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ORIGINAL RESEARCH

Condition assessment criteria evaluation of asymmetric aged and fully aged silicone rubber insulators based on leakage current harmonics

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Abstract

The leakage current characteristic monitoring of transmission line insulators is considered a worthy technique for insulator state prediction. In this paper, the harmonic analysis of leakage current signals has been performed to analyze the composite insulator condition. Experimental studies of asymmetrically aged, fully aged, and virgin insulators have been conducted. The effects of different aging types, pollution, and humidity on leakage current components, such as harmonics and the phase differences with the applied voltage, have been investigated. The analysis of the results shows that the effect of asymmetric aging on leakage current components is non-linear, and this non-linearity increases with the degree of pollution. Also, the type of insulator aging can be determined by the ratio of the third- and fifth-order leakage current harmonics. For instance, the classification of insulators into virgin, asymmetrically aged, and fully aged can be determined by examining the corresponding value ranges of 0–0.5, 0.5–0.9, and $>$ 0.9, respectively. Similarly, the phase difference values of $<$ 15% and those $>$ 15% indicate the clean and polluted operating conditions individually.

1 | INTRODUCTION

The increasing worldwide demand for electrical energy has led to a range of technological challenges in maintaining the reliability of electrical distribution and transmission systems. Among these challenges, two crucial factors stand out: the appropriate design and functioning of the components utilized in various systems, with insulators being of particular importance. Insulators play a vital role in ensuring the reliability of power systems, serving as integral components in transmission power lines. Any failure of these insulators poses a significant risk to the overall stability and functionality of the power systems. Electrical insulators are commonly fabricated using glass and ceramic materials. Unfortunately, their efficiency can be compromised by adverse weather conditions and pollution. As a solution, composite insulators have considerable benefits over their ceramic and glass counterparts in terms of dielectric performance, hydrophobic properties, and cost. However, they are prone to earlier aging and are difficult to diagnose [1, 2].

It has been reported [3] that the main cause of insulator failure is related to aging. The aging, in turn, is the result of conductive tracks formation that appears and grows on the surface of the insulating material. This process is also considered erosion. Furthermore, under contaminated conditions at normal operating voltages, aging contributes to the occurrence of flashovers.

Environmental factors like heat, humidity, ultraviolet in sunlight, corona phenomenon, and also leakage current (LC) are counted as the main reasons for aging. Among these, the leakage current that leads to dry band arcing is one of the main instigators of aging in insulators. When the composite insulator's hydrophobicity level diminishes, water stream forms on the surface of the insulator that causes LC to flow. When the LC density along the insulator surface is non-uniform, in some regions appropriate pulsation occurs to evaporate the water layer and form dry zones or dry bands. It leads to arcing across the dry areas. This arc is called a dry band arc. For this reason, the LC signal has been investigated experimentally by

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accelerated aging tests to monitor and distinguish the insulators' condition [4, 5].

Two main methodologies are mainly implemented to identify the insulator condition which are theoretical techniques based on diagnostic criteria and practical techniques that are used in power systems. Phase angle differences between the LC and applied voltage [6, 7], LC harmonic components ratio [8, 9], and leakage current amplitude [10–12] have been introduced in literature as main parameters for insulator condition diagnosis. Some practical methods and devices that have been presented in the literature are leakage current optical sampling [13], infrared thermal imaging [14], ultrasonic approach [15], acoustic fault detection technique [16], real-time fault detection in a microphone array [17].

The primary drawback of these techniques is their dependence on a single indicator for identifying the insulator condition. This has a negative impact on the reliability of the classification technique since the aforementioned indicators can be easily influenced by environmental conditions and other factors within the industry.

A deep learning framework for remote and accurate contamination sensing on the surface of outdoor insulators has been proposed in [18]. The experiment specifically focuses on an 11-kV porcelain disc insulator and aims to create a comprehensive database of images depicting various insulator surface conditions, including clean surfaces as well as surfaces contaminated with sand, mud, and ash. To automate the process of feature extraction and recognition, the researchers used a customized convolutional neural network (CNN) architecture. In order to monitor the condition of insulators, a deep learning neural network model is utilized, using aerial images of the insulators [19]. The effects of pollution on insulators in overhead lines were investigated in [20]. While these approaches primarily concentrate on the physical aspects of the insulators, the LC characteristic unveils the inherent feature of the insulator. In addition, LC analysis is simpler and more precise than other parameters in identifying the insulation condition [10–12].

Numerous studies have been conducted to analyze the surface pollution conditions of insulators by examining LC waveforms and frequency characteristics. Experimental findings suggest that the condition of the insulator surface, pollution level, and aging can be effectively evaluated by assessing the magnitude of LC and the low-frequency harmonic components. In [5], the authors investigated the impact of uniform pollution and relative humidity on the waveform and phase angle of LC through experimental tests. The results indicate that phase angle analysis of LC proves useful in predicting the surface wetness of porcelain and polymeric insulators. Additionally, LC waveforms of SiR insulators were evaluated in a clean fog chamber under uniform and non-uniform pollution conditions from the top to bottom surface [21]. The results demonstrate that the magnitude of LC decreases as the Salt Deposit Density (SDD) ratio on the top to bottom surface decreases. In [6], a condition assessment of un-aged porcelain and glass insulators is conducted using the phase angle index under uniform pollution. The obtained results reveal a strong correlation between the surface conditions of the insulators and the phase difference between LC and the applied voltage. In [22], the contamination, wetting rate, non-soluble deposit density, and non-uniform distribution pollution are all studied and executed on the virgin porcelain, glass, and SiR insulators.

Several alternative methods have been explored to predict the occurrence of insulator pollution. These methods involve analyzing LC components such as the third and fifth odd harmonics, as well as the total harmonic distortion (THD). Many researchers have utilized these components, employing techniques such as fast Fourier transform (FFT) and wavelet transform to analyze the LC signal in the frequency domain. The results of these studies indicate that pollution leads to an increase in the first and third frequency components, as well as THD. In simpler terms, the growth of LC harmonics directly impacts THD, and this change is dependent on the contamination level and the harmonics present in the applied voltage [23, 24].

An intelligent detection device has been introduced in [25, 26] which is able to predict the overhead line insulator's condition based on three indicators including the third to fifth harmonic ratio, the phase angle differences between leakage current and applied voltage, and electrical field distribution along the insulator string. The review in this reference is comprehensive, but the research was carried out only on virgin samples and the effect of aging was not considered.

For aged samples, an extensive analysis of leakage current has been carried out in [27–32]. The investigation has been conducted on non-uniform and also longitudinal conditions based on experimental tests. The proposed results represented that the leakage current harmonics increase with aging time, humidity, and pollution levels. Moreover, the non-uniform contamination has a small effect on the phase angle difference.

The simultaneous impact of pollution and aging on composite insulators has been investigated in [29]. It determines that the insulator erosion comprises silica-like material that has hydrophilic properties. Hydrophobicity can reduce surface resistance and leads to a more conductive surface. Therefore, the electrical flashover activities increase which is considered as the main degradation factor of insulators. Consequently, LC monitoring and harmonic content analysis are suitable and convenient methods for aging degree identification and insulator condition monitoring [30]. This paper encompasses various diagnostic techniques applied to hydrophobicity, Equivalent Salt Deposit Density (ESDD), Flashover Voltage, LC, and surface conductivity to investigate the impact of insulator aging over time. The observed discharges are categorized into PD (which typically occurs between water droplets) and arc discharges (which usually transpire between dry bands on the surface of SiR) based on the analysis of LC, cumulative charge, and visual examination of the emitted light [31]. The effect of pollution severity, ageing, geometrical structure, and hydrophobicity class on polymeric insulators' LC amplitudes have been studied in [32]. The experimental tests of the insulators' electrical properties such as leakage current and flashover voltage, after assessing the initial characteristics of insulators is necessary based on their age and supply voltage.

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As shown in reviewed references, most of the reported work to date is concerned with fully aged insulators. According to the represented results, insulator aging is able to vary the harmonic component of leakage current, so the variation of leakage current components can be implemented as diagnostic criteria for insulator state identification. However, in real life, due to the installation position of the insulators, there is a probability that not all parts of the insulators are completely exposed to UV rays' radiation. This situation leads to the possibility of asymmetric ageing of insulators. The effect of asymmetric ageing of polymer insulators on insulator performance and leakage current signals has not been studied up to now. This paper aims to investigate the effects of pollution level, humidity, and also asymmetric aging of SiR insulator on the harmonic components and phase angle of LC. In our work, attempts will be made to investigate this research gap by studying experimentally the leakage current signal variation and its corresponding harmonic contents for virgin, fully aged, and asymmetrically aged insulators, under different test conditions such as humidity and pollution. According to the represented results, it is obvious that humidity and pollution have a non-linear influence on harmonic components, so the non-linear equation has been utilized to fit the experimental achieved data. It was obvious that the aging degree has a positive influence on LC amplitude, and first-order and third-order harmonics but it has a great negative effect on fifth-order harmonics, so an iterative least-squares fitting model in terms of pollution density and aging degree is recommended to represent the aging effect. According to the experimental data, it is concluded that the humidity has a superior effect on the phase angle difference of applied voltage and leakage current in the light contamination condition compared to other conditions whereas asymmetric aging has no remarkable impact on these parameters.

The paper structure is as follows: Section 2 of the paper discusses the experimental setup and test procedures. Section 3 presents the leakage current test results under different test scenarios. Section 4 describes the harmonic contents of the leakage current under various conditions. Section 5 reveals the phase angle difference analysis and the ratio of harmonic current contents. Section 6 concludes this investigation.

A comprehensive comparison of the recommended method in literature is proposed in Table 1.

TABLE 1 A comprehensive comparison of the recommended method for insulator condition monitoring.

References	Distinguishing method	Disadvantages
[14]	Microphone array and infrared thermal imaging	It is utilized to distinguish insulator thermal condition and it is not applicable for another abnormal situation
[15, 16]	Acoustic fault detection technique	Acoustic noise can impress on its accuracy
[17]	Real-time fault detection in a microphone array	It can be implemented for offline condition approaches
[18, 19]	UAV imaging	It is able only to classify pollution condition
[20]	Photo thermal radiometry and infrared camera	Expensive method and it is not easy to be implemented
[5, 6, 21–26]	Leakage current analysis	Investigation has been done only on virgin samples.
[27–32]	Leakage current analysis	Only the effect of fully aged has been investigated Lack of asymmetric aging analysis

TABLE 2 Data of the two insulator types.

