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Impact of Natural Contamination on the Harmonic Distortion of Leakage Current in 150 kV Ceramic Insulators

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ABSTRACT

Ceramic insulators on High Voltage Overhead Lines (SUTT) in Indonesia, particularly on the Payakumbuh-Koto Panjang transmission line, are often exposed to natural contamination. This research evaluated the impact of natural contamination on the Total Harmonic Distortion (THD) of leakage current in 150 kV insulators, representing a new approach to understanding insulator performance in contaminated environments. Tests were conducted at the High Voltage Laboratory at Universitas Gadjah Mada using various types of contamination: moss, dust, flashover marks, and clean insulator conditions. The results showed that insulators contaminated with moss exhibited a maximum leakage current of 0.306 mA, with the highest THD reaching 36%, while insulators in clean condition had an average THD of 32.5%. Insulators contaminated with moss, dust, and flashover marks showed THD values of 25.37%, 19.03%, and 28.71%, respectively. Moss and flashover can significantly increase THD, especially when the number of disc-type insulators increases. These findings underscored the importance of a more intensive and targeted maintenance strategy for insulators to minimize the negative impacts of natural contamination, particularly in mountainous areas. This approach contributes to the enhancement of the reliability of high-voltage transmission lines in Indonesia.

1. INTRODUCTION

Contamination on an insulator's surface can degrade its performance [1-5]. Specific environmental conditions, long-term use, and contaminants such as dust, salt, and other particles can increase leakage current and reduce electrical performance, ultimately resulting in flashover [6-9]. Ceramic insulators contaminated in foggy coastal areas experience a decline in electrical performance, caused by surface wetting due to the accumulation of salt fog, which can lead to flashover [10-12]. Layers formed from the accumulation of contaminants on the insulator's surface can form conductive paths, thereby increasing leakage current from the line to the ground [12]. Increased humidity can reduce the flashover voltage gradient for all contamination profiles [13, 14]. Increased leakage current can degrade the insulation's strength and surface, leading to failure in the form of flashover [15-17]. Research comparing leakage current across various types of insulators with varying humidity levels revealed that changes in environmental conditions significantly affect the performance of insulators installed in the field [18, 19]. Leakage current has been studied to understand the characteristics of the flashover process stages and to predict the level of contamination [10].

Prior research examining the effect of contaminants on insulators primarily focused on the use of artificial contaminants, which provided greater control over experimental conditions and facilitated laboratory-scale testing [20-23]. However, such artificial contaminants did not accurately replicate the real environmental conditions in the field, necessitating a new study that introduces the use of natural contaminants. This recent study was done to address that need by using natural contaminants collected from the Payakumbuh-Koto Panjang High Voltage Overhead Line (PKPSUTT), Unlike previous studies, which predominantly used artificial contaminants in laboratory settings, this study employs natural contaminants, providing a more realistic understanding of insulator performance in actual environments. This approach introduces novelty by demonstrating a more relevant impact of contamination on insulator performance, particularly in mountainous regions, and by providing insights that are more reflective of real-world conditions.

Characterizing the leakage current in the ceramic insulators of PKPSUTT and examining their surfaces are necessary. PKPSUTT' towers are vulnerable to contamination [24, 25] as they are installed in hilly areas [18, 19]. As approximately 63%, 20%, and 16% of PKPSUTT's towers are piled in hilly areas, rice fields, and desert areas, respectively, flashovers occurring in those areas reach 82%, 16%, and 2%, respectively [26]. Hilly areas' environmental conditions increase insulators' vulnerability to contamination, leading to a high incidence of flashovers and the presence of leakage current [27]. PKPSUTT applies 150 kV ceramic insulators. Each single string consists of 11 (eleven) insulators [28].

In this study, Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) were used to determine the contaminants' masses on the insulators' surfaces, employing the swab technique as per the IEC TS 60815-1-2008 standard (Annex C). Both ESDD and NSDD can help measure the contamination levels quantitatively, allowing for an accurate evaluation of how different types of contaminants affect leakage current and dielectric strength.

PKPSUTT's 150 kV insulators were measured for their leakage currents and voltages through Fourier Transform analysis [29, 30]. By converting time-domain leakage current data into the frequency-domain data using the Fast Fourier Transform (FFT), the study aimed to measure the THD of the currents. This analysis helps classify the disturbances occurring and provides valuable insights into the mechanism of degradation of contaminated insulators [31]. The data were collected under laboratory conditions, with temperature and humidity adjusted to match actual field conditions, enabling a detailed investigation of how environmental factors impact an insulator's performance [32-34]. The use of natural contaminants offers a more accurate understanding of field conditions, allowing for better evaluation of the real effects of contamination on the dielectric properties of insulators.

This structured approach—from determining the contamination level using ESDD and NSDD, applying high voltage, conducting leakage current measurements, and using FFT analysis to quantify THD—ensures a comprehensive evaluation of insulator performance under contaminated conditions.

Furthermore, this research is significant as it introduces a novel approach to measuring THD in the leakage current of contaminated insulators. This approach aids in classifying disturbances and provides deeper insights into the degradation mechanisms of insulators, an aspect not explained in detail in previous studies, which primarily focused on the impact of contaminants on flashover without considering harmonic effects. It emphasizes that THD can be an important indicator in evaluating insulator health and electrical system stability. Ultimately, this study aimed to assess the impact of natural contaminants on leakage current and THD, providing insights into degradation mechanisms and offering data to enhance the reliability of high-voltage transmission systems in real-world rocky areas.

2. METHODOLOGY

This research was an experimental study focused on measuring and analyzing the leakage current patterns of 150 kV ceramic insulators, which had already experienced flashover, under natural contamination conditions (refer to Figure 1). The test insulators were categorized into four groups: dust-contaminated insulators, moss-contaminated insulators, clean insulators with flashover marks, and clean insulators which had already experienced flashover (new insulators), totaling 12 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. Future studies with a larger sample size are expected to enhance the robustness and generalizability of the findings. The aim was to understand the distinct characteristics and effects of different types of contaminants on the performance of insulators and identify factors influencing insulator pollution, particularly in terms of leakage current behavior.

