Leakage Current Waveforms and Arcing Characteristics of Epoxy Resin for Outdoor Insulators under Clean and Salt Fogs

Suwarno & S.K. Ardianto

School of Electrical Engineering and Informatics
Bandung Institute of Technology
Jl. Ganesha 10 Bandung 40132, INDONESIA
Email: suwarno@ieee.org

Abstract. Ceramic outdoor insulators have been used in high voltage transmission lines since long time ago. Due to superiority in their resistance to pollution, recently, polymeric outdoor insulators are widely used. Epoxy resin is one polymer which shows good properties for outdoor insulation. During service, outdoor insulators may severe a certain degree of pollution which may reduce their surface resistance. Leakage current (LC) usually increase and degradation may take place. This paper reports experimental results on the leakage current waveforms and arcing characteristics of epoxy resin under clean and salt fog. The samples used are blocks of epoxy resin with dimension of 250 x 50 x 20 mm^3. The samples were put in a test chamber with dimension of 900x900x1200 mm^3 with controllable humidity and pollution conditions. Clean and salt fog were generated according to IEC 60-1 and 507. The arcing experiment was done with incline plane test in accordance with IEC 587. AC voltage in the range from 5 kV to 50 kV with frequency of 50 Hz was applied. 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 elaborated. Visual observation of the arc on the sample surfaces was observed using a video camera. Experimental results indicated that LC magnitude on clean samples was slightly affected by humidity (RH). However, under salt fog, RH greatly affected the LC magnitude. The flashover voltage of clean samples under salt fog reduced significantly for fog conductivity of more than 1.2 mS/cm. Kaolin-polluted samples under salt fog showed an Ohmic behaviour. The LC magnitude was high and a large discrepancy of LC magnitude was observed for high applied voltage of larger than 25 kV. The largest LC magnitude was observed on salt-kaolin polluted samples under clean fog at high RH. LC waveforms analysis indicated that in general LC waveforms were distorted from sinusoidal. For clean samples under clean fog, THD of LC decreased with RH but slightly increased with the applied voltage. Large distortion at the peak of LC waveform was observed on kaolin polluted sample under salt fog of 3.6 mS/cm and high RH and high applied voltage. This correlates with corona arc on the sample surface. Similar behaviour was observed on kaolin-salt polluted samples under clean fog. Tracking arc experiment indicated that arc length LC magnitude and arc intensity increased with the pollutant conductivity. The THD also significantly increased with pollutant conductivity. At conductivity of less than 0.6 mS/cm the unsymmetrical LC waveforms were obtained. However, symmetrical LC waveforms were observed for conductivity of 0.9 and 1.2 mS/cm. The change of LC magnitude and waveform at different condition of samples may be useful for the diagnostics of insulator condition.

Keywords: *dry band; epoxy resin; humidity; leakage current; waveform; THD; surface resistance.*

1 Introduction

In a power system, insulator plays an important role 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].

Due to some superior properties such as lightweight, good water repellance and resistance to pollution, recently, polymeric insulating materials are introduced to substitute conventionally used insulators like porcelains and glasses [2,3]. During service, several severe conditions such as high humidity, coastal and industrial pollutions as well as biological contaminations may be exposed to the outdoor insulators [4-6]. For development of outdoor insulator, laboratory test is useful [7-11].

Laboratrory investigations on a number of polymeric outdoor insulators such as silicone rummber, Ethylene Prophylene Diene Monomer (EPDM), Cycloalipatic resin, Polydimethylsiloxane (PDMS) and RTVand silicone compound coatings have been reported [12-17].

Epoxy resin is one of polymeric materials used for high voltage insulators. Epoxy resin showed a considerable good tracking and errosion resistance and suitable for outdoor use. There are several reports explained good insulation properties of epoxy resin used in polluted conditions [18,19]. However, almost no paper has been reported concerning leakage current and its waveforms for epoxy resin although it is important for insulator diagnostics. This paper reports the experimental results on the leakge current and its waveforms of epoxy resin under various artificial contaminations using clean and salt fog methods.

2 Experiment

2.1 Sample

The samples used in this experimet were epoxy resin formed from diglycidil ether of bisphenol-A (DGEBA) and metaphenylene-diamine (MPDA) at 27^0 C and 1 atm. The samples were prepared in the form of blocks with dimension of 250 x 50 x 20 mm^3 as shown in Figure 1(a) clean and 1(b) kaolin-salt polluted. For obtaining good contact with electrode, the two ends of the samples were coated with conductive silver paint. The samples was subjected to various test conditions such as clean fog and salt fog, kaolin pollution and kaolin-salt pollution under clean or salt fog. Kaolin-salt pollution was obtained by adding 40 g kaolin into 1 liter water. Salt was added into the solution for obtaining the desired conductivity. The conductivity was varied from 0.6 mS/cm – 4.0 mS/cm which represented the degree of pollution from light to heavy derived from Equivalent Salt Deposit Density (ESDD) according to IEC 507[20].

(a)

(b)

Figure 1 Epoxy resin samples used in experiment (a) clean (b) kalin-salt polluted.