Insulator characteristic		
Insulator type	A	B
Voltage class (kV)	20	20
Height (mm)	270	300
Creepage distance (mm)	698	601
Shed number	7	10
Insulator type or shape		

2 | EXPERIMENTAL TEST SETUP

The schematic diagram of an experimental setup for leakage current measurement is shown in Figure 1a, which conforms to the IEC 60507 standard [33]. In Figure 1a, the secondary of the high-voltage transformer is connected to the insulator sample under test via a 10-MΩ current-limiting resistor (R_1) and a 50-Ω shunt resistor (R_{sh}) that is used to measure the leakage current. The two back-to-back Zener diodes across the shunt resistor prevent overvoltage, and both the current and the high-voltage probes are connected to a digital Oscilloscope. Figure 1b represents the laboratory test setup, which consisted of a 220 V/100 kV high-voltage transformer, a fog chamber, and all the associated measuring devices. The test data are stored on a PC in the CSV file format that is provided by the digital oscilloscope.

2.1 | Insulator types

Test samples are composite insulators that are generally used in 20-kV transmission lines. The data for the two insulator types are shown in Table 2. Three identical samples from each insulator type are examined for the study of the influence of ageing type, namely virgin, fully, and asymmetric, on the leakage current components such as harmonic contents and their corresponding phase difference with the applied voltage.

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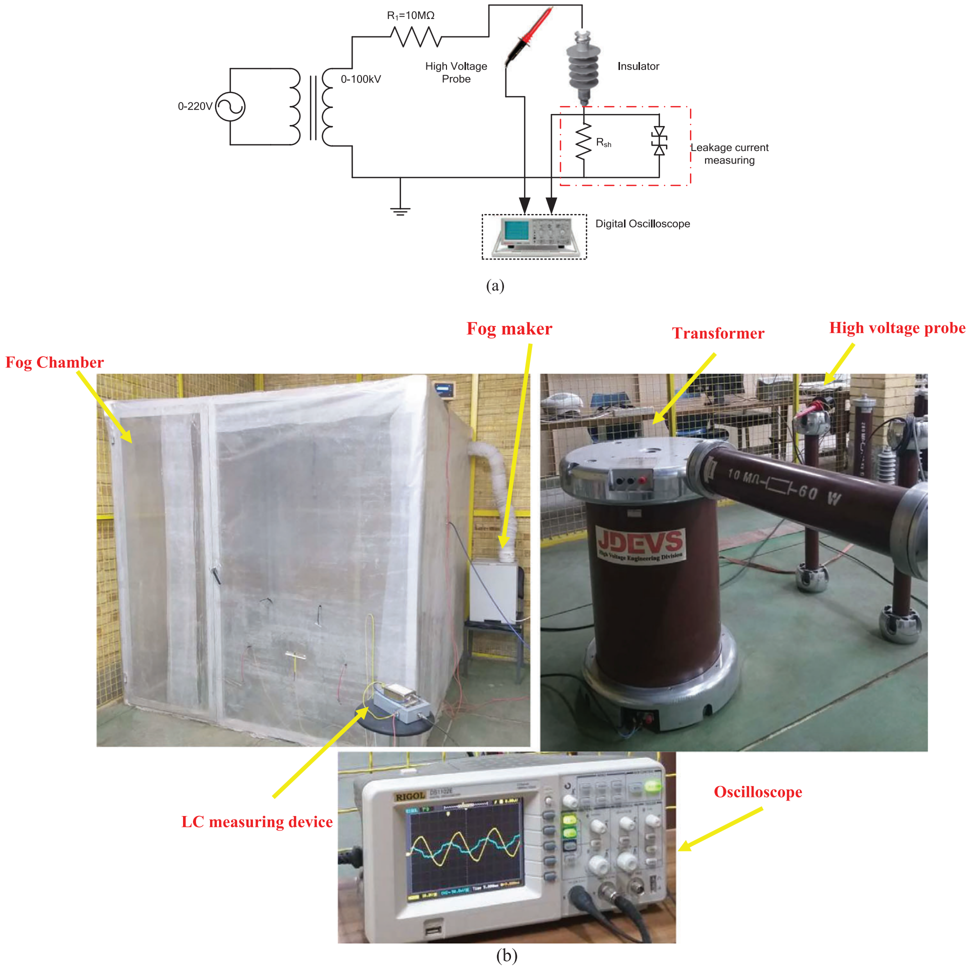

FIGURE 1 The experimental setup for leakage current. (a) Schematic diagram of test setup. (b) Test setup devices.

2.2 | Accelerated aging test

The accelerated ageing process facilitates the simulation of a long-term influence of environmental and electrical stresses on the insulators within a shorter time. To age insulators, the IEC 62217 (Ed. 2) [34] and IEC 1109 [35] standards are adopted, and a 1000-h accelerated ageing test is considered for two samples from each insulator type/shape under different environmental stress conditions such as electric field voltage, ultraviolet, heater, and humidity. To mimic asymmetric ageing, half of an insulator sample is coated with aluminium foil for ageing prevention. Table 3 shows the different environmental stress conditions cycle used for the fully and asymmetrically ageing types of insulators.

TABLE 3 Insulator aging procedure.

Time duration (h)	1	2	3	4	5	6	7	8	9	10	11	12
Voltage												
UV												
Heater												
Humidity												
Asymmetric aging of Type A												

2.3 | Artificial contamination

The solid layer contamination method of the IEC 60507 [33] and IEC 60815 [36] standards is followed for virgin and aged samples. 40 g of Kaolin, or 'china clay', a suitable amount of distilled water, and sodium chloride (NaCl), or 'salt' are diluted and then sprayed on the samples. The conductivity meter is used before and after the spray process for the determination of

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FIGURE 2 The polluted insulators and pollution process.

contamination levels. Figure 2 displays the polluted insulators. After the contamination process, each insulator is placed in the chamber, and its leakage current is measured under different humidity levels.

3 | EXPERIMENTAL TEST RESULTS

Three levels of Equivalent Salt Deposit Density (ESDD) of 0.015, 0.030, and 0.070 mg/cm^2 are used to contaminate the test samples. These ESDDs represent the light, moderate, and heavy pollution levels. The LC signals of various aged (D represents degree of age) such as virgin ($D = 0\%$), asymmetric ($D = 50\%$), and fully aged ($D = 100\%$) samples from both A and B types of insulator are measured experimentally in clean (ESDD = 0.000 mg/cm^2) and polluted (ESDD > 0.000 mg/cm^2) conditions. The LC characteristics of Type A and Type B, clean insulators, for dry (0% humidity), and 80% humidity (H denotes humidity) conditions are shown in Figures 3 and 4, respectively. The rms value of nominal applied voltage is set to 11.54 kV.

Inspection of Figures 3 and 4 suggests that the leakage current amplitude increases with increased humidity, and this increase is less noticeable in dry conditions. The LC waveforms at various pollution conditions and humidity levels for Type A and Type B insulators with reference to virgin, asymmetric, and fully aged conditions are shown in Figures 5–10. Observation of these results reveals that the increase in insulator leakage current amplitude is directly proportional to the increase in pollution and humidity. This is also true for the degree of ageing.

4 | INSULATOR LEAKAGE CURRENT ANALYSIS

4.1 | Harmonic analysis

Tables 4 and 5 show the effect of ageing on the first, third, and fifth harmonics of leakage current for Type A and Type B insulators, respectively. The data in these tables represents the average reading from 10 repeated tests for each condition. The harmonic contents of the LC waveforms are extracted with the aid of the Fast Fourier Transform (FFT). A closer inspection of Tables 4 and 5 suggests that for any fixed pollution and ageing type, the amplitude of harmonics increases with the increase in humidity. This is related to diminishing surface resistivity.

Furthermore, for both Type A and Type B insulators, the amplitude of the third harmonic increases and the fifth harmonic decreases with the degree of ageing. Also, the amplitude of the third harmonic content decreases with aging, e.g., Virgin < Asymmetric < Fully aged insulator. Despite the increasing trend of the third harmonic component of the leakage current, the fifth harmonic component has decreased with the increasing aging degree. A comprehensive analysis of test results is represented in the following sections.

4.2 | The effect of humidity on the first, third, and fifth harmonics of LC

The leakage current harmonic variation of Type A insulator for different pollution types against humidity levels is shown in Figures 11–13. Due to characteristics similarly of both A and B Type insulators, in this section only results related to Type A will be shown and discussed.

The study of Figures 11–13 suggests that nonlinearity in the harmonic contents of the leakage current increases with increasing humidity for virgin, asymmetric, and fully aged samples tested at a fixed pollution type. The degree of nonlinearity is more pronounced for heavily polluted type insulator. Furthermore, the sensitivity of the leakage current harmonic component to humidity and pollution increases with the increment in the degree of aging (0% to 100%). For example, for moderately polluted insulator, I_{t1} of the virgin sample varies from 63 to 441 μA whereas this variation for fully aged sample is between 76 and 570 μA. Similarly, when humidity increases from 60% to 90%, I_{t1} magnitude of the asymmetric aged sample increases from 49.5 to 377 μA, I_{t3} increases from 3.12 to 5.38 μA , and I_{t5} increases from 6.43 to 50.5 μA. These findings conclude that humidity has a non-linear influence on harmonic components. And the non-linear Equation (1) could be utilized to fit the experimental data. This equation also has the ability to estimate a full range of harmonic components of leakage current (I_{th}) at different humidity levels (H).

$$I_{th} = aH^2 + bH + c \tag{1}$$

where parameters a, b, and c are function of % H.