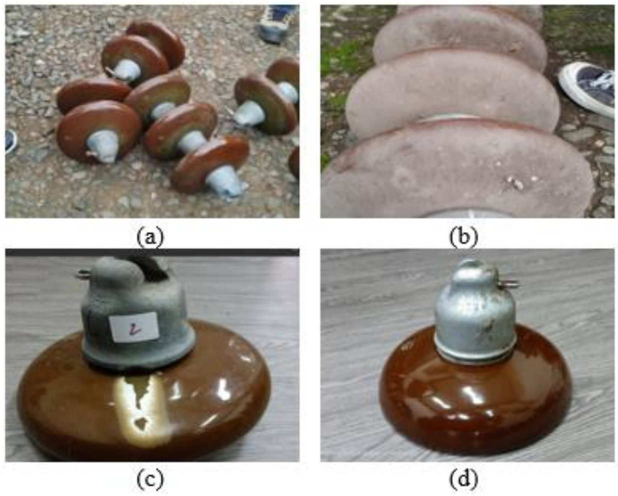


Figure 1. Ceramic insulator samples (a) Moss-contaminated insulators; (b) Dust-contaminated insulators; (c) Insulators with flashover marks and (d) Clean insulators having experienced flashover (new insulators)

To determine the contaminant mass on the insulator's surfaces, the Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) values were measured using the swab technique as per IEC TS 60815-1-2008 standards (Annex C). The measurement of ESDD and NSDD provides a reliable quantitative method for assessing the level of contamination, which is crucial for evaluating its impact on leakage current and dielectric strength. For these measurements, a volume of 250 cm^3 of distilled water was used, and conductivity was measured at 20°C. The results of the contaminant tests on the ceramic insulators are as follows:

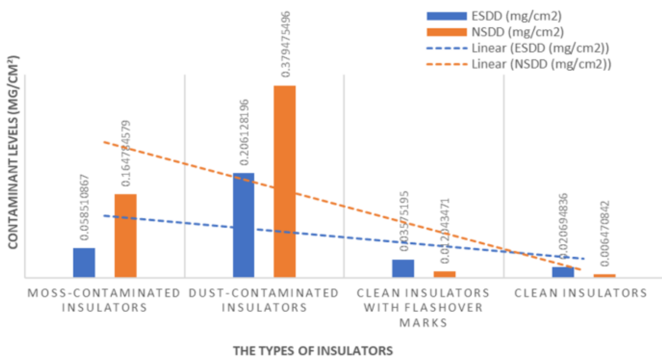


Figure 2. Comparison of ESDD and NSDD levels on different types of insulator

Figure 2 shows a comparison of ESDD and NSDD levels across different types of insulators. Based on the ESDD and NSDD test results from PKPSUTT's insulators, and in reference to the IEC 60815 standard, a dust-contaminated insulator, with an ESDD of 0.206 mg/cm^2 and an NSDD of 0.379 mg/cm^2, is classified as heavily contaminated (ESDD > 0.10 mg/cm^2). A moss-contaminated insulator, with an ESDD of 0.058 mg/cm^2 and an NSDD of 0.165 mg/cm^2, falls under the moderate contamination category (0.03 mg/cm^2 ≤ ESDD ≤ 0.10 mg/cm^2). A flashover-marked insulator, with an ESDD of 0.035 mg/cm^2 and an NSDD of 0.012 mg/cm^2, is classified as lightly contaminated (ESDD < 0.03 mg/cm^2), as is the clean insulator, which shows the lowest contamination levels.

