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RESEARCH ARTICLE

Humidity and Harmonic Current Considerations for Indices to Estimate Contamination Levels on HV Insulators

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ABSTRACT Measuring the leakage current and voltage of an insulator is widely used to calculate indices for the pollution estimation of overhead line insulator strings. These indices are intended to be used for the online condition monitoring of insulators to prevent flashover failure. The variability of the data over time causes questionable results when these indices are used in real time. To improve the performance of the indices, this study focuses on analyzing the leakage current and its harmonics over a time dimension to demonstrate the amplitude changes and their causes. For this purpose, the concept of harmonic impedance for insulators was introduced. In an artificial fog chamber, a U120B insulator is subjected to several tests with different levels of contamination and varying levels of constant humidity. The results showed that the equivalent impedance of the insulator varied significantly over time (up to four times). This variation is due to the water absorption process captured by the insulator and depends on the level of contamination and humidity. The 5th and 7th-order harmonic impedances are stable over time, with exceptional variations of less than 9%; therefore, harmonic currents depend only on the voltage harmonics. In contrast, the 3rd and 9th-order harmonic impedances exhibited amplitude variations of up to 9.1 times. Finally, several indices are evaluated. The phase difference angle (PD) index performed best at a constant humidity and steady-state leakage current.

INDEX TERMS Condition monitoring, insulator, leakage current, pollution estimation, overhead lines.

I. INTRODUCTION

The IEC 60815-1 standard provides recommendations for the proper sizing of insulator strings in electrical systems, ensuring that the string length is sufficient to avoid single-phase faults owing to the shortened creepage distance. This sizing is essential, particularly in light of the main cause of insulation failure being environmental contamination of high-voltage (HV) insulator strings [1]. This negatively affects the reliability and stability of electrical systems and can lead to high economic losses [2]. Several sources of contamination exist in HV insulators. These include the sea, deserts, arid areas, and polluting industries (e.g., cement, lime, and mining). Therefore, further research is required to determine the level of contamination. The degree of contamination can be estimated by calculating the equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD) [3]. In addition, contamination will cause a change in the leakage current (LC) in the insulators, which can be monitored [4].

To prevent HV insulator failure, utilities continuously wash insulators with pressurized jets of demineralized water. This process removes surface contaminants and keeps insulators clean, thereby reducing the likelihood of flashover [3]. The frequency of washing should be sufficient to prevent failure,

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but this is also expensive [1]. In dry areas, the cost of insulator washing is estimated to be the highest annual cost for electric utilities [2]. Companies use their experience and failure statistics to determine the frequency of washing. However, this tool is sometimes ineffective because of the occasional changes in climatic conditions and increased environmental pollution. Therefore, it is necessary to implement a tool to determine the real-time contamination level, so the variations in the contamination of insulator strings can be detected. Eventually, this will enable accurate and appropriate scheduling of insulator cleaning [5]. In addition, high relative humidity and light rain play important roles in HV insulators [6]. When water molecules bind to the contaminated layer of an insulator, they allow the dilution of soluble salts by increasing electrical conductivity. This causes an increase in the LC.

Various LC parameters have been used to evaluate the status of the HV insulators. As a result, LC is generally accepted as an effective indicator for establishing the contamination level [4], [7]. Researchers have proposed utilizing specific indices to establish a correlation between the degree of insulator contamination and the particular characteristics of an LC passing through insulators. According to [8] and [9], a correlation exists between the total harmonic distortion of the LC (THD_i), humidity, and the contamination level. In [9], it was shown that the THD decreased as the ambient humidity increased; THD_i was 24.5% at 28.6% humidity and 18.7% at 91% humidity. In contrast, a different viewpoint was presented in [8], which indicated that at a contamination level of 0.2 mg/cm^2, THD_i was 25% at 20% humidity, but increased to 40% at 80% humidity. Changes in THD values may occur because of variations in humidity and contamination levels. However, there is currently no consensus as to whether this relationship is directly or indirectly proportional. The time integral index calculated from the area under the LC curve studied in [10] is effective at constant humidity levels of 50-60%, 65-70%, and 80-90%, showing a direct relationship with humidity and contamination. Notably, its performance remains unaffected by the main voltage harmonics even though it has only been tested at certain working points. The phase difference angle (PD or PI) index [11] measures the cosine of the angle between the voltage of the insulator and the leakage current. This method distinguishes between clean and normal insulators (PD $<$ 30%) and contaminated insulators with humidity (PD $>$ 30%). A PD index $>$ 85% indicated a significant risk of flashover. However, measuring the insulator voltage is necessary for effective use, and this method has only been tested in specific scenarios. LC harmonics are important for assessing the level of contamination caused by insulators. For instance, R_{hi} is an indicator that correlates the amplitudes of the 3rd, 5th, and 7th harmonics of the LC [7], revealing a direct correlation between the index and the level of insulation contamination and a direct relationship between the index and humidity. As the contamination or humidity levels increased, so did the index. The results are outlined for specific operating points and extended to intermediate humidity. Therefore, these

FIGURE 1. Glass insulator type US120B for laboratory tests.

indices have been proven effective under specific operating conditions with constant humidity and when the insulator and pollution layer are stable. This implies that the humidity was applied to the insulator for a sufficient amount of time. In practice, the humidity levels within a geographic area are subject to variability, and in practical applications, the LC measurements are discrete over time. Hence, it is essential to ascertain LC fluctuation over time, not solely during steady-state periods, as this may affect the index performance. Furthermore, studying the source and evolution of LC harmonic changes over time is crucial.

This paper presents a detailed analysis of the effects of humidity on LC amplitude and harmonics. The study concluded that humidity significantly affects the indices used to assess the contamination levels of insulators. Furthermore, research has indicated that the relative humidity of an insulator is crucial for recognizing contamination levels through LC measurements. A series of tests were conducted in an artificial fog chamber. The HV insulators were exposed to varying humidity and artificial contamination levels to validate the findings. This analysis should be considered essential for industrial development, as it provides important background information to enhance the use of leakage-current-based indices in the online monitoring of contamination on insulators in the industry.

II. LABORATORY SET-UP AND INDEX CALCULATION

This section presents the laboratory setup and U120B type insulator used for the humidity, pollution, and humidity tests developed in this work.

