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Classification of leakage current odd harmonic component of aged insulator surface condition under different relative humidity using crest factor

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Abstract: The impact of pollution on insulator surface performance has been extensively studied to continuously improve the insulator performance using suitable condition monitoring, including using the leakage current harmonic component analysis. However, the analysis of harmonic components, particularly in relation to the odd harmonics of the leakage current in aged insulators under the influence of contamination and humidity, is still not fully understood and remains deficient. In this paper, the leakage current of aged and polluted insulators under different environmental conditions are investigated. The study was conducted experimentally using twelve samples of insulators with varying degrees of aging. The crest factor was employed as an indicator of the leakage current index. The findings showed that the odd harmonic crest factor demonstrates high sensitivity in classifying the degree of aging in contaminated insulators.

Key words: condition monitoring, contamination, crest factor, harmonic component, insulator, leakage current

1. Introduction

Determination of the leakage current (LC) on the surface of insulators proved to be one of the most effective ways to assess the surface condition of insulators, especially the insulator contamination level. The flow of leakage current along the surface of contaminated insulators may eventually lead to the insulator flashover. In fact, most of the unplanned outages in transmission lines are related to outdoor insulator flashovers which are mainly due to pollution [1]. Therefore, it is important to develop a technique to assess the outdoor insulator surface contamination condition. The presence of the insulator leakage current is dependent on the surrounding pollution level and the contamination salinity; both of these can be quantified in terms of the conductivity of the contamination layer. The insulator leakage current is known from many studies to contain significant information on the insulator surface conditions, especially in terms of the equivalent salt deposit density (ESDD), and the non-soluble salt deposit density (NSDD) [2].

Most previous investigations on polluted insulator surface conditions focus on the variation of the leakage current (LC) parameters such as peak magnitude, number of pulses, root mean square (I_{RMS}), and maximum value (I_{Max}). These parameters are initially used to indicate and monitor the contamination level of insulators [3, 4]. However, the LC variation is influenced not only by the insulator's surface contamination level but also by the atmospheric conditions such as temperature, humidity, fog, and rainfall [5]. This makes it very challenging to distinguish the influencing factors when analysing the LC in the time domain [6].

This makes it very challenging to distinguish the influencing factors when analysing the LC in the time domain [7, 8]. Frequency domain analysis is more effective and accurate than time domain analysis for assessing insulator performance, utilizing the odd harmonic components of the leakage current. Zhao *et al.* [9] explored the implementation of the fast fourier transform (FFT) and the wavelet transform on LC signals. They found that the contamination on the insulator surface leads to an increase in the first and third frequency components of the LC, as well as an increase in the total harmonic distortion (THD). Several researchers [10–12] also agree with the superiority of the frequency domain analysis, especially when using the THD parameter in predicting the insulator flashover voltage. As the contamination levels increase, the magnitude of the higher-order harmonic components of the LC becomes more prominent, making the harmonic components as reliable indicators for diagnosing aged insulators [8, 13]. The effectiveness of the frequency domain analysis, particularly using the THD parameter to predict the insulator flashover voltage, is well-supported by several authors [14–17]. Laboratory tests investigating the leakage current in aged insulators under various non-uniform conditions showed that the LC harmonics increase with age, humidity, and pollution severity [18–20]. Additionally, Salem *et al.* [13] examined the impacts of pollution, wetting rate, non-soluble deposit density, and uneven pollution distribution on porcelain, glass, and SiR insulators. They found that as the contamination level increases, the magnitude of the higher order harmonic component of the LC increases and becomes more significant. Hence the harmonic component of the LC could be used as a good indicator in diagnosing aged insulators [20–22] It is to be noted that all the research work undertaken above was using fixed age, hence no variation in the environmental factors affecting aging is considered.

Various researchers have utilized the 3rd and 5th odd harmonic components and the total harmonic distortion (THD) to predict the contamination on insulators [3, 5, 23–26]. Studies have demonstrated that the 1st and 3rd harmonic components of the leakage current as well as the THD increase with both the pollution rate and the applied voltage [27–29]. As the contamination level increases, the magnitude of the higher-order harmonic components of the LC becomes more significant [30]. Compared to the lower-order components. It is crucial to have an indicator that accurately reflects the condition of insulators. For predicting flashover occurrences, the $5^{\text{th}}/3^{\text{rd}}$ harmonic ratio and THD were previously employed as one of the key indicators [31]. Khodsuz *et al.* [32] established that the experimental results indicate that the criteria ($I_{t3/5}$, PI%, and PD%) were not able to identify and categorize insulator conditions based on its aging or contamination. However, by introducing two new criteria, namely, $100 \cdot I_{t3/5}$ and $100 \cdot$ PI%, a significant variation with aging was observed, all while keeping the humidity and the insulator contamination constant. However, Banik *et al.* [33] established that the harmonics from the supply voltage distortion has also contributed an impact on the LC performance of the contaminated outdoor insulators under non-uniform conditions.

Neglecting the impacts of the 7^{th} and 9^{th} harmonic components of the LC may affect the accuracy of results representing the insulator's condition. Therefore, the objective of this research is to develop indices based on the characteristics of the LC and the applied voltage, considering the significant impacts of environmental conditions on the LC performance of various insulators. In this work, the effects of varying the surrounding humidity on the insulator LC measurement are investigated. It is proposed that analysing the odd harmonic components of the insulator LC, especially the crest factor values, can help identify the effects of varying surrounding humidity on the insulator's performance.

