Investigation on Leakage Current Waveforms and Flashover Characteristics of Ceramics for Outdoor Insulators under Clean and Salt Fogs

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Abstract: - Outdoor insulators play an important role in high voltage transmission lines. Since long time ago, ceramic insulators are widely being used in power systems at medium, high and extra high voltage levels. During operation, the insulators may severe a certain degree of pollution which may reduce their performances such as surface resistance and flash over voltages. Under these conditions a large leakage current (LC) may flow on the surface and degradation may take place. In long term the degradation may lead to the flash over of the insulators. This paper reports the experimental results on the leakage current characteristics of ceramics under various simulated environmental conditions. The samples used are blocks of ceramics with dimension of 250 x 50 x 20 mm^3. The samples were made from same materials for outdoor ceramic insulators. The samples were put in a test chamber with controlled humidity and artificial pollution conditions. AC voltage with frequency of 50 Hz was applied. The tests were conducted according to IEC 60-1 (1989) and IEC 507 (fog test). The LC waveforms up to flash over were measured. The magnitudes as well as harmonic content of the LC were analyzed. The correlation between LC waveforms and dry band arching phenomenon was also elaborated. Experimental results showed that for clean insulators leakage current was much smaller than polluted insulators. The waveform distortion was observed particularly at positive half cycle when applied voltage was increased to higher than 20 kV. This indicated that electric discharges initiated from air proximity of the sample surface. For kaolin-salt polluted insulators, the LC amplitude was much higher than clean insulators. LC waveform distortion started at 10 kV. Unbalance distortion of LC waveforms was observed similar to those of clean samples. However, for kaolin-salt polluted samples, the distortion was observed mainly at negative half cycles which indicated that the electric discharges were initiated from the salt-kaolin layer embedded on the sample surface. Observation of LC waveforms during the process of flashover revealed that THD of increased with the applied voltage.

Key-Words: - outdoor insulator, ceramics, leakage current, harmonic, dry band, flashover

1 Introduction

Due to large demand on electric power, the electric power generation, transmission and distribution in the world has been steadily increased. For transmitting and distributing the electric power, insulators is one of the most important parts. Outdoor insulator are commonly used in an electric power system to isolate among live parts and between live part and ground and as mechanical protector. The insulators are widely used at substations, transmission as well as distribution networks[1].

Ceramic insulators are widely used in power system since long time ago. At present time the insulators are still widely being used. Ceramic insulator has good mechanical and electrical properties and less expensive. As outdoor insulator it may severe a certain degree of pollution and other environmental factors which may reduce their surface resistance. The reduction of surface resistance may enhance the leakage current to flow on the surface[2]. Leakage current (LC) with large magnitude flow on the surface for long period may cause degradation of the insulator surface[3]. In long term the degradation may lead to the flashover of the insulators and it is necessary to estimate[4]. Therefore, investigation on the leakage current on the ceramic insulators under polluted condition is important. The flashover of the insulator is also necessary to be investigated. This paper reports the experimental results on the investigation on leakage current, and flash over characteristics of ceramic insulators.

2 Experiment

2.1 Sample

The samples used in this experimet were ceramic blocks with dimension of 250 x 50 x 20 mm^3 as shown in figure 1. The sample was made by ceramic insulator producer in Indonesia. The same material is used to produce 20 kV insulators which are widely used in Indonesian power system. The two ends of the sample were covered by silver paste to make good contact with the electrodes.

A test hamber made from aluminium panel with dimension of 900 x 900 x 1200 mm^3 was used to simulate pollution exposed to the samples. The front opening of the thest chamber was made from acrylic facilitate the observation of arcing on the sample surface. The samples were subjected to tests according to IEC 507(1991) (fog chamber test)[5] and IEC 60-1 (1989) High voltage test technique[6].

Fig. 1 Ceramic sample used in the experiment

2.2 Leakage Current measurement.

An AC high voltage of 50 Hz was applied to the insulators. The applied voltage was adjusted to get various conditions such as normal condition, small or high activity of dry band arcing and even to make flashover on the insulator surface. The leakage current flowed on the insulator surface was measured by measuring the voltage across a series resistance using a Digital Oscilloscope TDS 220 with digitizer of 8 bit, bandwidth of 100 MHz, and the maximum sampling rate of 1 GS/s. LC waveforms including low and high frequency components were obtained. The digital data was transferred to a personal computer trough a GPIB for further analysis. Harmonic content of LC was analyzed using FFT (Fast Fourier Transform).