Fig. 1 is a photograph of the insulator. The creepage distance of this insulator was 320 mm, and its diameter

TABLE 1. Pollution level test.

Level No.	Level	ESDD	NSDD
L1	Clean	0	0
L2	Medium 1	0.015	0.180
L3	Medium 2	0.052	0.088
L4	High 1	0.056	0.215
L5	High 2	0.186	0.331
L6	Very High	0.571	0.313

was 255 mm. Fig. 2 shows the laboratory setup, which consists of a step-up transformer, an artificial fog chamber, and sensors for variables such as current, voltage, humidity, and temperature. The insulator was subjected to a voltage of 9,800 volts. This value corresponds to the nominal voltage applied to the insulator in the 220-kilovolt insulator string. The artificial fog chamber was designed and manufactured according to IEC 60507. The measured variables were acquired using DAQ equipment (National Instruments) and processed using MATLAB software.

Tests involve contaminating insulators with a mixture of demineralized water, salt (NaCl), and kaolin. The combination of these compounds generates different levels of pollution on the insulators. The ESDD and NSDD values used in this study are listed in Table 1. For the medium- and high-pollution ranges, two pollution levels were used.

The classification of the pollution level for the studied indices was based on the measurement of LC flowing through the insulator. For some indices, measurement of the voltage between the cap and pin of the insulator is also required. Next, the theory for calculating some of the indices used in the literature for the classification of pollution level is described, such as the THD, Rhi index, time-integral index, and phase difference cosine (PD) index.

THD index:

The THD index was calculated for the current or voltage variables by considering the amplitudes of fundamental and odd harmonics. In this study, harmonics up to the 11th harmonic were used and calculated using the fast Fourier transform (FFT). Equation (1) is as follows:

$$THD = \frac{\sqrt{\sum_{n=2}^{11} I_n^2}}{I_1} \cdot 100\% \tag{1}$$

where I_1 is the RMS value of the first harmonic, and I_n is the RMS value of the harmonics of order n.

R_{hi} Index:

The index presented in [7] determines the pollution level using the ratio of the amplitudes of some harmonics of the current signal. The equation defining this is (2):

$$Rhi = \frac{I_3}{I_5 + I_7} \tag{2}$$

where I_3, I_5, and I_7 represent the amplitudes of the 3rd, 5th, and 7th harmonics.

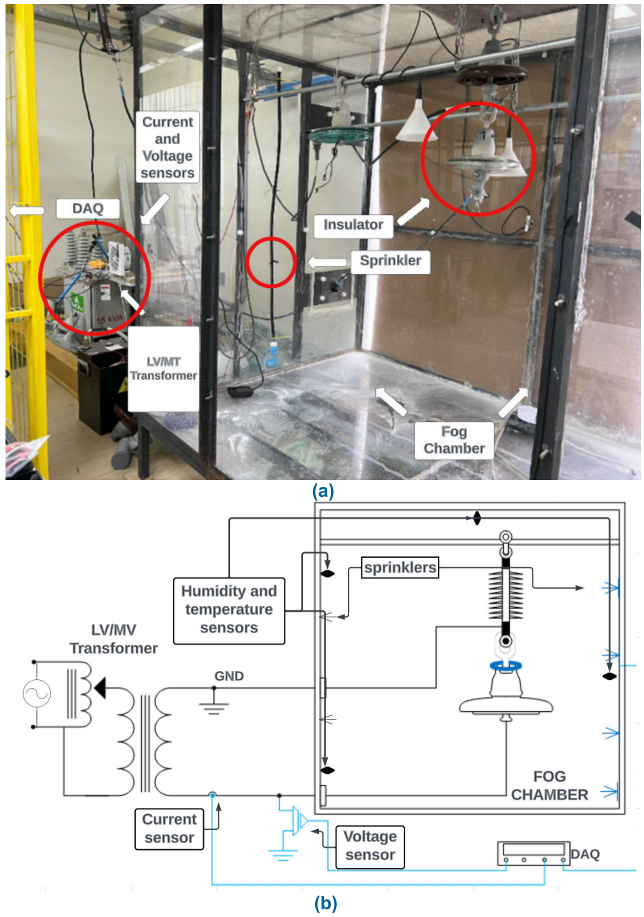

FIGURE 2. Laboratory set-up. (a) Real photography (b) Schematic design.

Time-Integral Index:

This index [10] is related to the cumulative charge of the LC. It was calculated as the integral of the absolute value of the current over a period of time. After mathematical deductions, the cumulative charge for each harmonic is as presented in (3).

$$Q_n = \frac{P_n}{n} \cdot Q_1 \cdot cos\theta_n \tag{3}$$

where Q_n and Q_1 are the cumulative charges for the fundamental harmonic and the nth order, respectively. P_n is the peak amplitude of the nth harmonic, n is the harmonic number, and θ_n corresponds to the phase difference between the fundamental and nth harmonics.

The sum of all cumulative charges of the n harmonics is equal to the cumulative charge of LC (4).

$$Q = \sum_{k=1}^{N} Q_n \tag{4}$$

Although θ_n is dependent on the external variables, it has a low influence, especially for higher-order harmonics. Moreover, it is limited to only one cycle because it is eliminated as the area is negative and cancels out in the second half of the fundamental cycle.

PD Index:

The PD index [11] is similar to the power factor multiplied by 100. The equation is shown in (5):

$$PD = cos\left(\theta_{v1} - \theta_{i1}\right) \cdot 100\% \tag{5}$$

The pollution levels were defined for the 30 and 85% boundary lines as follows:

$$PD < 30\% \rightarrow Clean$$
$$30\% \leq PD \leq 85\% \rightarrow Extreme\ conditions$$
$$PD > 85\% \rightarrow Flashover\ probability\ high$$

Thus, it can be deduced that the power factor of the insulator is lower when the insulator is clean, whereas the power factor increases when it is contaminated.

III. ANALYSIS AND TEST RESULTS

The indices to classify pollution levels are primarily related to the fundamental current and its harmonics. Other factors are also related to the phase difference between the voltage and current. This section presents a detailed description of the behavior of insulator impedance and LC harmonics under different contamination conditions (Table 1) and humidity. The tests were performed at constant humidities of 50, 80, 90, and 100%. All values were computed over 50 cycles. The plots show the average of the data recorded every 5 s.