4.3 | The effect of aging on LC harmonic component

In order to deduce a relation between the LC harmonic current (I_{th}) and the degree of ageing (D), Figures 14–16 are plotted for various pollution types (ESDD in mg/cm^2). Analysis of these results demonstrates that the LC harmonics amplitude increases with the degree of ageing. This increase is related to the decrease

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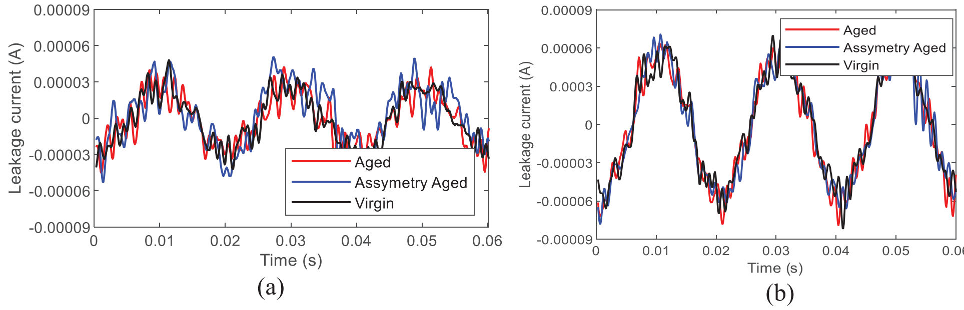

FIGURE 3 Shows LC characteristics of Type A clean insulator: (a) dry condition, (b) 80% humidity.

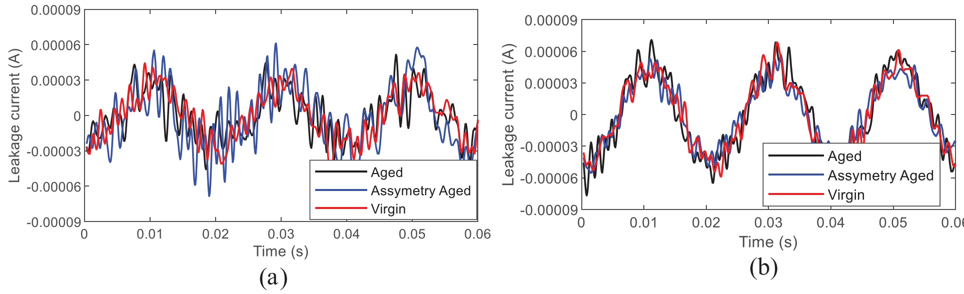

FIGURE 4 Shows LC characteristics of Type B clean insulator: (a) dry condition, (b) 80% humidity.

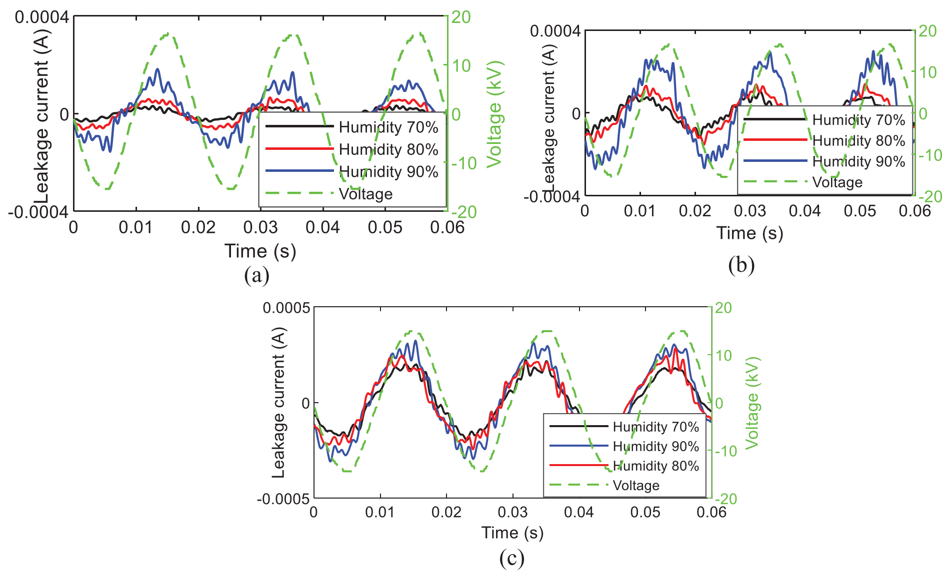

FIGURE 5 The LC patterns of lightly polluted Type A insulator: (a) virgin, (b) asymmetric aged, (c) aged (fully).

in the surface hydrophobicity of the aged sample, which results in greater surface conductivity and consequently greater leakage current flow over the insulator surface. It is also observed that the effect of ageing led to an increase in the magnitude of the leakage current I_{th} which is more noticeable with heavily polluted insulators. As a whole, I_{t1} and I_{t3} amplitudes increase with the degree of ageing, but the opposite is true for I_{t5}.

It is obvious that the first-order and third-order harmonic amplitudes increase with aging degree increment, but the fifth-order harmonic amplitude decreases. For example, under heavy pollution (ESDD 0.07 mg/cm^2) when the aging degree increases from 0 to 0.5 and 1, the first-order harmonic increases from 0 0.000546541 A to 0.000735989 A, and 0.000740517 A, respectively. It means that the first-order harmonic increases by 34.6% and 35.5% compared to virgin condition for aging degrees 0.5 and 1, respectively. For the same condition, the fifth-order harmonic shows 20.9% and 24.4% reduction compared to the fifth-order harmonic of the virgin sample. Equation (2)

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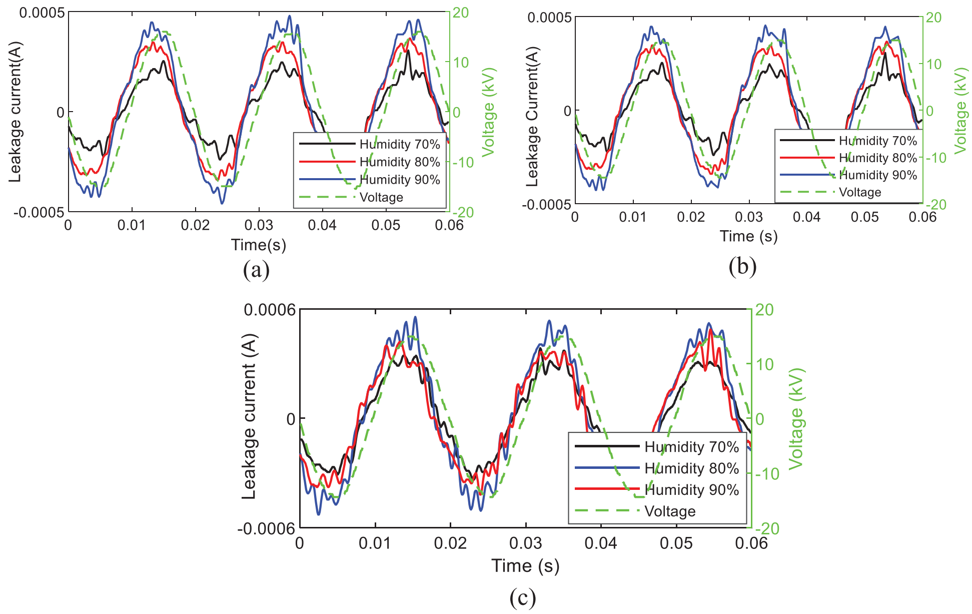

FIGURE 6 The LC patterns of moderately polluted Type A insulator: (a) virgin, (b) asymmetric aged, (c) aged (fully).

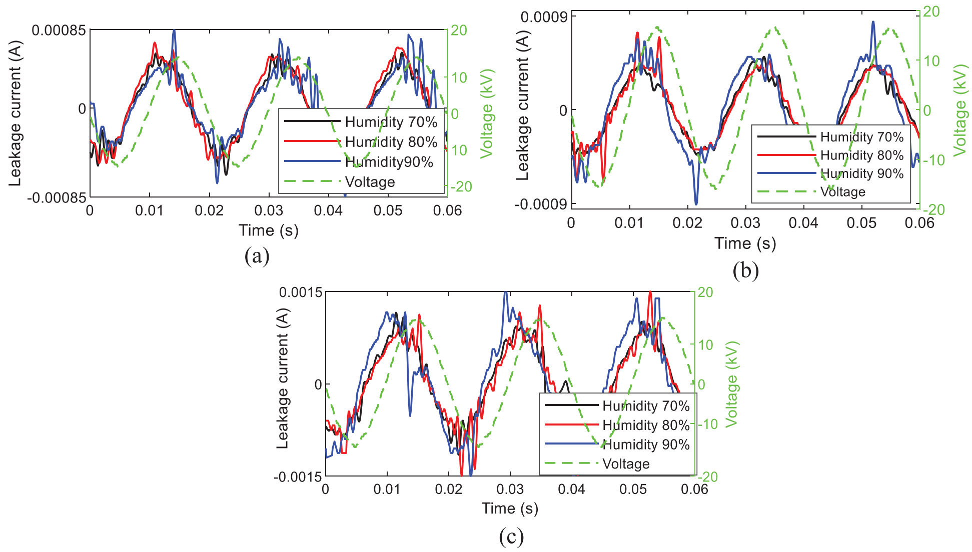

FIGURE 7 The LC patterns of heavily polluted Type A insulator: (a) virgin, (b) asymmetric aged, (c) aged (fully).

well describes the presented test results. The values of a, b, and c parameters for various test scenarios are shown in Table 6.

$$I_{th} = aD^2 + bD + c \tag{2}$$

4.4 | The simultaneous effect of aging and pollution on LC harmonic component

The variation of first-, third-, and fifth-order harmonics under the simultaneous effects of ageing and pollution on leakage current harmonics at different humidity levels is illustrated in Figure 17. For the results presented in Figure 17, an iterative least-squares fitting model expressed with Equation (3) can describe I_{th} in terms of ESDD (mg/cm^2) and ageing degree (D%):

$$I_{th} = a \times ESDD^b \times D^C \tag{3}$$

The values of a, b, and c under different humidity levels and ageing degrees are given in Table 7.