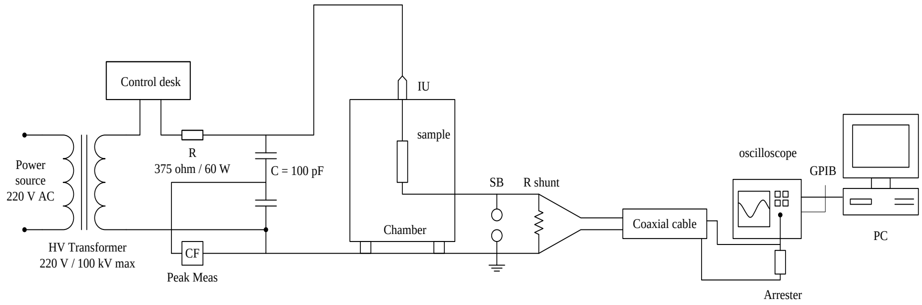


Figure 2 Measurement system

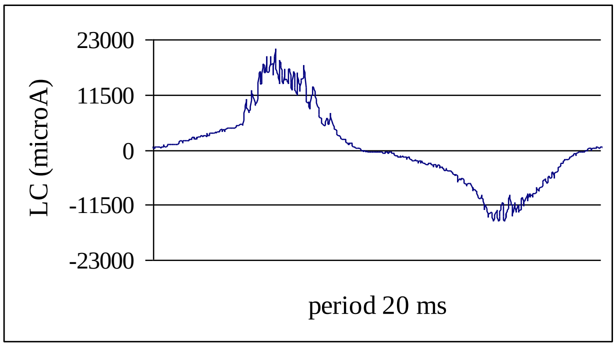
The humidity (RH) of the fog chamber was conditioned at humidity of 50-60 % (low RH), 70-80 % (medium RH) or 90-98 % (high RH). The tests were conducted according to IEC 60-1 (1989)[21] and IEC 507 (fog test) [20].

2.2 Leakage Current Measurement

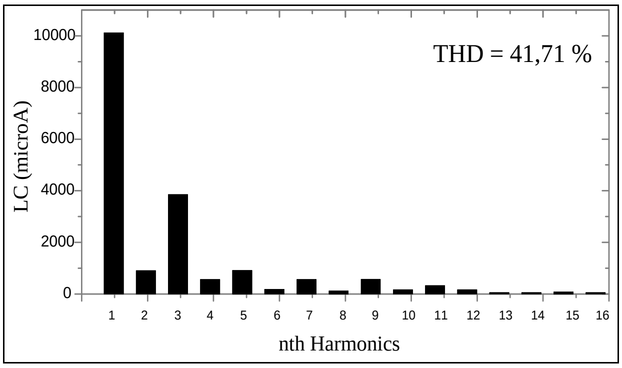
The leakage current flowed on the insulator surface was measured by measuring the voltage across a series resistance of 10 kΩ using a Digital Oscilloscope with bandwidth of 100 MHz, and the maximum sampling rate of 1 GS/s. LC waveforms were digitized and the digital data was transferred to a personal computer trough a GPIB for further analysis. The measurement system is shown in Figure 3. Harmonic content of LC was analyzed using FFT (Fast Fourier Transform). Under polluted conditions, leakage current on the outdoor insulators usually distorted from its sinusoidal form as shown in Figure 3. The degree of distortion is expressed as Total Harmonic Distortion (THD) which is defined as

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^{\,2}}}{I_1} \tag{1}$$

where I_1 is fundamental component of LC (1st harmonic) and I_n is *nth* harmonic component of LC.



(a)



(b)

Figure 3 Typical leakage current on insulator surface (a) and harmonic components (b).

2.3 Arc Measurement

In order to observe the arc on the samples, an inclined plane method according to IEC 587 (inclined plane test) [22] was used. The samples were put inclined 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 measured using LC measurement system as described before.

2.4 Surface Resitance Measurement

In order to know the surface resistance of the samples, the resiatance was measured using mega ohm meter at operating voltage of 1000 V. The two ends of the samples were coated with silver paint to form electrodes.

3 Experimental Results

3.1 Leakage Current Characteristics of Clean Samples under Clean Fog

Figure 4 shows the dependences of leakage current on applied voltage for clean samples under clean fog at low, medium and high humidity. The figure indicates that leakage current increases almost linearly with applied voltage at clean condition. Increase of humidity result in a slight increase of leakage current magnitude. The increase of humidity at clean condition slightly reduced the surface resistance from 145.7 MΩ at low RH ro 134.5 MΩ at medium RH and 115.8 MΩ at high RH.

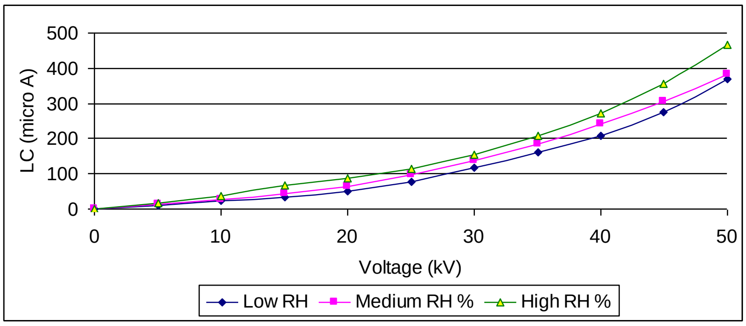
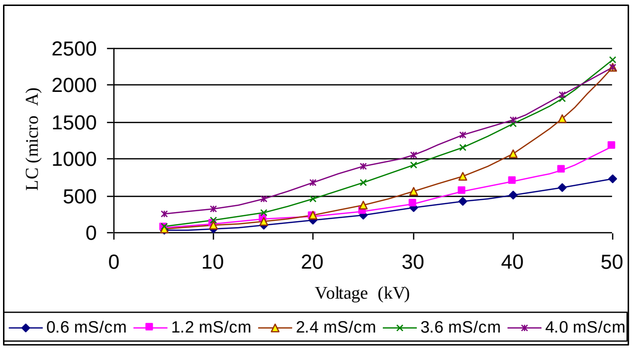