2. Methodology

2.1. Experimental setup

Experiments have been performed using twelve sets of 11 kV glass insulators, as shown in Table 1, in an artificial climatic chamber based on methods described in the IEC 60507. To determine the contamination level of the solution, a mixture of salt (NaCl) and water was prepared using 100 ml of distilled water under controlled room temperature. The three salt quantities (10 g, 20 g, and 60 g) were mixed with distilled water and measured using a conductivity meter. Under controlled environmental conditions, the contaminated insulator was sprayed with the salt solution, and allowed to dry naturally. The pre-contaminated samples were dried completely before being suspended vertically inside the chamber and then wetted by clean steam of distilled water. A varying operating voltage supply was applied to the surface of the contaminated insulator terminals at a step voltage of 5 kV. In the setup, a cascade of two 75 kVA, 220V/100 kV, –50 Hz transformers was used to supply high voltage to the wire conductor connected to the insulator. The secondary side of the high-voltage transformer was also connected to the oscilloscope through a capacitive divider.

A voltage from the transformer's secondary side was applied to the contaminated insulator specimen and the corresponding surface leakage current was measured using a current probe. The data acquisition system sampling frequency was set at 1000 samples per cycle of 20 ms. The LC flowing through the polluted insulator was recorded throughout the test period.

The test chamber in this research had a dimension of $1.0 \times 0.85 \times 0.75$ m^3 and was made of acrylic polycarbonate material. It can be used to characterize the LC and the flashover voltage value of the insulator string according to the IEC 60507 standard. A photo of the experimental setup is as shown in Fig. 1.

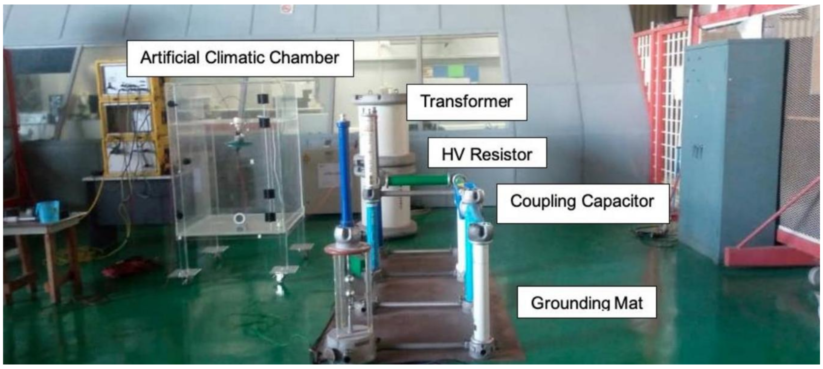

Fig. 1. Experiment setup

2.2. Test procedure

The experiment had been conducted under the following test conditions:

1. Single disc glass insulators under group A were made up of new insulators (E1, E2, E3 and E4) with ESDD = (0.06, 0.21, and 0.61) mg/cm^2, under relative humidities RH1 ($\leq$ 60%), RH2 (60–80%), and RH3 ($\geq$ 80%).
2. Single disc glass insulators under group B were made up of moderately aged insulators (M1, M2, M3 and M4) with ESDD = (0.06, 0.21, and 0.61) mg/cm^2, under relative humidities RH1 ($\leq$ 60%), RH2 (60–80%), and RH3 ($\geq$ 80%).
3. Single disc glass insulators under group C were made up of heavily aged insulators (T1, T2, T3 and T4) with ESDD = (0.06, 0.21, and 0.61) mg/cm^2, under relative humidities RH1 ($\leq$ 60%), RH2 (60–80%), and RH3 ($\geq$ 80%).

All the insulators are of the same type, specifically glass insulators, as shown in Fig. 2.

Fig. 2. Sample of the insulators

Table 1 shows the grouping of the 12 sets of insulators according to their degree of exposure to physical defects and long periods of service to cause natural ageing.

Table 1. Grouping of the samples according to the degree of physical exposure

Sample groups	**Insulators**	**Types**	**Level of ageing**
Group A	E1 E2 E3 E4	New	No rusting around the skirt or any surface discoloration
Group B	M1 M2 M3 M4	Moderately aged	Mild corrosion near the cap with exhibition of discoloration around the surface
Group C	T1 T2 T3 T4	Aged	Heavily corroded near the cap and showing surface erosion along the skirt

2.3. Conductivity measurement

The conductivity measured based on the equivalent salt deposit density (ESDD), which is measured in mg/cm^2, is calculated based on the measurement of the level of insulator contamination in a laboratory or field. The standard method for determining and measuring ESDD involves dissolving a known amount of surface salt deposits in a specified volume of distilled water (500 ml) that has low conductivity in microSiemens per centimeter (< 5 μS/cm) [34–37]. A thermometer and conductivity meter are used to determine the suspension's temperature and conductivity. The measuring range of the conductivity tester is 0.01–19.99 ms/cm. The resulting conductivity is used to determine the ESDD value, which is adjusted to 20°C. The IEC 60815 standard defines categories of insulator contamination, ranging from light contamination to very high contamination, in accordance with the results of the ESDD calculation [38]. Table 2 shows the contamination levels based on the IEC 60815 which summarizes the contamination categories used in the experiment into light, medium, and heavy contamination levels for polluting the surface of the insulators.