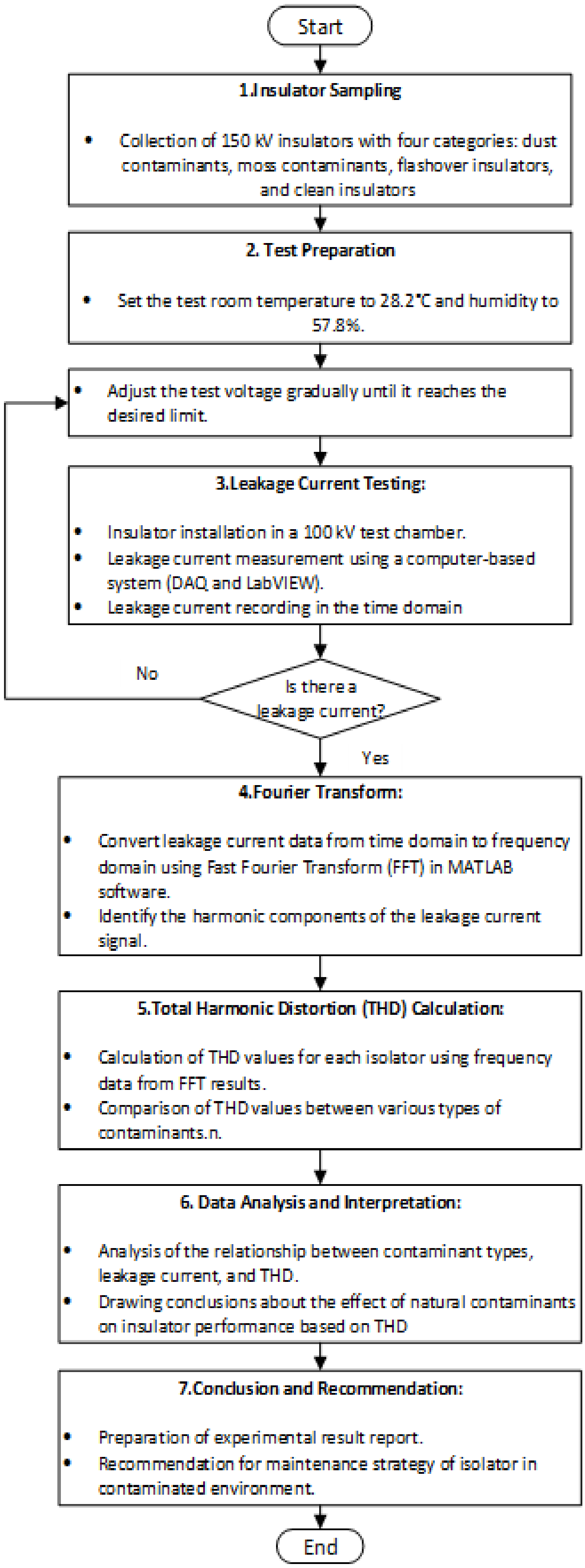


Figure 3. Research flowchart

The testing was carried out at the High Voltage Engineering Laboratory of Universitas Gadjah Mada (UGM), using a 100 kV MWB Germany test chamber set to a temperature of 28°C and 58% humidity to simulate real field conditions. The test transformer, manufactured by Messwandler-Bau GmbH, Bamberg, is of a TEO type, with a rated voltage of 2×(0.22/200) kV, a rated current of 10 kVA, a frequency of 50 Hz, and an impedance voltage of 14%. Due to equipment limitations, the number of disc insulators tested did not match the actual field configuration, so the insulators were tested incrementally, starting with a single disc insulator until leakage current was observed, followed by adding additional disc insulators for subsequent tests.

The leakage current testing was performed using a computer-based system capable of accurately recording and measuring current, utilizing National Instruments equipment. The specifications included an NI-9246 current input module, which is a three-channel, 22 Arms module designed for direct ring lug connectivity to three-phase high-current measurements of 1A and 5A current transformers (CTs).

Additionally, a Fluke 360 leakage clamp (300 V, 60 A, 50/60 Hz) was used for the measurements. The resulting waveforms were analyzed using Fourier Transform in Matlab, providing insight into the characteristics of the leakage current.

The step-by-step research procedure employed in this study is explained in Figure 3. The testing approach followed a systematic process of progressively adding disc insulators to understand the impact of increasing insulator count and contamination type on leakage current. By integrating the use of advanced measuring tools, this study aimed to correlate the observed leakage current to specific contamination levels, ultimately providing a deeper understanding of insulator performance under real-life conditions.

The tested insulators consisted of 3 dust-contaminated insulators, 3 moss-contaminated insulators, 3 insulators with flashover marks, and 3 clean insulators. Leakage current testing was performed using a computer-based system, where the installed insulators were subjected to a gradually increasing high voltage. The leakage current flowing through the insulators was continuously monitored and recorded by the system for further analysis.

The testing took place within a test chamber, where the magnitude of the leakage current was directly displayed on the Data Acquisition (DAQ) and LabView systems, which were connected in series with the insulator string. The applied voltage was incrementally increased at each stage of the testing, and the corresponding leakage current was measured. This process was repeated three times for each voltage level to ensure accuracy, and the average current values were calculated for analysis.

To further understand the behavior of the leakage current, the recorded time-domain data were converted into the frequency domain using the FFT algorithm implemented in MATLAB. The frequency-domain data were then visualized using bar graphs to display the presence and magnitude of harmonic components. To quantify the harmonic content, THD was calculated from the frequency-domain current data using Microsoft Excel. The THD value was calculated using the formula:

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{n_{max}} M_2 n}}{M_1} \times 100\%$$

where, M_2 represents the magnitude of the fundamental harmonic (50 Hz), and M_1 represents the magnitude of the harmonic.

This structured approach—starting from the application of high voltage, monitoring leakage current, converting the data to the frequency domain, and calculating THD, combined with the use of ESDD (Equivalent Salt Deposit Density) and NSDD (Non-Soluble Deposit Density) methods to determine the contaminant mass—ensures a comprehensive understanding of the effects of different contamination types on insulator performance. By quantifying the harmonic content of the leakage current and analyzing the amount of contaminants using ESDD and NSDD, this study aimed to provide valuable insights into the degradation mechanisms of contaminated insulators and the resulting impact on the stability and reliability of high-voltage transmission systems.

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. This study employed an experimental research method to investigate the effects of contaminants, specifically moss and dust, on the leakage current of insulators, as depicted in Figure 4.

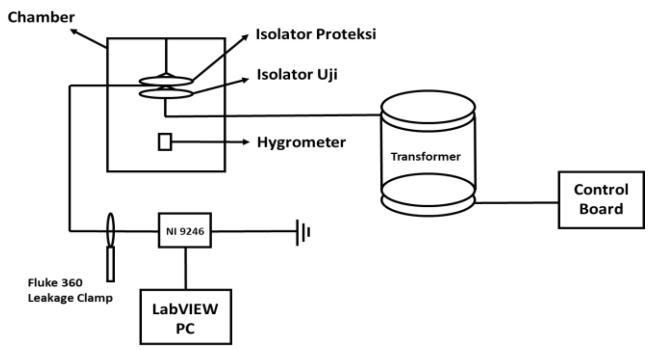
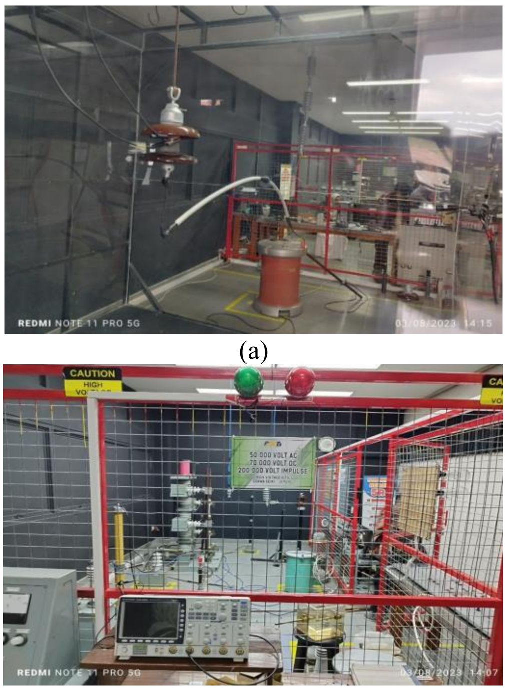


Figure 4. Leakage current measurement procedure series



(a)

(b)

Figure 5. Insulator measurement chamber (a) Insulator measurement chamber for leakage current (b) control board

The experimental setup was implemented in the High Voltage Laboratory at Universitas Gadjah Mada. Figure 4 illustrates the experimental procedure at the laboratory scale, while Figure 5(a) represents the test chamber used for measuring the insulators' leakage current, and Figure 5(b) shows the control board used for regulating the testing parameters.