From Table 7, one can observe that under different humidity levels, a, b, and c for I_{t1} and I_{t3} are always positive, and C is negative for I_{t5}. This suggests that, with reference to Figure 17, for

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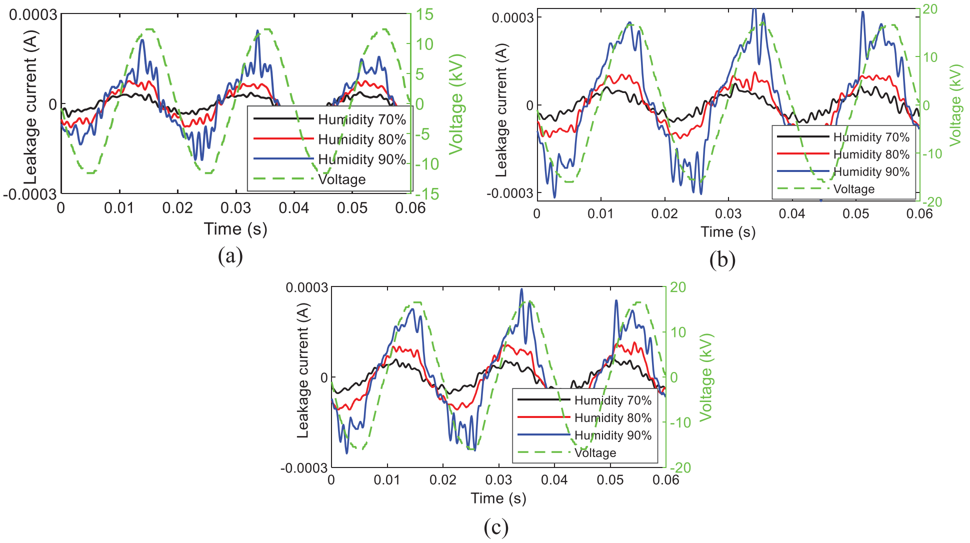

FIGURE 8 The LC patterns of lightly polluted Type B insulator: (a) virgin, (b) asymmetric aged, (c) aged (fully).

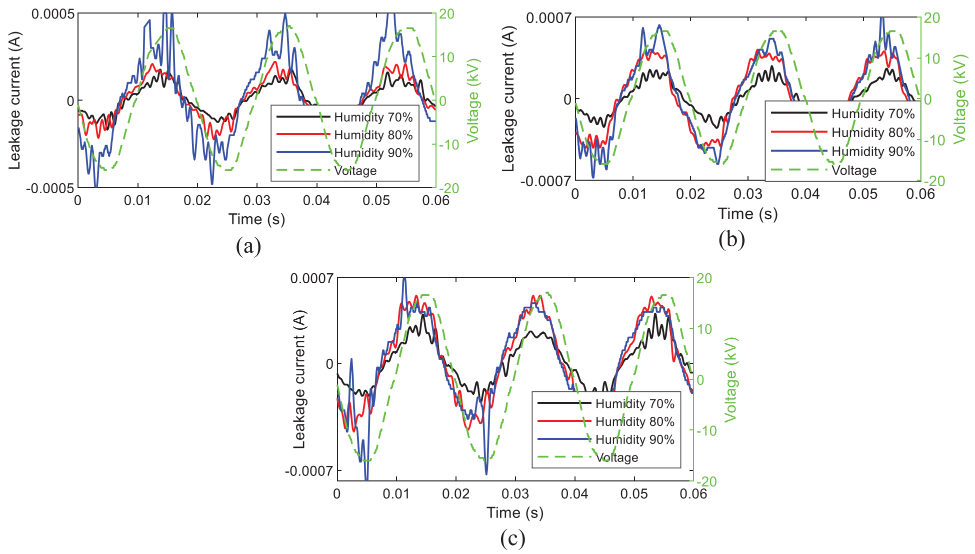

FIGURE 9 The LC patterns of moderately polluted Type B insulator: (a) virgin, (b) asymmetric aged, (c) aged (fully).

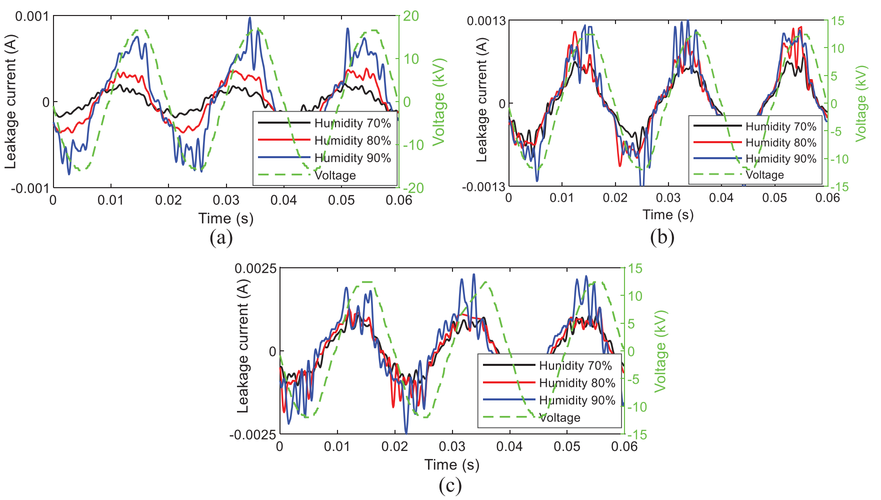

FIGURE 10 The LC patterns of heavily polluted Type B insulator: (a) virgin, (b) asymmetric aged, (c) aged (fully).

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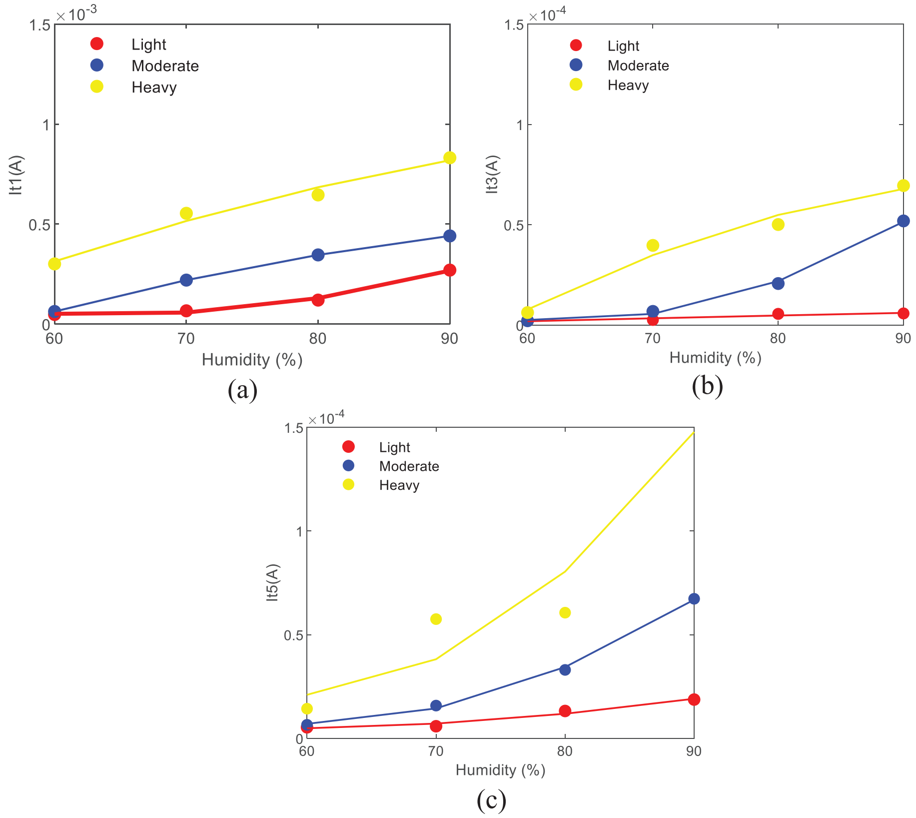

FIGURE 11 LC harmonic component of virgin samples (Type A) (a) I_{t1}, (b) I_{t3}, (c) I_{t5}.

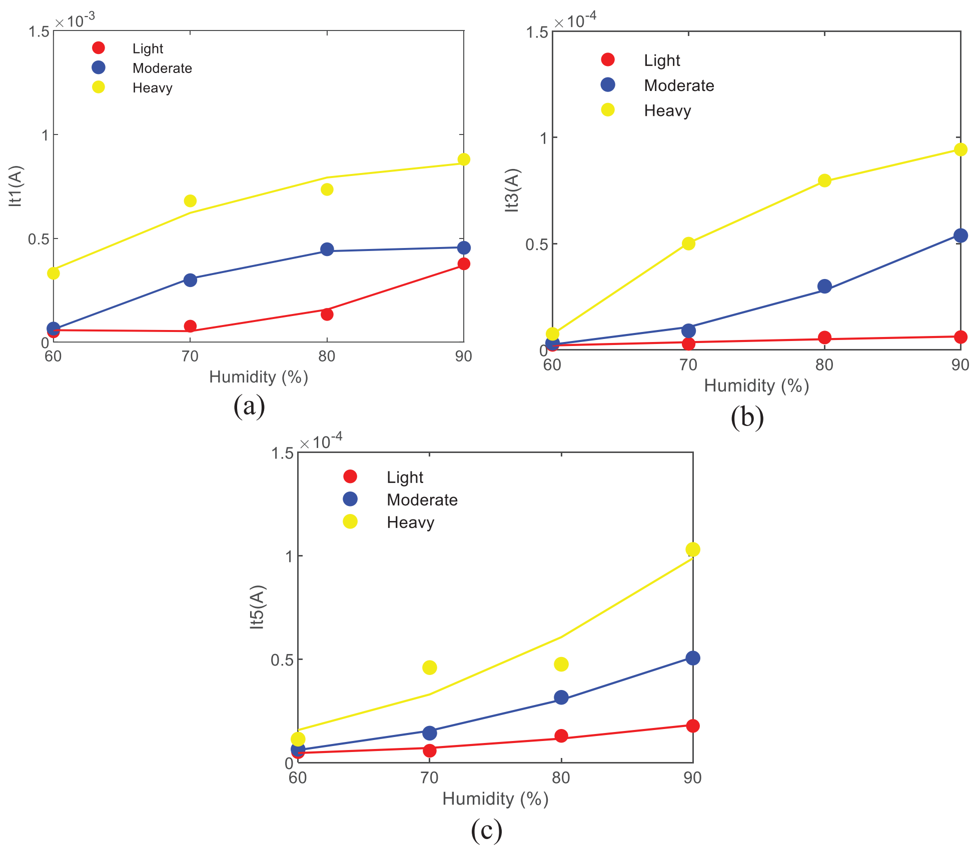

FIGURE 12 LC harmonic component of asymmetric aged samples (Type A) (a) I_{t1}, (b) I_{t3}, (c) I_{t5}.

