Effects of Humidity and fog conductivity on the Leakage Current Waveforms of Ceramics for Outdoor Insulators

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Abstract: - Since long time ago, ceramic insulators are widely being used in power systems. The performances of the insulators such as surface resistance and flash over voltages greatly affected by environmental conditions such as pollution and humidity. The pollution may arise in the form of fogs. 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 effects of humidity and fog conductivity on leakage current characteristics of ceramics. 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 magnitudes as well as harmonic content of the LC were analyzed. The experimental results indicated that under clean fog, LC magnitude almost linearly increased with applied voltage at low and medium RH. At high RH, LC magnitude drastically increased compared to those of low RH. At low RH the dominant harmonics number are 5th , 3 rd and 7th with relatively large amplitude while at medium and high RH the dominant harmonic components of the LC waveforms are 5th and 3rd with smaller amplitude compared to it fundamentals resulting in smaller THD. Under fog condition, LC magnitude increase with fog conductivity. Compared to the LC magnitude under clean fog, the LC magnitude under salt fog was much higher than those from clean fog. At high fog conductivity the oscillation behaviour of LC magnitude dependence on applied voltage was observed due to the wetting effect of sample surface by the fog and drying effect caused by the higher LC. The THD of leakage current under salt fog increased with the applied voltage. LC amplitude increases with applied voltage and RH. LC waveforms distortion significantly decreased with the salt fog conductivity resulting in smaller THD. At given applied voltage the harmonic components decrease with the increase of fog conductivity.

Key-Words: - ceramic insulator**,** clean fog, salt fog, humidity, leakage current, waveform, harmonics

1 Introduction

Consumption of electric energy steadily increased in the world. In order to deliver the huge amount of the electric energy efficiently, high voltage transmission systems are required. Insulators is one of the most important parts in modern electric power system. There are glasses, ceramic and polymeric outdoor insulators widely used in an electric power system. They 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]. Among them ceramic insulators are the most intensively used worldwide since long time ago[2-3]. This type of insulators show good mechanical and electrical properties and less expensive. During operation some pollution such as coastal pollution with high salt content may attach to the ceramic insulators which significantly reduce their properties such as reduction of the surface resistance particularly during high humidity climate[4-6]. The reduction of surface resistance may enhance the leakage current to flow on the surface and bolster the aging of the insulator surface[7-9]. The combination of humidity and pollutant conductivity may cause insulator flashover[10-13]. For diagnostics of insulators investigation on the leakage current waveforms on the ceramic insulators under polluted condition and the role of humidity is important[14-18]. This paper reports the experimental results on the investigation on the effects of humidity and fog conductivity on leakage current characteristics of ceramic insulators.

2 Experiment Setup

Ceramic block samples with dimension of 250 x 50 x 20 mm^3 were used in the experiment. The picture of the sample is shown in figure 1.

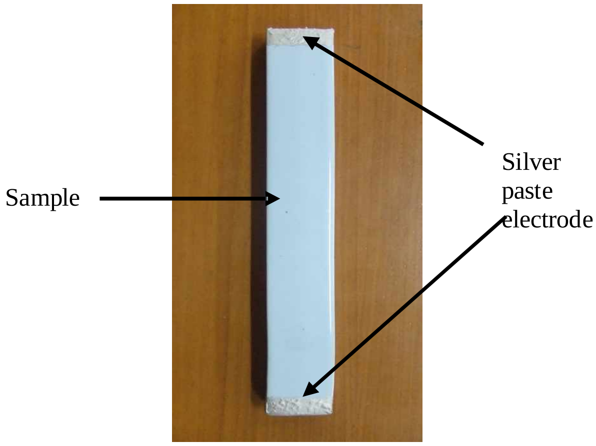


Fig. 1 Ceramic block sample

The two ends of the sample were covered by silver paste to make good contact with the electrodes. The sample was put in a test chamber made from aluminium panel with dimension of 900 x 900 x 1200 mm^3. The sample was subjected by clean fog with certain humidity in the range of 50-98 % or salt fog with various level of conductivity and humidity. AC high voltage of 50 Hz was applied to the sample in the test chamber. The leakage current flowed on the sample surface was measured by measuring the voltage across a resistance put in series with the sample using a Digital Oscilloscope TDS 220. The voltage waveforms recorded by oscilloscope reflected the LC waveforms. The oscilloscope has bandwidth of 100 MHz, and the maximum sampling rate of 1 GS/s. 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).

The degree of distortion of the leakage current waveform from its sinusoidal form of the applied voltage is indicated by Total Harmonic Distortion (THD) which 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. High THD indicates a large LC distortion.