For indicating the distortion of the leakage current waveform from its sinusoidal form of the applied voltage, Total Harmonic Distortion (THD) is used. THD is defined as

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^{\ 2}}}{I_1} \qquad (1)$$

where I_1 is fundamental component of LC (1st harmonic) and I_n is nth harmonic component of LC. The higher the THD is the higher the degree of LC distortion is.

2.3 Flashover masurement

Flashover experiment was conducted under kaolin-salt pollution condition. The samples were put in a chamber. The pollution and humidity were adjusted and the AC voltage was applied. Arcing took place on the sample surface was observed using a camera, and the corresponding leakage current was also measured.

3 Experimental Results

3.1 Analysis of Leakage Current magnitude and THD

3.1.1 Leakage current for clean sample at clean fog condition

Figure 2 shows the dependences of leakage current of clean sample on the applied voltage under various relative humidity obtained from clean fog. It is clearly seen that LC increase with the applied voltage. The figure also indicates that LC magnitude increases with the relative humidity around the samples. The increase of humidity from 50 % to more than 85 % may double the magnitude of the leakage current. The leakage current waveform was distorted from its sinusoidal form of the applied voltage. This distortion of leakage current waveforms will be discussed later in this paper.

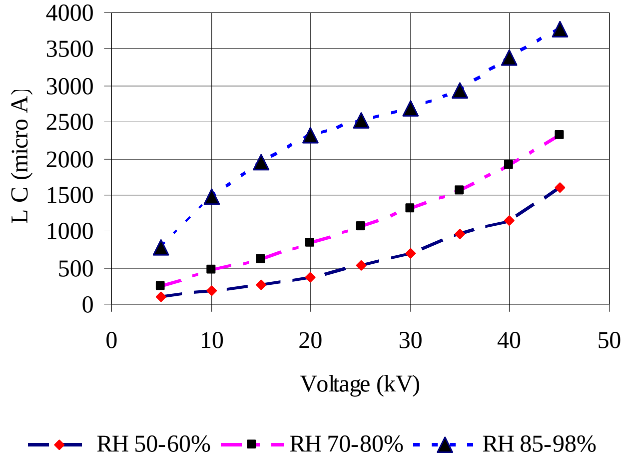


Fig. 2 LC magnitude as function of applied voltage for clean sample under clean fog at various humidity

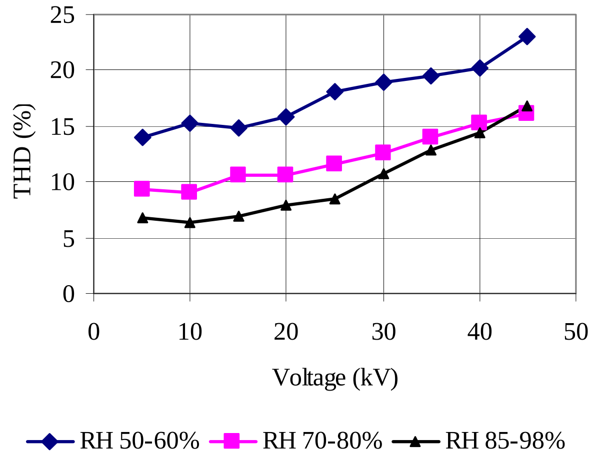


Fig. 3 THD as function of applied voltage for clean sample under clean fog with various humidity

Figure 3 shows the dependence of total harmonic distortion of LC waveform of clean sample on the applied voltage at low, medium and high humidity. The figure indicates that THD values for clean sample at low humidity is higher than those THD at high humidity. This is caused by low value of fundamental component of LC under low RH since the insulator surface is able to maintain the high value of resistance at low humidity. At high RH, the absolute harmonic components were large. However, the value of fundamental component of LC was also high resulting in a relatively low THD.

3.1.2 Leakage Current for clean sample under salt fog condition

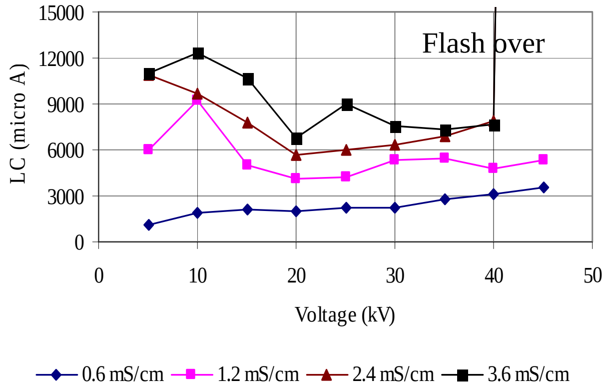


Fig. 4 LC magnitude as function of applied voltage for clean samples under salt fog with various conductivity

