, to estimate flashover characteristics and insulator conditions[15][16]. Among these approaches, the Mamdani Fuzzy Logic method has attracted considerable attention because it effectively represents uncertain environmental conditions while maintaining transparent and interpretable decision rules [15][17][18]**.** Despite these advances, existing studies primarily focus on flashover prediction or leakage current estimation, whereas relatively few studies investigate contamination assessment using fuzzy reasoning as a practical decision-support tool for transmission maintenance. Moreover, limited research has been conducted using field data from naturally contaminated ceramic insulators operating under tropical environmental conditions, particularly on the Koto Panjang–Payakumbuh transmission line. Consequently, a reliable contamination assessment model that can assist utilities in evaluating insulator condition before flashover occurs remains unavailable.

Therefore, this paper aims to develop a Mamdani Fuzzy Logic-based contamination assessment model for 150-kV ceramic insulators operating on the Koto Panjang–Payakumbuh transmission line. The proposed model evaluates contamination severity based on Equivalent Salt Deposit Density (ESDD) and analyzes its relationship with flashover voltage. The developed approach is expected to provide an effective decision-support tool for insulator condition assessment and to support condition-based maintenance strategies for improving the reliability of high-voltage transmission systems.

2. Materials and Methods

2.1 Materials

This study was conducted using naturally contaminated porcelain suspension insulators collected from the 150-kV Koto Panjang–Payakumbuh transmission line, Indonesia. The transmission line extends approximately 86 km and consists of 248 transmission towers operating under tropical environmental conditions. A total of nine porcelain insulator specimens were selected as the experimental dataset, consisting of three dust-contaminated insulators, three moss-contaminated insulators, and three insulators contaminated by flashover residue. In addition, clean insulators were used as reference samples for comparison. Before laboratory testing, each specimen was visually inspected to verify its contamination condition and ensure consistency in contamination classification. The contamination severity was evaluated using the Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) methods in accordance with IEC 60507 and IEC 60815 standards [12]. Flashover voltage tests were performed using an AC high-voltage test system in the High Voltage Laboratory. Each insulator specimen underwent three repeated high-voltage tests to improve the reliability and repeatability of the experimental data. During each test, the applied voltage was gradually increased from 10 kV to a maximum of 30 kV or until flashover occurred. Ambient temperature and relative humidity were recorded throughout the experiments to minimize the influence of environmental variations on the test results.

The Mamdani Fuzzy Logic model was developed using MATLAB R2023a (MathWorks Inc., Natick, MA, USA) with the Fuzzy Logic Toolbox. The fuzzy inference system employed two input variables, namely Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD), while the output variable represented the flashover condition of the porcelain insulator. Triangular membership functions were selected for all input and output variables because they provide a simple mathematical representation, low computational complexity, and smooth transitions between contamination levels. Furthermore, triangular membership functions are widely adopted in engineering applications involving limited experimental datasets and expert-based knowledge. The fuzzy inference system consisted of nine IF–THEN rules developed from the combination of IEC contamination classifications and the experimental observations obtained during laboratory testing. The inference process employed the MIN operator for implication and the MAX operator for aggregation, while the final crisp output was determined using the centroid defuzzification method. The predicted contamination level and flashover condition obtained from the Mamdani Fuzzy Logic model were subsequently compared with the experimental measurements to evaluate the model's performance.

2.2 Experimental Procedure

The experimental procedure consisted of five sequential stages, as illustrated in Figure 1.

