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Leakage Current Harmonic Index as A Diagnostic Technique Tool to Assess the Surface Condition Assessment of Aged Insulator Surface Under Varying Humidity

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Abstract: Leakage current has been widely utilized as an effective means to monitor the pollution severity of outdoor insulators. The indices of the odd harmonic components of the leakage current have proven to be reliable indicators of insulator performance, particularly in the third to fifth harmonic orders. However, significant challenges exist in using these indices to monitor and classify the leakage current of aged insulators under varying harmonic and pollution conditions. This paper introduces the harmonic index $\boldsymbol{K}_{(3/(5+7)}$ which employs third up to seventh odd harmonic component of the leakage current as a diagnostic tool to determine the pollution severity of aged insulators under light, medium and heavy contamination levels. The experiments were conducted using 12 different sets of 11kV insulators with varying degrees of aging. The findings indicate that the harmonic index $\boldsymbol{K}_{\boldsymbol{i}}$ decreases by 14.56% as the contamination level increases for new and moderately aged insulators, and it decreases by 29.16% for heavily aged insulators, which is twice the reduction compared to the moderately aged insulators.

Keywords: Leakage Current, Harmonic Index, Third Harmonics, Insulators

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1. INTRODUCTION

Electrical power equipment, such as insulators, plays a crucial role in the transmission lines of power systems. The performance of insulators is influenced by environmental factors such as pollution, aging, humidity, wind, and temperature, which affect the condition of the insulator surfaces. This causes the flow of leakage current across the surface of the insulator causing arcing activities that can lead to dry band formation resulting the complete flashover[1]. Flashovers are undesirable in transmission line because it causes loss of power supply that can lead to economic loss. Thus, it important to assess and monitor the leakage current flow at the early stage of degradation to safeguard the overall healthy working condition of insulator[2]. LC extraction is a technique utilized to predict the severity of pollution on the surface of the insulator. This is achieved by analysing the frequency domain harmonic content of the LC using Fast Fourier Transform (FFT)[3]. Research studies has shown that odd harmonic components of leakage current can be used to determine insulator pollution level performance[4]. Studies by H.Kordkheili et.al [5] have shown that odd harmonic components of leakage current can be used to determine the performance of insulator pollution levels. Based on these findings, the LC harmonic index can be employed to reflect the working conditions of the insulator, as proposed by A.A Salem[6] by using the third to fifth harmonic ratio $\left(I_{3th}/I_{5rd}\ index\right)$ of the leakage current to predict the surface flashover of the insulator. The results indicate a strong and distinctive correlation between the LC harmonic index and the severity of the pollution level. This is further supported by J.Li [7] that this correlation can be used to determine the pollution severity and the flashover voltage occurrence. Other researcher used the 3rd, 5th, and 7th $I_{3rd}/\left(I_{5th}+I_{7Th}\right)$ to analyse the LC under different environmental condition where it has been reported that the 7th harmonic has a considerable effect on the performance of the LC under wetting conditions[8-11]. N.Bashir [12] used the third to fifth harmonic ratio of the LC to determine the effect of pollution severity on the aged glass insulator. He concluded that the aging of the insulator has a significant effect on the LC odd harmonic components. This can be used as a diagnostic tool to determine the surface condition of insulators. This observation suggests that it can serve as a diagnostic tool for determining the surface condition of aged insulators.

The main contribution in this paper are summarized as follows:

- This work emphasizes the use of the LC harmonics as statistical tool for characterizing polluted insulators.

- It aims to illustrate the possible correlation between the effect of ageing on the insulator and the harmonic index.
- The use of odd harmonic component index (K_i) as a diagnostic technique to assess leakage current of aged insulator under different humidity and contamination level.