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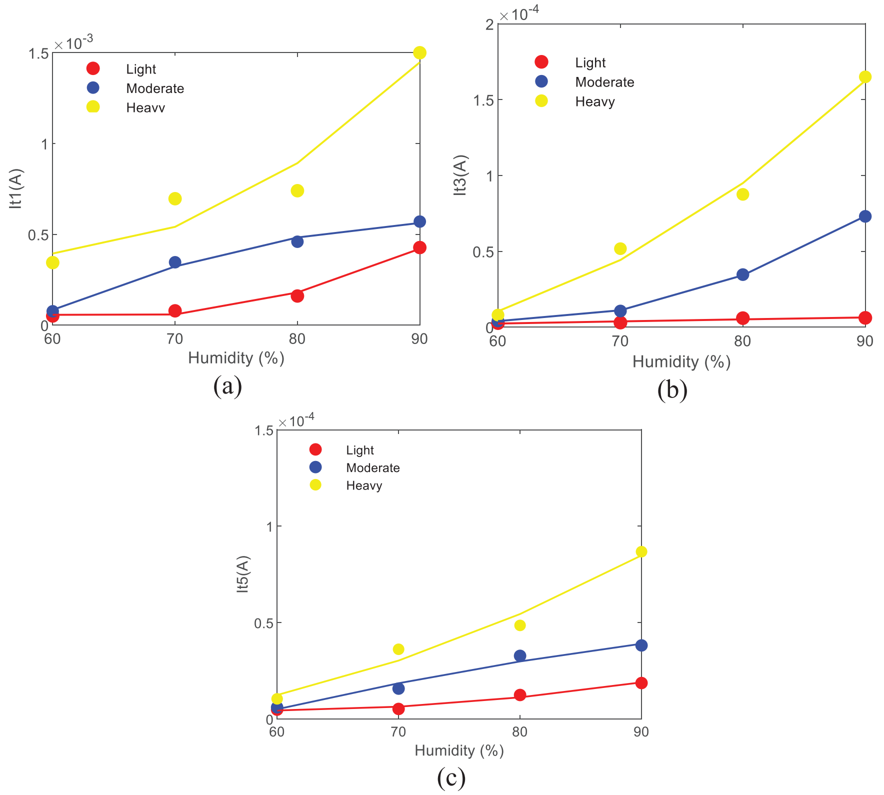

FIGURE 13 LC harmonic component of aged samples (Type A) (a) I_{t1}, (b) I_{t3}, (c) I_{t5}.

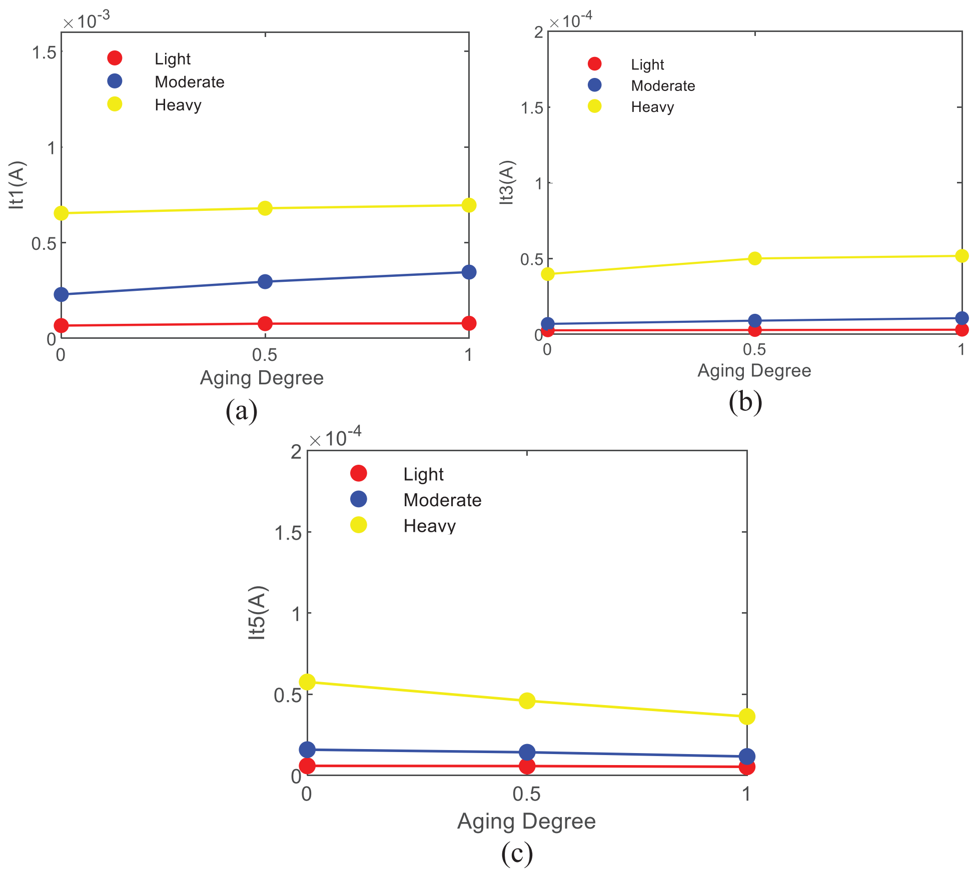

FIGURE 14 LC harmonic component of tested insulators for 70% humidity (Type A) (a) I_{t1}, (b) I_{t3}, (c) I_{t5}.

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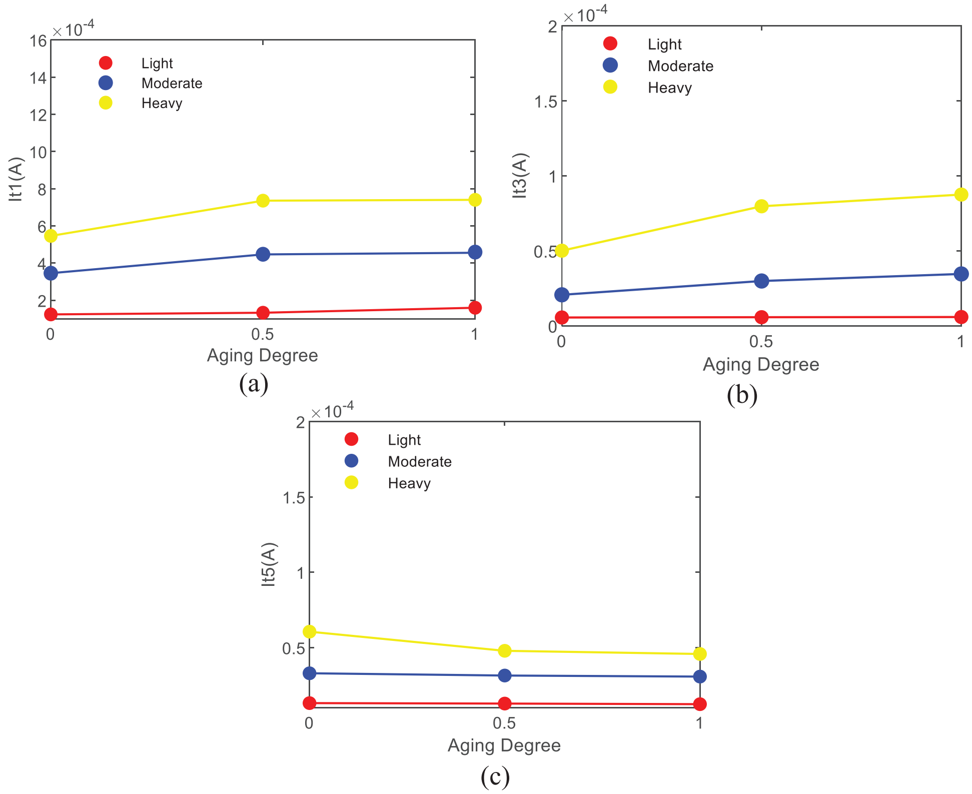

FIGURE 15 LC harmonic component of tested insulators for 80% humidity (Type A) (a) I_{t1}, (b) I_{t3}, (c) I_{t5}.

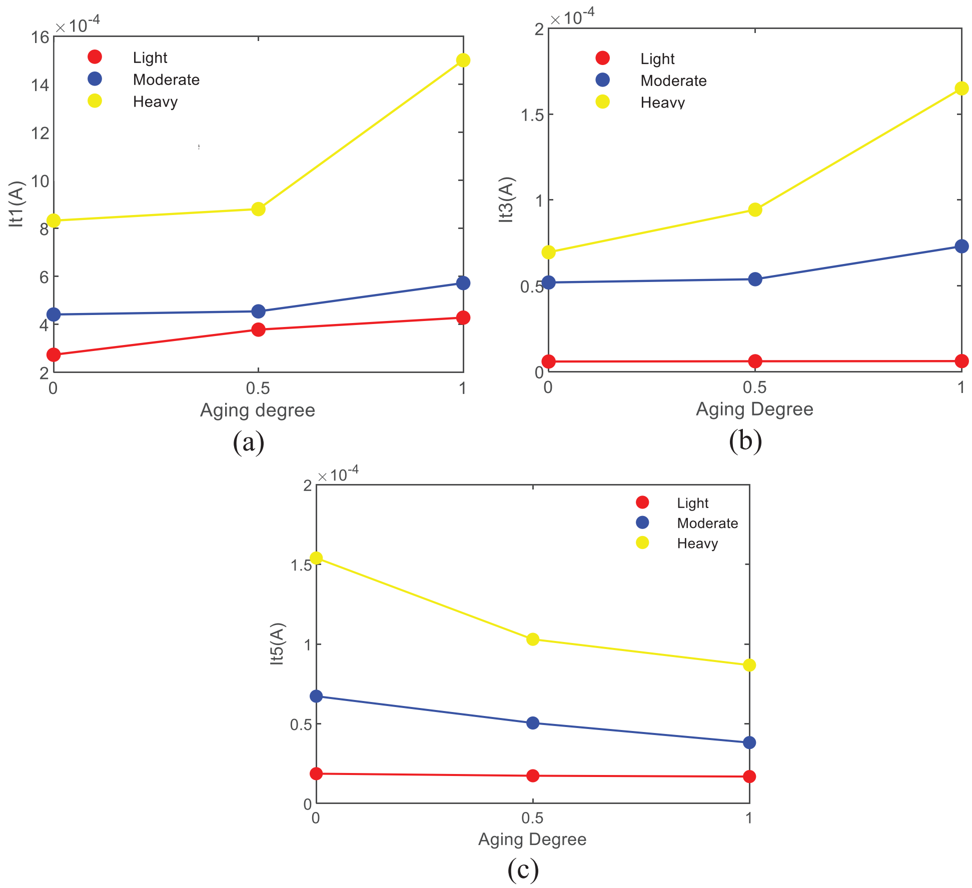

FIGURE 16 LC harmonic component of tested insulators for 90% humidity (Type A) (a) I_{t1}, (b) I_{t3}, (c) I_{t5}.