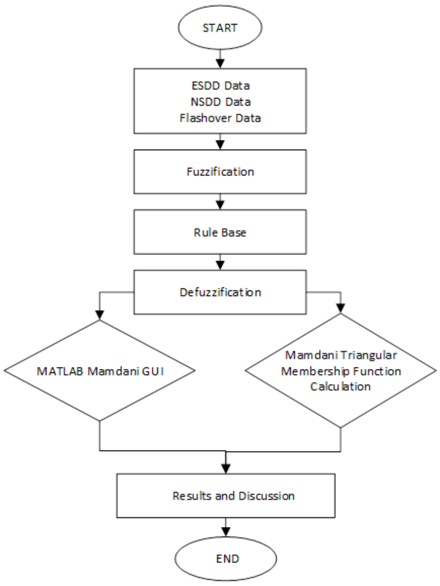


Figure 1. Experimental Procedure

2.2.1 Sample Preparation

The porcelain insulators used in this study were collected from the 150-kV Koto Panjang–Payakumbuh transmission line. A total of nine ceramic insulator specimens were used as the experimental dataset, consisting of three dust-contaminated insulators, three moss-contaminated insulators, and three insulators with flashover residue contamination. Before laboratory testing, each specimen was visually inspected to verify its contamination condition and ensure consistency in the contamination classification. Subsequently, each specimen underwent three repeated high-voltage tests. During each test, the applied voltage was gradually increased from 10 kV up to a maximum of 30 kV or until flashover occurred. The repeated measurements were performed to improve the reliability and repeatability of the experimental data, which were subsequently used to calculate the Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) values as inputs to the proposed Mamdani Fuzzy Logic model.

2.2.2 Contamination Measurement

Surface contamination was quantified using the Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) methods following IEC 60507 [12]**.** The corrected conductivity at 20°C was calculated as

$$\sigma_{20} = \sigma_t[1 - k_t(t_s - 20)] \tag{1}$$

where σ_{20} = conductivity corrected to 20^0C (μs/cm) ; σ_t= measured conductivity (μs/cm) ; k_t=temperature correction coefficient, t_s = solution temperature (‘C)

The ESDD value was calculated using

$$\mathrm{ESDD} = S_a \frac{V}{A} \tag{2}$$

Where ESDD = equivalent salt deposit density (mg/cm²); S_a salt concentration ; V = washing water volume (cm³) ; A= washed surface area (cm²)

The NSDD value was determined as

$$\mathrm{NSDD} = \frac{(1000(W_f - W_i)}{A} \tag{3}$$

Where NSDD = non-soluble deposit density (mg/cm²) ; W_f = filter paper weight after drying (mg) ; W_i = clean filter paper weight (mg) ; A = sampling area (cm²)

2.2.3. Flashover Voltage Test

Flashover tests were carried out using an AC high-voltage transformer. The applied voltage was increased gradually until flashover occurred. The measured flashover voltage was corrected to standard atmospheric conditions according to IEC 60060-1.

$$V_b = \delta V_s \tag{4}$$

Where V_b=corrected flashover voltage (kV) ; V_s = measured flashover voltage (kV) ; δ = air-density correction factor

2.2.4 Mamdani Fuzzy Logic Model

The contamination assessment model was developed using the Mamdani Fuzzy Inference System (FIS) implemented in the MATLAB Fuzzy Logic Toolbox (MATLAB R2023a, MathWorks Inc., Natick, MA, USA). The proposed model employed two input variables, namely Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD), while the output variable represented the flashover voltage level of the porcelain insulator. The input variables were defined based on the contamination measurements obtained from the laboratory tests and the contamination severity classifications specified in IEC 60507 and IEC 60815. Three linguistic terms (Low, Medium, and High) were assigned to each input variable using triangular membership functions. For the ESDD variable, the membership ranges were defined as Low (0–150 mg/cm²), Medium (50–250 mg/cm²), and High (150–300 mg/cm²). Similarly, the NSDD variable was divided into Low (0–0.55 mg/cm²), Medium (0.22–0.88 mg/cm²), and High (0.55–1.00 mg/cm²).

The output variable represented the flashover voltage level of the porcelain insulator and was also described using three triangular membership functions, namely Low (300–350 kV), Medium (320–380 kV), and High (350–400 kV). The overlapping regions between adjacent membership functions were intentionally introduced to represent uncertainties in contamination severity and to provide smooth transitions during the fuzzy inference process. Triangular membership functions were selected because they provide a simple mathematical formulation, low computational complexity, and efficient computation while maintaining sufficient accuracy for engineering decision-making problems. Moreover, this type of membership function is widely adopted in fuzzy-based insulation diagnostics, particularly when the available experimental data are limited and expert knowledge is incorporated into the inference process.

