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Condition Monitoring of Silicone Rubber Insulators Using Criteria Established through Wavelet Transform Analysis

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P A P E R   I N F O

A B S T R A C T

The condition assessment of silicon rubber insulators has always been a crucial requirement in power systems. Utilizing leakage current as a fast and online method has played a significant role in this regard. However, variations in operating conditions can lead to substantial errors in decisions regarding insulator condition. Under the influence of environmental conditions on the leakage current, it is difficult to define criteria capable of distinguishing different operating conditions. In this regard, achieving a model with minimal complexity for decision-making is considered as a suitable solution. In this study, an index based on leakage current is presented to categorize the performance of insulators into three states: normal, caution, and critical. For this purpose, experimental data were practically collected under light, medium, and heavy pollution conditions in varying humidity levels up to 90%. All tests were performed under different environmental conditions on healthy and aged insulators to investigate the effect of surface degradation on leakage current and their harmonic components. To analyze the leakage current, wavelet transform was employed, and the standard deviation of wavelet detail coefficients was used. Also, distinguishing a healthy insulator from one that has been aged by UV radiation based on detail coefficients is introduced in this paper. From the wavelet transform results, it appears that a D6 standard deviation above 0.01 reliably separates healthy insulators from aged ones. Furthermore, by using the standard deviation of D7 and defining threshold limits for healthy and aged insulators, it became possible to differentiate their performance. In order to evaluate the accuracy and sensitivity of the proposed indicators, the confusion matrix was used, which is able to distinguish different operating conditions with an accuracy of 89.58%.

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Graphical Abstract
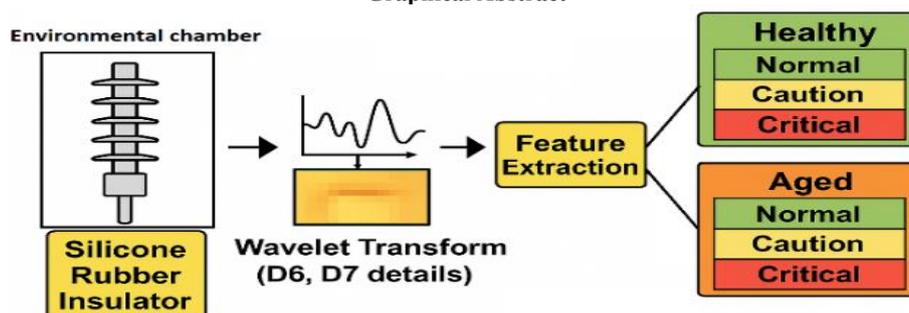
1. INTRODUCTION

Insulators play a critical role in electrical power transmission systems by ensuring adequate insulation distances and withstanding the electromechanical stresses inherent in power systems. Given their direct influence on system reliability and operational stability, the monitoring and assessment of insulator conditions

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have attracted considerable research interest (1, 2). Among the various factors affecting insulator performance, environmental conditions are particularly significant, as they can compromise the operational integrity of insulators under both steady-state and fault scenarios. Humidity, pollution, solar radiation, and wind are key environmental parameters that markedly impact the functional behavior of insulators.

Under normal operating conditions, the coexistence of humidity and surface contamination can initiate leakage currents along the insulator surface. These currents can subsequently lead to surface discharges, accelerating degradation processes and potentially triggering electrical discharges. Such phenomena not only deteriorate the physical integrity of insulators but also pose severe risks to grid reliability, including short circuits and service interruptions (3-6). Moreover, partial discharges occurring on the insulator surface, influenced by the material composition, contribute to progressive aging and deterioration of dielectric properties, which adversely affect long-term performance (7, 8). Notably, the magnitude of leakage current tends to increase with surface degradation and the worsening of environmental factors, which promote the retention of moisture and pollutants (9, 10).

Numerous studies have demonstrated that leakage current characteristics can serve as diagnostic indicators for assessing the operational state of insulators. Consequently, the analysis of leakage current has been widely recognized as an effective diagnostic tool (11-14). Beyond the magnitude of leakage current, its harmonic components have also been shown to vary under changing environmental and operational conditions. Researchers have employed Fourier Transform (FT) and Fast Fourier Transform (FFT) techniques to investigate these harmonic variations (15-17). Such analyses have revealed strong correlations between harmonic behavior and environmental stressors such as humidity and pollution levels (18). For instance, literature review (19-22) evaluated the third, fifth, and seventh harmonic components under diverse contamination levels, establishing the potential of odd harmonic signatures to discriminate between different insulator conditions. Similarly, Total Harmonic Distortion (THD) has been utilized to assess the influence of environmental variations on harmonic content (23). While contamination and humidity remain critical factors influencing leakage current behavior, their impact is strongly modulated by the deposition pattern of pollutants on the insulator surface. Silicone rubber insulators (SIR) exhibit inherent hydrophobicity, which initially resists pollution adhesion. However, prolonged exposure to ultraviolet (UV) radiation results in surface aging and a gradual loss of hydrophobicity (24). This degradation facilitates pollutant accumulation, elevates leakage current levels, and significantly reduces flashover voltage (25, 26). Structural changes in the silicone rubber due to aging particularly alter the progression of harmonic components, notably the third and fifth harmonics (27). The study conducted by Seyyedbarzegar (28) highlighted how these harmonic changes can effectively differentiate aged insulators from their healthy counterparts, proposing relevant diagnostic indicators.

Although leakage current-based diagnostics are regarded as reliable and cost-effective, their performance is highly dependent on the employed signal processing methodologies (29). In this context, wavelet transform (WT) has emerged as a powerful analytical tool, offering simultaneous time–frequency localization capabilities that are particularly suited for non-stationary signals such as leakage currents. Several studies have demonstrated the effectiveness of wavelet-based techniques in characterizing contamination severity and discharge phenomena on insulator surfaces. For example, the STD-MRA method derived from wavelet analysis was employed by Douar et al. (16) to assess pollution severity on ceramic and polymeric insulators. Wavelet-based analyses were further used by several researchers (30-33) to investigate discharge behavior and extract relevant frequency components, enabling the detection of localized discharges and their spatial characteristics. Additionally, Narayanan et al. (34) proposed an advanced diagnostic system integrating Discrete Wavelet Transform (DWT) with fuzzy data mining for the assessment of pollution severity in high-voltage transmission systems.

This paper extends prior work by simultaneously investigating the influence of environmental factors such as humidity and pollution levels and UV-induced aging on insulator performance, utilizing wavelet-based analysis. We proposed a novel diagnostic indicator based on the standard deviation of wavelet detail coefficients and validate it through controlled laboratory experiments. Results show that this indicator effectively categorizes insulators as healthy or aged and further differentiates three operational states: normal, caution, and critical. This provides a robust framework for condition monitoring and preventive maintenance in power systems. The confusion matrix was employed to evaluate the accuracy and sensitivity of the proposed indicators. Figure 1 illustrates the overall method for insulator condition assessment based on features extracted from the wavelet transform.