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TABLE 4 Leakage current harmonic content for Type A insulator.

Aged-type (D)	Pollution type Humidity level (H)	First harmonic amplitude $It1$ (μA)				Third harmonic amplitude $It3$ (μA)				Fifth harmonic amplitude $It5$ (μA)			
		60%	70%	80%	90%	60%	70%	80%	90%	60%	70%	80%	90%
Virgin or un-aged $D = 0\%$	Clean ESDD = 0.000 mg/cm^2	40.6	51	65.2	70	1.93	2.52	2.09	2.98	4.7	4.58	5.83	6.04
	Light ESDD = 0.015 mg/cm^2	48	66.4	120	270	2.19	2.56	5.58	5.8	5.32	5.84	13.2	18.7
	Moderate ESDD = 0.030 mg/cm^2	63	220	346	441	2.16	6.81	20.7	51.9	6.53	15.8	33	67.3
	Heavy ESDD = 0.070 mg/cm^2	301	654	546	832	6.22	39.7	30.1	69.5	14.3	57.5	60.6	154
Asymmetric aged $D = 50\%$	Clean ESDD = 0.000 mg/cm^2	43	53	66.2	72.4	2.75	2.95	2.3	2.3	4.39	4.05	5.49	6.15
	Light ESDD = 0.015 mg/cm^2	49.5	76.4	133	377	2.31	4.77	8.77	9.99	5.05	5.7	12.9	17.7
	Moderate ESDD = 0.030 mg/cm^2	65	298	447	454	3.12	8.93	29.9	53.8	6.43	14.2	31.5	50.5
	Heavy ESDD = 0.070 mg/cm^2	331	680	735	880	7.46	50	39.7	94.3	11.3	45.9	47.5	103
Fully aged $D = 100\%$	Clean ESDD = 0.000 mg/cm^2	45.6	51	68	75	3.9	3.16	3.2	2.98	3.76	3.46	5.1	6.04
	Light ESDD = 0.015 mg/cm^2	50	78.4	160	427	5.6	4.96	15.89	31.08	4.9	5	12.5	16.4
	Moderate ESDD = 0.030 mg/cm^2	76	346	459	570	8.07	10.6	34.6	73	6.11	13.8	32.8	38.2
	Heavy ESDD = 0.070 mg/cm^2	344	696	740	1500	11.93	51.7	87.5	165	10.5	36.2	48.5	86.8

any particular ageing degree (D%) and humidity (H%) for a case with ESDD (pollution level) increasing from 0 to 0.07 mg/cm^{2,} the variation in I_{t1} and I_{t3} is much greater than that in I_{t5}.

As an example, for $D = 1$ and humidity 70%, the fifth-order harmonic increases from 5.19 to 41.48 μA with ESDD increasing from 0.015 to 0.07 mg/cm^2. But this variation for 80% humidity is between 13.58 and 53.5 μA. In these cases, the variation of third-order harmonics varies between 2.86 and 48.98 μA and from 7.6 to 90.4 μA for 70% and 80% humidity levels, respectively.

The accuracy of the fitted curve based on Equation (3) and the curve based on the experimental data for I_{t1}, I_{t3}, and I_{t5} at 70% humidity is shown in Figure 18.

Based on the variation of the leakage current harmonic discussed earlier, a percentage Variation Index (VI%) of the leakage current harmonic is expressed as

$$VI\% = \frac{i_h - i_{hh}}{i_{hh}} * 100 \tag{4}$$

where VI% is the percentage variation index for any aged type insulator, i_h and i_{hh} are the leakage current harmonics of the aged and virgin samples, respectively, that are placed in a chamber with a known ESDD in mg/cm^2.

Table 8 shows the variation of leakage current harmonics for Type A insulators. Analysis of Table 8 yields that I_{t5} increases negatively with increased humidity and insulator age, whereas I_{t1} increases positively.

The negative effect on decreasing trend of fifth-order harmonic for asymmetric aged samples is more than full-aged

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TABLE 5 Leakage current harmonic content for Type B insulator.

Aged-type (D)	Pollution type Humidity level (H)	First harmonic amplitude $It1$ (μA)				Third harmonic amplitude $It3$ (μA)				Fifth harmonic amplitude $It5$ (μA)			
		60%	70%	80%	90%	60%	70%	80%	90%	60%	70%	80%	90%
Virgin or un-aged $D = 0\%$	Clean ESDD = 0.000 mg/cm^2	33.1	41	56.9	78	2.35	2.11	2.45	3.43	2.84	3.55	5.06	5.5
	Light ESDD = 0.015 mg/cm^2	35.4	54.2	124	244	1.38	2.87	5.93	6.9	3.11	4.09	10.3	27.4
	Moderate ESDD = 0.030 mg/cm^2	63.4	272	494	586	5.23	26.5	34.7	75.1	4.78	11.7	24.2	34.8
	Heavy ESDD = 0.070 mg/cm^2	297	635	890	980	24	73.3	131	261	8.2	39.7	88.2	92.3
Asymmetric aged $D = 50\%$	Clean ESDD = 0.000 mg/cm^2	34.7	41.5	48.8	74.5	2.54	2.64	2.74	4.52	2.82	3.32	4.37	5.05
	Light ESDD = 0.015 mg/cm^2	39.2	57.1	122	296	2.96	2.75	5.95	22.6	3.07	4.34	8.57	25.2
	Moderate ESDD = 0.030 mg/cm^2	62.3	273	618	808	4.16	8.5	19.1	38.6	5.82	13.5	30.7	50.2
	Heavy ESDD = 0.070 mg/cm^2	356	754	1120	1280	5.6	28.3	60.2	76	9.53	40.7	89.2	95.2
Fully aged $D = 100\%$	Clean ESDD = 0.000 mg/cm^2	29.4	36.6	57.8	70.5	2.67	2.83	2.95	5.85	2.43	3.1	3.52	4.88
	Light ESDD = 0.015 mg/cm^2	50.8	71.5	156	290	3.02	3.25	9.88	29.7	2.63	3.75	7.16	17
	Moderate ESDD = 0.030 mg/cm^2	60.1	212	324	696	2.64	7.2	24.3	30.4	6.85	14.1	50.8	65.5
	Heavy ESDD = 0.070 mg/cm^2	359	688	1090	2450	17.5	20.3	53.9	30.8	13.5	45.4	93.3	101.7

TABLE 6 The aging effect on leakage current parameters.

Leakage current harmonic	Humidity (% H)	Light pollution ESDD = 0.015			Moderate pollution ESDD = 0.03			Heavy pollution ESDD = 0.07		
		a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*C*
1st order $It1$	70	−1.60E-005	2.80E-005	6.64E-005	−3.40E-005	0.000151	0.000229	−2.00E-005	6.20E-005	0.000654
	80	3.59E-005	−1.49E-007	0.0001245	−0.0001804	0.0002938	0.0003461	−0.0003698	0.0005638	0.0005465
	90	−0.0001091	0.0002638	0.0002733	0.0002097	−7.88E-005	0.000441	0.001144	−0.000476	0.000832
3rd order $It3$	70	−4.00E-008	4.40E-007	2.56E-006	0.0001217	−0.0001792	6.81E-005	−9.00E-007	4.69E-006	6.81E-006
	80	−1.40E-007	4.50E-007	5.58E-006	−9.00E-006	2.29E-005	2.07E-005	−4.36E-005	8.10E-005	5.01E-005
	90	−1.40E-007	3.90E-007	5.83E-006	3.46E-005	−1.35E-005	5.19E-005	9.18E-005	3.70E-006	6.95E-005
5th order $It5$	70	−5.80E-007	1.00E-008	5.84E-006	−2.00E-006	−2.20E-006	1.58E-005	3.80E-006	−2.51E-005	5.75E-005
	80	−2.00E-007	−5e-07	1.32E-005	1.60E-006	−3.80E-006	3.30E-005	2.12E-005	−3.60E-005	6.06E-005
	90	1.60E-006	−3.40E-006	1.87E-005	9.00E-006	−3.81E-005	6.73E-005	6.96E-005	−0.0001368	0.000154