The Mamdani fuzzy inference system consisted of nine IF–THEN rules developed from the combination of IEC contamination classifications and the experimental observations obtained during laboratory testing. These rules describe the relationship between the contamination parameters (ESDD and NSDD) and the corresponding flashover voltage level. The complete fuzzy rule base is presented in table 1. The inference mechanism employed the MIN operator for fuzzy implication and the MAX operator for aggregation of all activated rules. Finally, the aggregated fuzzy output was converted into a crisp flashover voltage value using the centroid defuzzification method. The predicted flashover voltage obtained from the fuzzy model was subsequently compared with the experimental measurements to evaluate the effectiveness of the proposed contamination assessment model.

Table 1**.** Input and Output Variables of the Mamdani Fuzzy Logic Model

Variable	Linguistic Term	Membership Function	Domain
ESDD (mg/cm²)	Low	Triangular	0 – 150
	Medium	Triangular	50 – 250
	High	Triangular	150 – 300
NSDD (mg/cm²)	Low	Triangular	0 – 0,55
	Medium	Triangular	0,22 – 0,88
	High	Triangular	0,55 – 1,00

Flashover Voltage (kV)	Low	Triangular	300 – 350
	Medium	Triangular	320 – 380
	High	Triangular	350 –400

Table 2. Mamdani Fuzzy Rule Base

Rule	ESDD	NSDD	Flashover Voltage
R1	Low	Low	High
R2	Low	Medium	Medium
R3	Low	High	High
R4	Medium	Low	Medium
R5	Medium	Medium	High
R6	Medium	High	Medium
R7	High	Low	High
R8	High	Medium	Medium
R9	High	High	Low

2.2.5 Model Validation

The proposed model was validated by comparing fuzzy prediction results with experimental measurements. Prediction accuracy was calculated using

$$\text{Accuracy} = \frac{N_c}{N_t} x100\% \tag{5}$$

Where N_c= number of correctly predicted observations; N_t= total observations

The agreement between predicted and measured flashover voltages was also evaluated. All computations were performed using MATLAB R2023a.

3. Results and Discussion

3.1 Contamination Assessment Using the Mamdani Fuzzy Logic Model

The proposed Mamdani Fuzzy Logic model was developed to evaluate contamination severity on 150-kV ceramic insulators based on the Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) parameters. The overall research framework is illustrated in Figure 1, which summarizes the data acquisition, fuzzification, inference, and defuzzification processes used for contamination assessment. The fuzzy inference system was implemented using MATLAB Fuzzy Logic Toolbox with two input variables (ESDD and NSDD) and one output variable representing the flashover condition. Triangular membership functions were selected because they provide simple implementation and efficient computation while maintaining satisfactory prediction performance. The input variables were classified into three linguistic levels (Low, Medium, and High), whereas the output variable consisted of Low, Medium, and High flashover risk. Nine fuzzy IF–THEN rules were established based on IEC contamination classifications and field observations collected from the Koto Panjang–Payakumbuh transmission line. Similar fuzzy inference structures have been successfully applied for uncertainty modeling in high-voltage insulation assessment.

3.2 Effect of Contamination on Flashover Voltage

The contamination assessment results obtained from the Mamdani Fuzzy Logic model are summarized in Table 3 The results indicate that increasing contamination severity significantly reduces the flashover voltage of ceramic insulators. For example, when the ESDD increased from 160.8 mg/cm² to 284.4 mg/cm², the flashover voltage decreased from 346.8 kV to 341.2 kV, indicating deterioration of the dielectric performance due to surface contamination. Higher contamination levels promote the formation of conductive paths on the insulator surface, thereby increasing leakage current and reducing insulation strength.

This observation agrees with previous investigations reporting that soluble and non-soluble contaminants significantly influence flashover performance under humid environmental conditions.