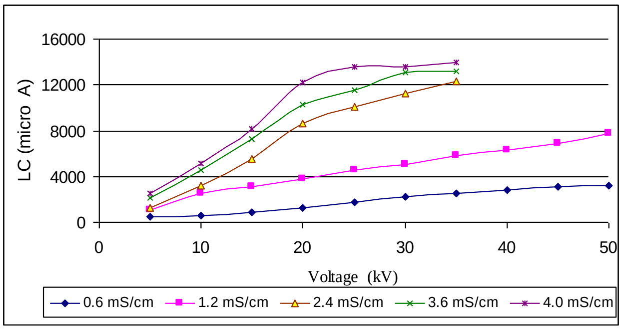
Figure 4 Dependences of leakage current on applied voltage under low, medium and high humidity

3.2 Leakage Current Characteristics of Clean Samples under Salt Fog

Figure 5 shows the dependences of leakage current on applied voltage for clean samples under salt fog with fog conductivity varied from 0.6 mS/cm to 4.0 mS/cm at low (a), medium (b) and high humidity (c) under applied voltage ranged from 5 kV to 50 kV. Figure 5 (a) showed that at low RH the magnitude of leakage current slightly increased with applied voltage. LC magnitude varied from less than 250 μA at applied voltage of 5 kV for all samples to about 2300 μA for salt fog conductivity of more than 1.2 mS/cm. No flashover was found at this condition. Significant increase of LC magnitude was observed compared to those of clean samples under clean fog at all RH. The increase of LC magnitude was due to smaller surface resistance of the clean samples under salt fog. The resistance varied form 63.6 mΩ at fog of 0.6 mS/cm to 20.5 mΩ at 4.0 mS/cm.



(a)



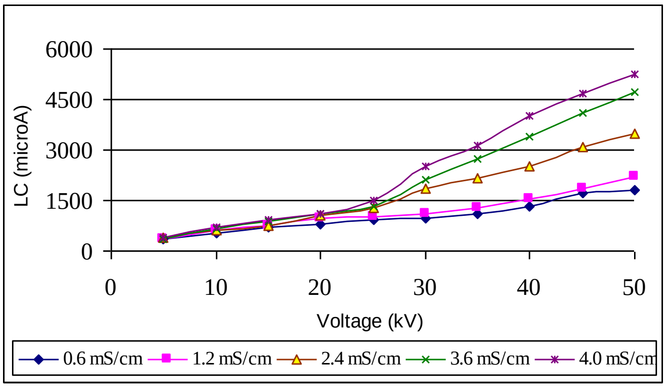
(b)

Figure 5 Dependences of LC magnitude on applied voltage for clean samples under salt fog of different conductivity.

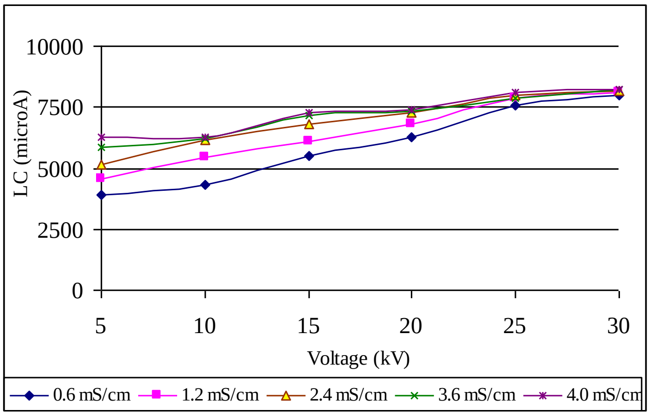
Figure 5(b) showed the LC dependency on applied voltage at different fog conductivities. At fog of 0.6 mS/cm and 1.2 mS/cm LC magnitude increased almost linearly with applied voltage. No Flashover was observed up to 50 kV. Non linear dependency of LC magnitude on applied voltage was clearly observed at fog of 2.4 mS/cm and higher with applied voltage of larher than 20 kV. During this condition electric arc appeared with large distortion of LC waveforms which will be explained later. Flashover was observed at 40 kV for 2.4 mS/cm, 37.8 kV for 3.6 mS/cm and 37 kV for 4.0 mS/cm.

3.3 Leakage Current Characteristics of kaolin-polluted Samples under salt fog

Figure 6 showed the dependences of LC magnitude on applied voltage for kaolin polluted samples under salt fog with fog conductivity varied from 0.6 mS/cm to 4.0 mS/cm at (a) low and (b) high humidity. Figure 6(a) showed that at low RH the magnitude of leakage current slightly increased with applied voltage and only slight deviation from each other up to applied voltage of 25 kV. LC magnitude varied from less than 500 μA at applied voltage of 5 kV for all samples to about 1100 μA at applied voltage of 25 kV. At higher applied voltage, the increasing rate of LC magnitude increased with the salt fog conductivity. The figure indicated an Ohmic behavior of insulator sample (i.e. LC almost linearly increased with the applied voltage). No flashover was found at this condition for applied voltage up to 50 kV. Compared to those from clean samples (i.e. figure 4(a)) the LC magnitude was almost twice. This was caused by the higher reduction of surface resistivity since kaolin-polluted samples had higher ability to absorb salt fog compared to clean samples.