Figure 4 shows the dependences of LC magnitude on applied voltage for clean insulators under salt fog with conductivity of 0.6 , 1.2, 2.4 and 3.6 mS/cm and at high relative humidity of 95 %. From the figure it is seen that salt fog conductivity greatly affected the magnitude of the LC. Compared to the LC magnitude under clean fog, the LC magnitude under salt fog was much higher than those from clean fog. At fog conductivity of 0.6 mS/cm, the LC magnitude increased almost linearly with the applied voltage. However, at fog conductivities of 1.2 , 2.4 and 3.6 mS/cm the oscillation behaviour of LC magnitude dependence on applied voltage was observed. This phenomenon was due to the wetting effect of sample surface by the fog and drying effect caused by the higher LC flew on the surface of sample in fog with high conductivity.

Flash over of the samples were observed at fog conductivities of 2.4 and 3.6 mS/cm. The flashovers were observed at applied voltage of about 40 kV. At this applied voltage no flashover was observed under clean fog experiment.

Figure 5 shows the total harmonic distortion(THD) as function of applied voltage at different fog conductivity. The figure indicates that in general the THD of leakage current under salt fog increased with the applied voltage. This means that the increase rate of harmonic components of the leakage current were larger than those of fundamental component.

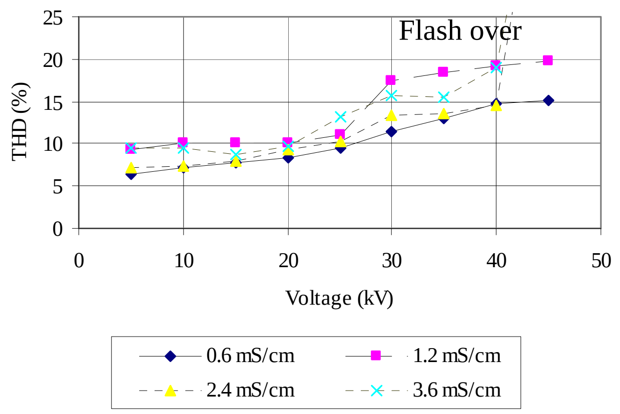


Fig. 5 THD as function of applied voltage for clean sample under clean fog with various humidity

3.1.3 Leakage Current for kaolin polluted sample under salt-fog

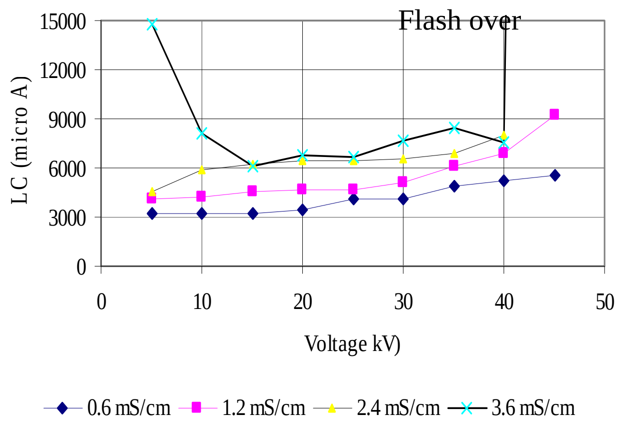


Fig. 6 LC magnitude as function of applied voltage for kaolin polluted samples under salt fog with conductivity of 0.6, 1.2, 2.4 and 3.6 mS/cm

Figure 6 shows the dependences of LC magnitude on applied voltage for kaolin-polluted ceramic samples under salt fog with conductivity of 0.6 , 1.2, 2.4 and 3.6 mS/cm. From the figure it is seen that salt fog conductivity greatly affected the magnitude of the LC.

LC magnitude increased monotonically under salt fog with conductivity up to 2.4 mS/cm. No wetting-drying effect was observed under these conditions. Wetting-drying effect was observed for salt fog with conductivity of 3.6 mS/cm.

The results can be explained as follows. Kaolin polluted surface exhibit a hydrophilic property. Under salt fog with low conductivity the trapped conductive water increases the surface conductivity. The leakage current increases linearly with applied voltage. The current flows on the surface only slightly affects the surface conductivity since no drying effect takes place. This leads to the linear dependence of leakage current on applied voltage.