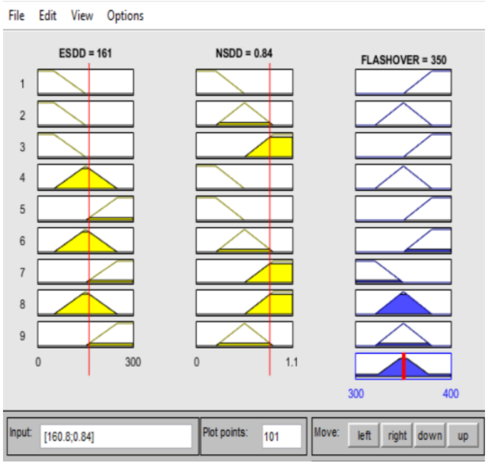
Table 3. The contamination assessment results obtained from the Mamdani Fuzzy Logic

No	Contamination Type		MATLAB Prediction
	ESDD	NSDD	
1	160.8	350	285,065
2	284.4	325	337,64
3	258.6	318	325
4	247.1	320	339,33
5	232.9	330	338,366

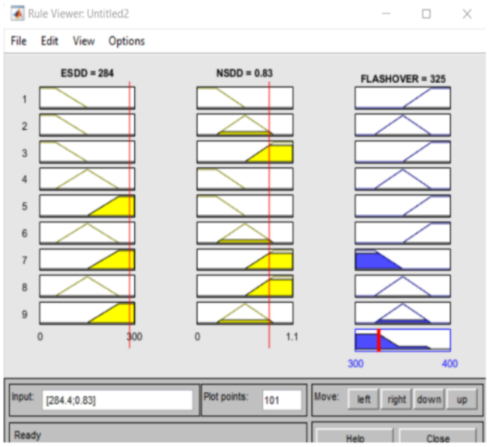
3.3 Model Validation

To evaluate the performance of the proposed Mamdani Fuzzy Logic model, a two-stage validation process was conducted. In the first stage, the flashover voltages obtained from the analytical calculation were compared with the experimental measurements obtained from laboratory testing. The percentage difference between the two datasets was calculated for each test case, and the overall agreement was determined based on the average percentage difference. The comparison showed a cumulative percentage difference of 17%, corresponding to an overall agreement of approximately 83%. This result indicates that the analytical calculation provides a reasonably accurate representation of the experimentally measured flashover voltages under different contamination conditions. In the second stage, the flashover voltages predicted by the Mamdani Fuzzy Logic model implemented in the MATLAB Fuzzy Logic Toolbox were compared with the analytical calculation results. As presented in Table 4.6, the percentage differences between the analytical calculation and MATLAB prediction ranged from 1% to 2%, resulting in a cumulative percentage difference of 6%. Consequently, the proposed Mamdani Fuzzy Logic model achieved an overall agreement of approximately 94%, demonstrating that the fuzzy inference system accurately reproduced the analytical calculation with only minor deviations. The small differences observed can be attributed to the approximation characteristics of the fuzzy inference process and the overlapping triangular membership functions used in the model.

Overall, the validation results demonstrate that the proposed Mamdani Fuzzy Logic model provides satisfactory prediction performance for estimating flashover voltage based on the ESDD and NSDD contamination parameters. The agreement level of 94% between the analytical calculation and the MATLAB prediction confirms the consistency of the proposed fuzzy inference system, while the 83% agreement between the analytical calculation and the experimental measurements indicates that the developed model can effectively represent the contamination characteristics of naturally polluted ceramic insulators under tropical operating conditions. These findings suggest that the proposed approach can serve as a practical decision-support tool for contamination assessment and maintenance planning of high-voltage transmission line insulators.



(a)



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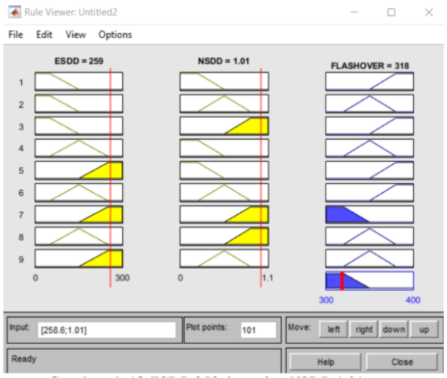