Table 2. Insulator contamination level

Measured ESDD (mg/cm^2)	**Contamination level**
0.06	Light
0.21	Medium
0.61	Heavy

2.3.1. Conductivity measurement

The ESDD was determined using the characteristics of water conductivity, as well as the water temperature and volume. The water conductivity (σ_t) was measured using a conductivity probe at a temperature t, then adjusted and corrected to the conductivity at 20°C (σ_{20}) using the formula in [39]

$$\sigma_{20} = \sigma_t[1 - b(t - 20^\circ)], \tag{1}$$

where σ_t is the conductivity measured at temperature t (μS/cm), t is the temperature of the solution (°C), σ_{20} is the corrected conductivity at 20°C, and b is the factor dependent on the temperature t.

The degree of pollution is given by [40] as

$$\text{ESDD} = \frac{S_a \times V}{A}, \tag{2}$$

where V is the volume of the suspension mixed with distilled water (cm^3), A is the area of the washed surface of the test insulator (cm^3), and S_a is the salinity of the solution in kg/m^3 or mg/cm^3 and is given by [31] as

$$S_a = (5.7 \times \sigma_{20})^{1.03}\,. \tag{3}$$

The ESDD on the insulator surface can be calculated using (1) and (3).

$$b = -3.2 \times 10^{-8} t^3 + 1.032 \times 10^{-5} t^2 - 8.272 \times 10^{-4} t + 3.544 \times 10^{-2}. \tag{4}$$

2.4. Leakage current measurement

In this research work, the measurement and diagnosis of the pollution severity on the surface insulator were carried out in an artificial climatic chamber connected to high voltage transformers described earlier. The applied voltage ranged from 5 to 35 kV, increasing in 5 kV steps until the flashover voltage was reached. To ensure uniformity on the surface of the test insulator, steam fog was applied for 10 minutes. The time and frequency power spectra waveforms were captured and stored in Picoscope 6 software CSV files for further processing in MATLAB.

3. Result and discussion

Figure 3 shows the sample of the measured LC signal, after applying multi-resolution analysis (MRA) wavelet transform analysis. Figure 3(a) shows the unprocessed or raw LC signal. Figure 3(b) shows the smoothed signal version of the original signal after approximation, and Fig. 3(c) shows the final denoised signal.

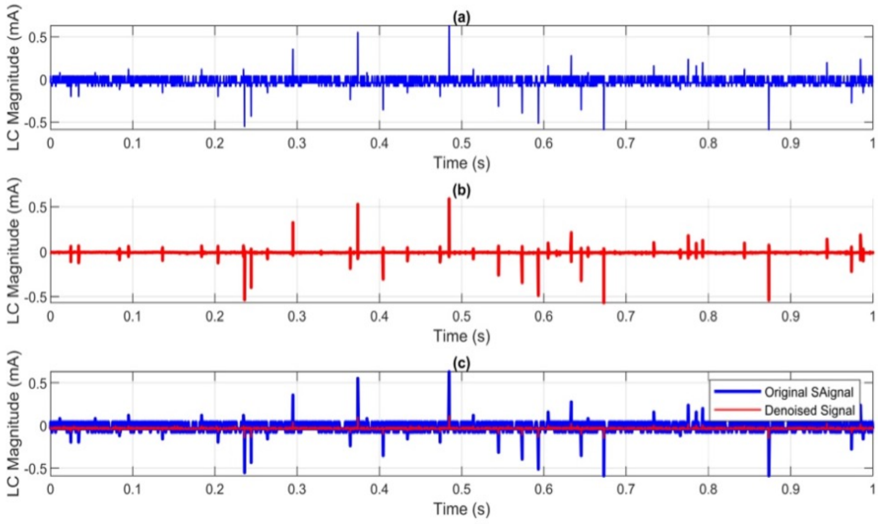

Fig. 3. Signal waveform of the leakage current: (a) the original signal; (b) smoothed signal after denoising, and (c) original waveform and the final processed signal waveform

The experiment was conducted and classified according to its different relative humidity (RH) levels with ranges of RH1(60–80%) and RH2 (≥ 80%). Table 3 shows the obtained values of odd harmonic components of contaminated new insulators labelled as samples E1, E2, E3, and E4, contaminated moderately aged insulators labelled as samples M1, M2, M3, and M4, and contaminated aged insulators labelled as samples T1, T2, T3, and T4. Using moderate and heavy contamination, the LC harmonic components were captured for new, moderately aged, and aged insulators as tabulated in Table 3 for RH2 and in Table 4 for RH3, respectively.