3. RESULTS AND DISCUSSION

3.1 Preliminary data

Figure 6 presents initial experimental data from the laboratory, illustrating the relationship between test voltage and leakage current in 150 kV insulators subjected to various natural contaminants, including dust, moss, flashover marks, and clean conditions. The data analysis indicated a strong linear correlation between increasing test voltage and increasing leakage current for all types of insulators tested. However, each type of contaminant exhibited distinct leakage current characteristics.

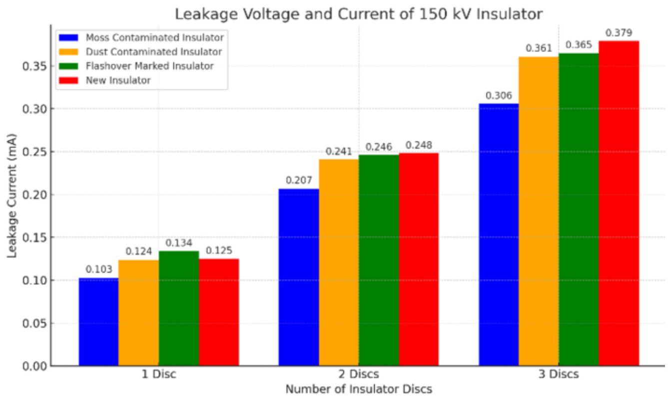


Figure 6. Relationship between voltage and leakage current of 150 kV insulator

For instance, the insulator contaminated with moss showed a leakage current of 0.103 mA at a test voltage of 10,578 V that increased to 0.306 mA at a test voltage of 30,569 V. Similarly, the dust-contaminated insulator exhibited an increase in leakage current from 0.124 mA at a test voltage of 10,625 V to 0.361 mA at 30,616 V. The insulator affected by flashover recorded a leakage current of 0.134 mA at a test voltage of 11,510 V that increased to 0,365 mA at the highest test voltage of 30,756 V. Even the new insulator, despite being in optimal condition, showed a significant increase in leakage current, from 0.125 mA at 10,485 V to 0.379 mA at 21,175 V.

The ANOVA results showed an F-statistic value of 0.100 and a *p*-value of 0.958. A *p*-value greater than 0.05 indicated no statistically significant difference in leakage current between the various types of insulators (moss-contaminated, dust-contaminated, flashover-affected, and new insulators) for 1, 2, and 3 disc-type insulators.

This suggests that the differences in leakage current between the different contaminant types are likely due to random variation rather than the effects of contamination itself, at the 95% confidence level. However, the trend of increasing average leakage current with more disc insulators and varying contaminant types indicates a pattern that warrants attention for insulator maintenance strategies.

Subsequently, an analysis was conducted to determine the impact of each insulator condition with various natural contaminants on THD and to evaluate how variations in the number of disc insulators affect the performance of the insulator system under high voltage conditions. THD calculations were then be performed for each type of contaminant, and additional testing was conducted to further explore the effects on insulator performance.

3.2 Case 1: Moss-contaminated insulator

3.2.1 Leakage current analysis for a single moss-contaminated insulator

For a single insulator contaminated with moss, leakage current was measured at various frequencies with a test voltage of 10,578 V. The results are summarized in Table 1.

Table 1. Leakage current spectrum at a test voltage of 10,578 v for a single moss-contaminated insulator

Frequency (Hz)	Leakage Current (A)
50	9.7E-05
150	5.5E-06
200	6.5E-06
250	6.9E-06
350	4.6E-06
400	6.3E-06
450	1.6E-05
600	4.9E-06
650	1.6E-06

For a single insulator contaminated with moss, THD was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{4.48184E-10}}{9.7E-05} 100\% = 21.18\%$$

These results indicated significant waveform distortion caused by moss contamination, identifying that even a single insulator can induce substantial harmonic distortion in the system.

3.2.2 Leakage current analysis for two contaminated insulators

The experiment was repeated for two insulators contaminated with moss at a test voltage of 21,063 V. The results are presented in Table 2.

Table 2. Leakage current spectrum at a test voltage of 10,063 V for two moss-contaminated insulators

Frequency (Hz)	Leakage Current (A)
50	0.00029
150	1.5E-05
200	7.3E-06
250	1.3E-05
350	6.5E-06
400	6.6E-06
450	4.5E-05
550	1.2E-05
600	5.6E-06
650	1.3E-05

THD for two insulators was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{2.88094E-09}}{2.9E-04} \times 100\% = 18.26\%$$

The reduction in THD compared to a single insulator indicates that distributing contamination across multiple insulators can mitigate some of the harmonic effects, although the distortion remains significant.

3.2.3 Leakage current analysis for three contaminated insulators

In the third experiment, leakage current was measured for three moss-contaminated insulators at a test voltage of 30,569 V. The results are presented in Table 3.