2. EXPRIMENTAL SETUP

The high-voltage laboratory setup includes a 220 V / 100 kV transformer, with an output adjustable between 0 and 100 kV. To protect the transformer against short-circuit currents, a 10 MΩ resistor is connected in series with the
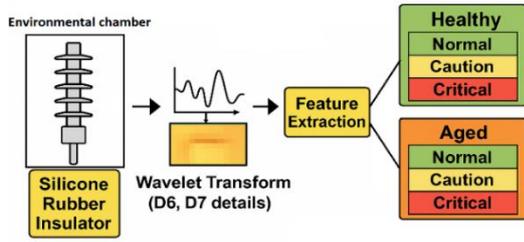
Figure 1. Overview of the insulator condition assessment method based on wavelet transform

transformer in the circuit. Additionally, to measure the leakage current, a pure resistor is connected in series with the insulator. The voltage across the resistor is measured and recorded using a digital oscilloscope with a sampling frequency of 10 kHz. Finally, the current is calculated by dividing the voltage by the resistance.

Figure 2 illustrates the high-voltage experimental setup and the equipment used. To investigate the effect of environmental conditions on leakage current, a standard chamber with dimensions of 2×2×2 meters is employed. The required humidity is provided using a fog generator and regulated by a dedicated controller to ensure precise control of the experimental conditions. To create a pollution layer on the insulator, the solid layer method based on IEC 60507 standard was used. In this method, a solution made from salt (NaCl), kaolin, and high-purity distilled water is sprayed onto the insulator.

To evaluate the electrical conductivity of the pollution layer on the insulator, the conductivity of the pollution solution was measured using a conductivity meter, and the equivalent salt deposit density (ESDD) was calculated based on IEC 60507 standards and according to Equation 1. Based on the obtained ESDD values, different pollution levels can be achieved, as outlined in Table 1.

$$ESDD = (S_a \times V)/A \qquad (mg/cm^2) \qquad (1)$$

$$S_a = (0.57 \, \sigma_{20}) \cdot 1.03 \qquad (mg/cm^3) \qquad (2)$$
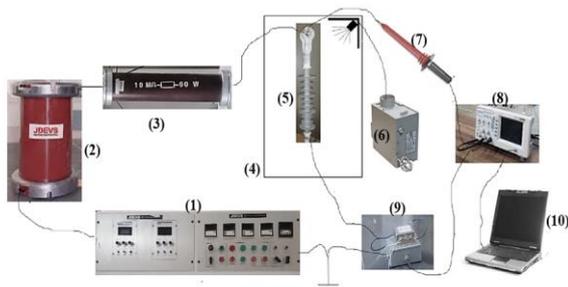
$$\sigma_{20} = \sigma_\theta \, (1 - b \, (\theta - 20)) \qquad S/cm \qquad (3)$$

where S_a is the salinity of the distilled water, V is the volume of distilled water, A is the cleaned surface area (cm²), σ_{20} is the conductivity at 20°C (S/m), σ is the measured conductivity at temperature θ, and b is the temperature coefficient.

Figure 3 shows the appearance of the insulators used under light, medium, and heavy pollution levels. The structural specifications of these insulators are provided in Table 2.

For aging the insulator surface, a wooden chamber with dimensions of 2×2×2 meters and internal walls covered with aluminum sheeting was designed and constructed. The aging process considered the effects of UV radiation, humidity, voltage, and heat. A 40 W/m² UV lamp was used to simulate the effects of solar UV radiation, two heaters were used for heat generation, and a fog generator was utilized to produce fog and humidity during the aging process. Additionally, an automatic control system was developed to schedule the on/off times for each aging factor, such as humidity, heat, and UV. The tested insulators were placed inside the chamber for 3000 hours during the aging process. Table 3 details the aging procedure for the insulators under investigation.

Also, in order to show the effect of UV radiation on the insulator and the aging of its surface, Figure 4 has been prepared. As can be seen in this figure, UV radiation has greatly reduced the hydrophobicity of the insulator surface.

TABLE 1. Amount of kaolin, salt, and distilled water for different pollution levels

| Pollution level	SDD (mg/cm²)	Distilled water (l)	Salt (g/l)	Kaolin (g/l)
Light (LP)	0.01-0.04	1	20	40
Medium (MP)	0.04-0.15	1	40	40
Heavy (HP)	0.15-0.4	1	80	40

Figure 2. High voltage laboratory setup: 1) Control Desk, 2) Transformer, 3) Resistor, 4) Fog chamber, 5) Insulator, 6) Fog maker, 7) High voltage probe, 8) Digital oscilloscope, 9) Leakage current meter, 10) Computer
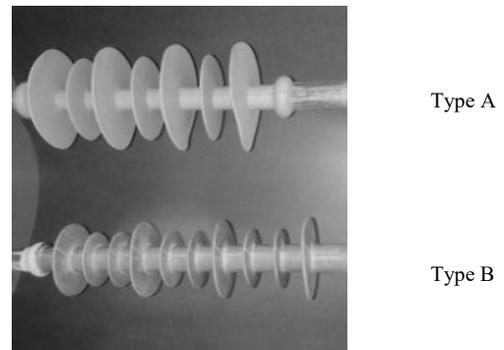

Figure 3. Shape of studied insulators for 20kV distribution power system

TABLE 2. Timing of factors affecting the aging of insulators in a 24-hour period

Duration (Hour)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Voltage																								
UV																								
Heater																								
Humidity																								

TABLE 2. Features of distribution class silicon rubber insulators

Insulator Type	A	B
Voltage Level	20 kV	20 kV
Height	270 mm	300 mm
Creepage Distance	698 mm	601 mm
Shed Number	7	10

A Type -Virgin   B Type- Virgin
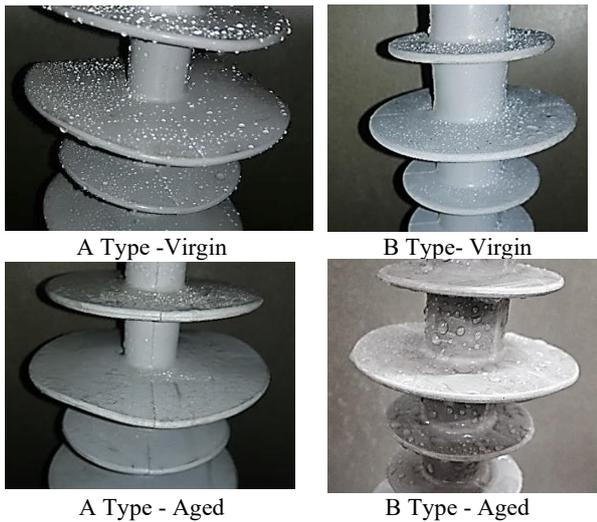
A Type - Aged   B Type - Aged