(a)



(b)

Figure 6 Dependences of LC magnitude on applied voltage of kaolin-polluted samples under salt fog at (a) low RH and (b) high RH.

Figure 6(b) described the dependence of LC magnitude on applied voltage for kaolin-polluted samples under salt fogs at high RH. LC magnitude increased with applied voltage and fog conductivity. However, at applied voltage of 30 kV almost constant LC magnitude was observed. This was correlated with the appearance of arc and large distortion of LC waveforms. This will be discussed later in this paper.

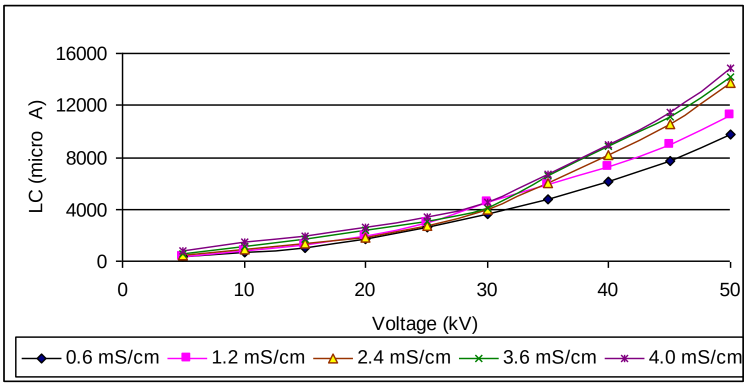
3.4 Leakage Current Characteristics of kaolin-salt polluted Samples under clean fog

Figure 7 shows typical leakage current magnitude of kaolin-salt polluted insulators as a function of applied voltage under clean fog at (a) low RH and (b) high RH. Figure 7(a) shows that the discrepancies of LC magnitudes of different pollution levels at low RH is larger at higher applied voltage. This indicates that the effect of kaolin-salt pollution becomes stronger at higher voltage. Similar pattern was reported for glass insulator [23]. Figure 7(b) shows that at high RH the LC magnitude was higher. Under high humidity, the water molecules were absorbed by pollutant leading to the increase of surface conductivity and LC magnitude [24,25]. However, at high RH large discrepancy of LC magnitude was not observed at high applied voltage. This was caused by the fact that at high LC magnitude the drying effect took place and the effect of high RH reduced leading to the reduction of LC magnitude.

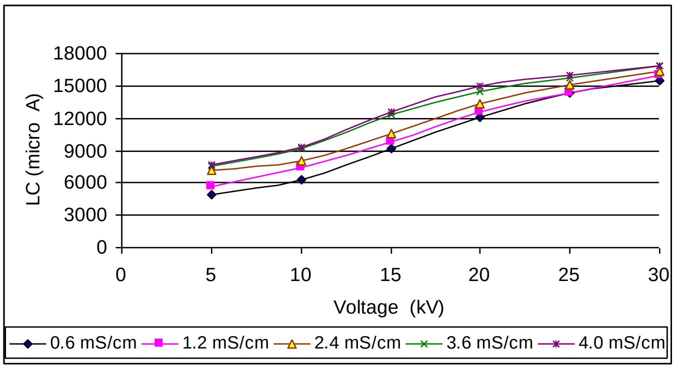
Table 1 Surface resistance (Rs) of sample under various conditions.

Sample	Conductivity (mS/cm)	Rs at Low RH (MΩ)	Rs at Medium RH (MΩ)	Rs at High RH (MΩ)
Clean sample under clean fog	-	145.7	134.5	115.8
Clean sample under salt fog	0.6	63.6	21.9	16.6
	1.2	43.8	9.6	7.3
	2.4	22.8	8.5	3.6
	3.6	22.4	7.6	2.6
	4.0	20.5	7.5	2.4
Kaolin-polluted under salt fog	0.6	32.8	27.7	11.3
	1.2	26.9	20.8	10.4
	2.4	14.8	14.3	8.3
	3.6	13.9	10.2	6.8
	4.0	13.7	8.8	5.7

Sample	Conductivity (mS/cm)	Rs at Low RH (MΩ)	Rs at Medium RH (MΩ)	Rs at High RH (MΩ)
Kaolin-salt polluted under clean fog	0.6	4.9	3.4	2.6
	1.2	4.1	3.3	2.5
	2.4	3.5	3.1	2.4
	3.6	3.4	2.9	2.3
	4.0	3.3	2.8	2.2



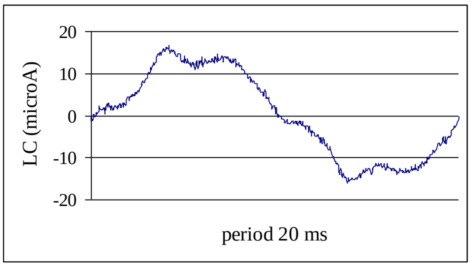
(a)



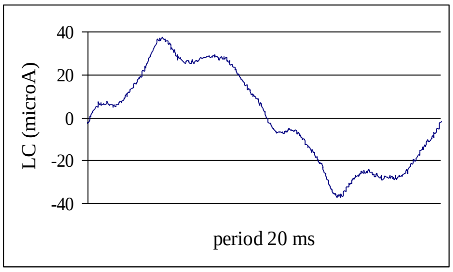
(b)

Figure 7 Dependence of LC magnitude on applied voltage for kaolin-salt polluted samples under clean fog at (a) low RH and (b) high RH.