3 Experimental Results

3.1 Leakage current under clean fog condition

3.1.1 Effects of humidity on Leakage Current magnitude and THD

Figure 2 shows the dependence 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.

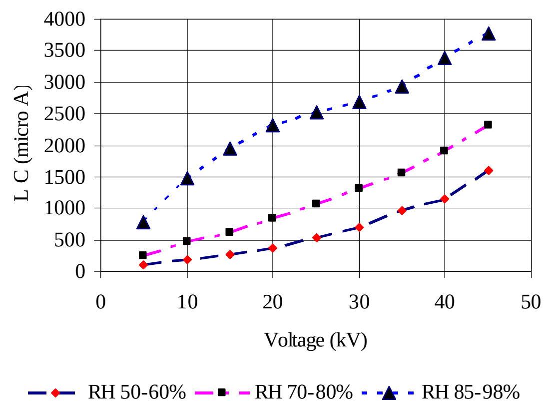


Fig. 2 LC magnitude as function of applied voltage for clean sample under clean fog at various humidity

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.

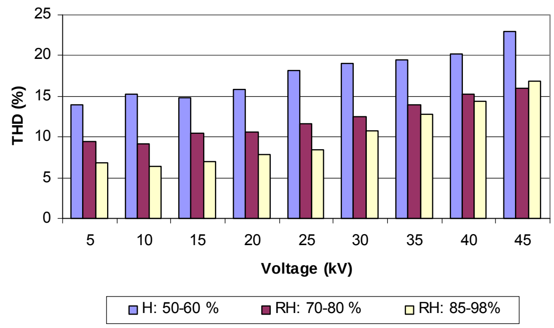


Fig. 3 THD as function of applied voltage for clean sample under clean fog with various humidity

3.1.2 Influences of clean fog humidity on the leakage current waveforms

Figure 4 shows leakage current waveforms of clean sample under clean fog at low (a), medium (b) and high (c) humidity for applied voltage of 15 , 20 and 25 kV. At low RH the amplitude of LC is small and the waveform distortion is high. There is great distortion at positive half cycle for high applied voltage as indicated by LC at 20 and 25 kV. These are caused by the occurrence of discharges which easily initiated at positive half cycles compared to those negative one. The LC magnitudes are much larger than observed on epoxy resin samples as reported in[20].