Figure 4. Comparison of new and old insulation based on the surface hydrophobicity of the polymer material

Figures 5 and 6 show the variations in leakage current passing through insulators of type A and B in both healthy and aged states at 80% humidity, under clean conditions and three levels of pollution: light, medium, and heavy. By comparing these waveforms, it can be seen that the increase in the level of pollution in constant humidity has caused an increase in the magnitude of the leakage current in all cases. In addition, aging also leads to the increase of the main component and the change in the waveform of the leakage current, which is caused by the change in the harmonic components.
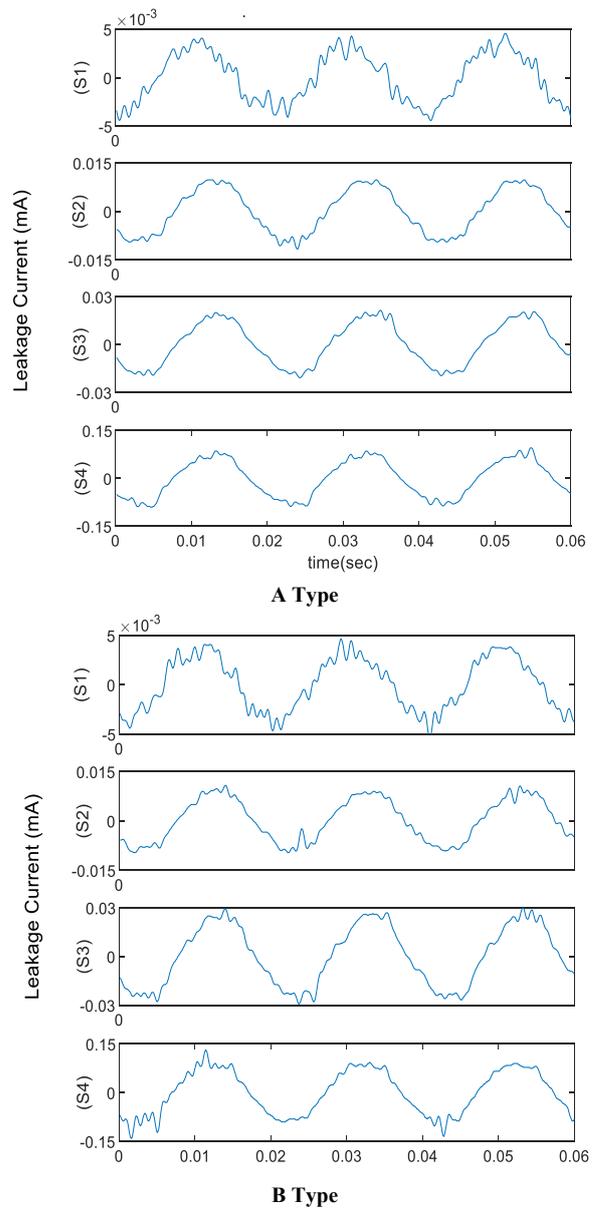

A Type

B Type

Figure 5. Leakage current waveform for virgin insulator in 80% humidity: (S1) clean surface, (S2) light pollution, (S3) medium pollution; (S4) heavy pollution
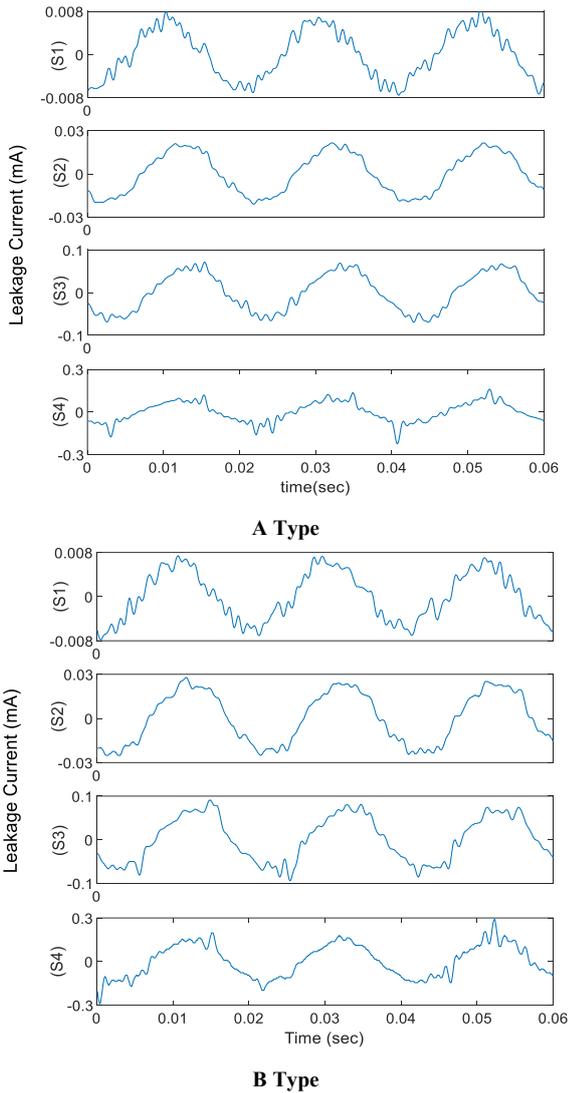
A Type

B Type

Figure 6. Leakage current waveform for aged insulators in 80% humidity: (S1) clean surface, (S2) light pollution, (S3) medium pollution; (S4) heavy pollution

3. WAVELET TRANSFORM

Wavelet Tansform is a powerful tool widely used for processing transient and non-transient signals. This transformation provides the possibility of simultaneous analysis of time and frequency of the signal. Also, by using this transformation, the characteristics of different signals can be extracted or their noise can be removed. Wavelet analysis involves dividing a signal into modified and scaled versions of a prototype function called the original or mother wavelet, which itself has a finite length and is a highly damped oscillation. Two main types of wavelet transforms are generally used for signal analysis: Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). The CWT requires more computational time and utilizes continuous scales and

shifts. The mathematical expression for the Continuous Wavelet Transform is given as:

$$CWT_\omega(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{a}\right)dt \qquad (4)$$

where, $x(t)$ is a continuous signal and ψ is the mother wavelet scaled by parameter a and shifted by a factor b. Also, the values $a > 1$ and $b > 0$.

The DWT has a shorter computational time than the continuous one and uses a certain range of scales and shifts. The mathematical expression for DWT is:

$$DWT_\chi^\psi(m,n) = \frac{1}{\sqrt{a}} \int x(t)\psi^*\left(\frac{t-nba^m}{a^m}\right)dt \qquad (5)$$

where $x(t)$ is the discrete signal and ψ represents the mother wavelet scaled by a^m and shifted by a factor nba^m. The values of m and n are positive integers and the values of $a > 1$ and $b > 0$.