A. IMPEDANCE ANALYSIS AT CONSTANT HUMIDITY

An analysis of the effect of humidity on the characteristic impedance of the insulator is presented. The insulator is modeled as a resistor and capacitor in series. The impedance calculation is the result of the quotient between the voltage (cap to pin) and the LC through the insulator. The equivalent resistance (R) is calculated using the real part of the characteristic impedance $|R| = |Z| \cdot cos(\alpha)$, where α is the angle between voltage and current. The equivalent capacitive reactance (X_c) is the imaginary part of the characteristic impedance $|X_c| = |Z| \cdot sin(\alpha)$.

The maximum, minimum, and steady-state values of each of the three parameters are presented.

Fig. 3 shows the results for different contamination levels at constant humidity. Each color represents the pollution level in Table 1. For each humidity test (50, 80, 90, and 100%), the minimum value (on the left), stable value (in the middle), and maximum value (on the right) were calculated.

Fig. 3(a) shows a clear tendency for the insulator impedance to decrease with increasing humidity in the artificial fog chamber. In the case of the clean insulator, the same behavior was observed but less pronounced. This indicates that the impedance under clean conditions remains practically constant. The variation in amplitude was due to the effect of the water droplets on the surface. Consequently, wetting of the insulator surface affects the insulator equivalent impedance.

In the tests at 50% humidity (dry insulation), the impedance remained practically constant regardless of the level of contamination, with a difference of 13% between the medium and very high levels of contamination. This suggests that the effect of contamination on insulator impedance is less important under dry conditions. This was because the water fog did not dilute the salt. Therefore, the electrical conductivity of the insulator is not favored. As the humidity in the chamber increased, a decrease in impedance was observed. This was caused by the dilution of soluble salts (NaCl) with water fog. However, the decrease in impedance became more significant as the contamination level increased. This trend increased with humidity. Fig. 3 (b) shows the resistance under different conditions. For humidities between 50 and 90%, the resistance exhibits an opposite trend to the equivalent impedance, increasing in magnitude with higher pollution. In addition, the resistance increases in the same humidity range with increasing relative humidity in the chamber.

In the case of 100% humidity, the resistance increased for the clean and medium pollution insulators. The observed trend was not maintained for high pollution levels, as the resistance decreased considerably. Fig. 3 (c) shows the equivalent capacitive reactance of the insulator. The reactance trend was similar to that of impedance. The modulus of reactance is determined mainly by humidity rather than pollution level.

Finally, under constant-humidity conditions, the impedance modulus decreased with increasing humidity. As pollution increased, the modulus difference became more significant from one humidity value to another. The amplitude difference is less significant when the insulator is clean, or pollution levels are low.

In addition, there were significant differences among the minimum, maximum, and steady-state values for each level of contamination. This was due to the humidity absorption of the contaminant layer. The differences are smaller when the humidity is low, or the insulator is dry; however, the differences become greater as contamination increases. Fig. 4 provides an example, which shows the modulus of the parameters of a clean insulator with a constant humidity of 80%. The magnitude of the modulus remained constant throughout the test period. This was repeated for all tests with a clean insulator and humidity level. For insulators with low and medium pollution, the dynamic behavior of the impedance presents a difference in magnitude in the order of 20%, as shown in Fig. 3. In Fig. 5, when the pollution level is high or very high, the variations in the impedance amplitude over time can reach 300% with a constant humidity of 90% and very high pollution. The impedance modulus increases with values ranging from 10 MOhm to stabilize at 30 MOhm. Similar results were obtained for resistance and reactance.

In summary, the impedance, resistance, and reactance modulus change over time when the humidity is constant and above 80% until they reach their steady state. This dynamic phase may affect the performance of certain indices used in the literature under conditions of constant humidity and in geographical areas where humidity has a high variation rate.

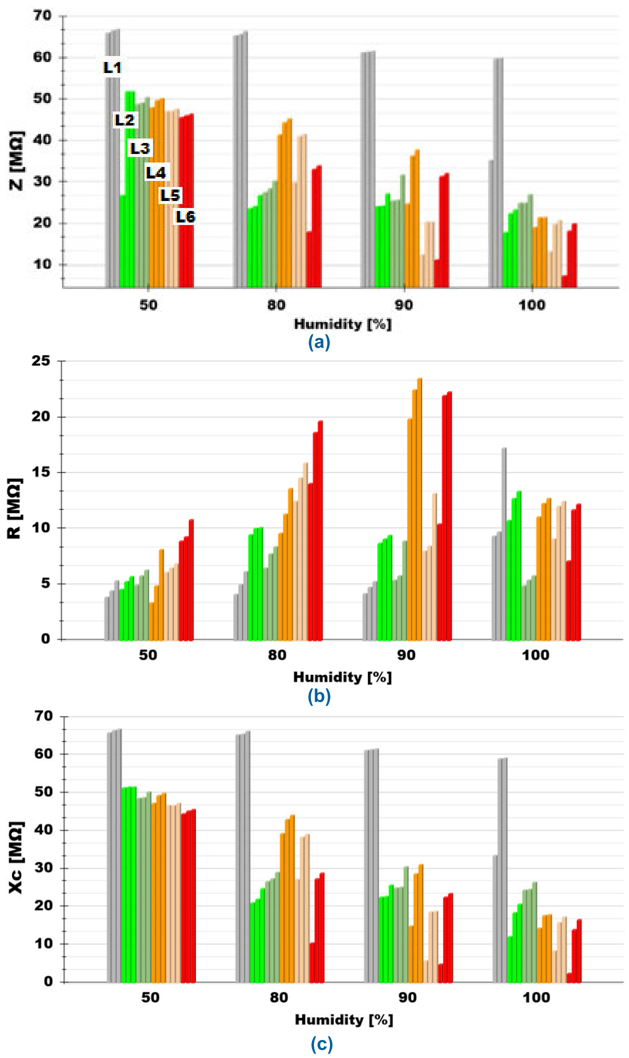

FIGURE 3. Insulator parameters for different humidity and pollution conditions (a) Impedance (b) Resistance (c) Reactance.