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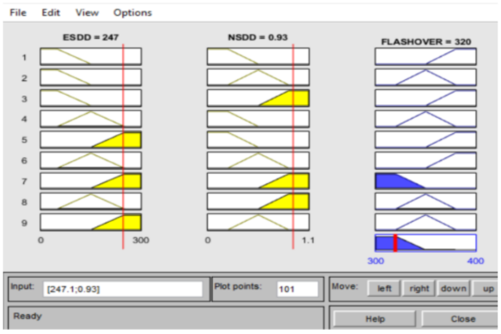

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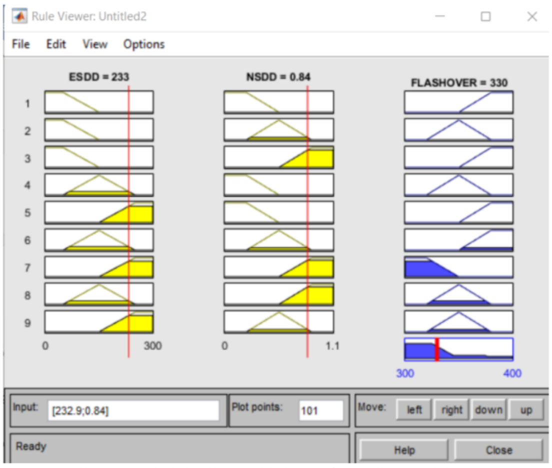

(e)

Figure 2. Research framework of the Mamdani Fuzzy Logic model for contamination assessment (a) ESDD 160.8 mg and NSDD 0.84mg (b) ESDD 284,4 mg and NSDD 0,83mg (c) ESDD 258,6 mg and NSDD 1,01mg. (d) ESDD 247,1 mg and NSDD 0,93 mg (e) ESDD 232,9 mg dan NSDD 0,84 mg

Table 1. Comparison between experimental flashover voltage and Mamdani Fuzzy Logic prediction

No	Contamination Type		Experimental Calculation	MATLAB Prediction	Accuracy (%)
	ESDD	NSDD			
1	160.8	0.8401	285,065	350	1%
2	284.4	0.8309	337,64	325	1%
3	258.6	1.0151	325	318	1%
4	247.1	0.9309	339,33	320	2%
5	232.9	0.8417	338,366	330	1%
TOTAL					94%

3.4 Discussion

The validation results demonstrate that the proposed Mamdani Fuzzy Logic model provides a reliable approach for predicting the flashover voltage of naturally contaminated porcelain insulators. The comparison between the analytical calculation and the MATLAB implementation yielded an agreement of 94%, while the analytical calculation showed an agreement of 83% with the experimental measurements. These results indicate that the proposed fuzzy inference system can effectively represent the relationship between contamination severity and flashover voltage with satisfactory prediction accuracy. From a physical perspective, the contamination layer deposited on the insulator surface significantly influences its dielectric performance. An increase in the Equivalent Salt Deposit Density (ESDD) increases the conductivity of the contamination layer. Under humid or wet environmental conditions, the conductive layer promotes leakage current flow along the insulator surface, resulting in localized heating and the formation of dry bands. These dry bands create highly non-uniform electric fields that facilitate partial discharge activity and eventually initiate flashover at lower voltages. Consequently, higher ESDD values generally correspond to lower flashover voltages.

Similarly, an increase in the Non-Soluble Deposit Density (NSDD) affects the surface characteristics of the contamination layer by increasing its roughness and its ability to retain moisture and pollutants. Although NSDD is not directly conductive, it contributes to maintaining a wet contamination layer, thereby enhancing the effect of soluble contaminants on surface conductivity. As a result, the combined influence of ESDD and NSDD accelerates leakage current development and reduces the dielectric withstand capability of the insulator. This phenomenon is consistent with the contamination mechanisms described in IEC 60815 and IEC 60507, which identify both soluble and non-soluble contaminants as important factors influencing flashover performance under polluted service conditions. Unlike conventional deterministic threshold methods that classify contamination using fixed limits, the proposed Mamdani Fuzzy Logic approach accommodates the inherent uncertainty associated with contamination measurements through overlapping membership functions and rule-based inference. This enables smooth transitions between contamination levels and produces more realistic flashover voltage predictions, particularly for contamination conditions that lie near classification boundaries.