The Multi-Resolution Analysis (MRA) using DWT allows decomposition of a discrete-time signal $x(t)$ at various decomposition and shift levels. and the studied signal is separated in different frequency bands using MRA analysis, and this process continues until the required resolution is achieved. The time domain signal is decomposed by passing through the successive high-pass and low-pass filters. If h and g represent the values of the high-pass and low-pass filters, respectively, and $c[n]$ is the signal sequence, the decomposition starts with the convolution of $c_0[n]$ with h and g, resulting in the components $c_1[n]$ and $d_1[n]$. Subsequently, the next component is decomposed into $c_2[n]$ and $d_2[n]$. This process continues until the desired resolution is reached. Mathematically, this process is obtained through the following equations:

$$c_m[n] = \sum h[k-2n]\, c_{m-1}[k] \qquad (6)$$

$$d_m[n] = \sum g[k-2n]\, c_{m-1}[k] \qquad (7)$$

This decomposition process enables the signal to be analyzed without loss of information. In addition, the original signal can be reconstructed using the inverse DWT. By employing multiresolution signal decomposition, two important features of the leakage current can be calculated. The first feature is time localization, which manifests as a large coefficient at the time of the disturbance. The second feature is the ability to distinguish the signal energy in different frequency bands. According to the sampling frequency, the leakage current signals are decomposed into 7 levels using the Daubechies 4, which is shown in Figure 7. Also, the frequency bands corresponding to the detailed components are shown in Table 4.

4. STANDARD DEVIATION

Standard deviation can be expressed as a significant

parameter in the analysis of leakage current signals for monitoring of insulators. This parameter can be considered as a measure of the energy present in a zero-mean signal. Therefore, the standard deviation values for the detailed components are calculated from D1 to D7 in order to identify the transient energy present in the signal at different levels of decomposition. The standard deviation of the nth level of the signal can be calculated using Equation 8:

$$STD = \sqrt{\frac{1}{N_n-1} \sum_{j=1}^{N_n} [d_n(j) - \mu_n]^2} \qquad (8)$$

where d_n is the signal detail vector and μ_n and N_n are the mean and length of the signal detail vector in different frequency bands, respectively.

5. RESULTS

In order to analyze the insulator leakage current under the influence of humidity, contamination and UV aging for
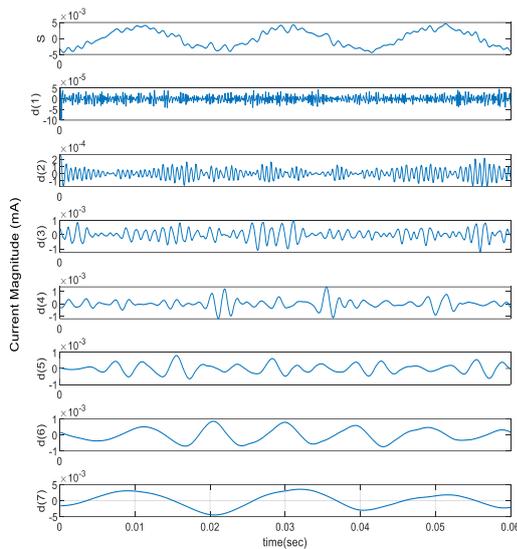

Figure 7. DWT: (S) Main signal, (d1) -(d7) Seven level detailed coefficients

TABLE 4. Frequency Band of DWT Detailed Components of leakage current

Detailed Components of DWT	Frequency Band (Hz)
D1	2500 - 5000
D2	1250 - 2500
D3	625 - 1250
D4	312.5 - 625
D5	156.25 - 312.5
D6	78.125 - 156.25
D7	39.0625 - 78.125

providing a suitable monitoring index, laboratory results were extracted and examined. Accordingly, the independent and simultaneous effect of each parameter on the D1 to D7 of the wavelet transform was evaluated. Finally, an appropriate index based on D6 and D7 was presented along with the definition of threshold limits for distinguishing operating conditions. In general, the main logic in choosing D6 and D7 as condition detection indicators is related to their frequency band. Since environmental conditions and aging have the greatest impact on the main and the third harmonic component, the selection of these two parts of the wavelet transform details can be very effective.

5. 1. Effect of Pollution on Standard Deviation
Figure 8 shows the impact of ESDD on the standard deviation across different pollution levels under 80% humidity for insulators A and B. Examining the changes of standard deviation in two insulators A and B showed that with the increase in pollution level, the standard deviation from D1 to D7 in both insulators had an increasing trend. In both insulators, the most changes were observed in the conditions of heavy pollution, which reached its highest value in D7. Also, the studies show that the changes of D7 show an acceptable trend compared to other detail components in medium pollution. The results of this level of separation of harmonic components can be considered as a suitable indicator for different pollution levels. In addition, it can be seen that insulator A is more sensitive to the increase in the level of pollution compared to insulator B, and its standard deviation has increased more than insulator B. However, the trend of changes in the standard deviation of both insulators is similar for the pollution level changes, and by defining the same threshold limits, the severity of pollution can be completely recognized for both insulators.

5. 2. Effect of Humidity on Standard Deviation
Figure 9 illustrates the effect of humidity on the standard deviation under heavy pollution conditions for both Insulator A and Insulator B. The analysis reveals that as the humidity level increases from 50% to 90%, the standard deviation correspondingly rises in both
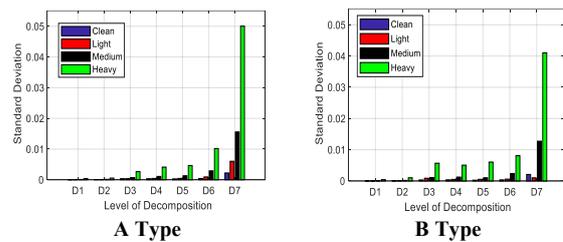

A Type   **B Type**

Figure 8. The effect of pollution on the standard deviation of the wavelet transform at 80% humidity and different pollution

insulators. This increasing trend is particularly pronounced under heavy pollution, where the highest standard deviation is recorded in D7 at 90% humidity. Consistent with the observations in the previous section, the standard deviation in D7 is significantly higher than in other components, indicating its potential as a key parameter for distinguishing the operational conditions of insulators.

5. 3. Combined Effect of Pollution and Humidity on Standard Deviation
In order to provide a comprehensive analysis of the effect of pollution and humidity on the standard deviation of the wavelet transform detail components, the combined effect of these factors is shown in this section. In this regard, Figure 10 displays the combined effect of humidity and pollution on the standard deviation of details D6 and D7 for the two insulators.