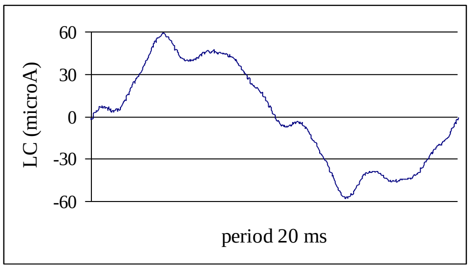
3.5 Dependent of Leakage Current Waveforms on Applied Voltage at Low RH



5 kV

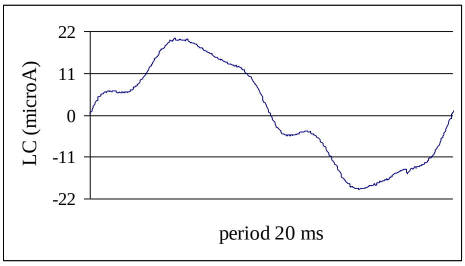


10 kV

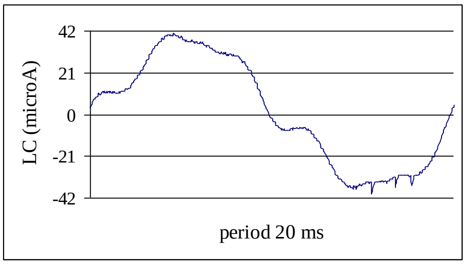


15 kV

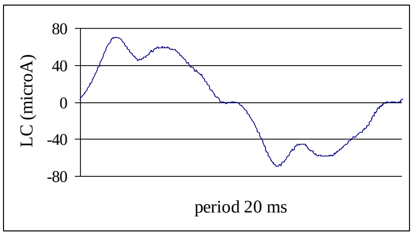
(a)



5 kV

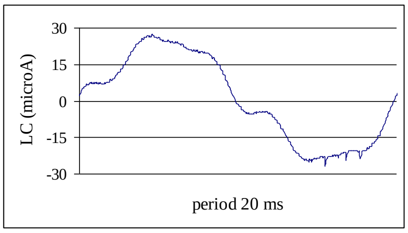


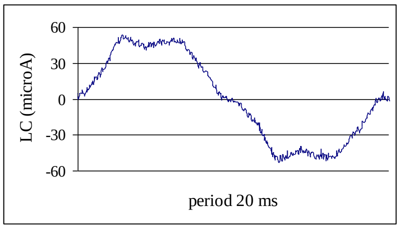
10 kV



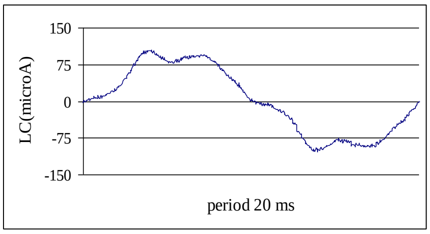
15 kV

(b)





5 kV 10 kV



15 kV

(c)

Figure 8 Typical leakage current waveforms for clean insulators under clean fog and applied voltages of 5 kV, 10 kV and 15 at (a) low RH (b) medium RH and (c) high RH.

Figure 8 shows typical leakage current waveforms of clean samples under clean fog and applied voltage of 5, 10 and 15 kV at (a) low RH (b) medium RH and (c) ahigh RH. Al figure clearly show that LC waveforms are distorted from sinusoidal form. The amplitude of LC increased with applied voltage and humidity. At a given RH, the waveform distortion as indicated by THD increased with applied voltage. However, at a given applied voltage THD decreased with RH. The comparison of THD for clean sample at different RH and applied voltage are shown in Figure 9.

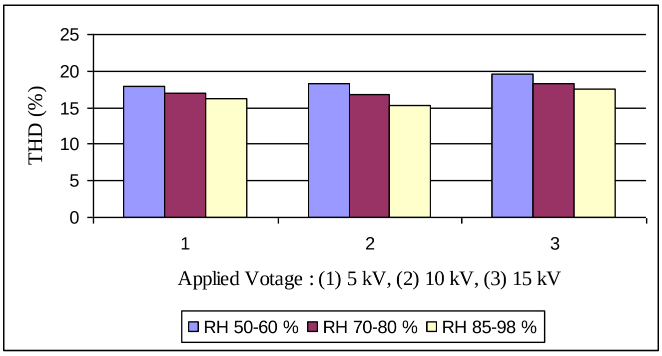
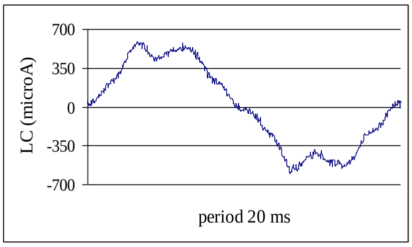
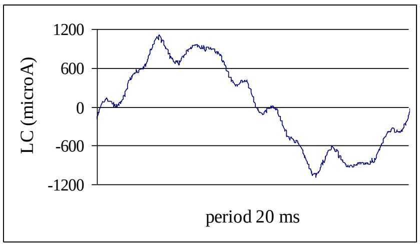


Figure 9 Typical THD of LC waveforms for clean samples under clean fog.