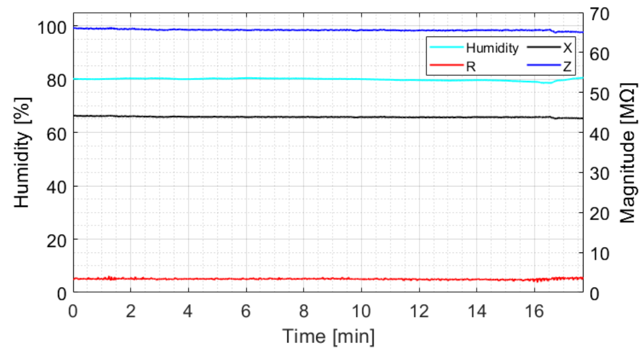

FIGURE 4. Impedance, resistance and reactance for clean insulator and RH° = 80%.

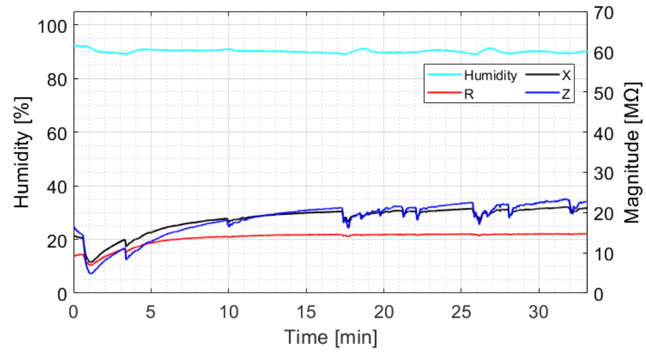

FIGURE 5. Impedance, resistance and reactance for very heavy pollution and RH° = 90%.

B. THD ANALYSIS

This section analyzes THD and leakage current harmonics through insulators under different conditions. The calculated harmonics were the 3rd, 5th, 7th, 9th, and 11th. The tests were performed at constant humidities of 50, 80, 90, and 100%. Equation (1) was used for these calculations.

Fig. 6 shows THD_i at different humidity levels. The THD_i ranged from 3.8 to 11%, averaging 7.6%. This is an average THD voltage (THD_v) of approximately 1.8%. THD_i showed a slight tendency to decrease with increasing humidity and contamination. This is because of the increase in the fundamental component resulting from the decrease in the impedance, as discussed in the previous section. The variations in the THD_i within the same test can reach a difference of up to 54% between the minimum and maximum values. This may affect the setting of current THD-based limits for contamination levels as a function of the current harmonics [8].

C. HARMONIC IMPEDANCE ANALYSIS

This section introduces the concept of harmonic impedance in high-voltage insulators. The harmonic impedance concept involves calculating the insulator impedance for each harmonic to be studied. This concept is used to identify the origin of the harmonics of the leakage current and determine their behavior over time. This is important because some harmonics in the LC may be products of harmonics in the voltage. This can affect the accuracy of the indices. The nth-order harmonic impedance was calculated by dividing the nth voltage harmonic by the nth current harmonic. The calculation was performed for the 3rd, 5th, 7th, 9th, and 11th-order harmonics.

1) CLEAN INSULATOR

Fig. 7(a) and 7(b) show the current, voltage, and impedance harmonics amplitudes for 90% humidity with a clean insulator. It was observed that the amplitude of the current harmonics had a direct relationship with the harmonic voltage. Fig. 7(c) shows the calculation of the equivalent impedance for each of the analyzed harmonics (3rd, 5th, 7th, 9th, and 11^{th}-order harmonics).

The harmonic impedance is constant over time for the 5th, 7th, 9th, and 11th harmonic. However, for the 3rd harmonic impedance, time-varying values in the order of 10 MOhm were noted.

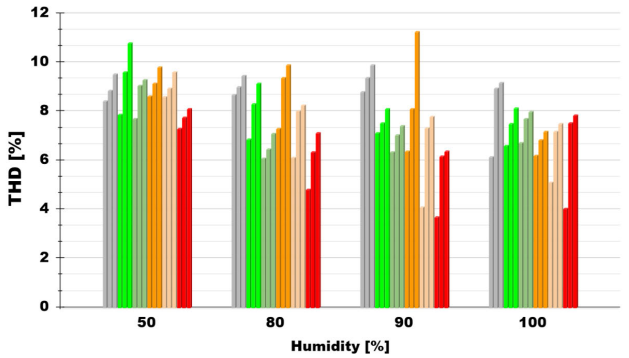

FIGURE 6. THD current for different humidity levels and pollution levels.

Fig. 8(a) shows the harmonic impedances at 50% humidity, and Fig. 8(b) shows the harmonic impedances at 100% humidity. Except for the 3rd harmonic, the harmonic impedances in Fig. 8(a) were constant over time. In Fig. 8(b), large amplitude variations are observed, with a difference of 50 MOhm. This is because of the larger amount of water on the insulator surface. The 5th, 7th, and 11th current harmonics remained constant despite the humidity level. In the 9th harmonic, some minor amplitude variations appear.

For these two humidity levels (50 and 100%), it can be concluded that the 3rd-order impedance modulus had an average value between 20 and 30 MOhm in each test. The variation of the 3rd harmonic average value increases with increasing humidity.

Fig. 9(a) shows the current waveform, and Fig. 9(b) shows the harmonic spectrum of this current as a percentage of the fundamental current. This was performed for 15 min at 100% humidity (clean insulator). The 7th and 5th-order harmonic current amplitudes are the most significant (5.5% and 4.4%, respectively). However, the 3rd-order impedance at 15 min is the lowest amplitude of the harmonic impedance. At this instant, the 3rd-order current harmonic has a very low amplitude, close to 0.6% of the fundamental harmonic. When the 3rd-order harmonic impedance is high (40 min), the 3rd-order current harmonic decreases significantly and reaches 0.08% of the fundamental harmonic. This is an important variation in the amplitude that can affect the performance of indices that use current harmonics.

2) MEDIUM POLLUTION ON INSULATOR

This section presents the electrical test results for an insulator with medium-level pollution.

Fig. 10 shows the impedance modulus for each harmonic with constant humidity and a medium pollution level. Fig. 10(a) shows the harmonic impedance at 50%. Fig. 10(b) shows the harmonic impedance at 90%, and Fig. 10(c) shows the harmonic impedance at 100%.

These figures illustrate that the 5th-, 7th, and 11th-order harmonic impedances remain constant throughout the tests, with only some low variations at specific time points.