The results show that with the simultaneous increase in humidity and contamination levels, the standard deviation increases continuously in all tests. As shown, the D7 component consistently serves as a better indicator compared to D6, and its increasing trend is such that it

Figure 9. The effect of humidity on the standard deviation of the wavelet transform at heavy pollution and different humidity levels

Figure 10. Simultaneous effect of humidity and pollution on D6 and D7 in healthy condition of insulator

enables the use of D7 for diagnosing the condition of insulators. Although the increase of humidity and pollution increases the harmonic components of the leakage current, however, the range of changes of the D6 component is very small, and this behavior makes it difficult to use it as an indicator to evaluate the condition of insulators.

5. 4. Performance Criterion Based on the Impact of Humidity and Pollution
Based on the results of the effect of pollution and humidity on STD and the comparison of the values obtained for D7, the operating conditions of the insulator can be classified into three categories: normal, caution, and critical. This classification is based on the insulator's need for immediate washing and periodic washing to reduce the probability of electrical discharge occurring on the insulator surface. Table 5 shows the range of variations in D7 with respect to the effects of humidity and pollution on the classification of insulator operating conditions. The threshold limits of this classification were determined based on the results obtained from the analysis of the laboratory test samples. The results showed that the values obtained for D7 follow a normal distribution and there is no scattered data among the results obtained. Accordingly, the [mean ±2 standard deviation $(\bar{X} + 2S)$] method was used to determine the threshold limits.

The results of the investigations have shown that heavy pollution under humidity conditions of 70% to 90% is consistently considered as critical conditions. Under these circumstances, insulators are exposed to the most significant fluctuations in leakage current, and the probability of electrical discharges occurring increases considerably. On the other hand, medium pollution within the humidity range of 80% and 90%, and heavy pollution under humidity conditions of 60% to 70% are categorized as caution conditions. In this case, there is a possibility of increased leakage current, but its magnitude is lower compared to critical conditions. All other conditions in terms of pollution level and humidity will be classified as normal. It is worth noting that when the ambient humidity is less than 60%, there is no noticeable effect on the leakage current and the insulator performance is not affected by pollution. Accordingly, all pollution levels under humidity less than 60% are classified as normal conditions.

Examining the results for the D6 component compared to the D7 component has shown that this component does not have the ability to distinguish between the operating conditions. The reason for this is that the harmonic components have less influence on the standard deviation than the fundamental component. In other words, the fundamental component of the leakage current exhibits a greater increase with rising humidity and pollution levels than the other harmonic components.
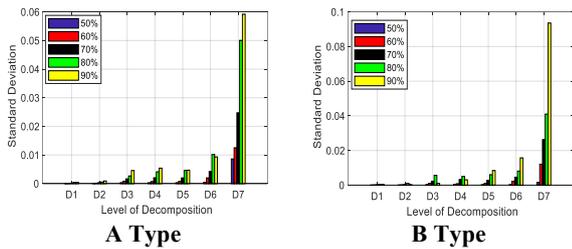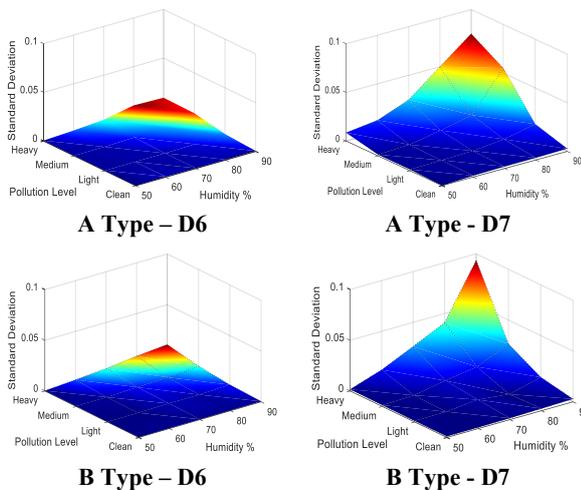
TABLE 3. The criterion for diagnosing the condition of insulation by considering the effect of pollution and humidity

Performance criteria	Range
Normal	$STD_{D7} < 0.02$
Caution	$0.02 < STD_{D7} < 0.03$
Critical	$STD_{D7} > 0.03$

TABLE 4. The criterion for diagnosing the condition of insulation considering aging effect

Performance criteria	Range
Normal	$STD_{D7} < 0.04$
Caution	$0.04 < STD_{D7} < 0.08$
Critical	$STD_{D7} > 0.08$

5. 5. Effect of Aging on Standard Deviation and Performance Criterion   As stated and shown in Figure 6, aging as a factor influencing the performance of the insulator increases the range of the leakage current. Accordingly, in this article, this factor has been investigated along with humidity and pollution and its effect on standard deviation has been evaluated. Figure 11 also shows the results of the effect of aging on the standard deviation index for D6 and D7. As can be seen, aging has a significant effect on the increase in the standard deviation. These conditions lead to a change in the defined threshold limits for detecting the insulator condition, so that their values will exceed the thresholds set for a healthy insulator.

The criterion for diagnosing the condition of the insulator considering the effect of aging is shown in Table 6. According to this criterion, if the standard deviation is greater than 0.08, the insulator is in a critical state of its performance. This condition typically occurs under heavy pollution with humidity ranging from 70 to 90%, as well as under medium pollution with humidity ranging from 80 to 90%. Furthermore, under heavy pollution with 60% humidity, medium pollution with 60 and 70% humidity, and light pollution with 90% humidity, the standard deviation falls within the range of 0.04 to 0.08, which is considered a caution condition. Finally, considering the various classifications of humidity and pollution for an aged insulator, the remaining regions are classified as normal conditions, in which case the standard deviation will be less than 0.04.

Considering the distinctly different threshold limits established for healthy and aged states, a clear separation of these two conditions at the initial stage is crucial. Based on the results presented by Ahmadi-Veshki et al. (1), it has been observed that under the influence of the aging process, the third harmonic component of the leakage current passing through the insulator increases and its fifth component decreases. This condition leads to a change in the D6 component of the wavelet transform, distinguishing it from the healthy state. Therefore, examining the results for the D6 component along with the D7 component allows the detection of the aged state and the determination of the appropriate threshold limits. The conducted investigations show that the D6 standard deviation values greater than 0.01 indicate aging of the insulator, while the standard deviation of D6 for a healthy insulator is significantly less than 0.01 under all defined operating conditions. Overall, by having the standard deviation values of D6 and D7 and considering the defined threshold limits, it will be possible to detect the insulator condition.