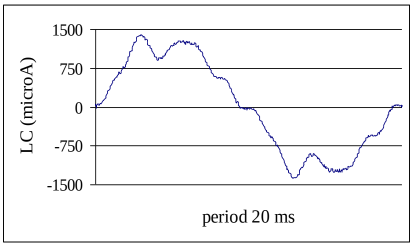
3.6 LC for Kaolin Polluted under Salt Fog 3.6 mS/cm



5 kV

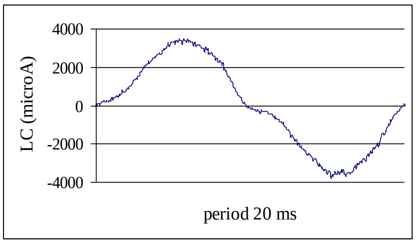


10 kV

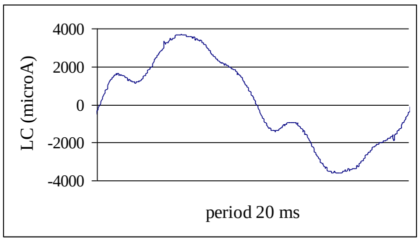


15 kV

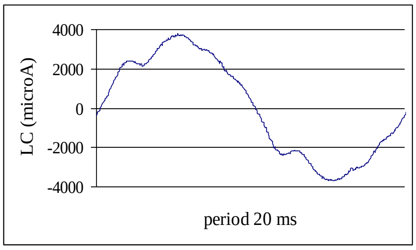
(a)



5 kV

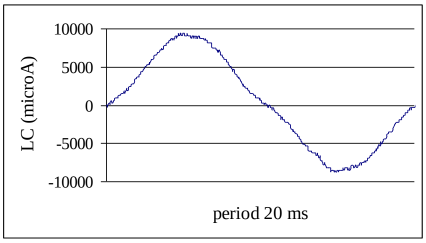


10 kV

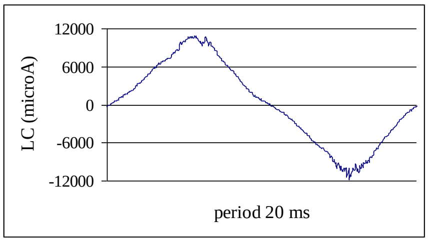


15 kV

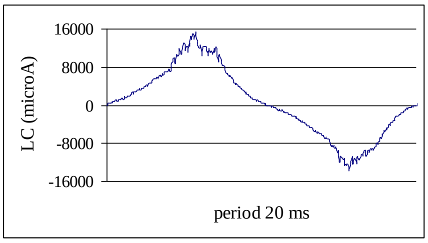
(b)



5 kV



10 kV



15 kV

(c)

Figure 10 Typical LC Waveforms for kaolin polluted samples under salt fog of 3.6 mS/cm at (a) low RH (b) medium RH and (c) high RH.

Figure 10 shows the typical LC Waveforms for kaolin polluted samples under salt fog of 3.6 mS/cm at (a) low RH (b) medium RH and (c) high RH. The figure clearly indicates that at a given RH the LC amplitude increased with the applied voltage. At low RH and low applied voltage, the LC waveforms were strongly distorted. The distortion decreased with RH. However, at high RH and high applied voltage, the THD increased greatly. The THD values of samples with various values of applied voltages and RH are shown in Figure 11.

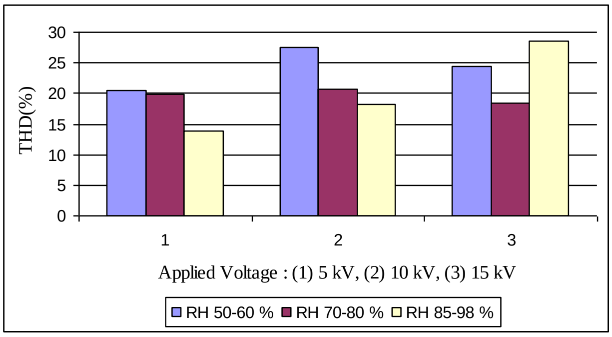
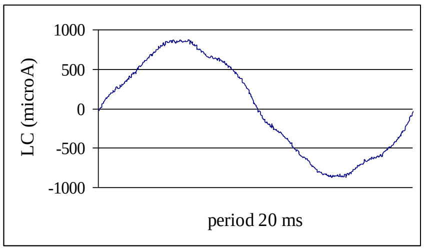
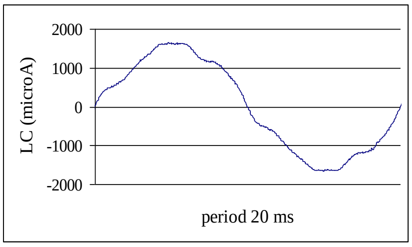


Figure 11 THD for kaolin polluted under salt fog.