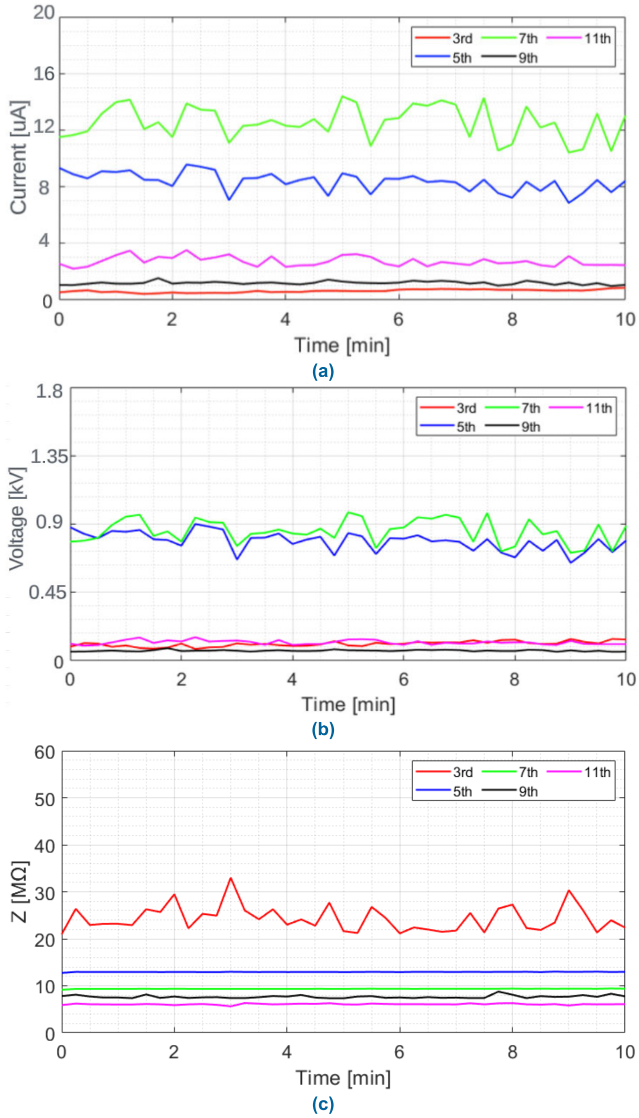

FIGURE 7. Harmonics and harmonics impedance for clean insulator and RH=90% (a) Current harmonics (b) Tension harmonics (c) Impedance harmonic.

A slightly decreasing trend in the modulus of the impedances was observed as the humidity increased. The impedance of the 9th harmonic varied with 100% humidity; it remained constant for the other humidity values. The 3rd harmonic shows significant amplitude variations ranging from 10 to 110 MOhm at 90% humidity. These amplitude variations of the 3rd harmonic may be related to water particles on the insulator or dry bands generated on the surface owing to contamination. This result suggests that the indices using the 3rd harmonic current may yield erroneous results, particularly when the measurements are discrete over time.

3) VERY HIGH POLLUTION ON INSULATOR

Fig.11 shows the impedance of the harmonics under very heavy conditions. Fig. 11(a) shows the harmonic impedance

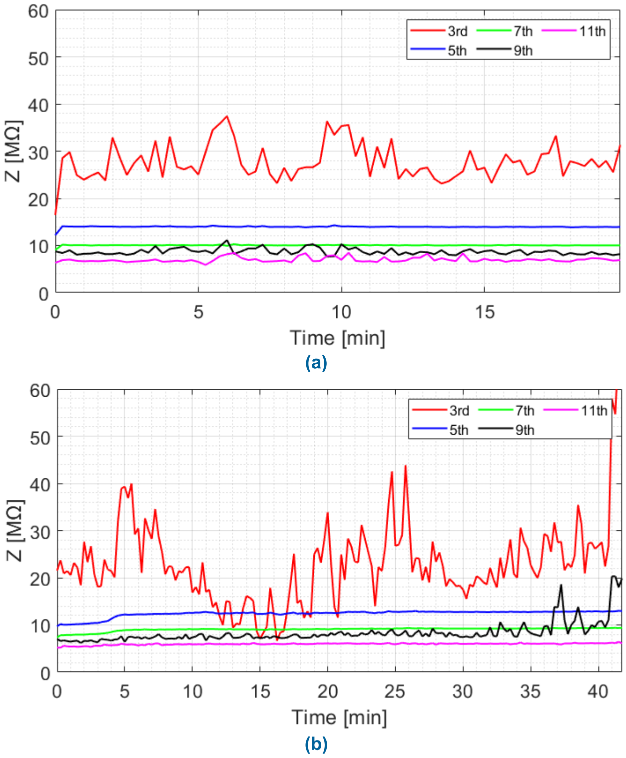

FIGURE 8. Harmonic impedance for clean insulator (a) RH=55% (b) RH=100%.

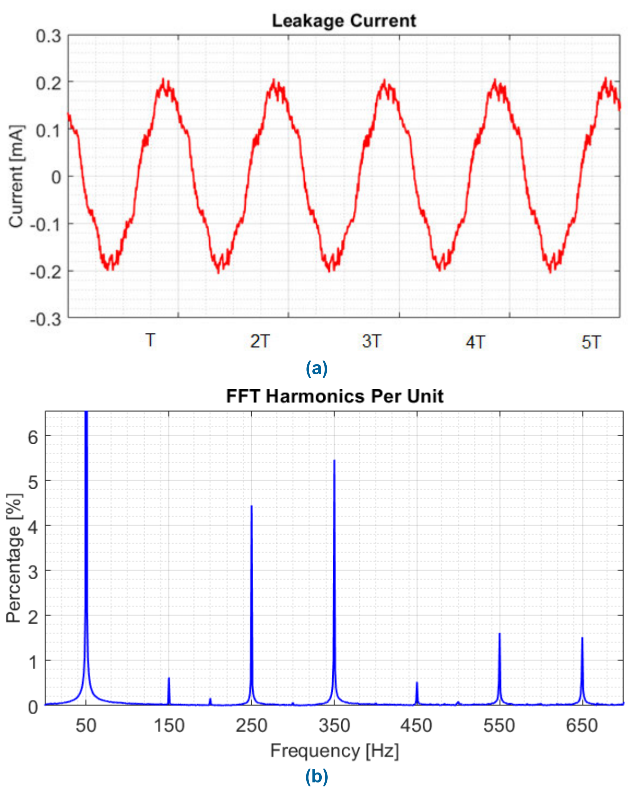

FIGURE 9. Clean insulator, RH=100% (a) Current waveform (b) Current harmonic spectrum.