2. METHODOLOGY

The insulator sample is shown in Figure 1, they are selected base on their service years and physical deterioration such as rusting around the cap as explained in Table 1. The experiment was done using 12 different set of 11kV insulators and are grouped according to the degree of physical surface deterioration of the insulator. Based on methods described in IEC 60507[13-15], a solution of mixture of salt and 100ml of distilled water are mixed under room temperature and allowed to be dissolved. The insulators are thoroughly washed to remove dirt, grease and dried before they are pre contaminated with the mixed salt and water solution under controlled environment. The insulator is suspended vertically inside the artificial climatic chamber with its cap point connected to the ground terminal and the other end connected to the secondary transformer high voltage side. The parameters of the insulator are tabulated in Table 1. The experimental setup consist of the test chamber, a transformer of 75kVA,220V/100kV, 50Hz used to supply the high voltage to the insulator terminal. An oscilloscope is connected to the transformer high voltage through the capacitive voltage divider as shown in Figure 2. Through this oscilloscope the injected voltage to the insulator is measured. The leakage current is measured by the LC clamp sensor and is stored in the laptop using Picoscope 6, the data acquisition sampling frequency is set to 1000 samples per cycle of 20 milliseconds. All the experiments tests were carried out in the artificial climatic chamber of measured dimension 1.0×0.85×0.75 m^2 acrylic polycarbonate material that was designed in *Institut Voltan Arus Tinggi* (IVAT) laboratory as shown in Figure 2.

Figure 1. Sample of the insulators

Figure 2. Experimental setup

The following test conditions have been set for the experiment:

a. insulator under group A are new insulators (E1, E2, E3 and E4) under contamination level (0.06, 0.21, and 0.61) mg/cm^2, and relative humidity RH1(≤60%), RH2 (760-80%), and RH3(≥80%).
b. insulator under group B is moderately aged insulators label (M1, M2, M3 and M4) and contaminated level (0.06, 0.21, and 0.61) mg/cm^2. The relative humidity levels RH1(≤60%), RH2 (60-80%), and RH3(≥80%).
c. The group C are heavily aged insulators label (T1, T2, T3 and T4) and ESDD of (0.06, 0.21, and 0.61) mg/cm^2. The relative humidity levels are also grouped under RH1(≤60%), RH2 (60-80%), and RH3(≥80%).

2.1 Leakage Current Harmonic index (Ki)

The leakage current 3rd harmonic component increases as the level of the contamination increased along with the 5th and 7th harmonic component, it is observed that the 3rd harmonic exceeds both the 5th and 7th components. Thus, the 3rd,5th, and 7th odd harmonic component variation with the contamination level can be used as the harmonic index to evaluate the insulator surface condition due to ageing. The proposed criterion is based on the odd harmonic index given in equation (1):

$$K_i = \frac{I_3}{(I_5+I_7)} \quad (1)$$

Where I_3, I_5, and I_7 are the leakage current magnitude of the 3rd, 5th, and 7th odd harmonic components.

2.2 Conductivity Measurement

The measurement of the conductivity of the contamination solution is based on the equivalent salt deposit density (ESDD) measured in mg/cm2 which determine the level of insulator contamination in a laboratory or field. The standard method for ESDD measuring is by dissolving the salt deposits on the surface in a specified quantity of distilled water [70]. The temperature is measured by a thermometer and the suspension conductivity by a conductivity meter are used. The conductivity tester range is between 0.01-19.99 ms/cm. based on the conductivity reading, the ESDD value is determined after the temperature is adjusted to $20°C$ as in equation (2). The IEC 60815 standard serve as the measure of the degree of contamination according to the range from light contamination to very high contamination after of the

Table 1. Insulator samples based on the degree of physical exposure

Sample Groups	Insulator label	Type	Conditions of the sample
Group A	E1 E2 E3 E4	New	There is no presence of surface degradation, discoloration, or rusting around the edges of the skirt.
Group B	M1 M2 M3 M4	Moderately Aged	Mild rusting close to the cap, with surface discoloration visible.
Group C	T1 T2 T3 T4	Aged	The surface along the skirt is heavily corroded, and the area around the cap is rusty.