Table 3. Leakage current spektrum at a test voltage 30,569V for three moss-contaminated insulators

Frequency (Hz)	Leakage Current (A)
50	0.00035
150	2.1E-05
200	7.7E-06
250	2.2E-05
350	0.00001
400	6.9E-06
450	0.00012
550	7.1E-06
600	5.3E-06
650	6.8E-06
800	3.9E-06

THD was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{1.56664E-08}}{3.5E-04} \times 100\% = 36\%$$

A higher THD value indicates that as the number of contaminated insulators increases, harmonic distortion becomes more pronounced, reflecting the cumulative effect of contamination on the overall system performance.

3.3 Case 2: Dust-contaminated insulator

3.3.1 Leakage current analysis for a single dust-contaminated insulator

For a single dust-contaminated insulator, leakage current was measured at various frequencies with a test voltage of 10,578 V. The measurement results are presented in Table 4.

Table 4. Leakage current spectrum at a test voltage of 10,578 V for one dust contaminated insulator

Frequency (Hz)	Leakage Current (A)
50	0.00018
150	9.1E-06
200	4.7E-06
250	7.5E-06
350	4.7E-06
400	3.1E-06
450	1.3E-05
550	6.2E-06
600	3.1E-06
650	1.3E-05

For a single insulator contaminated with dust, THD was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{5.76032E-10}}{1.8E-04} \times 100\% = 13.3\%$$

This THD value indicates that a single dust-contaminated insulator contributes a moderate level of harmonic distortion to the system.

3.3.2 Leakage current analysis for two insulators contaminated with dust

Leakage current measurements were conducted for two dust-contaminated insulators at a test voltage of 20,551V. The results are summarized in Table 5.

Table 5. Leakage current spectrum at a test voltage of 20,551 V for two dust-contaminated insulators

Frequency (Hz)	Leakage Current (A)
50	0.00031
150	1.8E-05
200	5.1E-06
250	1.5E-05
350	1.3E-05
400	3.6E-06
450	4.7E-05
550	1.6E-05
600	3.8E-06
650	9.4E-06

The THD value was calculated as follows:

$$\text{THD} = \frac{\sqrt{3.26072E-09}}{3.1E-04} \times 100\% = 18.5\%$$

The increase in THD value for two insulators indicates that adding more contaminated insulators enhances harmonic distortion within the system.

3.3.3 Leakage current analysis for three insulators contaminated with dust

The final measurements were conducted for three dust-contaminated insulators at a test voltage of 30,616V. The results are presented in Table 6.

Table 6. Leakage current spectrum at a test voltage of 30,616 v for three dust-contaminated insulators

Frequency (Hz)	Leakage Current (A)
50	0.00051
150	0.000031
200	5.92E-06
250	2.54E-05
350	1.89E-05
400	4.5E-06
450	0.00012
550	1.27E-05
650	7.04E-06

The THD value was calculated as follows:

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{n_{max}} M^2 n}}{M_1} \times 100\% = 25.3\%$$

A higher THD value indicates that as the number of contaminated insulators increases, harmonic distortion, which can have a substantial impact on the stability and overall performance of the system, becomes more significant.

3.4 Case 3: Flashover-affected insulator

3.4.1 Leakage current analysis for a single flashover-affected insulator

Leakage current measurements were conducted for a single flashover-affected insulator at a test voltage of 11,510 V. The leakage current data at various frequencies are summarized in Table 7.

Table 7. Leakage current spectrum at a test voltage of 11,510 V for a single flashover-affected insulator

Frequency (Hz)	Leakage Current (A)
50	0.00018
150	7.08E-06
200	6.5E-06
250	7.67E-06
350	4.78E-06
400	6.36E-06
450	0.000016
650	0.000013

For a single flashover-affected insulator, THD was calculated as follows:

$$\text{THD} = \frac{\sqrt{6.39503E-10}}{1.8E-04} \times 100\% = 14.05\%$$

This THD value shows that a flashover-affected insulator causes significant harmonic distortion, but less than insulators with moss or dust.

3.4.2 Leakage current analysis for two flashover-affected insulators

Leakage current was measured for two flashover-affected insulators at a test voltage of 20,876 V. The results are presented in Table 8.

Table 8. Leakage current spectrum at a test voltage of 20,876 V for two flashover-affected insulators

Frequency (Hz)	Leakage Current (A)
50	0.00025
150	1.63E-05
200	7.57E-06
250	2.02E-05
350	1.25E-05
400	6.77E-06
450	6.52E-05
550	1.64E-05
600	5.23E-06
650	1.11E-05

THD for two flashover-affected insulators was calculated as follows:

$$\text{THD} = \frac{\sqrt{5.60368E-09}}{2.5E-04} \times 100\% = 30\%$$

The increase in the THD value indicates that adding two flashover-affected insulators has a greater impact on harmonic distortion, compared to having just a single insulator.

3.4.3 Leakage current analysis for three flashover-affected insulators

Measurements were conducted on three flashover-affected insulators at a test voltage of 30,576 V. The leakage current data at various frequencies are presented in Table 9.

Table 9. Leakage current spectrum at a test voltage of 30,576 V for three flashover-affected insulators

Frequency (Hz)	Leakage Current (A)
50	0.00037
150	2.3E-05
200	6.2E-06
250	2.5E-05
350	1.9E-05
400	8E-06
450	0.00015
550	5.9E-06
600	5.5E-06
650	7E-06

The THD value was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{2.423E-08}}{3.7E-04} \times 100\ \% = 42.07\%$$

The significant increase in THD value indicates that adding more flashover-affected insulators directly contributes to higher harmonic distortion. This impact has the potential to disrupt operational stability and reduce the overall efficiency of the electrical power system.

3.5 Case 4: New Insulator

3.5.1 Leakage current analysis for a single new insulator

Leakage current measurements were conducted on a single new insulator at a test voltage of 10,485 V. The leakage current data at various frequencies are summarized in Table 10.