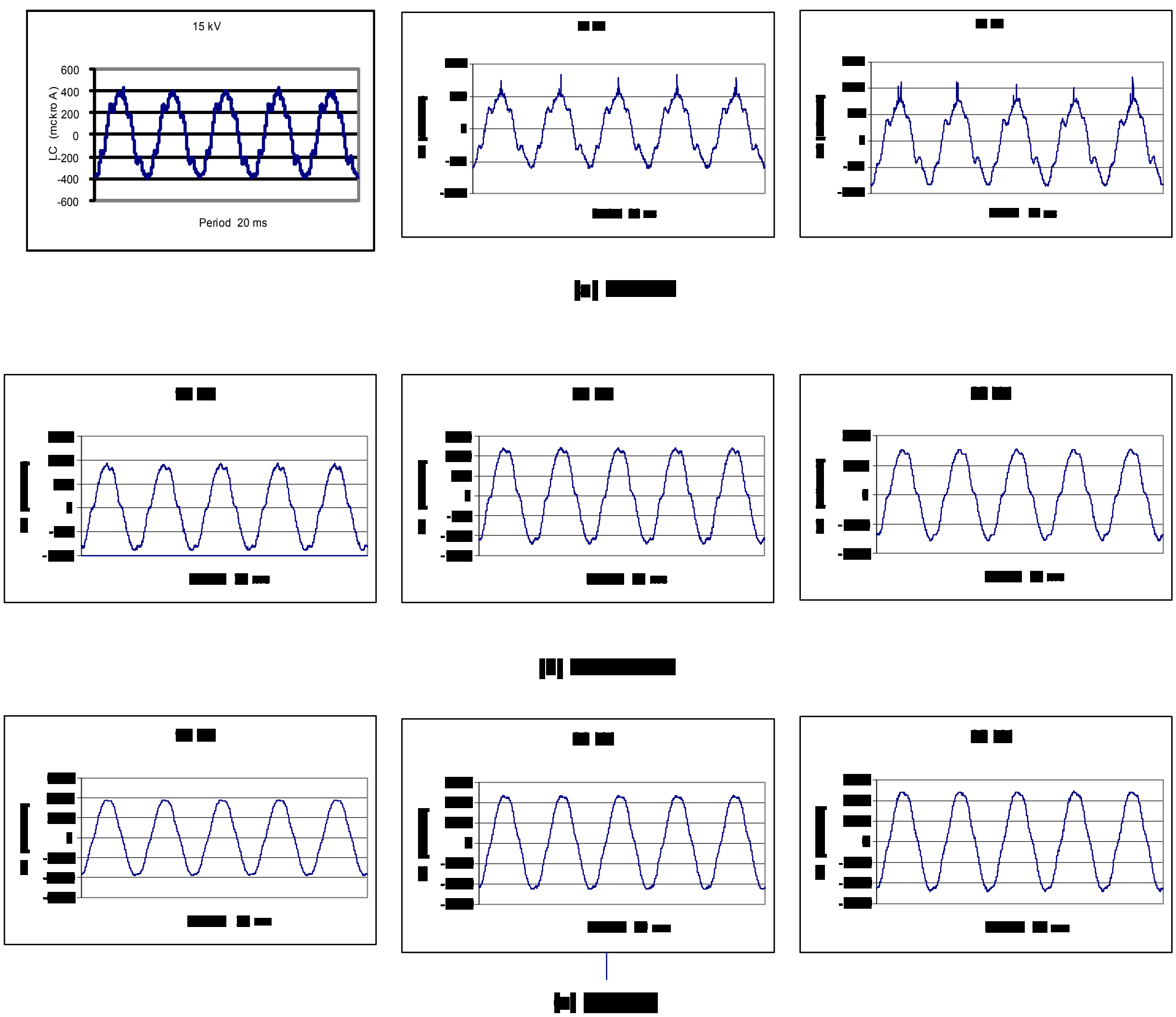


Fig. 4 LC waveforms for clean sample under clean fog at low , medium and high humidity at applied voltage of 15, 20 and 25 kV