ESDD calculation results [35]

$$\sigma_{20} = \sigma_t[1 - b(t - 20^0)] \quad (2)$$

where:
σ_t – conductivity measured at temperature t (µS/Cm)
t – temperature of the solution (°C)
σ_{20} – corrected conductivity at 20 °C
b – is a factor depending on temperature t given by equation (2)

$$b = -3.2 \times 10^{-8}\, t^3 + 1.032 \times 10^{-5}\, t^2 - 8.272 \times 10^{-4}\, t + 3.544 \times 10^{-2} \quad (3)$$

The degree of pollution is given by:

$$ESDD = \frac{S_a \times V}{A} \quad (4)$$

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 given by:

$$S_a = (5.7 \times \sigma_{20})^{1.03} \quad (5)$$

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

2.3 Leakage Current Measuring Data System

In the experimental setup illustrated in the Figure 2, the LC sensor. inside the control room, there is voltage monitoring and control unit, a laptop and a Picoscope. The data captured by the LC sensor are captured and saved by in CSV format file using the Picoscope 6 software. The leakage current signal waveforms obtained from the surface of the insulators are analogue signal that need to be converted to its digital form[8]. Subsequently, the captured data are analysed using MATLAB software, where the LC data are transformed from time domain signal to frequency domain signal data by using Fast Fourier Transform (FFT). This can be obtained by considering the analogue signal in the form of the equation 4 written as follows[16]:

$$x_s(t) = g(t)x(t) \quad (6)$$

$$=(\textstyle\sum_{n=-\infty}^{\infty} C_n\, e^{jn2\pi f_s t})x(t)$$
$$=\textstyle\sum_{n=-\infty}^{\infty} C_n x(t)e^{jn2\pi i f_s t} \quad (7)$$

Where T is the period of the x(t) signal, n is the sample number, g(t) is the function sample, f_s is the sample frequency and C_n is the coefficient value of the Fourier at any T. the frequency domain of the signal is written as follow[17]:

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi f t}dt \quad (8)$$

However, there is need to transform the numerical signal to digital signal of the Fourier transform. The corresponding Discrete Fourier Transform (DFT) is given as[18].

$$X_k = \textstyle\sum_{n=0}^{N-1} x_n e^{-j2\pi kn/N} \quad (9)$$

Where k =1,2, 3, ……N. From this digital waveform signal, the leakage current characteristics parameters are obtained in frequency domain analysis.

3. RESULTS AND DISCUSSION

In this section, the insulator leakage current characteristics results obtained from the experiment are discussed. The measured parameter to be discussed is the frequency harmonic component index and its significant in analyzing the insulator condition. The leakage current harmonic frequency components are tabulated in Table 2, Table 3, and Table 4. From this harmonic component of the LC is used to evaluate and assess the reliability of the insulators. Table 2 is the LC characteristic under light contamination and the relative humidity inside the artificial chamber is maintained between ≤60% during the experiment. Likewise, in Table 3 and Table 4 the contamination level is medium (0.21 mg/cm^2) and heavy (0.61 mg/cm^2) and the relative humidity 60-80% and ≥80% respectively.

Table 2. Leakage Current Characteristic Parameters under Light Contamination

Sample	LC Harmonic Component (Hz)				Ki=3rd/ (5+7) th	Critical Voltage (V)	Relative Humidity (%)	ESDD (mg/cm^2)
	1st	3rd	5th	7th				
E1	0.1019	0.0357	0.0439	0.0121	0.6375	50	≤60	0.06
E2	0.1124	0.0953	0.176	0.0514	0.4191	53		
E3	0.1114	0.0574	0.0364	0.0579	0.6087	51		
E4	0.2094	0.0839	0.0862	0.073	0.5270	52		
M1	0.2078	0.0122	0.2139	0.1164	0.0369	40		
M2	0.2001	0.0135	0.0888	0.0394	0.1053	40		
M3	0.2736	0.1194	0.0779	0.0693	0.8111	40		
M4	0.3467	0.1239	0.0689	0.0621	0.9458	40		
T1	0.4932	0.1759	0.1139	0.0893	0.8657	30		
T2	0.3017	0.1383	0.0742	0.0531	1.0864	31		
T3	0.3814	0.1526	0.0844	0.0258	1.3847	30		
T4	0.4132	0.1515	0.0772	0.0467	1.2228	30		