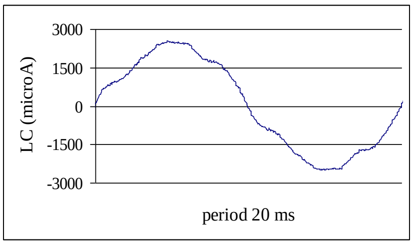
3.7 LC for Kaolin-Salt Polluted at 3.6 mS/cm under Clean Fog



5 kV

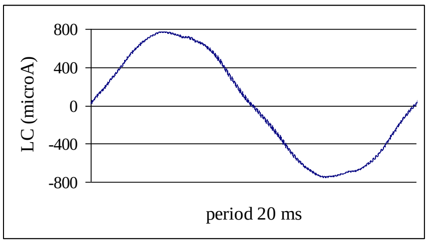


10 kV

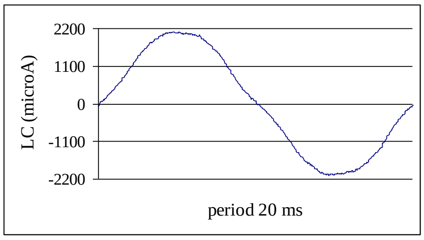


15 kV

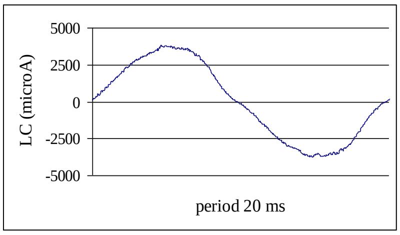
(a)



5 kV

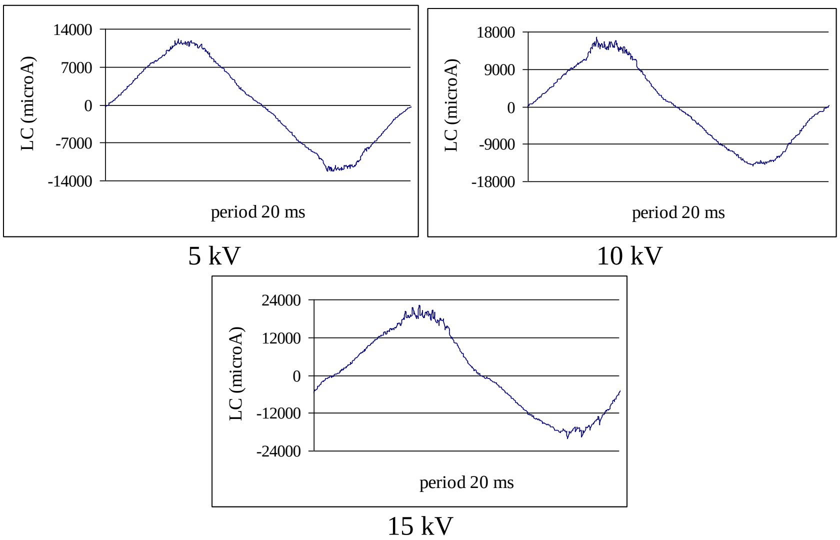


10 kV



15 kV

(b)



(c)

Figure 12 Typical LC waveforms for kaolin-salt polluted at 3.6 mS/cm under clean fog and applied voltage of 5, 10 and 15 kV at (a) low RH (b) medium RH and (c) high RH

Figure 12 shows typical LC waveforms for kaolin-salt polluted at 3.6 mS/cm under clean fog and applied voltage of 5, 10 and 15 kV at (a) low RH (b) medium RH and (c) high RH. The figure clearly indicates that LC magnitude of kaolin-salt polluted samples greatly affected by both applied voltage and humidity. In general the LC magnitude significantly larger than those from kaolin-polluted samples under salt fog condition at same conductivity but the distortion of the LC waveforms from its sinusoidal was smaller as indicated by THD. THD was slightly increased with applied voltage and strongly affected by humidity. At high RH the LC amplitude was large and the waveform distortion was also high especially at the peak of the LC waveforms. This correlated with local arc due to corona since corona usually occurs at the highest part/peak of the applied voltage [26]. Harmonic analysis indicated that odd harmonics components especially 3rd, 5th and 7th appeared with relatively high magnitude. Similar behavior was reported for suspension insulators [27] and post pin EPDM insulator [28]. This symmetrical LC waveform with dominant odd harmonic components was correlated with the appearance of spark on the sample surface at high RH which enhanced the distortion of LC waveforms leading to the increase of THD. The values of THD as function of voltage and RH is shown in Figure 13.

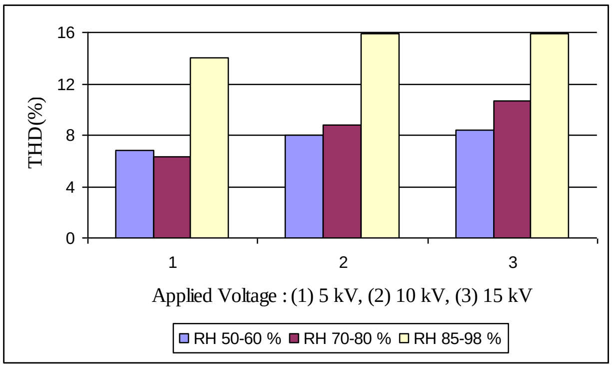
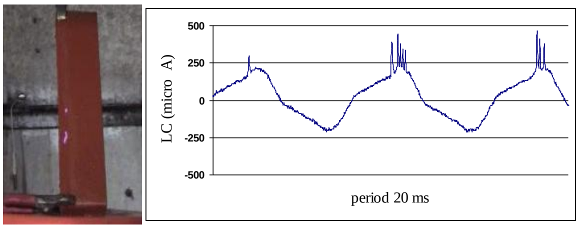


Figure 13 THD for kaolin-salt polluted at 3.6 mS/cm under clean fog.