Table 10. Leakage current spectrum at a test voltage of 10,485 V for a single new insulator

Frequency (Hz)	Leakage Current (A)
50	0.00016
150	9.06E-06
200	8.35E-06
250	7.25E-06
350	4.09E-06
400	6.12E-06
450	1.53E-06
550	5.99E-06
600	4.53E-06
650	1.31E-05
800	4.65E-06

For a single new insulator, THD was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{5.10526E-10}}{1.6E-04} \times 100\% = 14.12\%$$

This THD value indicates that although the new insulator is in good condition, harmonic distortion still occurs, albeit at a lower level compared to contaminated insulators.

3.5.2 Leakage current analysis for two new insulators

Leakage current measurements were conducted for two new insulators at a test voltage of 20,377 V. The results are summarized in Table 11.

Table 11. Leakage current spectrum at a test voltage of 20,377 V for two new insulators

Frequency (Hz)	Leakage Current (A)
50	0.00029
150	1.88E-05
200	6.35E-05
250	1.82E-05
350	9.01E-06
400	6.05E-06
450	6.49E-05
550	1.32E-05
600	5.29E-06
650	8.89E-06

THD for two new insulators was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{9.32798E-09}}{2.9E-04} \times 100\% = 33.3\%$$

The increase in THD for two new insulators indicates that even though the insulators are new, using multiple insulators can increase overall harmonic distortion.

3.5.3 Leakage current analysis for three new insulators

The final measurements were conducted on three new insulators at a test voltage of 31,175 V. The leakage current data at various frequencies are presented in Table 12.

Table 12. Leakage current spectrum at a test voltage of 31,175 V for three new insulators

Frequency (Hz)	Leakage Current (A)
50	0.00039
150	2.37E-05
200	6.33E-06
250	3.27E-05
350	1.45E-05
400	6.58E-06
450	0.00019
550	7.03E-06
600	5.36E-06
650	5.5E-06
800	4.7E-06

THD was calculated as follows:

$$\mathrm{THD} = \frac{\sqrt{3.81551E-08}}{3.9E-04} \times 100\% = 50.08\%$$

The high THD value indicates that, although the insulators are new and uncontaminated, the number of insulators used in the system has a significant impact on increasing harmonic distortion.

4. CONCLUSIONS

4.1 Analysis of the number of 150 kV disc insulators on THD values for various types of natural contaminants

Figure 7 illustrates the relationship between the number of disc insulators and the resulting THD values for various types of contaminants, involving moss-contaminated insulators, dust-contaminated insulators, flashover-affected insulators, and new insulators.

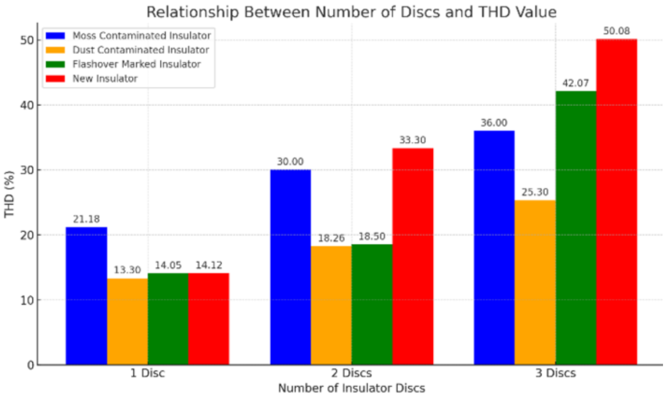


Figure 7. Graph of the relationship between the number of disc insulators and THD values for moss-contaminated, dust-contaminated, flashover-affected, and clean insulators

This study demonstrates that the number of disc insulators plays a crucial role in affecting the THD values of insulators contaminated by various natural contaminants. The results showed that for moss-contaminated insulators, THD increased significantly from 21.18% with a single disc insulator to 36% with three disc insulators, despite a slight decrease to 18.26% when two disc insulators were used. This indicates a cumulative effect of moss contamination on harmonic distortion. Dust-contaminated insulators exhibited a more stable increase in THD, from 13.30% with one disc insulator to 18.50% with two disc insulators, and 25.30% with three disc insulators. Flashover-affected insulators showed a marked increase in THD, from 14.05% with one disc insulator to 30.00% with two disc insulators, reaching 42.07% with three disc insulators, suggesting ongoing structural degradation due to flashover.

Even for new insulators, THD values increased significantly with the addition of more disc insulators, from 14.12% with one disc insulator to 33.30% with two disc insulators, and eventually to 50.08% with three disc insulators. This indicates that even in optimal conditions, using more disc insulators can lead to considerable harmonic distortion, potentially compromising system stability.

The ANOVA analysis showed that the differences in THD values between different types of contamination were not statistically significant (p-value > 0.05). However, the clear trend of increasing THD with more disc insulators emphasizes the importance of considering this factor in insulator design and maintenance. Increased THD can lead to greater harmonic distortion, reducing system reliability and increasing the risk of insulator failure. Therefore, THD monitoring and appropriate maintenance measures are essential to manage the potential for harmonic distortion in power systems.

4.2 Analysis of leakage current and harmonic distortion in insulators with various types of natural contamination

This study successfully identified and analyzed leakage current and THD in 150 kV insulators contaminated with natural contaminants such as moss, dust, and flashover effect, and new clear insulators using Fourier Transform. The results indicated a linear relationship between test voltage and leakage current for all types of insulators, suggesting that insulators' surface contamination significantly impacts their electrical performances. The impact of different types of natural contaminants on THD and leakage current varied, with moss-contaminated insulators showing an increase in THD from 21.18% to 36% at higher voltages, while dust-contaminated insulators exhibited a more moderate increase from 13.30% to 25.30%. Flashover-affected insulators experienced a rise in THD from 14.05% to 42.07%, indicating significant structural damage at all voltage levels. Even new insulators showed an increase in THD from 14.12% to 50.08% as the number of disc insulators increased.