Table 3. Leakage current odd harmonic under moderate contamination with humidity RH2

Harmonic (Hz)	**Group A Magnitude of LC (mA)**				**Group B Magnitude of LC (mA)**				**Group C Magnitude of LC (mA)**			
	E1	E2	E3	E4	M1	M2	M3	M4	T1	T2	T3	T4
1st	0.3702	0.4132	0.2987	0.3885	0.555	0.4953	0.6764	0.7253	1.0761	1.0867	1.0257	0.9453
3rd	0.1255	0.1515	0.1459	0.0947	0.1901	0.1487	0.1654	0.1996	0.3765	0.3515	0.3816	0.3224
5th	0.0931	0.0723	0.0723	0.066	0.1116	0.1409	0.1245	0.1334	0.0289	0.2008	0.2339	0.1837
7th	0.0363	0.0278	0.0278	0.0701	0.0786	0.1104	0.1231	0.1124	0.1456	0.1579	0.1494	0.1132
9th	0.039	0.045	0.045	0.0356	0.0999	0.0678	0.0786	0.0828	0.1497	0.1347	0.1479	0.0984
11th	0.0472	0.0307	0.0307	0.0099	0.0569	0.062	0.0502	0.0515	0.094	0.097	0.1074	0.0671
13th	0.0191	0.0421	0.0421	0.0414	0.0544	0.0471	0.0384	0.0367	0.0168	0.0581	0.1038	0.0856
THD%	7.807	8.378	7.337	8.27	9.781	11.633	13.225	11.643	20.887	25.69	16.835	15.416

Table 4. Leakage current odd harmonic magnitude under heavy contamination with humidity RH3

Harmonic (Hz)	**Group A Magnitude of LC (mA)**				**Group B Magnitude of LC (mA)**				**Group C Magnitude of LC (mA)**			
	E1	E2	E3	E4	M1	M2	M3	M4	T1	T2	T3	T4
1st	0.505	0.496	0.651	0.651	0.945	0.895	0.896	0.803	1.367	1.998	1.867	1.757
3rd	0.090	0.065	0.1035	0.247	0.322	0.267	0.053	0.100	0.602	1.044	0.352	0.382
5th	0.027	0.051	0.0111	0.018	0.184	0.177	0.156	0.084	0.125	0.228	0.201	0.234
7th	0.038	0.071	0.0056	0.027	0.113	0.143	0.060	0.151	0.019	0.163	0.158	0.149
9th	0.017	0.132	0.0088	0.077	0.098	0.081	0.083	0.078	0.108	0.035	0.135	0.148
11th	0.034	0.015	0.00	0.084	0.067	0.039	0.084	0.055	0.041	0.054	0.097	0.107
13th	0.084	0.051	0.088	0.088	0.086	0.054	0.080	0.048	0.020	0.052	0.058	0.104
THD%	6.5721	6.338	5.337	5.2042	10.425	8.508	7.8077	7.6928	11.317	17.940	16.890	16.148

Figure 4 to Fig. 13 show the various leakage current waveforms and their FFT signal under 0.06 (mg/cm^2), 0.21 (mg/cm^2) and 0.61 (mg/cm^2) at different humidities.

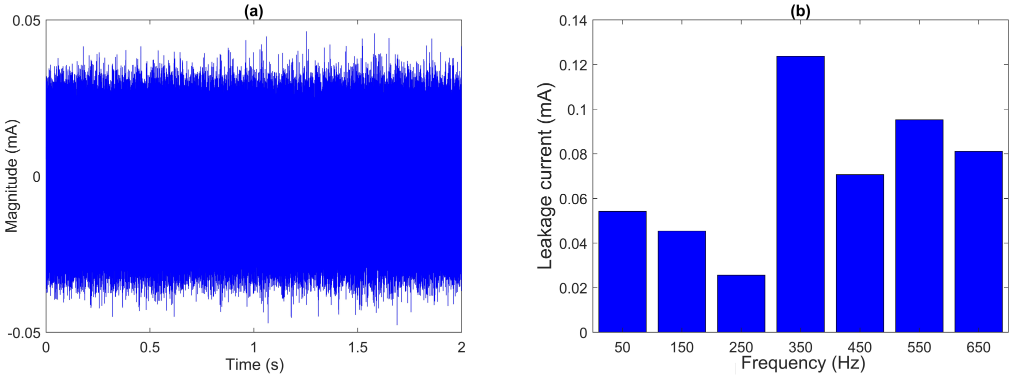

Fig. 4. The leakage current waveform and its FFT for clean new insulator

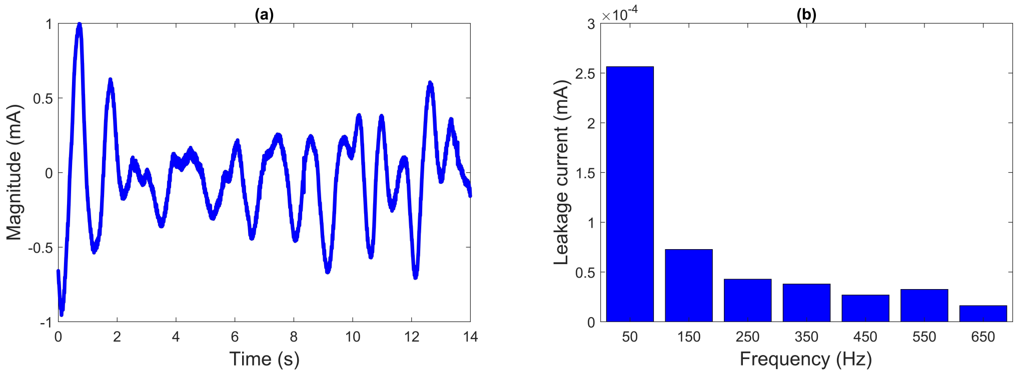

Fig. 5. The leakage current waveform and its FFT for new insulator under 0.06 (mg/cm^2)