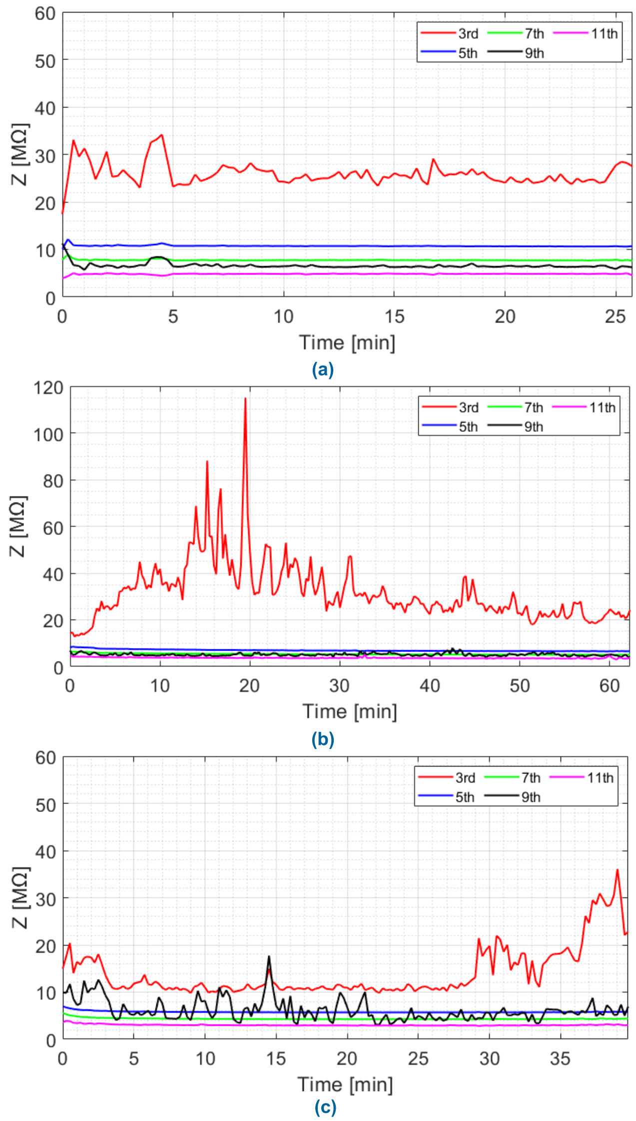

FIGURE 10. Harmonic impedance for pollution: Medium (a) RH 55% (b) RH 90% (c) RH 100%.

at 50%. Fig. 11(b) shows the harmonic impedance at 90%, and Fig. 11(c) shows the harmonic impedance at 100%. It was observed that the 3rd harmonic impedance variations were smaller than those in previous cases (clean and medium pollution). As the humidity increased, the impedance of the 3rd harmonic presents less variation in magnitude over time, as shown in Fig. 11(b) and Fig. 11 (c). In Fig. 11(a), at 50% humidity, the 3rd harmonic impedance is higher than the rest of the harmonic impedances. However, at this pollution level, the amplitude of the 3rd-order impedance decreases if the humidity in the 3rd-order impedance increases. In addition, the increased humidity in the chamber makes the 3rd harmonic impedance flatter and becomes more constant over time. Some trends were observed for this level of contamination; however, the harmonic impedances over time changed significantly in magnitude, which may have affected the performance of some indices.

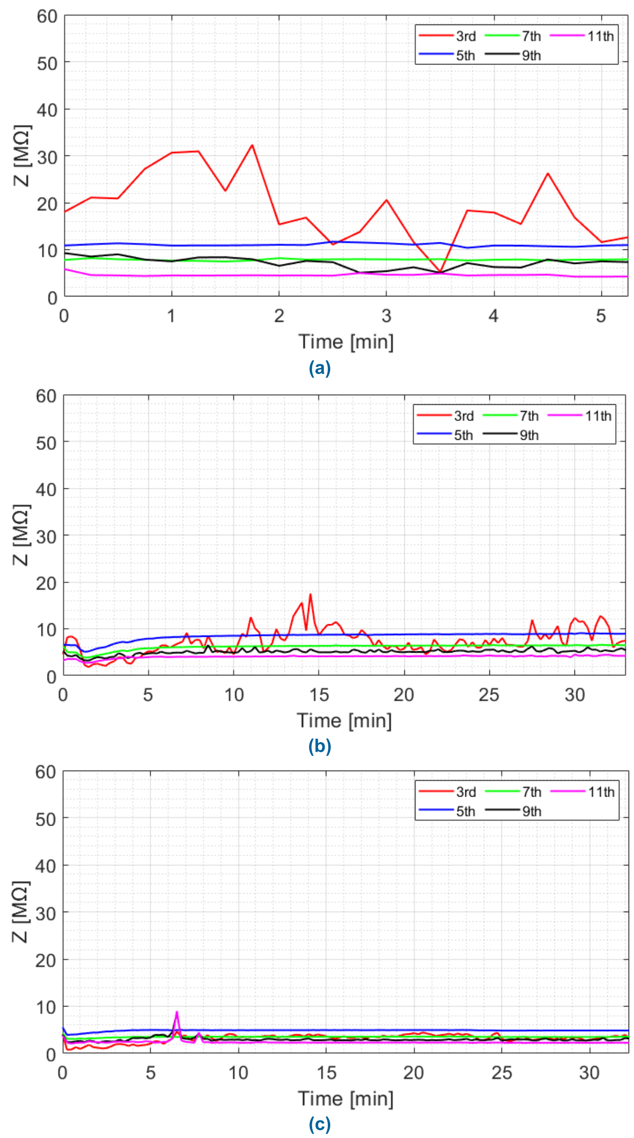

FIGURE 11. Harmonic impedance for pollution: Very heavy (a) RH 55% (b) RH 90% (c) RH 100%.