The ANOVA analysis revealed no statistically significant difference in THD values between the different types of contaminants at a 95% confidence level (p-value > 0.05). Despite the lack of statistical significance, the observed trend of increasing THD highlights that surface contamination and the number of disc insulators are crucial factors affecting harmonic distortion. These results should be taken into account in operational and maintenance strategies.

Frequency spectrum analysis of leakage current using Fourier Transform showed the dominance of fundamental harmonic components at 50 Hz across all insulator types, with varying odd harmonics depending on the contamination type. These findings underlined the importance of effective maintenance strategies to ensure the reliability of high-voltage transmission networks. Therefore, it is essential to consider both the number of disc insulators and contamination conditions when designing and maintaining high-voltage power systems, as contaminants like moss and flashover can significantly increase THD, particularly with more disc insulators.

Recommendations for future research include increasing the sample size of insulators and considering more variables, such as chemical contamination or the effects of climate change on THD values. Additionally, developing sensor-based THD monitoring systems to detect real-time changes in insulator conditions will be highly beneficial for predictive maintenance. In practical applications, using THD values as an indicator of insulator health can help power system operators detect potential failures early and implement necessary mitigation measures, such as insulator cleaning or design adjustments, to enhance the stability and reliability of transmission networks.

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REFERENCES

[1] Salem, A.A., Abd-Rahman, R., Ishak, M.T.B., Lau, K.Y., Abdul-Malek, Z., Al-ameri, S., Al-Gailani, S.A., Ghoneim, S.S.M. (2023). Influence of contamination distribution in characterizing the flashover phenomenon on outdoor insulator. Ain Shams Engineering Journal, 14(12): 102249. https://doi.org/10.1016/j.asej.2023.102249

[2] Amalia, S., Azhar, H., Hidayatullah, B., Rajab, A., Novizon, N., Warmi, Y., Kasmar, A.F. (2024). The effect of humidity and temperature on flashover in high voltage transmission line ceramic insulators. TEM Journal, 13(1): 670-680. https://doi.org/10.18421/TEM131

[3] Cui, L., Ramesh, M. (2020). Prediction of flashover voltage using electric field measurement on clean and polluted insulators. International Journal of Electrical Power & Energy Systems, 116: 105574. https://doi.org/10.1016/j.ijepes.2019.105574

[4] Datsios, Z.G., Mikropoulos, P.N., Tsovilis, T.E., Thalassinakis, E., Pagonis, G. (2022). Investigation of line surge arresters application to the 150 kV system of Rhodes. Electric Power Systems Research, 213: 108763. https://doi.org/10.1016/j.epsr.2022.108763

[5] Dong, B., Zhang, Z., Xiang, N., Yang, H., Xu, S., Cheng, T. (2020). AC flashover voltage model for polluted suspension insulators and an experimental investigation in salt fog. IEEE Access, 8: 187411-187418. https://doi.org/10.1109/ACCESS.2020.3030326

[6] Slama, M.E.A., Krzma, A., Albano, M., Haddad, A.M. (2022). Experimental study and modeling of the effect of ESDD/NSDD on AC flashover of SiR outdoor insulators. Energies, 15(10): 3782. https://doi.org/10.3390/en15103782

[7] Ghayedi, M., Shariatinasab, R., Mirzaie, M. (2021). AC flashover dynamic theoretical and experimental model under fan-shaped and longitudinal pollution on silicone rubber insulator. IET Science, Measurement & Technology, 15(9): 719-729. https://doi.org/10.1049/smt2.12072

[8] Ghayedi, M., Shariatinasab, R., Mirzaie, M. (2022). AC flashover dynamic model suggestion and insulation level selection under fan-shaped pollution. International Journal of Electrical Power & Energy Systems, 134: 107438. https://doi.org/10.1016/j.ijepes.2021.107438

[9] Gonos, I.F., Stathopulos, I.A., Topalis, F.V. (2003). Lightning performance evaluation of hellenic high voltage transmission lightning performance evaluation of hellenic high voltage transmission lines. XIllth International Symposium on High Voltage Engineering, Netherlands.

[10] Hemour, S., Adhikari, S., Ghiotto, A., Wu, K. (2014). Low magnetic biased SIW-based isolator: Effect of the rising temperature on the performance of the isolator. In WAMICON 2014, Tampa, FL, USA, pp. 1-3. https://doi.org/10.1109/WAMICON.2014.6857801

[11] Khatoon, S., Khan, A.A., Tariq, M., Alamri, B., Mihet-Popa, L. (2022). Flashover voltage prediction models under agricultural and biological contaminant conditions on insulators. Energies, 15(4): 1297. https://doi.org/10.3390/en15041297

[12] Lan, L., Zhang, G., Wang, Y., Wen, X., Wang, W., Pei, H. (2019). The influence of natural contamination on pollution flashover voltage waveform of porcelain insulators in heavily polluted area. IEEE Access, 7: 121395-121406. https://doi.org/10.1109/ACCESS.2019.2936868

[13] Li, Z., Ding, W., Liu, Y., Li, Y., Zheng, Z., Liu, W., Gao, K. (2019). Surface flashover characteristics of epoxy insulator in C_4F_7N/CO_2 mixtures in a uniform field under AC voltage. IEEE Transactions on Dielectrics and Electrical Insulation, 26(4): 1065-1072. https://doi.org/10.1109/TDEI.2019.007847

[14] Mohsenzadeh, M.M., Hasanzadeh, S., Sezavar, H.R., Samimi, M.H. (2023). Flashover voltage and time prediction of polluted silicone rubber insulator based on artificial neural networks. Electric Power Systems Research, 221: 109456. https://doi.org/10.1016/j.epsr.2023.109456

[15] Mahdjoubi, A., Zegnini, B., Belkheiri, M., Seghier, T. (2019). Fixed least squares support vector machines for flashover modelling of outdoor insulators. Electric Power Systems Research, 173: 29-37. https://doi.org/10.1016/j.epsr.2019.03.010