The proposed model also offers practical advantages for condition monitoring because it estimates contamination severity using the measurable parameters ESDD and NSDD, which are widely adopted in insulation maintenance practices. Consequently, maintenance activities can be scheduled according to the actual contamination condition of the insulator rather than relying solely on fixed inspection intervals. This condition-based maintenance approach has the potential to reduce unnecessary maintenance costs while improving the operational reliability of high-voltage transmission systems. Overall, the proposed Mamdani Fuzzy Logic model provides a practical decision-support tool for transmission utilities by integrating contamination measurements with intelligent inference techniques. Although the present study was conducted using nine naturally contaminated porcelain insulators collected from a single 150-kV transmission line, the promising validation results indicate that the proposed approach can be extended to larger datasets and different environmental conditions. Future work should include a greater number of insulator samples, additional contamination types, and comparative studies with other intelligent prediction methods, such as the Adaptive Neuro-Fuzzy Inference System (ANFIS) and machine learning techniques, to further improve prediction accuracy and model generalization.

4. Conclusion

This study successfully developed a Mamdani Fuzzy Logic model for assessing contamination on 150-kV ceramic insulators operating along the Koto Panjang–Payakumbuh transmission line. The proposed model integrates Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) as input parameters to predict the flashover voltage level of naturally contaminated porcelain insulators. The experimental results confirmed that increasing contamination severity reduces the dielectric strength of the insulator, leading to lower flashover voltages. Specifically, the flashover voltage decreased from 346.8 kV at an ESDD of 160.8 mg/cm² to 341.2 kV at an ESDD of 284.4 mg/cm², while higher NSDD values also exhibited a decreasing trend in flashover voltage, indicating progressive insulation deterioration. The proposed Mamdani Fuzzy Logic model achieved an agreement of 94% with the MATLAB implementation and 83% with the experimental measurements, demonstrating that the developed fuzzy inference system is capable of reliably representing the relationship between contamination severity and flashover voltage. These results confirm that the proposed approach provides an effective and computationally efficient method for contamination assessment under uncertain operating conditions.

The main scientific contribution of this study lies in the integration of experimentally measured ESDD and NSDD parameters with a Mamdani Fuzzy Logic inference system for flashover voltage prediction using naturally contaminated porcelain insulators obtained from an operating 150-kV transmission line. This approach provides a practical framework for translating contamination measurements into engineering decisions, thereby extending the application of fuzzy logic from qualitative contamination classification to quantitative flashover voltage assessment. From a practical perspective, the proposed model can support condition-based maintenance (CBM) by enabling utilities to estimate insulator condition using measurable contamination parameters instead of relying solely on fixed maintenance intervals. Consequently, maintenance activities can be prioritized according to the actual contamination severity, potentially reducing maintenance costs while improving the reliability and operational performance of high-voltage transmission systems.

This study has several limitations. The experimental dataset consisted of only nine naturally contaminated porcelain insulators collected from a single transmission line and included three contamination types (dust, moss, and flashover residue). Therefore, the developed model may not fully represent the wide range of environmental conditions and contamination characteristics encountered in different transmission systems. Future research should consider larger datasets collected from multiple transmission lines, additional contamination types, and different climatic conditions to improve the robustness and generalization capability of the model. Furthermore, comparative studies involving other intelligent prediction techniques, such as the Adaptive Neuro-Fuzzy Inference System (ANFIS), artificial neural networks, and machine learning algorithms, are recommended to further enhance prediction accuracy and support intelligent maintenance planning for high-voltage insulation system.

Authors' Contributions

S.A. conceived the study, conducted the experiments, analyzed the data, and drafted the manuscript. A.F.K. supervised the research, contributed to the methodology, and reviewed the manuscript. A.A., A.S., Z.Z., and E. contributed to data analysis, validation, and manuscript revision. D.H. supervised the project and reviewed the manuscript. All authors read and approved the final manuscript.

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