Finally, for the tests carried out at all levels of contamination and humidity, the 3rd and 9th-order harmonic impedances showed the greatest variation over time. The 3rd-order harmonic impedance can reach variations of up to 9.1 times, and the 9th-order harmonic impedance up to 3.6 times. In contrast, the 5th-, 7th, and 11th-order harmonic impedances show variations of less than 1.3 times.

IV. EFFECTS OF HUMIDITY ON INDICES

This section presents the effects of humidity on Rhi, time integral, and PD indices. Equations (2), (4), and (5) were used for calculations. Tests were conducted in an artificial fog chamber with varying humidity conditions and pollution levels: clean, medium, high, and very high.

Table 2 shows the results of the indices obtained for each humidity level and the steady state. The average value of the index was calculated for each pollution level.

For the Rhi index, the index value increased with increasing humidity for each level of contamination except for the clean insulator. There was no trend in the average values to distinguish between one pollution level and another. However, the index directly correlated with the humidity for the high and very high pollution levels. This is related to what was previously shown in the impedance analysis, where the 3rd-order impedance was much more stable and tended to decrease in amplitude as the pollution on the insulators increased. Owing to the highly variable 3rd-order impedance in most cases of humidity and contamination, it is difficult to determine the pollution level at all levels using the Rhi index.

The PD index tended to increase with increasing humidity at all pollution levels. A direct relationship was also observed between the average calculated PD index and the pollution level. It can be observed that the insulator changes from very capacitive to more resistive as the pollution increases. The same is noted for the direct relationship between PD index and humidity.

However, when considering the pollution level border limits defined in [11] for PD=50%, the index showed good results up to 90% humidity. Then, according to the observations in the previous sections, at 100% humidity, the index decreased in value, changing the trend. This is because the resistive part of the equivalent impedance increases its value compared with the reactance at 100% humidity. This is important when using this index to classify pollution levels.

In general, the PD index performed well in classifying pollution levels. However, it is important to consider that the analysis should always be performed by comparing index values for a given humidity value. This could be difficult for industrial applications where sampling is discrete, as sometimes not all the information is available.

The time-integral index directly correlates with increased humidity for the same pollution level. However, when comparing the index average for different pollution levels, it was impossible to observe a clear trend that ensured the correct classification of the pollution level. It is recommended only for use at specific humidity levels, such as dry insulators (50%) and 100% humidity.

Finally, the Rhi, PD, and time-integral indices showed good correlations with humidity for each pollution level studied. However, they did not show a direct correlation with the surface pollution of the insulator for all humidity levels and pollution levels. Only a few studied indices performed well at certain operational points.

A combination of the three indices is proposed to improve the performance of the classification of pollution levels.

It is recommended that the Rhi index be used to distinguish between high and very high pollution levels. However, it is important to exercise caution and ensure that comparisons are made under the same humidity conditions when identifying transitions from one pollution level to another.

TABLE 2. Steady condition index results.

Pollution Level	Humidity (%)	Rhi	PD (%)	Time Integral (μC)
Clean	50	0.0203	6.67	2.38
	80	0.0396	7.65	2.43
	90	0.0313	7.73	2.63
	100	0.0163	17.06	2.67
	Average	0.0269	9.78	2.53
Medium	50	0.0659	10.20	3.10
	80	0.0224	41.22	6.63
	90	0.0672	37.15	6.57
	100	0.0935	56.62	7.11
	Average	0.0623	36.30	5.85
High	50	0.0131	13.74	3.40
	80	0.0128	36.19	3.95
	90	0.0335	42.01	7.82
	100	0.0757	58.58	7.79
	Average	0.0338	37.63	5.74
Very High	50	0.0365	20.36	3.46
	80	0.0556	54.93	4.83
	90	0.0806	71.08	5.21
	100	0.0820	65.11	8.85
	Average	0.0637	52.87	5.59

The time-integral index can differentiate pollution levels only under dry insulating conditions and 100% humidity.

Finally, the PD index for the boundary conditions reported in the literature (PD < 30%) indicates that the insulator is clean, and when 30% < PD < 85%, the insulator is in an extreme condition. The index did not show any satisfactory results for tests performed in the laboratory. However, the index showed a good correlation between the increase in the index value and pollution level. The index can be used with good performance to identify different pollution levels, but only if a comparison is made at the same humidity level.

It is vital to expose a specific insulator to laboratory testing under various pollution and humidity conditions in order to properly establish the boundaries for each pollution level in relation to each index.

V. DISCUSSION AND CONTRIBUTION

This paper presents a new analysis of the effects of humidity on the impedance, resistance, and reactance of electrical insulators. In addition, the effect on some indices is used in the literature to determine the contamination level of an insulator by measuring the LC.

The concept of harmonic impedance has been introduced in the study of high-voltage insulators to understand the behavior of the current harmonics used by certain indices. An in-depth analysis was also conducted on the behavior of the equivalent impedance (resistance and reactance) of the insulator and pollution layer.

The amplitude of the characteristic impedance decreased as the humidity increased, particularly for insulators contaminated with high or very high humidity levels. At very high contamination levels, the impedance varied from 33 MOhm (RH = 80%) to 20 MOhm (RH = 100%), with a variation of 65%. For the clean case, the impedance varies from 30 MOhm (RH = 80%) to 26.7 MOhm (RH = 100%). This is only 13%. With low contamination of the insulators, the impedance remained almost constant as the humidity increased.

In addition, this study showed that the equivalent impedance, resistance, and reactance of the insulator are time-varying, even with constant humidity applied in the chamber, especially with high contamination or humidity (RH > 80%). The impedance modulus shows variable behavior over time, with minimum and maximum values that differ from steady values. The values were 3.5 MOhm (minimum), 23.5 MOhm (maximum), and 21 MOhm (steady state). This impedance characteristic can lead to errors in pollution level classification, especially where current measurements are not continuous over time and current leakage data are acquired every few minutes or hours.

For the different pollution levels studied, the impedance modulus of the 5th, 7th, and 11th harmonics remained constant over time. Amplitude variations of less than 9% were detected.

Furthermore, there was a small decrease in the impedance amplitude of these harmonics as the pollution or humidity level increased. For example, in the case of very high pollution, the 5th harmonic impedance decreases from 12 MOhm (RH=50%) to 6 MOhm (RH=100%). These tests showed a 100% difference in the amplitude between them when the humidity is constant and the level of contamination changes.