Based on the results obtained, a flowchart can be presented for monitoring the condition of silicon rubber insulators. This flowchart, illustrated in Fig. 12, utilizes the standard deviation index extracted from the harmonic analysis of the insulator leakage current through wavelet transform.
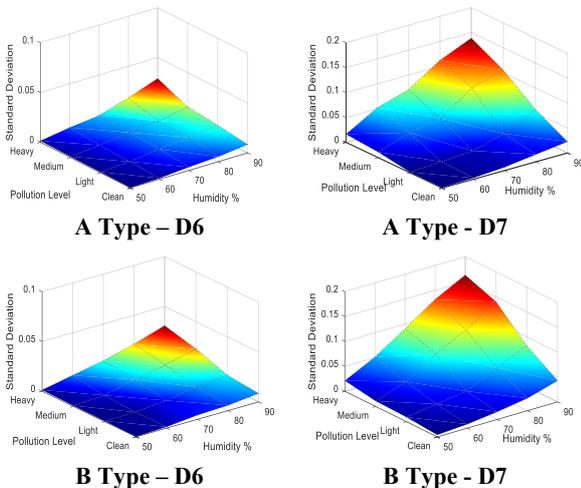
5. 6. Determination of Indices Performance   The performance of the suggested indicators to accurately estimate the insulator state from the 48 test observations was investigated. All tests were performed under new conditions for humidity levels of 65%, 75%, 85%, and 95% and SDD of 0.025, 0.095, and 0.25 mg/cm^2 on healthy and aged insulators, and the results were evaluated based on D6 and D7 indices.

The confusion matrix illustrated in Figure 13 was used to compute the sensitivity and accuracy of these indices. The values of the confusion matrix were determined based on the capability of the insulator indicator to predict the correct condition (35).

Accuracy measures the overall correctness of the model across all classes. It is the ratio of correctly predicted instances to the total number of instances. In

Figure 11. Simultaneous effect of humidity and pollution on standard deviation D6 and D7 in aged condition

this case the overall accuracy of the model is approximately 89.58%.

For multi-class analysis, Precision and Recall are calculated for each class, treating that class as the "Positive" class and all other classes as "Negative". Table 7 shows the results of the multi-class analysis.
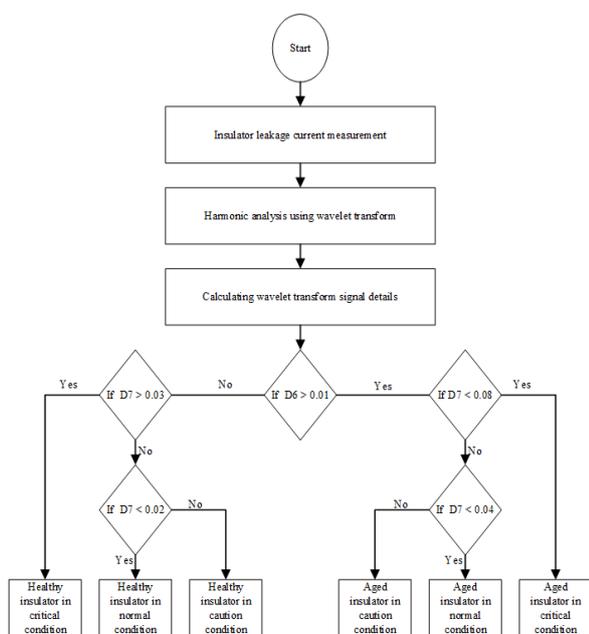

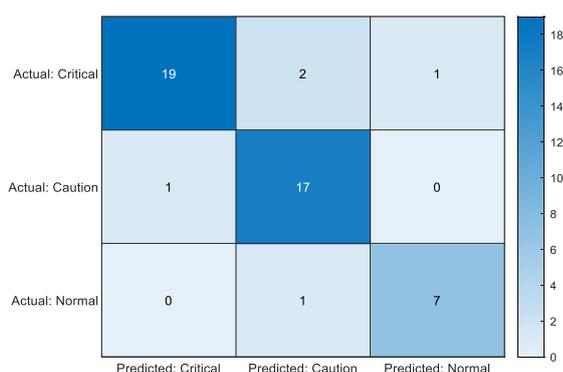**Figure 12.** Flowchart of monitoring the condition of silicon rubber insulators

Figure 13. Confusion matrix for determining indices' performance

TABLE 7. Precision and Recall are calculated for each class in three-class analysis

Class	Precision	Recall
Critical	0.95	0.86
Caution	0.85	0.94
Normal	0.88	0.88

According to this results the model exhibits its highest precision for the Critical state. This is a strong positive, meaning that when the model issues a "Critical" alert, it is highly reliable (95% of the time, the instance is truly critical). The model is most effective at identifying all actual Caution cases, with a Recall of 0.94. In fact, it only missed 1 Caution case. Also, the model's primary weakness is missing Critical cases. Specifically, 2 truly Critical cases were misclassified as Caution, and 1 was misclassified as Normal. Depending on the application, missing a Critical state (a False Negative) could be a severe and costly error. The model achieves a high overall accuracy (89.58%), demonstrating a generally robust performance across all three classes, although there is a trade-off between the Precision and Recall values for the Critical and Caution classes.

6. CONCLUSION

In this paper, a criterion for evaluating and diagnosing the condition of polymer insulators based on the analysis and investigation of leakage current using wavelet transform has been introduced. In this research, factors such as humidity, pollution and aging were considered as effective factors on leakage current. These factors can affect the operating conditions, the magnitude of the leakage current, and ultimately the diagnostic criterion for the insulator's condition. Research was done in a laboratory on a 20 kV polymer insulator. Accordingly, the leakage current was measured and analyzed for variations in humidity at 5 levels and ESDD at 4 levels for two types of insulators in both healthy and aged states. The results of this study can be presented as follows:

1. Among the parameters extracted from the wavelet transform, the standard deviation has shown the highest sensitivity to changes in environmental conditions and aging.
2. Considering the frequency range of wavelet transform, the standard deviation of D7 has been chosen as an indicator for detecting the condition of the insulator.
3. Examining the standard deviation in different conditions has shown that humidity has a greater effect than pollution on changing operating conditions. In other words, the changes in leakage current and wavelet transform components due to humidity changes at a constant level of ESDD are consistently greater than the changes in ESDD at a constant humidity level.
4. The threshold limit for the standard deviation of D7 for classifying insulator operating conditions, without considering the effect of aging, is less than 0.02 in the normal state. Conversely, values greater than 0.03 will place the insulator in a critical state.
5. Considering the effect of aging, the performance threshold in the normal state has been changed from

0.02 to 0.04 and from 0.03 to 0.08 in the critical state. This change indicates the significant effect of aging on the leakage current and wavelet transform components.

6. In order to distinguish between healthy and aged conditions, the standard deviation of D6 was utilized. Values greater than 0.01 for this component indicate an aged state and are considered a criterion for the change in the insulator's condition.