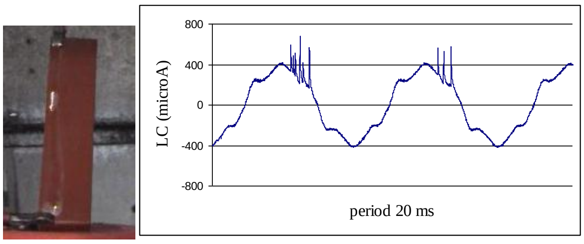
3.8 Arc during Tracking

Electric arc on the sample was investigated using incline plane experiment according to IEC 587. The sample was mounted in a chamber at an angle of 45^o. The peristaltic pump was used to continously deliver electrolite at a particular conductivity at fixed flow-rate of 0.15 ml/min. AC voltage of 12 kV was applied. The arc on the sample surface was observed using a camera and the corresponding leakage current was measured using LC measurement system as described before.



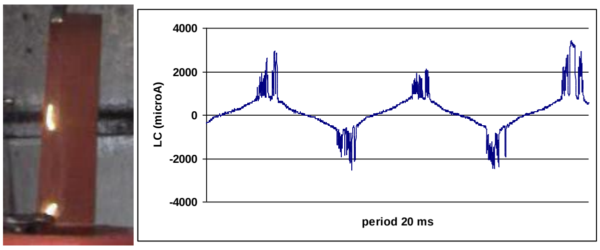
0.3 mS/cm , Irms = 139 mA, THD= 31.7 %

(a)



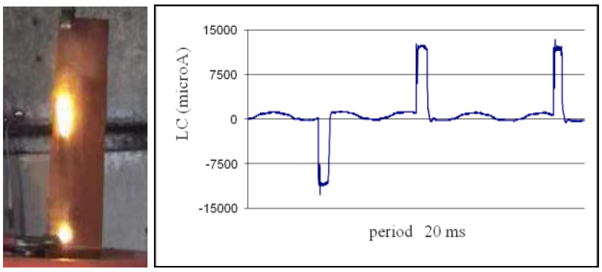
0.6 mS/cm, Irms = 278 mA, THD = 52.7 %

(b)



0.9 mS/cm, Irms = 873 mA, THD=55.1 %

(c)



(d)

Figure 14 Photographs of arcs on the samples and corresponding LC waveforms from incline plane test at different pollutant conductivity.

Figure 14 shows photographs of arcs on the samples and corresponding LC waveforms at pollutant conductivity of (a) 0.3 mS/cm (b) 0.6 mS/cm (c) 0.9 mS/cm and (d) 12 mS/cm. At pollutant conductivity of 0.3 mS/cm, small arc with length of 2 cm appeared at 223 s after the voltage application. The LC waveform indicated distortion at the peak of positive half cycle. This indicated that arc discharge was initiated from the surface of the pollutant and not from the surface of the sample. The results with pollutant conductivity of 0.6 mS/cm indicated similar characteristics with larger magnitude and higher THD as shown in Figure 14(b).

Figure 14(c) is photograph and LC waveform under pollutant conductivity of 0.9 mS/cm. The LC waveform became symmetrical and the distortion concentrated around the peak of the waveforms.

Figure 14(d) shows a different pattern of LC waveform obtained under pollutant conductivity of 1.2 mS/cm. The LC amplitude was high. The LC waveforms were strongly distorted with THD of 65.7 %. This is a highly distorted LC waveform which correlates with a large arc due to dry band formation [29]. The parameters of arc obtained from this experiment are summarized in Table 2.

Table 2 Arc parameters during tracking at incline plane test.

Arc Parameter	Conductivity of pollution (mS/cm)				
	0.3	**0.6**	**0.9**	**1.2**	**1.5**
Time (s)	223	185	121	98	67
Length (cm)	2	3	3	3,5	5
Intensity (lux)	8,1	9,5	13,4	15,7	18,6
Irms (μA)	139	278	873	3798	9384
THD (%)	31.7	52.7	55	65.7	72.9

4 Conclusion

Leakage current and arc characteristics for epoxy resin under clean and salt fogs have been investigated. Experimental results indicated that LC magnitude on clean samples was slightly affected by RH. However, under salt fog, RH greatly affected the LC magnitude. The flashover voltage of clean samples under salt fog reduced significantly for fog conductivity of more than 1.2 mS/cm. Kaolin-polluted samples under salt fog showed an Ohmic behaviour. The LC magnitude was high and a large discrepancy of LC magnitude was observed for high applied voltage of larger than 25 kV. The largest LC magnitude was observed on salt-kaolin polluted samples under clean fog at high RH. LC waveforms analysis indicated that in general LC waveforms were distorted from sinusoidal. For clean samples under clean fog, THD of LC decreased with RH but slightly increased with the applied voltage. Large distortion at the peak of LC waveform was observed on kaolin polluted sample under salt fog of 3.6 mS/cm and high RH and high applied voltage. This correlates with corona arc on the sample surface. Similar behaviour was observed on kaolin-salt polluted samples under clean fog. Tracking arc experiment indicated that arc length LC magnitude and arc intensity increased with the pollutant conductivity. The THD also significantly increased with pollutant conductivity. At conductivity of less than 0.6 mS/cm the unsymmetrical LC waveforms were obtained. However, symmetrical LC waveforms were observed for conductivity of 0.9 and 1.2 mS/cm. The change of LC magnitude and waveform at different condition of samples may be useful for the diagnostics of insulator condition.

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