Also, for the 5th harmonic impedance at 100% humidity, the impedance drops from 12.2 MOhm for a clean insulator to 6 MOhm for a very high level of contamination. When the contamination changes and humidity is constant, the tests also show significant amplitude differences of 100% between them.

For insulators with low and medium levels of contamination, the impedance of the 3rd harmonic shows significant variations over time (up to 9.1 times). Therefore, depending on the time instant, the amplitude may be larger or smaller than those of the other harmonic impedances. For tests with very high contamination, the amplitude of the 3rd harmonic impedance is less variable over time and decreases in value (average) with increasing humidity. The difference in amplitude was only five times greater. At 100% humidity, the impedance of the 3rd harmonic was stable and had an amplitude lower than those of the other impedances. This shows that the Rhi index can be used more confidently at 100% humidity, as the measured values may vary over time.

It is concluded that the behavior of the 3rd harmonic impedance shows a constant (flat) amplitude over time only under high-humidity conditions. The amplitude exhibited significant variations over time under the remaining humidity and contamination conditions. Therefore, the relationship between harmonics using the Rhi index is significantly affected. The impedance of the 9th harmonic exhibited variations over time, mainly at 100% humidity at low or medium pollution levels. Very high pollution levels did not exhibit any variations.

This new analysis of harmonic impedances provides relevant information for understanding the behavior of LC harmonics in insulators.

VI. CONCLUSION

An analysis of the behavior of harmonic impedances and the equivalent impedance of the insulator, along with their effects on the indices for determining the level of contamination on insulators, was carried out in this study. In this context, the concept of harmonic impedance for insulators was introduced.

The principal conclusions are as follows:

- Significant variations in the amplitude of the equivalent impedance of the insulator were observed during the tests.
- Differences of up to four times between the minimum and maximum values were noted. This is because of the humidity absorption process from the insulator.
- The harmonic impedance amplitudes of the 5th, 7th, and 11th orders are practically constant. Only small variations of less than 9% were observed. This indicates that harmonic currents in the insulator depend on the evolution of harmonics in the supply voltage.
- The 3rd and 7th-order harmonic impedances are time-varying and show significant amplitude variations, which may reach differences of up to 9.1 times. These harmonics are generated in the insulator due to the contamination and humidity.
- Therefore, the indices using LC harmonics depend on both the voltage harmonics and the high variability exhibited by the 3rd-order current harmonics, which strongly affect the performance of these indices.

Finally, the Rhi, time integral, and PD indices were evaluated. It was concluded that the steady-state leakage current data should be used to determine the level of contamination. In the test, the PD index yielded the best results for determining the level of contamination on the insulator.

REFERENCES

[1] O. E. Gouda, M. M. F. Darwish, K. Mahmoud, M. Lehtonen, and T. M. Elkhodragy, "Pollution severity monitoring of high voltage transmission line insulators using wireless device based on leakage current bursts," *IEEE Access*, vol. 10, pp. 53713–53723, 2022, doi: 10.1109/ACCESS.2022.3175515.

[2] M. E. Ibrahim and A. M. Abd-Elhady, "Rogowski coil transducer-based condition monitoring of high voltage insulators," *IEEE Sensors J.*, vol. 20, no. 22, pp. 13694–13703, Nov. 2020, doi: 10.1109/JSEN.2020.3005223.

[3] H. de Santos and M. Á. Sanz-Bobi, "A cumulative pollution index for the estimation of the leakage current on insulator strings," *IEEE Trans. Power Del.*, vol. 35, no. 5, pp. 2438–2446, Oct. 2020, doi: 10.1109/TPWRD.2020.2968556.

[4] S. Deb, S. Das, A. K. Pradhan, A. Banik, B. Chatterjee, and S. Dalai, "Estimation of contamination level of overhead insulators based on surface leakage current employing detrended fluctuation analysis," *IEEE Trans. Ind. Electron.*, vol. 67, no. 7, pp. 5729–5736, Jul. 2020, doi: 10.1109/TIE.2019.2934008.

[5] R. J. Villalobos, L. A. Moran, F. Huenupán, F. Vallejos, R. Moncada, and C. Pesce G., "A new current transducer for on-line monitoring of leakage current on HV insulator strings," *IEEE Access*, vol. 10, pp. 78818–78826, 2022, doi: 10.1109/ACCESS.2022.3191349.

[6] C. Ilomuanya, A. Nekahi, and S. Farokhi, "A study of the cleansing effect of precipitation and wind on polluted outdoor high voltage glass cap and pin insulator," *IEEE Access*, vol. 10, pp. 20669–20676, 2022, doi: 10.1109/ACCESS.2022.3148709.

[7] A. A. Salem, R. Abd-Rahman, S. A. Al-Gailani, Z. Salam, M. S. Kamarudin, H. Zainuddin, and M. F. M. Yousof, "Risk assessment of polluted glass insulator using leakage current index under different operating conditions," *IEEE Access*, vol. 8, pp. 175827–175839, 2020, doi: 10.1109/ACCESS.2020.3026136.

[8] A. A. Salem, R. Abd-Rahman, S. A. Al-Gailani, M. S. Kamarudin, H. Ahmad, and Z. Salam, "The leakage current components as a diagnostic tool to estimate contamination level on high voltage insulators," *IEEE Access*, vol. 8, pp. 92514–92528, 2020, doi: 10.1109/ACCESS.2020.2993630.

[9] Waluyo, D. Fauziah, and I. M. Khaidir, "The evaluation of daily comparative leakage currents on porcelain and silicone rubber insulators under natural environmental conditions," *IEEE Access*, vol. 9, pp. 27451–27466, 2021, doi: 10.1109/ACCESS.2021.3057626.

[10] R. Ghosh, B. Chatterjee, and S. Chakravorti, "A novel leakage current index for the field monitoring of overhead insulators under harmonic voltage," *IEEE Trans. Ind. Electron.*, vol. 65, no. 2, pp. 1568–1576, Feb. 2018, doi: 10.1109/TIE.2017.2733490.

[11] M. F. Palangar, S. Mohseni, A. Abu-Siada, and M. Mirzaie, "Online condition monitoring of overhead insulators using pattern recognition algorithm," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–11, 2022, doi: 10.1109/TIM.2022.3209729.

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