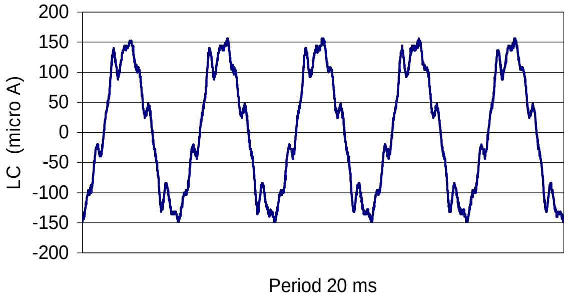
Under salt fog with high conductivity, the kaolin is trapping the salt-water and drastically increases the surface conductivity. This enhance the current to flow on the insulator surface. At certain applied voltage large leakage current flew on the surface and as the applied voltage was increased the magnitude of the leakage current also increased. This high LC heated the surface and reduced the surface conductivity and in turn reduce the leakage current magnitude. This process may take place again if the applied voltage is maintained in the same level. This phenomenon is similar to those observed in clean sample under salt fog and in general the fluctuation of leakage current magnitude as function of applied voltage in kaolin polluted samples is smaller than those of clean samples under same fog condition.

3.2 Analysis of Leakage Current waveforms

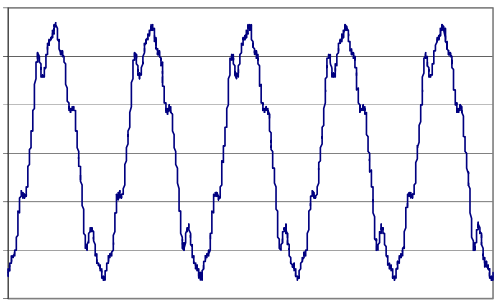
3.2.1 Leakage Current waveforms for clean sample under clean fog condition

Figure 7 shows typical leakage current waveforms for clean insulator under clean fog of low humidity at applied voltage of (a) 5 kV ,(b) 10 kV and (c) 15 kV and (d) 20 kV. The LC waveforms were slightly distorted from their sinusoidal due to presence of harmonic components especially 5^{th} and 3^{rd} components. Similar results were also reported for ceramic insulators coated with silicone[7] and silicone rubber (SIR) insulators[8].

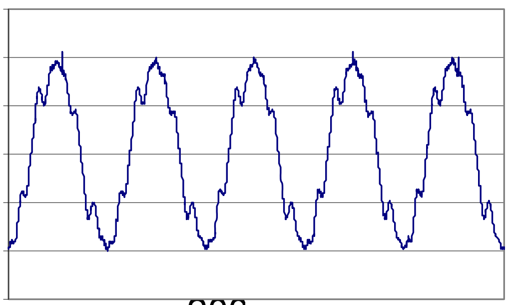
At applied voltage of 5 kV the LC amplitude was about 150 μA and the THD was 14 %. At higher applied voltage of of 10 kV the LC amplitude increased to 260 μA with THD of 15 %. At 15 kV LC increased to 400 μA with THD of 15 %.



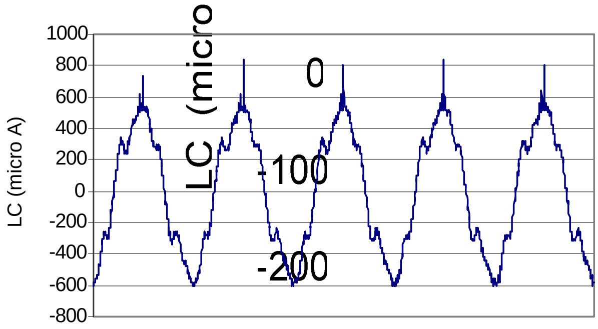
(a) 5 kV



(b) 10 kV



(c) 15 kV

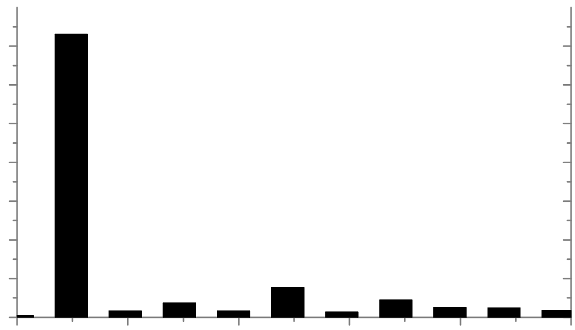


(d) 20 kV

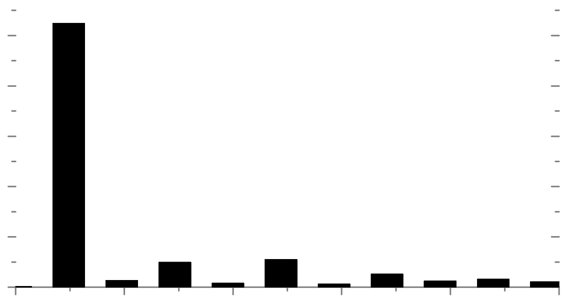
Fig. 7 Typical LC waveforms for clean samples under clean fog of low humidity at (a) 5 kV, (b) 10 kV, (c) 15 kV and (d) 20 kV

At applied voltage from 5 – 15 kV, the leakage current waveform distortion was almost symmetrical at both polarity (positive and negative half cycles) and the 5th harmonics greatly contributed to the THD. However, at applied voltage of 20 kV the amplitude of LC was 600 µA and spark was observed at the peak of positive half cycles and asymmetrical waveform was observed. The 3rd harmonic component became larger. The change of 3rd and 5th harmonic components are clearly seen in figure 8.