[16] Mahdjoubi, A., Zegnini, B., Belkheiri, M. (2019). Prediction of critical flashover voltage of polluted insulators under sec and rain conditions using least squares support vector machines (LS-SVM). Diagnostyka, 20(1): 49-54. https://doi.org/10.29354/diag/99854

[17] Negara, I.M.Y., Hernanda, I.S., Asfani, D.A., Wardani, M.K., Yegar, B.K., Syahril, R. (2021). Effect of seawater and fly ash contaminants on insulator surfaces made of polymer based on finite element method. Energies, 14(24): 8581. https://doi.org/10.3390/en14248581

[18] Panigrahi, B.K., Ray, P.K., Rout, P.K., Mohanty, A., Pal, K. (2018). Detection and classification of faults in a microgrid using wavelet neural network. Journal of Information and Optimization Sciences, 39(1): 327-335. https://doi.org/10.1080/02522667.2017.1374738

[19] Qiao, X., Zhang, Z., Jiang, X., Sundararajan, R., You, J. (2020). DC pollution flashover performance of HVDC composite insulator under different non-uniform pollution conditions. Electric Power Systems Research, 185: 106351. https://doi.org/10.1016/j.epsr.2020.106351

[20] Qu, S., Wang, Z., Song, Y. (2020). Research on fault diagnosis model of transmission line under lightning stroke based on neural network. Journal of Physics: Conference Series, 1684(1): 012151. https://doi.org/10.1088/1742-6596/1684/1/012151

[21] Richards, C.S., Benner, C.L., Butler-Purry, K.L., Russell, B.D. (2003). Electrical behavior of contaminated distribution insulators exposed to natural wetting. IEEE Transactions on Power Delivery, 18(2), 551-558. https://doi.org/10.1109/TPWRD.2003.809682

[22] Salem, A.A., Lau, K.Y., Rahiman, W., Abdul-Malek, Z., Al-Gailani, S.A., Mohammed, N., Rahman, R.A., Al-Ameri, S.M. (2022). Pollution flashover voltage of transmission line insulators: Systematic review of experimental works. IEEE Access, 10: 10416-10444. https://doi.org/10.1109/ACCESS.2022.3143534

[23] Salem, A.A., Abd-Rahman, R., Rahiman, W., Al-Gailani, S.A., Al-Ameri, S.M., Ishak, M.T., Sheikh, U.U. (2021). Pollution flashover under different contamination profiles on high voltage insulator: Numerical and experiment investigation. IEEE Access, 9: 37800-37812. https://doi.org/10.1109/ACCESS.2021.3063201

[24] Slama, M.E.A., Beroual, A., Hadi, H. (2013). Influence of pollution constituents on DC flashover of high voltage insulators. IEEE Transactions on Dielectrics and Electrical insulation, 20(2): 401-408. https://doi.org/10.1109/TDEI.2013.6508740

[25] Wang, X., Lu, S., Wang, T., Qin, X., Wang, X., Jia, Z. (2020). Analysis of pollution in high voltage insulators via laser-induced breakdown spectroscopy. Molecules, 25(4): 822. https://doi.org/10.3390/molecules25040822

[26] Warmi, Y., Michishita, K. (2018). Tower-footing resistance and lightning trip-outs of 150 kV transmission lines in west Sumatra in Indonesia. MATEC Web of Conferences, 215: 01022. https://doi.org/10.1051/matecconf/201821501022

[27] Yuanisa, C., Warmi, Y., Zulkarnaini, Z., Rajab, A. (2023,). Analysis of the influence of soil resistivity on back flashover for the 150 kV Payakumbuh–Koto Panjang transmission line tower. AIP Conference Proceedings, 2592(1): 060010. https://doi.org/10.1063/5.0117029

[28] Warmi, Y., Zulkarnaini, A.R., Yuanisa, C., Elyas, R.O., Putra, A.M.N., Anthony, Z. (2023). Proposal of analysis method to reduce back-flashover rate taking account of tower footing resistance. International Journal of Electrical and Computer Engineering, 13(1): 94-106. https://doi.org/10.11591/ijece.v13i1.pp94-106

[29] Wibowo, L., Syakur, A., Andromeda, T. (2019). Design Of temperature and humidity control devices in the leakage current test chamber of 20 kV insulator. In 2019 6th International Conference on Information Technology, Computer and Electrical Engineering (ICITACEE), Semarang, Indonesia, pp. 1-6. https://doi.org/10.1109/ICITACEE.2019.8904318

[30] Xu, J., Yin, F., Li, L., Wen, Q., Wang, H., Liu, S., Jia, Z., Farzaneh, M. (2019). Wet snow flashover characteristics of 500-kV AC insulator strings with different arrangements. Applied Sciences, 9(5): 930. https://doi.org/10.3390/app9050930

[31] Yang, Z., Jiang, X., Han, X., Zhang, Z., Hu, J. (2019). Influence of pollution chemical components on AC flashover performance of various types of insulators. High Voltage, 4(2): 105-112. https://doi.org/10.1049/hve.2018.5083

[32] Warmi, Y., Zulkarnaini, Z., Rajab, A., Yuanisa, C. (2023). Investigation into the effect of tower-footing resistance on the lightning trip-outs of 150 kV transmission lines in the rocky areas in West Sumatra in Indonesia. AIP Conference Proceedings, 2592(1): 060009. https://doi.org/10.1063/5.0115107

[33] Zulkarnaini, Z., Warmi, Y., Rajab, A., Windra, C.Y. (2023). Analysis of the effect of phase wire position upper, middle, and lower against distraction back flashover at transmission line 150 kV Koto Panjang-Payakumbuh. AIP Conference Proceedings, 2592(1): 060015. https://doi.org/10.1063/5.0117720

[34] Talib, M.M., Crook, M.S. (2023). AI-enhanced power management system for buildings: A review and suggestions. Journal Européen des Systèmes Automatisés, 56(3): 383-391. https://doi.org/10.18280/jesa.560304