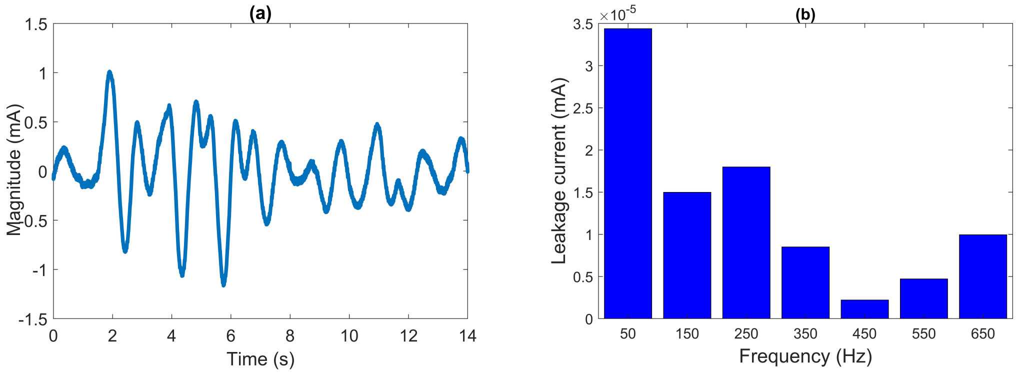

Fig. 6. The leakage current waveform and its FFT for new insulator under 0.21 (mg/cm^2)

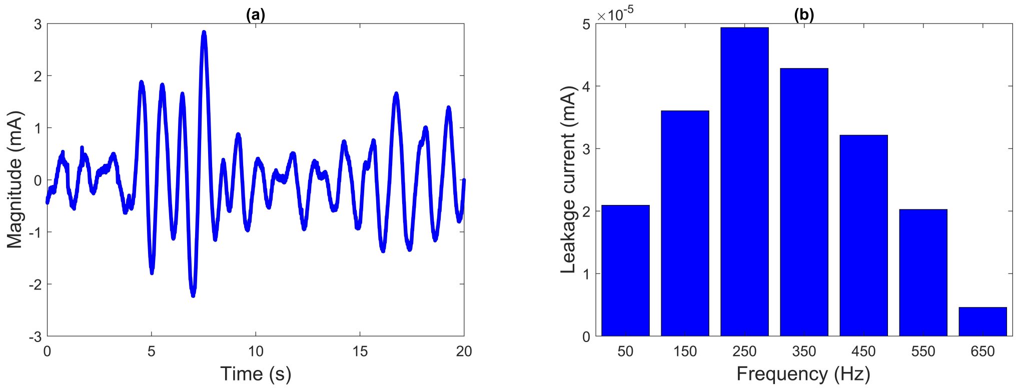

Fig. 7. The leakage current waveform and its FFT for new insulator under 0.61 (mg/cm^2)

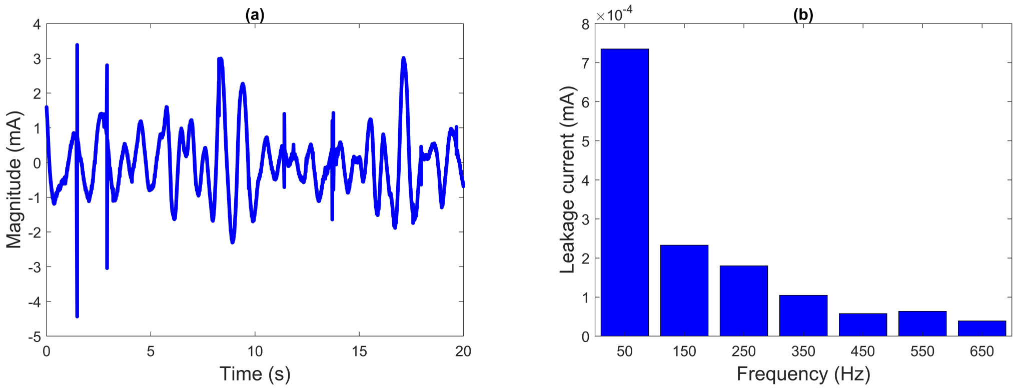

Fig. 8. The leakage current waveform and its FFT for moderately aged insulator under 0.06 (mg/cm^2)

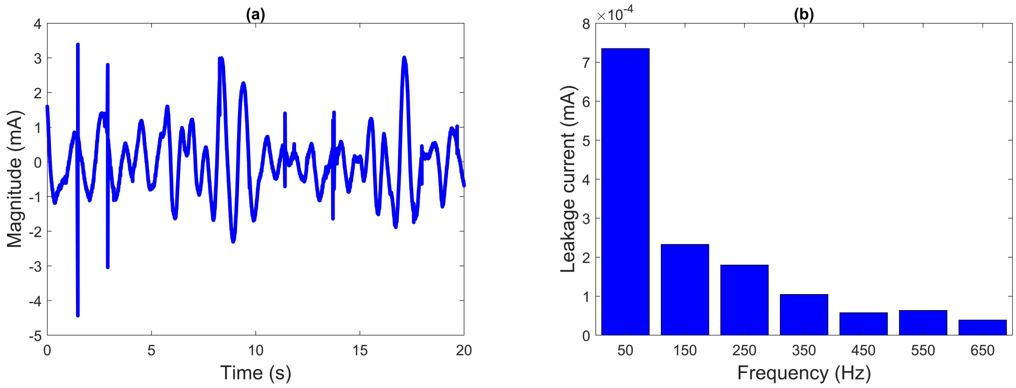

Fig. 9. The leakage current waveform and its FFT for moderately aged insulator under 0.21 (mg/cm^2)