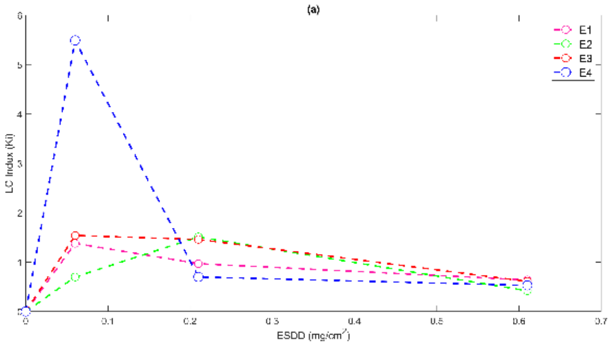
Table 3. Leakage Current Characteristic Parameters under Medium Contamination

Sample	LC Harmonic Component (mA)				Ki=3rd/ (5+7)th	Critical Voltage (V)	Relative Humidity (%)	ESDD (mg/cm^2)
	1st	3rd	5th	7th				
E1	0.3702	0.1255	0.0931	0.0363	0.97	25	80	0.21
E2	0.4132	0.1515	0.0723	0.0278	1.51	29		
E3	0.2987	0.1459	0.0723	0.0278	1.46	29		
E4	0.3885	0.0947	0.066	0.0701	0.70	25		
M1	0.555	0.1901	0.1116	0.0786	1.00	15		
M2	0.4953	0.1487	0.1409	0.1104	0.59	10		
M3	0.6764	0.1654	0.1245	0.1231	0.67	20		
M4	0.7253	0.1996	0.1334	0.1124	0.81	25		
T1	1.0761	0.3765	0.289	0.1456	0.87	5		
T2	1.0867	0.3515	0.2008	0.1579	0.98	6		
T3	1.0257	0.3816	0.2339	0.1494	1.00	10		
T4	0.9453	0.3224	0.1837	0.1132	1.09	15		

Table 4. Leakage Current Characteristic Parameters under Heavy Contamination

Sample	LC Harmonic Component (mA)				K_i=3rd/ (5+7) th	Critical Voltage (V)	Relative Humidity (%)	ESDD (mg/cm²)
	1st	3rd	5th	7th				
E1	0.505	0.09	0.027	0.038	0.64	15		
E2	0.496	0.085	0.051	0.071	0.42	20		
E3	0.651	0.1035	0.0111	0.056	0.61	25		
E4	0.651	0.247	0.018	0.027	0.53	30		
M1	0.945	0.322	0.184	0.113	0.04	10		
M2	0.895	0.267	0.177	0.143	0.11	12	≥80	0.61
M3	0.896	0.53	0.156	0.16	0.81	20		
M4	0.803	0.1003	0.084	0.151	0.95	22		
T1	1.367	0.602	0.125	0.19	0.87	3		
T2	1.998	0.44	0.228	0.163	1.09	4		
T3	1.867	0.352	0.201	0.158	1.38	6		
T4	1.757	0.382	0.234	0.149	1.22	6		

In the Figure 3, the leakage current harmonic index is plotted against the ESDD, for the insulators in Group A it can be observed that magnitude of the harmonic index is high which is due to the high applied voltage for the LC to start to flow. As the contamination level increase there is evidence decrease in the level of the LC index as seen in Figure 3(a). However, in Figure 3(b) and Figure 3(c) there is rapid change in the magnitude of the index. These are groups that their physical surface has deteriorated due to ageing, hence, the decrease in the index value can be associated with the insulator ageing. In addition, there is severe distortion which increases the amplitude of the discharge during the experiment that might affect the odd harmonic components thereby affecting the harmonic index as noticed in Figure 3 (c) under 0.6 mg/cm² even at lower supply voltage. This further demonstrate the correlation of the ageing effect of the insulator on the harmonic index.