This fact can be explained as follows. As applied voltage increase, the ionization may take place on the insulator surface. Electric discharge may take place if initial charge or electron is available and the instantaneous applied voltage exceeding a certain threshold value. For clean ceramic insulator, initial electron is easier to be released from air(fog) rather than from the ceramic surface. This occurred at positive half cycle when air at the proximity of the ceramic surface is negatively charged and released electron to initiate the discharge.



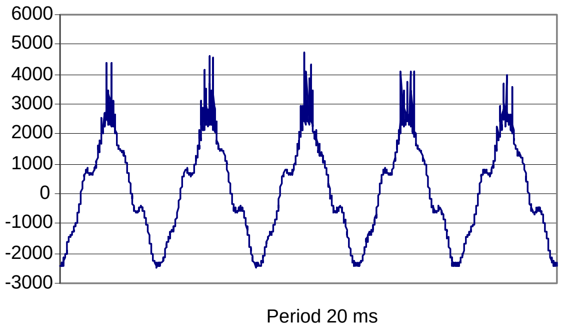
15 kV



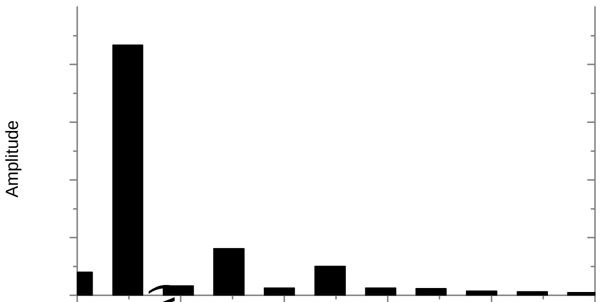
20 kV

Fig. 8 Harmonic components of LC for clean samples under clean fog of low humidity at (a) 5 kV and (b) 20 kV

Fig. 9 shows LC waveform and harmonic contents for clean sample under clean fog of low humidity at applied voltage of 45 kV. The magnitude of the LC increased significantly and big distortion of positive half cycle was observed. This correlated with the enhancement of the discharges on the sample surface. The 3rd harmonic component became dominant.



(a)

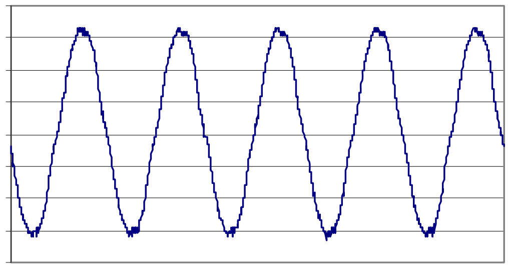


(b)

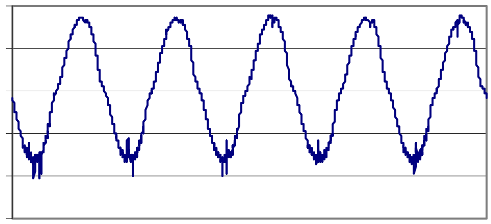
Fig. 9 LC waveform (a) and harmonic content (b) of clean sample under clean fog of low humidity at applied voltage of 45 kV

3.2.2 Leakage Current waveforms for kaolin-salt polluted sample under clean fog condition

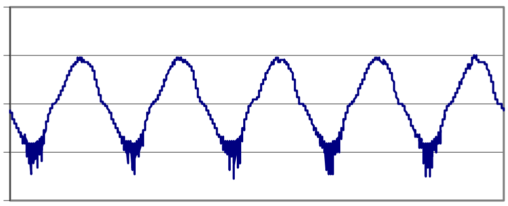
Figure 10 shows typical LC waveforms for kaolin-salt polluted at conductivity of 1.2 mS/cm and high RH for applied voltage of 5,10, 15 and 20 kV. Leakage current magnitude is much larger than those from clean sample. Kaolin-salt pollution on the ceramic sample absorb a large number of water molecules from clean fog at high humidity. Wet kaolin-salt pollution layer became conductive and drastically reduced the surface resistance and hence promote leakage current to flow.