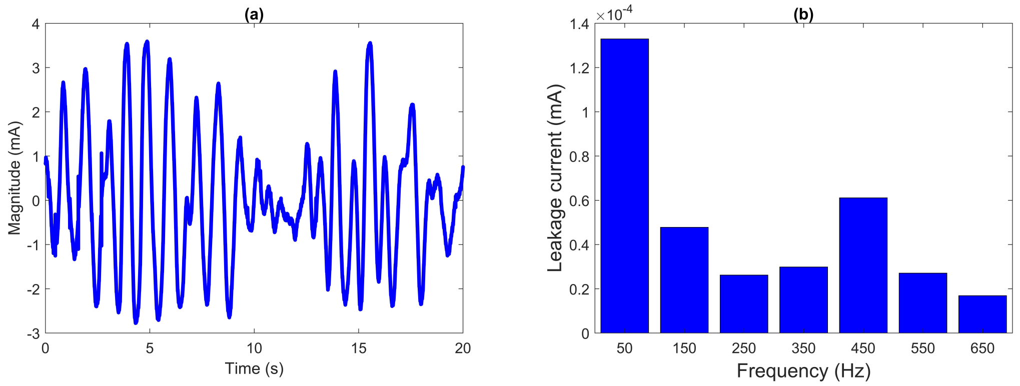

Fig. 10. The leakage current waveform and its FFT for moderately aged insulator under 0.61 (mg/cm^2)

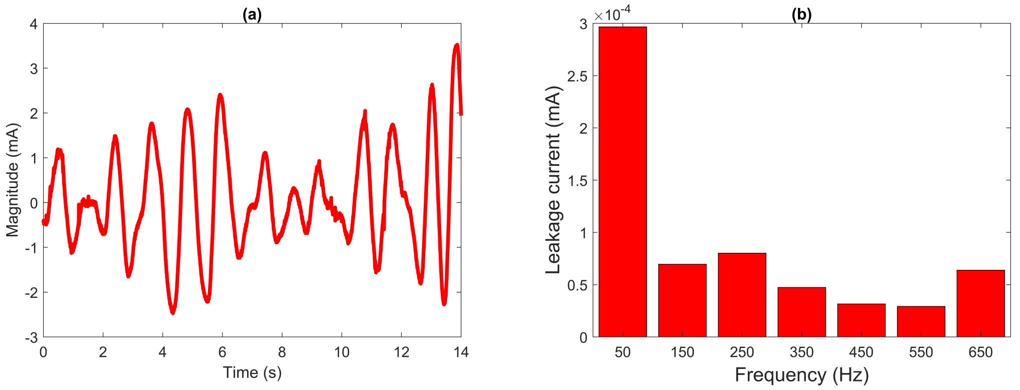

Fig. 11. The leakage current waveform and its FFT for aged insulator under 0.06 (mg/cm^2)

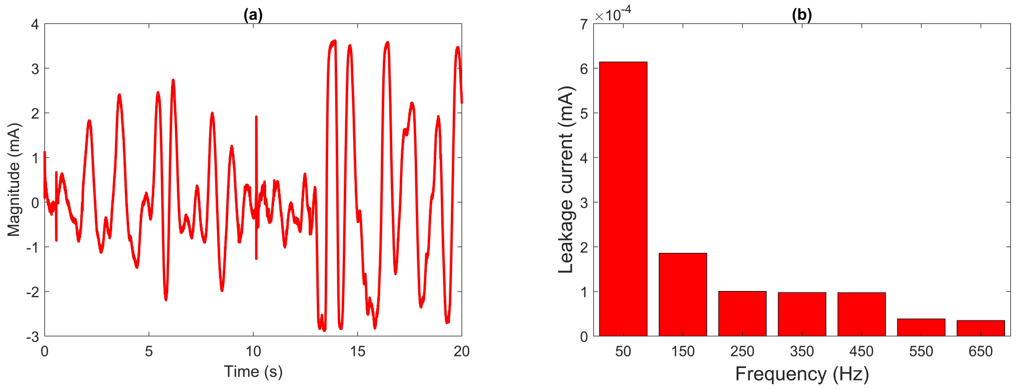

Fig. 12. The leakage current waveform and its FFT for aged insulator under 0.21 (mg/cm^2)