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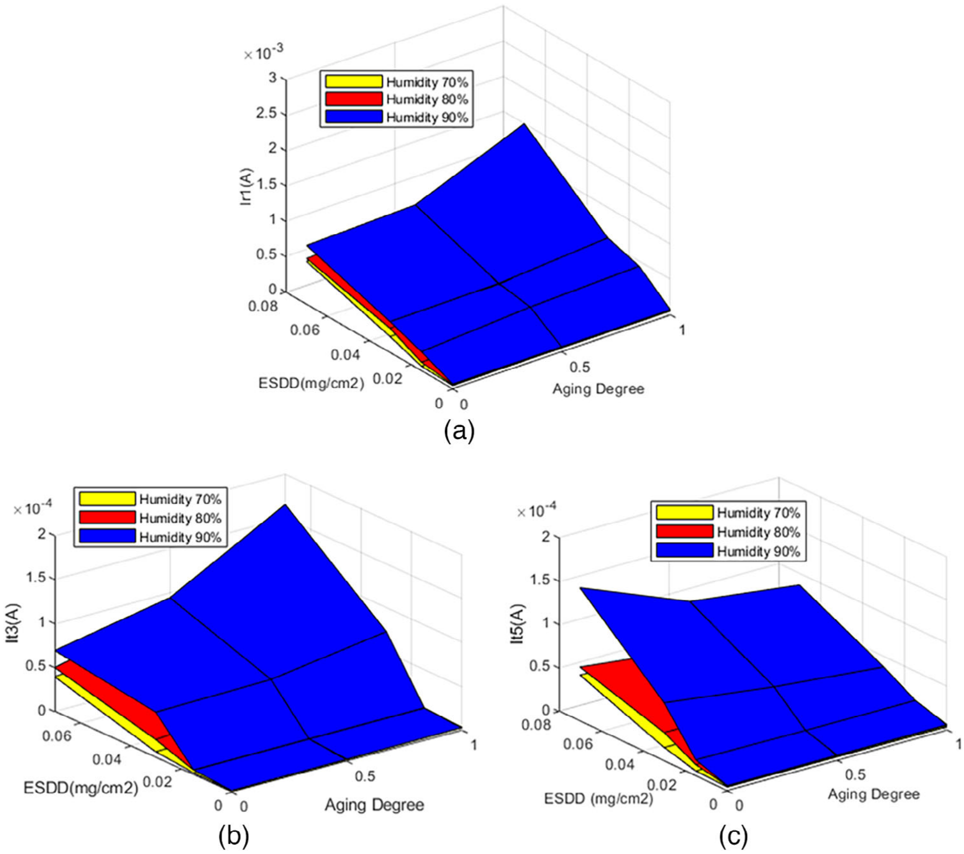

FIGURE 17 The effect of aging and pollution on LC harmonic components: (a) I_{t1} of leakage current, (b) $I_{t3}$of leakage current, (c) I_{t5} of leakage current.

TABLE 7 The fitting model results under different humidity levels.

Leakage current harmonic component	Humidity %	$I_{th} = a \times ESDD^b \times D^C$		
		a	*b*	*c*
I_{t1}	70	0.0334	1.4072	0.0091
	80	0.0134	1.0415	0.0084
	90	0.007	0.7024	0.0128
I_{t3}	70	0.0066	1.8439	0.0106
	80	0.0065	1.6076	0.0147
	90	0.0185	1.8035	0.0122
I_{t5}	70	0.0015	1.3492	−0.008
	80	0.00057	0.8897	−0.0057
	90	0.0025	1.1854	−0.0149

samples according to pollution degree increment. For I_{t3}, this is more severe for the fully aged insulator but not the asymmetrically aged insulator.

These findings indicate that the third and fifth harmonic components are quite sensitive to the insulator test conditions. This sensitivity makes the ratio of I_{t3} to I_{t5} an effective criterion for the Silicon Rubber (SiR) insulator state evaluation.

5 | THE EFFECT OF ASYMMETRIC AGING ON INSULATOR CONDITION MONITORING CRITERIA

All presented criteria so far indicate that the third and fifth harmonic components are quite sensitive to the insulator test conditions. Moreover, the third to fifth harmonic ratio (I_{t3}/I_{t5}) and cosine of Phase-angle Difference ($PD\% = \cos(\theta_i - \theta_v) \times 100$) are reported to be effective parameters and criteria for insulator state evaluation [3–10] and [19].

PD% is the phase angle of the fundamental component of the applied voltage and the leakage current. This section will evaluate the asymmetric ageing effect through the (I_{t3}/I_{t5}) ratio and cosine of the phase-angle difference, which have not yet been studied.

5.1 | Phase angle analysis

The phase angle difference between LC and applied voltage at the fundamental frequency (50 Hz) is calculated using FFT spectral analysis. The obtained results for Type A and Type B insulators are presented in Table 9, where it is shown that at a certain pollution level, θ_{i-v} decreases with an increase in humidity.

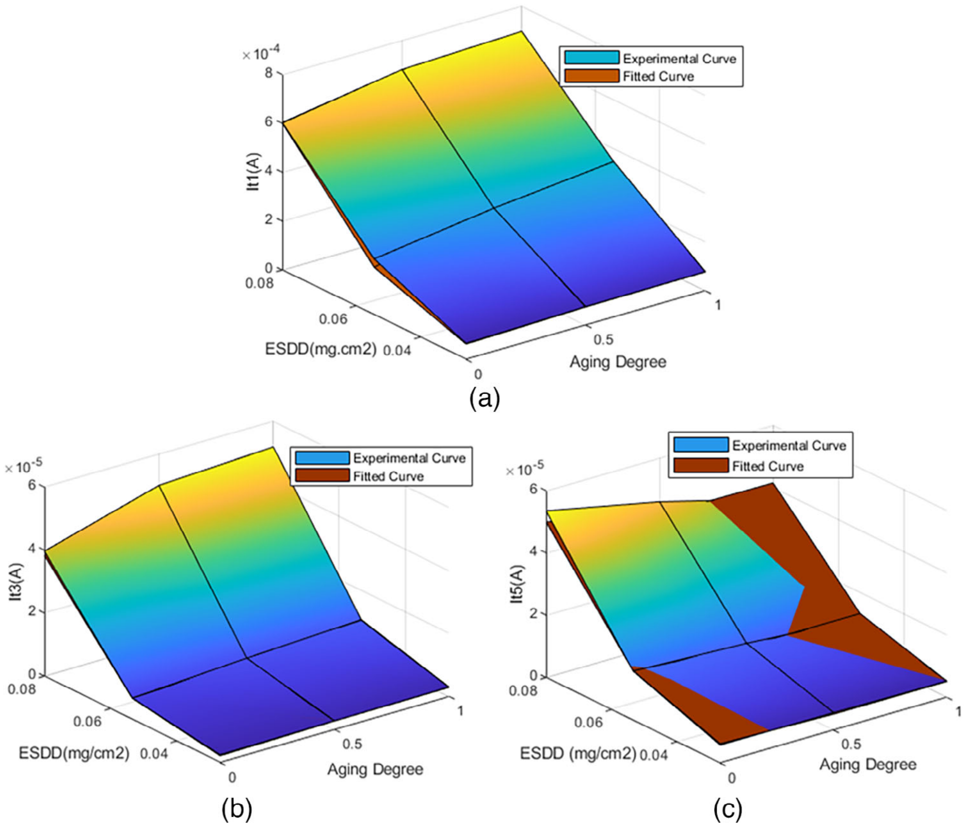

FIGURE 18 The fitted curve based on Equation (3) and the curve based on the experimental data: (a) I_{t1} of leakage current, (b) I_{t3} of leakage current, (c) I_{t5} of leakage current.

TABLE 8 The *VI*% variation of leakage current harmonic of Type A insulator.

VI% variation of leakage current harmonic	Light pollution ESDD in mg/cm^2				Heavy pollution ESDD in mg/cm^2			
	70% humidity (H)		90% humidity		70% humidity		90% humidity	
	Asymmetric aged	Fully aged	Asymmetric aged	Fully aged	Asymmetric aged	Fully aged	Asymmetric aged	Fully aged
VI% of It1	15	18	39	58	39	64	57	80
VI% if It3	86	81	72	91	25	30	35	137
VI% of It5	−2	−14	−5	−12	−20	−37	−33	−43

This indicates that the LC resistance component increased with humidity. For example, for virgin samples, the phase angle variation of the clean insulator is between 82.24 and 76.38 degrees under humidity levels of 60% and 90%, while θ_{i-v} varies from 48.34 to 24.2 degrees and from 34.38 to 24.32 degrees for moderate and heavy polluted samples, respectively. According to the presented result, asymmetric ageing does not have a tangible effect on this criterion and instead it is represented by an iterative least-squares fitting model in terms of ESDD (mg/cm^2) and ageing degree (D) as

$$\theta_{i-v} = a \times ESDD^{b} \times D^{C} \tag{5}$$

where a,b, and c are constant values. The fitting model of the results under different humidity levels for Type A insulator is given in Equation (6). As an example, the fitted curve and the experimental curve for 70% and 80% humidity is shown in Figure 19.

$$\theta_{i-v} = \begin{cases} 6.73 \times ESDD^{-0.57} \times D^{-0.0017} & 60\% humidity \\ 9.93 \times ESDD^{-0.37} \times D^{-0.0014} & 70\% humidity \\ 14.4 \times ESDD^{-0.1897} \times D^{0.003} & 80\% humidity \\ 16.11 \times ESDD^{-0.9} \times D^{-.0055} & 90\% humidity \end{cases} \tag{6}$$

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TABLE 9 The phase angle differences between the LC and voltage.

		θ_{i-v} in degree							
		Type A insulator				Type B insulator			
Aged type	Humidity Pollution type	60%	70%	80%	90%	60%	70%	80%	90%
Virgin	Clean	82.24	80	76.38	73.16	86	75.5	72.3	68.3
	Light	80.34	57.98	36.28	26.5	77.2	57	40	25
	Moderate	48.34	29.66	25.94	24.2	48.9	28.8	24.2	20
	Heavy	34.38	31.34	28.2	24.32	32	31.58	27.4	26.2
Asymmetric aged	Clean	81.66	79.38	76.3	72.2	87	79.5	76	67.2
	Light	78.82	56.06	35.38	24.4	77.9	59	37.18	23.64
	Moderate	48.62	29.6	24.7	23.28	48.2	27.7	25.3	18.9
	Heavy	31.98	30.5	25.54	23.16	29.2	29.5	26.8	25.5
Aged	Clean	80.66	78.88	75.8	71.96	86.16	71.5	69.2	67.3
	Light	77.74	54.14	35.1	23	76.6	59.46	35.6	22.8
	Moderate	48.34	29.46	23.86	22.1	44.28	26.96	23.5	18.25
	Heavy	30.82	29.92	24.9	22.96	28.7	28.9	26.15	24.8

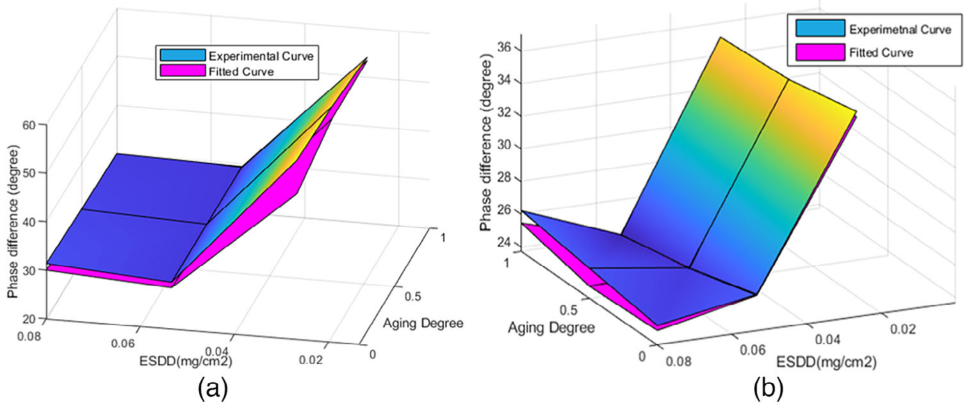

FIGURE 19 The fitted curve and the experimental curve: (a) 70% humidity, (b) 80% humidity.