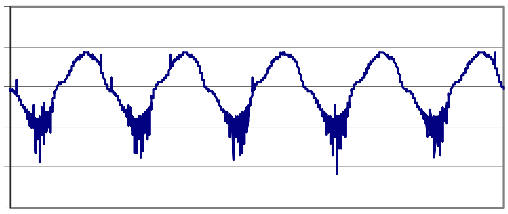
(a) 5 kV



(b) 10 kV



(c) 15 kV



(d) 20 kV

Fig. 10 Typical LC waveforms for kaolin-salt polluted sample under clean fog

Amplitude of the LC increased with the applied voltage from 6 mA at 5 kV to almost 9 mA at 20 kV. At 5 kV the LC waveform was slightly distorted with THD of 8 %. At 10 kV LC distortion started at negative half cycle with THD of 10.5 %. The distortion increased to 15.3 % at 10 kV and 17 % at 20 kV. This phenomenon is typical for polluted insulator surfaces. Under higher applied voltage the discharge pulse magnitude may reach as high as 30 mA.

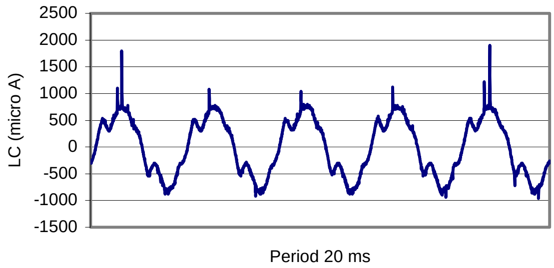
Differ from those of clean samples, electric spark initiated at negative half cycle as clearly seen in the waveforms obtained at applied voltage of 10 kV or higher. These indicated that initial electrons for starting the electric discharges came from the kaolin-salt pollution embedded on the insulator surface. As applied voltage increased, the number of initial electrons also increased and the excess electric field became higher. These caused in large number of discharges with higher magnitude. This is the reason why THD of kaolin-salt polluted sample increases with the applied voltage.

3.2.3 Effect of salt fog conductivity on Leakage Current waveforms

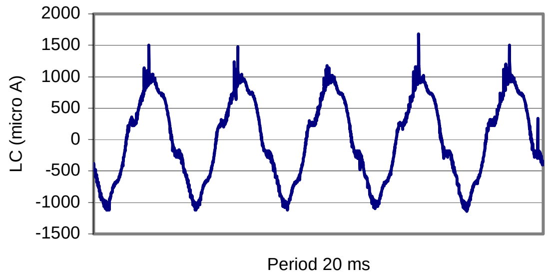
Figure 11 shows the typical LC waveforms of clean samples under salt fog with conductivity of 0.6 , 1.2 and 3.6 mS/cm respectively. It is clearly seen that the LC amplitude increased significantly from 800 μA at conductivity of 0.6 mS/cm to 1100 μA at conductivity of 1.2 mA and more than 5000 μA at conductivity of 3.6 mS/cm. This was caused by the increase of sample surface conductivity due to salt fog conductivity.

The figure also indicates that the waveforms distortion was significantly decreased with the salt fog conductivity. The THD reduced from 24.3 % at 0.6 mS/cm to 18.3 % at 1.2 mS/cm and further reduced to 9.9 % at salt fog conductivity of 3.6 mS/cm.

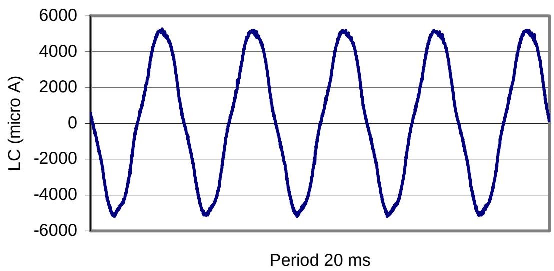
Figure 11(a) and (b) show that there are distortion of LC waveforms at positive half cycle. This is similar to those observed for clean sample under clean fog as depicted in figure 7(d). The electric discharges ceased under salt fog conductivity of 3.6 mS/cm. This is due to the increase of surface conductivity and reduction of electric field which is necessary to produce initial electron for initiating the electric discharges on the insulator surface.