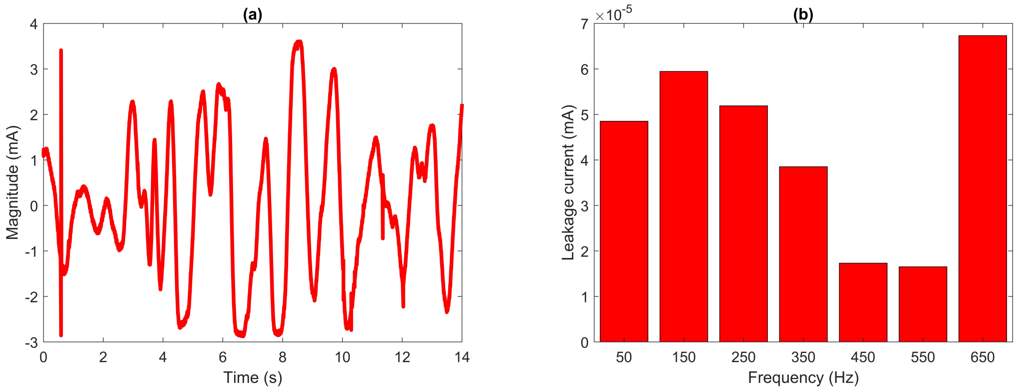

Fig. 13. The leakage current waveform and its FFT for aged insulator under 0.61 (mg/cm^2)

3.1. Crest factor of the LC harmonic component

Generally, the LC level is affected by the increase in the pollution level, wetting rate, and the ageing of the insulator. The odd harmonics component can be used as an indicator for assessing the insulator condition. The crest factor (CF) can be used as a suitable indicator to provide a condition assessment of the insulator due to its sensitivity to sudden change to signal change [13]. The crest factor can be defined as the ratio of the signal peak value to its RMS value. Thus, for the leakage current signal, it is expressed as in Eq. (6) [6].

$$\text{Crest Factor} = \frac{I_{\text{peak}}}{I_{\text{RMS}}}, \tag{5}$$

where I_{peak} is the peak value of the LC and I_{RMS} is the RMS value of the LC.

If a signal waveform has a high CF, it indicates transient, sharp peaks that will affect the amplitudes of the harmonic, thereby influencing the quality of the waveform too. The following observation can be made from Fig. 14. Under different contamination and relative humidity, the CF highest peak value is 0.15 for the test sample labelled E, a CF of 0.23 for the test sample designated under M, and a CF of 0.40 for the aged insulators labelled T.

The three clusters contain the medium contaminated samples at ESDD (0.21) which shows a CF between 0.3–0.40 for the new insulators labelled E, a CF between 0.45–0.70 for sample M, and a CF between 0. 90–1.1 for the aged, polluted insulators while maintaining the temperature constant.

Since the CF under light pollution is low when compared to those for the medium and high contamination levels, the average value of the test LC odds harmonic CF is plotted in Fig. 15. The mean value increases along with an increase in the contamination and insulator age as shown in Fig. 15, with mean values of E1, E2, E3, and E4 tag E, same for M1, M2, M3, and M4, as well as T1, T2, T3, and T4. The fundamental frequency here is the 1$^{\text{st}}$ harmonic component of the measured LC signal. It can be observed that the crest factor (CF) is highly sensitive to changes in contamination levels and the surface conditions of insulators, including its aging condition. It has been found that as the duration of wetting increases for aged insulators, the CF value of the fundamental harmonic

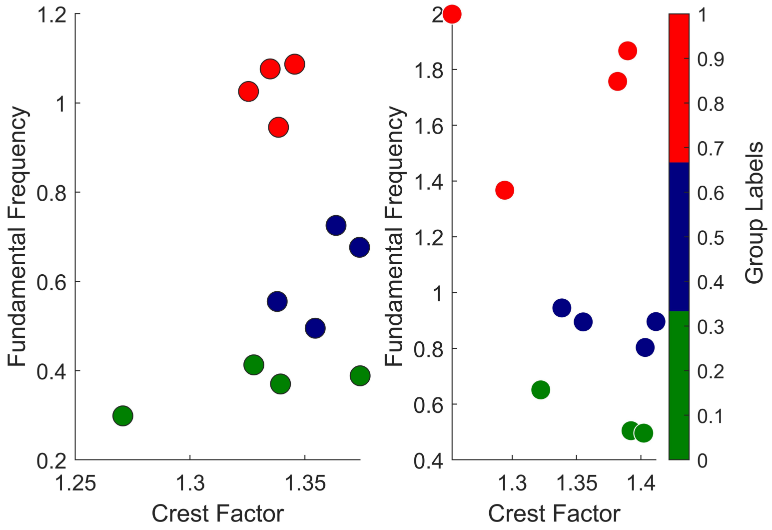

Fig. 14. A graph of crest factor, a function of various harmonic component

rapidly decreases, while the RMS value of the leakage current (LC) increases. This behaviour is consistent across all samples M and T under different contamination conditions as shown in Fig. 16, where E, M, and T represent the mean values of each group of the insulator.

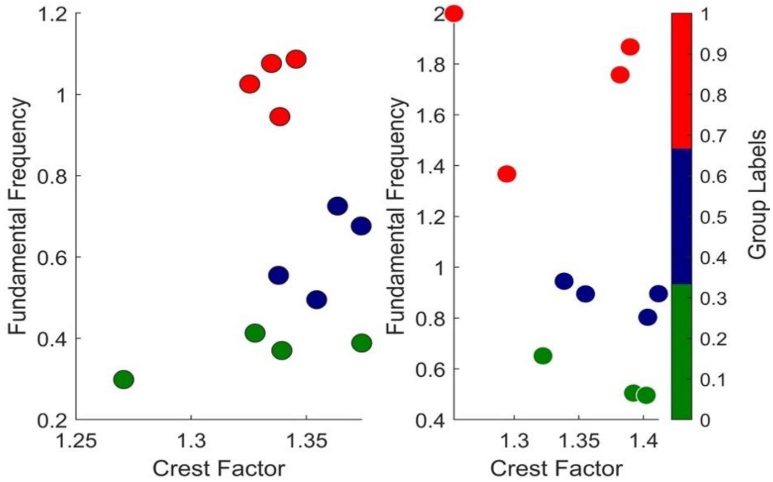

Fig. 15. LC odd harmonic crest factor of the sample insulators under: (a) ESDD 0.21 and (b) 0.61 (mg/cm^2)

It can be concluded that based on the pollution level, the crest factor can be used as a pollution index in determining the behaviour of aged insulators under different severity of the pollution. Table 5 shows the operating conditions of the insulator under various contaminations and their corresponding effects.