7. Evaluation of the method presented in this paper shows the optimal performance of the standard deviation as a unique indicator, in addition to distinguishing healthy insulators from aged ones, for determining the level of insulation contamination into three states: normal, precautionary, and critical.

8. The proposed classification model (based on indices D6 and D7) demonstrated strong overall performance in differentiating the three states achieving an overall accuracy of 89.58%.

9. This model has a very high reliability in predicting Critical states, where its detection is very important for power system stability and preventing interruptions in its continuous operation. The Precision for the Critical class was calculated to be 95%.

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Ethics Approval and Consent to Participate

This article does not involve any studies with human participants or animals performed by any of the authors. Therefore, ethics approval and consent to participate are not applicable.

Competing Interests

The author declares no financial or organizational conflicts of interest.

Data Availability

The data that support the findings of this study are available upon reasonable request.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors did not use Generative AI and AI-assisted Technologies in the Writing Process.

REFERENCES

1. reza Ahmadi-veshki M, Mirzaie M, Sobhani R. Reliability assessment of aged SiR insulators under humidity and pollution conditions. International Journal of Electrical Power & Energy Systems. 2020;117:105679. https://doi.org/10.1016/j.ijepes.2019.105679

2. Salem AA, Lau KY, Rahiman W, Abdul-Malek Z, Al-Gailani SA, Mohammed N, et al. Pollution flashover voltage of transmission line insulators: Systematic review of experimental works. IEEE Access. 2022;10:10416-44. https://doi.org/10.1109/ACCESS.2022.3143534

3. Sopelsa Neto NF, Stefenon SF, Meyer LH, Bruns R, Nied A, Seman LO, et al. A study of multilayer perceptron networks applied to classification of ceramic insulators using ultrasound. Applied Sciences. 2021;11(4):1592. https://doi.org/10.3390/app11041592

4. Salem AA, Abd Rahman R, Kamarudin M, Othman N, editors. Factors and models of pollution flashover on high voltage outdoor insulators. 2017 IEEE Conference on Energy Conversion (CENCON); 2017: IEEE.

5. Ren A, Liu H, Wei J, Li Q. Natural contamination and surface flashover on silicone rubber surface under haze–fog environment. Energies. 2017;10(10):1580. https://doi.org/10.3390/en10101580

6. Sopelsa Neto NF, Stefenon SF, Meyer LH, Ovejero RG, Leithardt VRQ. Fault prediction based on leakage current in contaminated insulators using enhanced time series forecasting models. Sensors. 2022;22(16):6121. https://doi.org/10.3390/s22166121

7. Yasuda K, Arazoe S, Igarashi T, Yanabu S, Ueta G, Okabe S. Comparison of the insulation characteristics of environmentally-friendly oils. IEEE Transactions on Dielectrics and Electrical insulation. 2010;17(3):791-8. https://doi.org/10.1109/TDEI.2010.5492252

8. Salem AA, Abd-Rahman R, Al-Gailani SA, Kamarudin MS, Ahmad H, Salam Z. The leakage current components as a diagnostic tool to estimate contamination level on high voltage insulators. IEEE Access. 2020;8:92514-28. https://doi.org/10.1109/ACCESS.2020.2993630

9. Salem AA, Abd-Rahman R, Ahmad H, Kamarudin M, Jamal N, Othman N, et al., editors. A new flashover prediction on outdoor polluted insulator using leakage current harmonic components. 2018 IEEE 7th International Conference on Power and Energy (PECon); 2018: IEEE.

10. Abd-Rahman R, Haddad A, Harid N, Griffiths H. Stress control on polymeric outdoor insulators using zinc oxide microvaristor composites. IEEE Transactions on Dielectrics and Electrical Insulation. 2012;19(2):705-13. https://doi.org/10.1109/TDEI.2012.6180258

11. Gao S, Jia Y, Bi X, Cao B, Li X, Yang D, et al., editors. Prediction method of leakage current of insulators on the transmission line based on BP neural network. 2018 IEEE 2nd International Electrical and Energy Conference (CIEEC); 2018: IEEE.

12. Palangar MF, Amin U, Bakhshayesh H, Ahmad G, Abu-Siada A, Mirzaie M. Identification of composite insulator criticality based on a new leakage current diagnostic index. IEEE Transactions on Instrumentation and Measurement. 2021;70:1-10. https://doi.org/10.1109/TIM.2021.3052910

13. Seman LO, Stefenon SF, Mariani VC, dos Santos Coelho L. Ensemble learning methods using the Hodrick–Prescott filter for fault forecasting in insulators of the electrical power grids. International Journal of Electrical Power & Energy Systems. 2023;152:109269. https://doi.org/10.1016/j.ijepes.2023.109269

14. Jia Z, Chen C, Wang X, Lu H, Yang C, Li T. Leakage current analysis on RTV coated porcelain insulators during long term fog experiments. IEEE transactions on dielectrics and electrical insulation. 2014;21(4):1547-53. https://doi.org/10.1109/TDEI.2014.6879943

15. Joneidi I, Shayegani A, Mohseni H, Mohseni S, Jebeli-Javan M. Leakage current analysis and FFT calculation on polluted polymer insulator. International Journal of Computer and Electrical Engineering. 2013;5(1):133. https://doi.org/10.7763/IJCEE.2013.V5.676

16. Douar M, Mekhaldi A, Bouzidi M. Flashover process and frequency analysis of the leakage current on insulator model under non-uniform pollution conditions. IEEE Transactions on Dielectrics and Electrical Insulation. 2010;17(4):1284-97. https://doi.org/10.1109/TDEI.2010.5539685

17. Villalobos RJ, Moran LA, Huenupán F, Vallejos F, Moncada R, Pesce C. A new current transducer for on-line monitoring of leakage current on HV insulator strings. IEEE Access. 2022;10:78818-26. https://doi.org/10.1109/ACCESS.2022.3191349

18. Deb S, Ghosh R, Dutta S, Dalai S, Chatterjee B, editors. Effect of humidity on leakage current of a contaminated 11 kV Porcelain Pin Insulator. 2017 6th International Conference on Computer Applications In Electrical Engineering-Recent Advances (CERA); 2017: IEEE.