(a)



(b)

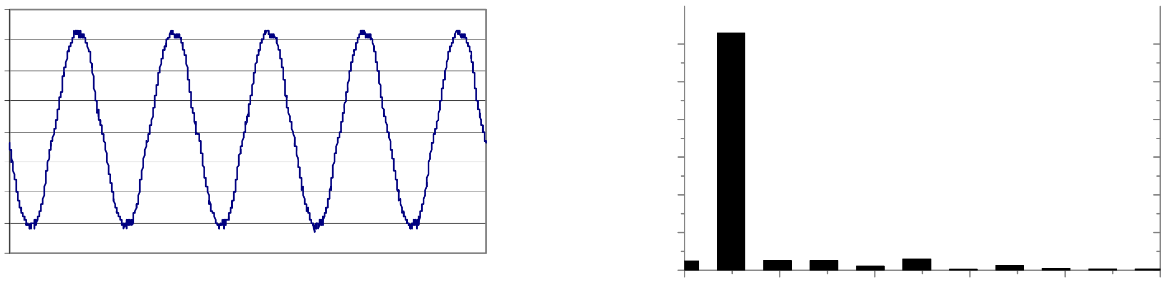


(c)

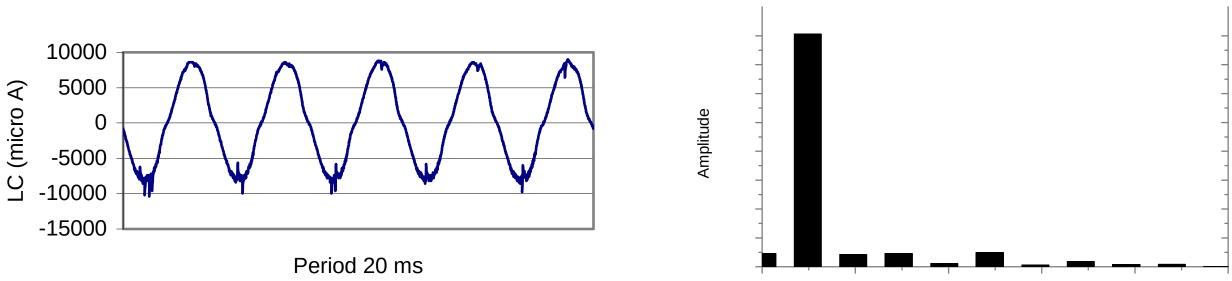
Fig 11 Typical LC waveforms for clean insulator under salt fog with conductivity 0.6, 1.2 and 3.6 mS/cm at RH of 65 % and 25 kV applied voltage

3.3 Flash over Characteristics

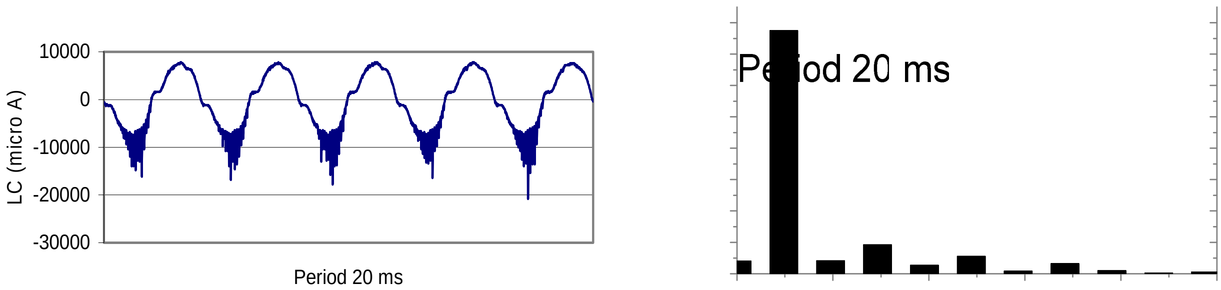
Flashover of ceramic sample was investigated under kaolin-salt pollution and clean fog at high humidity. This represents the most severe condition. Applied voltage was increased to make flashover on the sample surface.



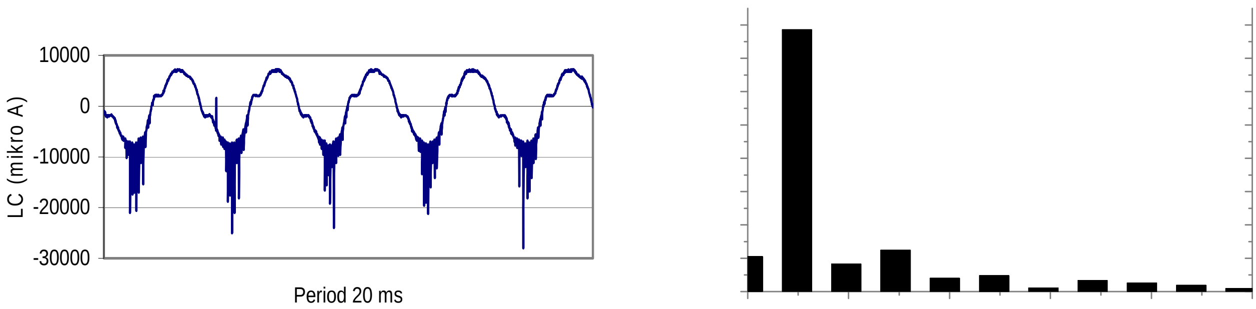
(a) 5 kV



(b) 10 kV



(c) 25 kV



(e) 35 kV

Fig. 12 Typical LC waveforms and their harmonic content for kaolin-salt polluted sample during prior to flashover