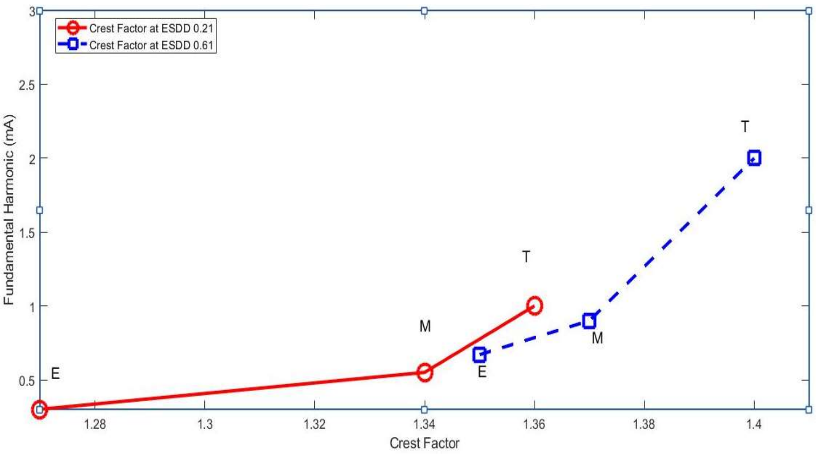

Fig. 16. Mean value plot of the two crest factors under different contamination level

Table 5. Crest factor as odd harmonic indicator

Relative humidity level	Insulator crest factor			
	New	**Moderately aged**	**Aged**	**Condition**
Below 60%	Low	Low	High	Transient
60–80%	High	Very high	Very high	Abnormal

3.2. Impact of harmonic components and total harmonic distortion on leakage current

The harmonic component gives an indication of how much the harmonic component contributed to the fundamental frequency component. A higher harmonic frequency means the signal contains more distortion. Likewise, higher THDs mean more distorted signals or higher harmonic frequency components made up a significant portion of the signal than the fundamental harmonic. These two parameters are very important to be used as a metric to diagnose the quality of the LC signal.

THD is given as [41, 42]:

$$\text{THD}\,(\%) = \frac{\sqrt{\sum I_H^2}}{I_1} \times 100\%, \tag{6}$$

where I_1 is the fundamental harmonic component and I_H is the odd frequency harmonics.

From the experiment results shown in Fig. 6, it follows that the behaviour of the odd harmonic LC further illustrates how insulator degradation affects the LC signal. Groups A and B exhibit lower LC values due to reduced resistive LC. However, spot arcing activities were significantly higher in Group B compared to Group A insulators, leading to higher LC values. This is partly attributed to the aging of these insulators, as evidenced by the heavily rusted skirts observed in Group C insulators. This is further shown in Fig. 17, where the THD is plotted against the harmonic components of the Group A, B, and C insulators.

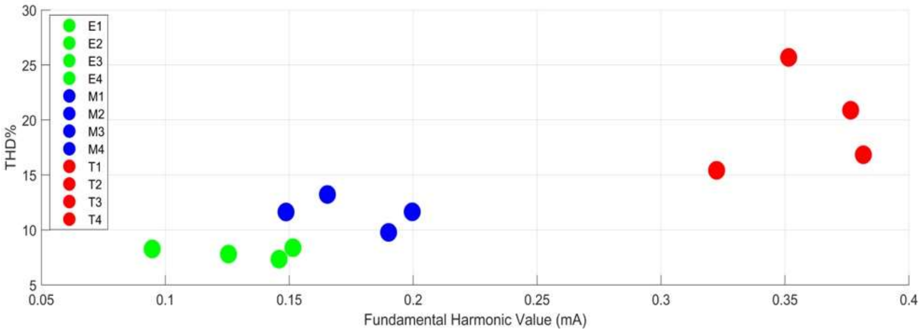

Fig. 17. THD's effect on the fundamental components

4. Conclusion

The investigation of insulators under various degrees of aging was successfully carried out for different contamination levels and relative humidities. The important conclusions are summarized below:

- The proposed crest factor (CF) indicates and describes the behaviour of the contaminated insulators and hence can be used to determine the insulator health condition according to the degree of pollution, humidity, and ageing.
- The THD of the odd harmonics and the fundamental harmonic component are correlated and hence can be used to determine the aging of insulators under varying contamination conditions.
- The analysis of the odd harmonics of the leakage current shows a promising result and therefore can be utilized to obtain information on the operating or health condition of aging insulators.

Based on the above experiment results it has been concluded that the crest factor, THDs and harmonic factor can serve as new indices in evaluating the condition of aged insulators.

Acknowledgements

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