The exponent of *ESDD* in Equation (6) is negative under various humidities, and θ_{i-v} decreases considerably with the increase of *ESDD*. With increased LC current, the electrical conductivity of the insulator surface increases, and the LC current becomes more resistive.

Also, it is found out that the EDDD has a significant impact on θ_{i-v} compared to other factors, and this increases with an increase in humidity. However, at higher humidity, the feature of ageing via θ_{i-v} is less prominent. According to Figure 18, at a specific ESDD and humidity level, there is no significant variation trend in θ_{i-v} with an increase in ageing degree. For example, at 70% humidity, and light pollution, the θ_{i-v} values are 57.98, 56.06, and 54.14 degrees for virgin, asymmetric, and fully aged samples, respectively.

The effect of ageing on *PD*% for different pollutants and humidity is summarized in Table 10. As shown in Table 10, *PD*% does not show an effective variation according to the aging degrees. Increasing the aging degree is able to change this parameter slightly. As an example, for light pollution and 90% humidity (Type A insulator), the variation of this parameter is between 89.4 and 92. Furthermore, for heavy pollution and 90% humidity, this parameter varies from 93.4 to 91. However, as shown in this table, humidity and contamination have superior effects on this criterion. In the same pollution level, *PD*% shows an increasing trend according to the humidity. The variation of this criterion for light pollution is more than other contamination levels.

5.2 | The third harmonic to fifth harmonic ratio (I_{t3}/I_{t5}) analysis

Leakage currents analysis gives useful information about the insulator's condition. In this section, the impact of

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TABLE 10 The effect of aging on *PD*% for different pollution and humidity levels.

		Clean	60%			70%			80%			90%		
		Dry	Light	Moderate	Heavy	Light	Moderate	Heavy	Light	Moderate	Heavy	Light	Moderate	Heavy
(Type A insulator)														
Virgin	*PD*%	0.3	16.7	66	82.5	53	86.9	85.4	80.8	89.9	90.7	89.4	91	93.4
Asymmetric aged	*PD*%	10	19.38	66.4	84.8	55.8	87.12	86.1	81.5	90.8	90	91	91.8	93
Aged	*PD*%	13	21.2	66.7	85.8	58.58	87	86.6	81.8	91.4	88.1	92	92.6	91
(Type B insulator)														
Virgin	*PD*%	3	22	65	84.8	54	87	84.9	76	91	88. 7	90	93	89.7
Asymmetric aged	*PD*%	5	20.9	66.6	87.2	51.5	88.5	87	79.7	90.4	89. 2	91.6	94.6	90.2
Aged	*PD*%	6	23.17	71.5	87.7	50.81	89.1	87.5	81.3	91.7	89. 7	92.1	94.9	90.7

TABLE 11 The effect of aging on I_{t3}/I_{t5} for different pollution and humidity levels.

		Clean	60%			70%			80%		90%			
		Dry	Light	Moderate	Heavy	Light	Moderate	Heavy	Light	Moderate	Heavy	Light	Moderate	Heavy
(Type A insulator)														
Virgin	I_{t3}/I_{t5}	0.53	0.41	0.330	0.436	0.43	0.430	0.690	0.42	0.626	0.49	0.311	0.771	0.452
Asymmetric aged	I_{t3}/I_{t5}	0.72	0.45	0.48	0.659	0.48	0.629274	1.090	0.8	0.950	0.82	0.67	1.063	0.914
Aged	I_{t3}/I_{t5}	0.91	1.14	1.3	1.13	1.01	0.914	1.427	1.27	1.053	1.9	1.65	1.910	1.907
(Type B insulator)														
Virgin	I_{t3}/I_{t5}	0.53	0.443	0.385	0.25	0.585	0.51	0.44	0.575	0.478	0.57	0.87	0.464	0.30
Asymmetric aged	I_{t3}/I_{t5}	0.8	0.96	0.714	0.58	0.633	0.634	0.695	0.694	0.622	0.674	0.896	0.768	0.798
Aged	I_{t3}/I_{t5}	1.098	1.14	1.09	2.92	0.866	2.26	1.846	1.3798	1.43	1.48	1.747	2.15	2.82

asymmetric aging on this criterion is investigated. The effect of aging on I_{t3}/I_{t5} value for different pollution and humidity levels is arranged in Table 11.

A tentative analysis of Table 11 suggests that ageing has a great impact on I_{t3}/I_{t5}, and this criterion increases by increment in the degree of ageing, assuming a fixed pollution and humidity condition. The increase in value of I_{t3}/I_{t5} is related to increase in It3 and decrease in It5. As an example, for light pollution and relative humidity of 90%, the variation for Type A insulator is 0.311, 0.67, and 1.65 for virgin, asymmetric, and fully-aged, respectively. Similarly, for heavy pollution and 90% humidity, this criterion value is 0.452, 0.914, and 1.907 for virgin, asymmetric, and fully-aged insulators, respectively. Hence, the ratio of the third- and fifth-order leakage current harmonics can determine the type of insulator ageing. For example, in this investigation, values between 0–0.5, 0.5–0.9, and > 0.9 are associated with virgin, asymmetrically, and fully aged insulators, respectively. However, to categorize the polluted and clean conditions of the virgin, asymmetric, and fully aged insulators, I_{t3}/I_{t5} index is not useful because it is not clear if the pollution effect on the criterion is increasing or decreasing. But the proposed *PD*% can be used to indicate clean and polluted operating conditions. Referring to Table 10 and our earlier discussion, the phase difference values of < 15% refer to the clean and values > 15% indicate polluted operating conditions.

6 | CONCLUSION

The examination of two types of silicon insulator under various test conditions for the study of leakage current analysis shows that the increase in insulator leakage current amplitude is directly proportional to the increase in pollution and humidity. This increase is related to diminishing surface resistivity or a decrease in the surface hydrophobicity of the sample, which results in greater surface conductivity. While the amplitude of the third harmonic (I_{t3}) increases and the fifth harmonic (I_{t5}) decreases with the degree of ageing, in general, the amplitude of the third harmonic for virgin insulators is less than that for asymmetric insulators, which in turn is less than that for fully aged insulators. Furthermore, humidity has a non-linear influence on the increase in magnitude of the first, third, and fifth harmonic components of LC for virgin, asymmetric, and fully aged samples. However, the increase in the magnitude of the leakage current components is more noticeable with heavily polluted. For any particular ageing degree and humidity, with

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ESDD increasing from 0 to 0.07 mg/cm^2, the variation in I_{t1} and I_{t3} is much greater than in I_{t5}.

The results from a series of laboratory-based experiments indicate that the third and fifth harmonic components are sensitive to the insulator test conditions, which makes the ratio of (I_{t3}/I_{t5}) an effective criterion for silicon rubber insulator state evaluation.

When the aging degree increases from 0 to 0.5, and 1, the I_{t3}/I_{t5} increases by 90% and 202% compared to virgin conditions for light pollution and 80% humidity. For light pollution and 90% humidity, the variation of this parameter is 215% and 513% compared to virgin conditions. It is clear that asymmetric aging and also full aging have a great influence on this criterion. Consequently, the ratio of the third- and fifth-order leakage current harmonics (I_{t3}/I_{t5}) is a credible candidate in determining the type of insulator ageing. For example, in this investigation, values between 0–0.5, 0.5–0.9, and greater than 0.9 are associated with virgin, asymmetric, and fully aged insulators, respectively. The increase in value of I_{t3}/I_{t5} is related to an increase in I_{t3} and a decrease in I_{t5}. However, to categories the polluted and clean conditions of the virgin, asymmetric, and fully aged insulators, I_{t3}/I_{t5} index cannot clearly determine whether the pollution effect on the criterion is increasing or decreasing.

The proposed *PD*% or better known as the cosine of phase-angle difference (θ_{i-v}) reveals that the phase difference values of less than 15% refer to clean conditions, and values greater than 15% refer to polluted operating conditions. Therefore, harmonic components and the phase angle of LC can be implemented for assessment and prediction of the silicon rubber insulator status, and in particular for the asymmetric insulator which is the focus of this research work.

Furthermore, a review of the literature revealed that no attempt has been made to analyze the comprehensive investigation of insulator condition. Due to exposure to different types of contaminants, insulators may experience both non-uniform and uniform contamination on their surfaces. Additionally, sunlight can cause asymmetric aging. Detecting the condition of insulators is a significant concern for the electricity industry, aiming to prevent electrical failures and fundamental faults within the power network. Thus, future research can focus on developing new criteria for the monitoring of insulator condition, including uniform pollution, non-uniform pollution, aging and asymmetric aging conditions. These criteria should have the capability to differentiate between the various states of insulators, such as pollution levels, pollution types, and degree of aging, including virgin, asymmetric, and aged samples. This research is crucial because accurate and prompt assessment of the severity of pollution and the aging status of insulators is essential for pollution flashover prevention.

AUTHOR CONTRIBUTIONS

Masume Khodsuz is responsible for Conceptualization, Methodology, and Investigation. Mehdi Esmaieli is responsible for Experimental Test and Writing original draft. Hassan Nouri is responsible for Conceptualization and Formal Analysis.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Required information is available upon formal request from the corresponding author

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