19. Salem AA, Lau KY, Rahiman W, Abdul-Malek Z, Al-Gailani SA, Rahman RA, et al. Leakage current characteristics in estimating insulator reliability: experimental investigation and analysis. Scientific Reports. 2022;12(1):14974. https://doi.org/10.1038/s41598-022-17792-x

20. Salem AA, Abd-Rahman R, Al-Gailani SA, Salam Z, Kamarudin MS, Zainuddin H, et al. Risk assessment of polluted glass insulator using leakage current index under different operating conditions. Ieee Access. 2020;8:175827-39. https://doi.org/10.1109/ACCESS.2020.3027226

21. Li J, Sima W, Sun C, Sebo SA. Use of leakage currents of insulators to determine the stage characteristics of the flashover process and contamination level prediction. IEEE Transactions on Dielectrics and Electrical Insulation. 2010;17(2):490-501. https://doi.org/10.1109/TDEI.2010.5442323

22. Teymourian MH SS. Proposing surge arrester monitoring indicators and their evaluation using correlation coefficient method: considering the effect of longitudinal and fan-shaped type non-uniform pollution. International Journal of Engineering Transactions C: Aspects. 2026;39(3):789–801. https://doi.org/10.5829/ije.2026.39.03c.17

23. Suda T. Frequency characteristics of leakage current waveforms of a string of suspension insulators. IEEE Transactions on power delivery. 2005;20(1):481-7. https://doi.org/10.1109/TPWRD.2004.838650

24. Ahmadi-Joneidi I, Majzoobi A, Shayegani-Akmal AA, Mohseni H, Jadidian J. Aging evaluation of silicone rubber insulators using leakage current and flashover voltage analysis. IEEE Transactions on Dielectrics and Electrical Insulation. 2013;20(1):212-20. https://doi.org/10.1109/TDEI.2013.6451437

25. Khodsuz M, Zamani SA. Novel criteria for silicone rubber insulators condition monitoring based on leakage current analysis: considering asymmetric aging and pollution. Engineering Applications of Artificial Intelligence. 2024;133:108175. https://doi.org/10.1016/j.engappai.2023.108175

26. Salem AA, Al-Gailani SA, Amer AAG, Alsharef M, Bajaj M, Zaitsev I, et al. Classification of RTV-coated porcelain insulator condition under different profiles and levels of pollution. Scientific Reports. 2024;14(1):22759. https://doi.org/10.1038/s41598-024-73520-7

27. Esmaieli M, Khodsuz M, Nouri H. Condition assessment criteria evaluation of asymmetric aged and fully aged silicone rubber insulators based on leakage current harmonics. IET Science, Measurement & Technology. 2024;18(4):163-81. https://doi.org/10.1049/smt2.12198

28. Seyyedbarzegar S. The evaluation of asymmetrically aging effect on silicon rubber insulators flashover voltage. World Journal of Engineering. 2025. https://doi.org/10.1108/WJE-09-2024-0535

29. Shaukat S, Arshad A, Shah WA, editors. Use of wavelet transform to analyze leakage current of silicone rubber insulators under polluted conditions. 2022 2nd International Conference of Smart Systems and Emerging Technologies (SMARTTECH); 2022: IEEE.

30. Algeelani NA, Piah MAM, editors. Characterization of leakage current on high voltage glass insulators using wavelet transform technique. 2012 4th International Conference on Intelligent and Advanced Systems (ICIAS2012); 2012: IEEE.

31. Li G, Huang L. Research on wavelet-based sparse representation of insulator leakage current signal. International Transactions on Electrical Energy Systems. 2015;25(1):72-88. https://doi.org/10.1002/etep.1800

32. Maadjoudj D, Mekhaldi A, Teguar M, editors. Wavelet transform of the leakage current to monitoring the insulator surface under non-uniform desert pollution. 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM); 2018: IEEE.

33. Maadjoudj D, Kherif O, Mekhaldi A, Teguar M. Features characterizing the surface state of HV insulator glass model under desert pollution. IEEE Transactions on Dielectrics and Electrical Insulation. 2022;28(6):1964-72. https://doi.org/10.1109/TDEI.2021.009739

34. Narayanan VJ, Sivakumar M, Karpagavani K, Chandrasekar S. Prediction of flashover and pollution severity of high voltage transmission line insulators using wavelet transform and fuzzy C-means approach. Journal of Electrical Engineering and Technology. 2014;9(5):1677-85. https://doi.org/10.5370/JEET.2014.9.5.1677

35. Khodsuz M, Teymourian MH, Seyyedbarzegar S. New criteria for metal oxide surge arrester condition monitoring based on leakage current analysis: Considering non-uniform pollution effect. IET Generation, Transmission & Distribution. 2024;18(5):1072-89. https://doi.org/10.1049/gtd2.13123

Persian Abstract

چکیده

ارزیابی وضعیت مقره‌های لاستیک سیلیکونی یکی از الزامات اساسی در سامانه‌های قدرت است. در این زمینه، استفاده از جریان نشتی به عنوان یک روش سریع و برخط نقش مهمی ایفا کرده است. با این حال، تغییرات در شرایط بهره‌برداری می‌تواند منجر به بروز خطاهای قابل توجهی در تصمیم‌گیری‌ها در مورد وضعیت مقره شود. تحت تأثیر شرایط محیطی بر جریان نشتی، تعریف معیارهایی که قادر به تمایز شرایط مختلف بهره‌برداری باشند، دشوار است. در همین راستا، دستیابی به یک مدل با کمترین پیچیدگی برای تصمیم‌گیری، به عنوان یک راه‌حل مناسب در نظر گرفته می‌شود. در این پژوهش، یک شاخص مبتنی بر جریان نشتی ارائه شده است تا عملکرد مقره‌ها را در سه حالت عادی، احتیاط و بحرانی طبقه‌بندی کند. بدین منظور، داده‌های آزمایشگاهی به صورت عملی تحت شرایط آلودگی سبک، متوسط و سنگین در سطوح رطوبت متغیر تا ۹۰ درصد جمع‌آوری شدند. تمام آزمون‌ها تحت شرایط محیطی متفاوت بر روی مقره‌های سالم و پیر شده انجام شدند تا تأثیر تخریب سطح بر جریان نشتی و مؤلفه‌های هارمونیکی آن‌ها بررسی شود. برای تجزیه و تحلیل جریان نشتی، از تبدیل موجک استفاده شد و انحراف معیار ضرایب موجک جزئیات مورد بهره‌برداری قرار گرفت. همچنین، در این مقاله، روشی برای تمایز مقره سالم از مقره‌ای که بر اثر اشعه فرابنفش پیر شده است، بر اساس ضرایب جزئیات معرفی شده است. بررسی نتایج به دست آمده از تبدیل موجک نشان داده است که انحراف معیار D6 بزرگتر از ۰.۰۱ از دقت بسیار خوبی برای تمایز مقره‌های سالم و پیر شده برخوردار است. علاوه بر این، با استفاده از انحراف معیار D7 و تعریف حدود آستانه‌ای برای مقره‌های سالم و پیر شده، تمایز عملکرد آن‌ها نیز ممکن شد. با هدف ارزیابی دقت و حساسیت شاخص‌های پیشنهاد شده از ماتریس سردرگمی استفاده شده است که با دقت ۸۹/۵۸ ٪ قادر به تفکیک شرایط مختلف بهره‌برداری است