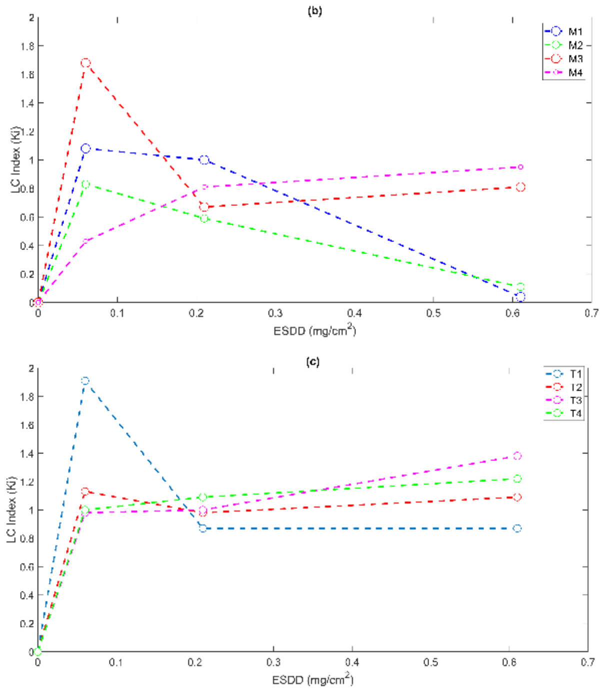


Figure 3. Variation of LC index against ESDD at 0.06 mg/cm², 0.21 mg/cm², 0.61 mg/cm² (a) for insulators Group A (b) insulators under Group B and (c) insulators under Group C

To able to determine extend of the individual LC harmonic index within the group, Figure 4(a) shows the graph of LC index K_i against ESDD of Group A (E, E2, E3, E4). As mentioned, the variations of the harmonic index are related to the surface pollution, it can be observed that the behaviour of the LC index E, E2, E3, E4 are significantly affected by increase in the contamination level. The magnitude of the index parameter decreases with increase in the contamination level from 0.21 mg/cm^2 to 0.6 mg/cm^2 for all the sample under this purview. The applied voltage increased from 28kV to 40kV resulted in sharp decrease in K_i value.

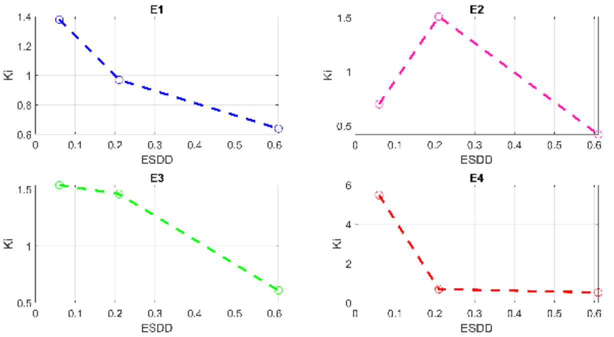


Figure 4. The leakage current harmonic index of new insulators under different contamination

The K_i index in the moderately aged insulators category indicates slight variation in the noticeable change observed in Figure 4. This is partly due to the increase in the distortion as the pollution level increased with the applied voltage as observed in Figure 5. The K_i index for Group A increases by 52.72% when the contamination level rises from 0.06 mg/cm² to 0.21 mg/cm², and by 12.96% from 0.21 mg/cm² to 0.61 mg/cm². For Group B, the increases are 38.16% and 23.65% for the same contamination level increments. In Group C, the increases are 9% and 21.67% for the respective contamination level rises. The increase in Ki value magnitude corresponds to an elevated risk of flashover. Based on the experiment result, the insulator harmonic index can be used to recognised surface conditions of insulator under critical condition.