Figure 12 shows typical LC waveform for kaolin-salt polluted sample at 1.2 mS/cm under high humidity. At low voltage of 5 kV (a), the LC amplitude was slightly higher than 6 mA and the LC waveform was only slightly distorted from sinusoidal. No spark or discharge was observed in this condition. The harmonic content indicates that there is 5th harmonic appears in the leakage current waveform

When applied voltage was increased to 10 kV the LC amplitude increased to 9 mA and a small distortion at negative half cycle of LC waveform was started to be observed. This correlates with the electric arc or discharge which also started to grow. At this condition 2nd, 3rd and 5th harmonic components appear which contribute to the increase of THD.

Distortion at the negative half cycle indicated that initial electrons for promoting the discharges (arc) released from the surface of the sample. In this condition kaolin-salt pollution which was tightly deposited on the ceramic surface became the source of the electrons for discharge initiation.

When the applied voltage was increased to 25 kV the LC amplitude only slightly increased but the waveforms distortion was drastically increased. The 3rd harmonic component is the largest while 2nd and 5th harmonic components also appear. The THD increased from 10.4 % at applied voltage of 10 kV to 16 % at 25 kV.

Under applied voltage of 35 kV no significant increase of LC amplitude was observed but the distortion of the LC waveform steadily increased. The 2nd and 3rd harmonic component become larger while 5th and other harmonic components almost remain constant. The appearance of even harmonic such as 2nd component is due to unsymmetrical behavior of the LC waveform.

In this voltage level THD increased to 21.5 %. This large distortion of leakage current waveforms correlated with the appearance of dry band arcing on the sample surface prior to the flashover. The dependence of THD on applied voltage is shown in fig 13.

The increase of THD prior to the flashover of insulators was also reported for polymeric insulators[9,10] and a string of suspension insulators[11]. Humidity greatly affects the flashover process on the insulators[12]. These experimental results revealed that severe condition of ceramic insulator surface may be indicated by the magnitude of the leakage current and the change of frequency components as indicated by the value of THD. The two LC parameters are important for diagnostics[9].

The change of the leakage current indicates a stochastic behavior in term of amplitude and frequency spectrum. A level crossing analysis was introduced[13]. The change of leakage current may be used for the diagnostics of ceramic insulators. The change may also useful for detecting dry band arcing as reported by El Haq[14].

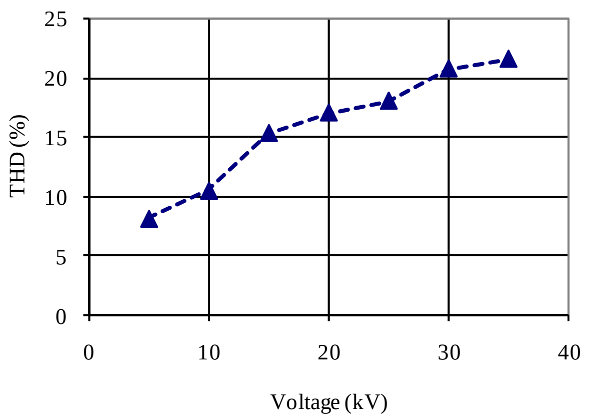


Fig 13 Dependence of THD on applied voltage for kaolin-salt polluted sample at conductivity of 1.2 mS/cm and high RH.

4 Conclusion

Leakage current and flashover characteristics of ceramic insulator have been investigated under artificially-simulated pollution. From the experimental results following conclusions can be drawn.

For clean insulators leakage current was much smaller than polluted insulators. The humidity affects the magnitude of the leakage current. The waveform distortion was observed particularly at positive half cycle when applied voltage was increased to higher than 20 kV. The 5th harmonic component

For kaolin-salt polluted insulators, the LC amplitude was much higher than clean insulators. LC waveform distortion started at 10 kV. Unbalance distortion of LC waveforms was observed similar to those of clean samples. However, for kaolin-salt polluted samples, the distortion was observed mainly at negative half cycles. The large distortion of leakage current during pre flashover of the sample strongly correlated with the dry band formation.

Observation of LC waveforms during the process of flashover revealed that THD of increased with the applied voltage. These results may be useful for diagnosis of ceramic insulators.

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