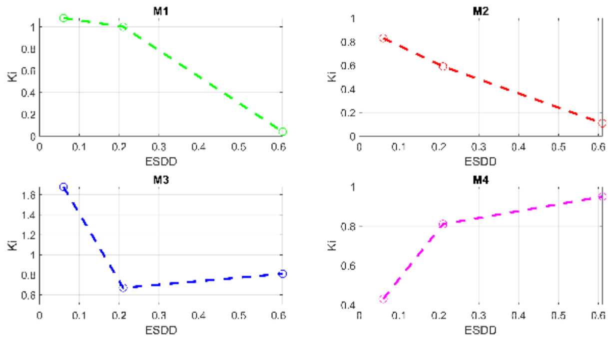


Figure 5. Leakage Current harmonic index of moderately aged insulators under different ESDD level

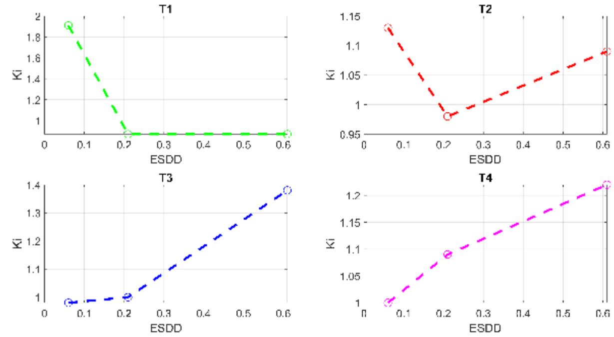


Figure 6. Leakage Current harmonic index of heavily aged insulators at ESDD 0.06 mg/cm2, 021 mg/cm2 and 0.61 mg/cm2

In figure 7 illustrate the LC harmonic index as function of critical flashover voltage under contamination level of ESDD 0.06 mg/cm^2, 0.21 mg/cm^2, and 0.61 mg/cm^2. The correlation between the ageing of the insulator and the magnitude of the critical flashover voltage (FOV) under different pollution level is further analysed as the sample of insulators indicates in the upsurge discharge activity with increase in the applied voltage level. The Group A (new insulators categories) it has been observed that their critical flashover voltage is much higher, reaching an average value of 50kV. The FOV magnitude value decreases further from Group B to Group C insulators due to increase in the discharge activities on the surface of the aged insulators. Group A FOV is the highest compared to the Group B, while Group C has the lowest FOV level. In this Group C scenario, although the supply voltage is low, the LC index becomes significantly high at 5-10kV for aged insulators due to the rustic surface of the insulators. The non-linearity caused by the dry band on the insulator's surface, which is non-uniform in nature, results in more distortion of the LC signal and hence a higher LC harmonic index in Group C.

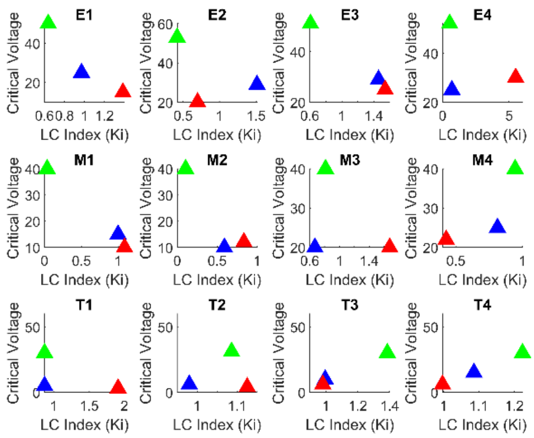


Figure 7. The LC harmonic index as function of the critical flashover voltage under different ESDD level

4. CONCLUSION

In conclusion, the harmonic index $K_{(3/(5+7)}$ proves to be a valuable diagnostic tool for pollution severity classifying of aged insulators across different contamination levels. The study, conducted with 12 sets of 11kV insulators exhibiting varying degrees of ageing demonstrate that the harmonic index $K_{(3/(5+7)}$ Specifically, for new and moderately aged insulators, the index decreased as contamination levels increased, indicating a sensitivity to pollution. In fact, the index is consistently lower for new and moderately aged insulators compared to heavily aged ones. for these insulators were found to be lower compared to heavily aged insulators. This suggests that the harmonic index is not only responsive to contamination levels but also demonstrates differentiation in severity between insulators of varying ages. These findings highlight the potential use of the harmonic index $K_{(3/(5+7)}$ as a reliable and effective tool for assessing the insulator performance under severe pollution in diverse environmental conditions. It is recommended that in future work, temperature should be included in the LC parameters instead of using fixed control temperature.

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