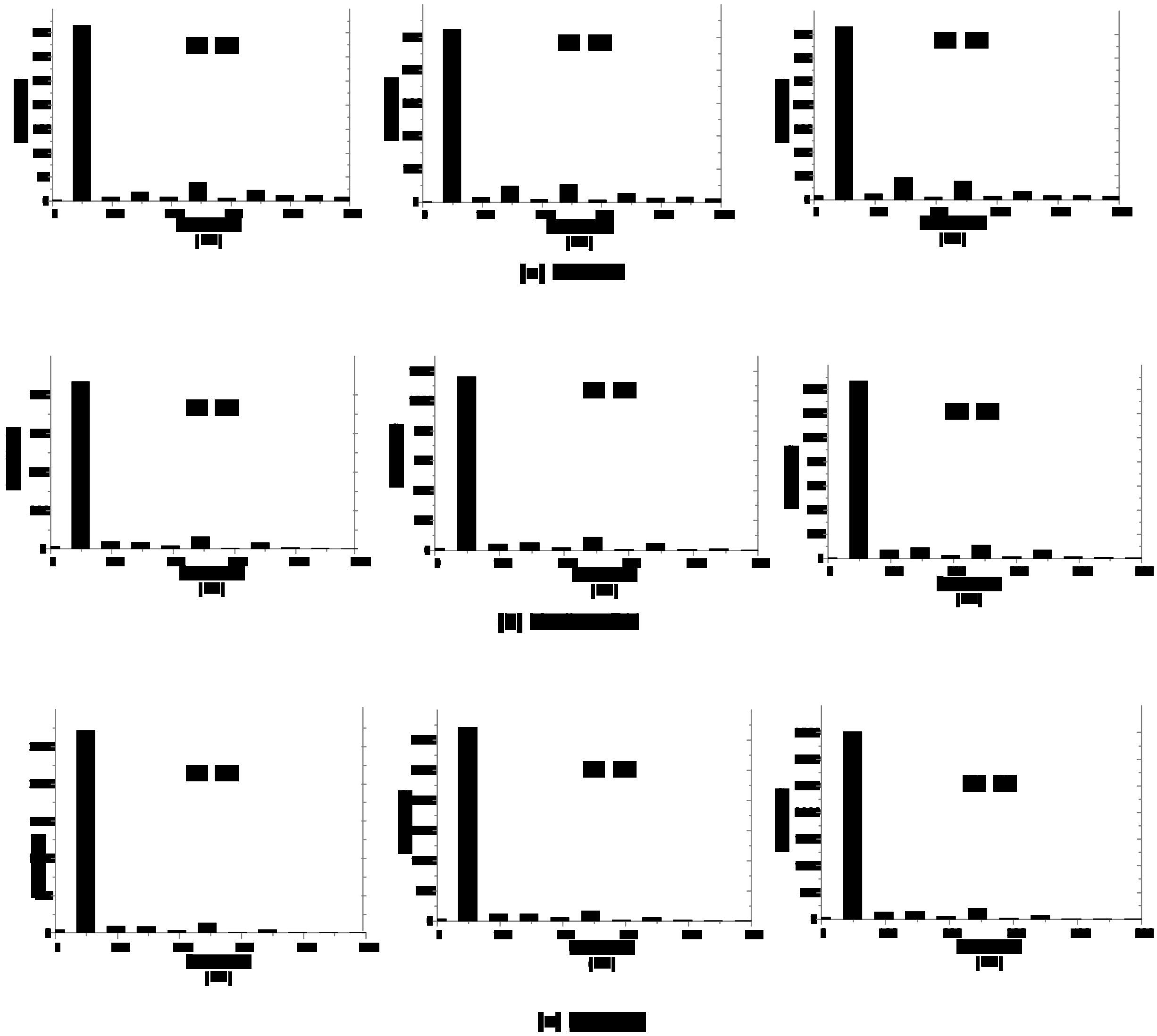


Fig 5. Harmonic components of LC waveforms under clean fog at low, medium and high RH at applied voltage of 15, 20 and 25 kV

At medium RH as indicated in figure 4 (b), the LC amplitude is larger than LC at low RH. The LC waveform distortion is also smaller and symmetrical between positive and negative half cycles. These are due to the increase of surface conductance which increases he fundamental component and reduces the harmonic components including discharges at positive half cycles which distorted the LC waveforms at low RH. The phenomenon is more clearly observed from LC measured under high RH as shown in figure 4 (c). Form the experimental results it can be concluded that the increase of RH of clean fog increases the LC magnitude but reduces the harmonic components and thus reduces also the THD. The harmonic components appeared in the LC waveforms are shown in figure 5. At low RH the dominant harmonics number are 5^{th} , 3 rd and 7^{th} with relatively large amplitude. At medium and high RH as indicated at figure 5 (b) and 5(c) the dominant harmonic components of the LC waveforms are 5^{th} and 3^{rd} with smaller amplitude compared to it fundamentals. This is the reason why THD decreased with the RH. The appearance of the harmonic components were also observed on polymeric insulators[21].

3.2 Leakage Current for clean sample under salt fog condition

3.2.1 Effects of Humidity and fog conductivity on LC magnitude and THD.

Leakage current under salt fog of Low RH

Figure 6 shows the dependence of LC magnitude on the applied voltage at various salt fog conductivity with low RH.

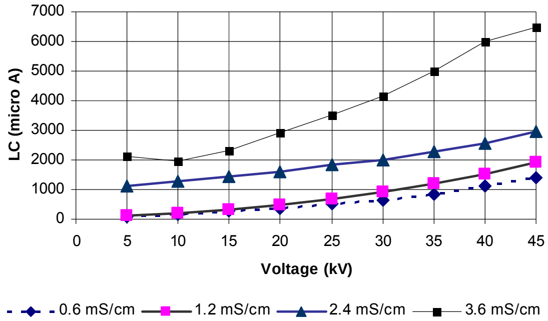


Fig. 6 Dependence of LC magnitude on applied voltage and fog conductivity at low RH

The figure indicates that in general LC magnitude increase with fog conductivity. At fog conductivity of 0.6 , 1.2 and 2.4 mS/cm the LC magnitude increases almost linearly with applied voltage. The approximate surface resistance is 26 MΩ for fog conductivity of 0.6 mS/cm, 20 MΩ for fog conductivity of 1.2 mS/cm and 18 MΩ for fog conductivity of 2.4 mS/cm. At fog conductivity of 3.6 mS/cm the LC magnitude is much higher than the rest of fog conductivity. The surface resistance drastically reduced to about 7 MΩ.

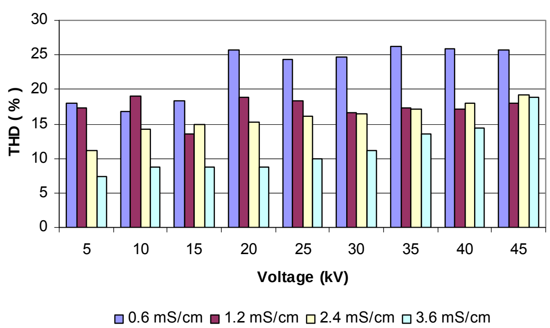


Fig. 7 Dependence of the THD of LC on applied voltage and fog conductivity at low RH

Figure 7 shows the dependence of the THD of LC on applied voltage and fog conductivity at low RH. The figure clearly shows that THD significantly reduced with the increase of fog conductivity particularly at applied voltage of lower than 30 kV. At higher applied voltage THD of LC waveforms tends to increase more rapidly for fog with higher conductivity. This is due to the appearance of intensive discharges which strongly distorts the LC waveforms at high fog conductivity and increases their THD.

Leakage current under salt fog of high RH

Figure 8 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 %.

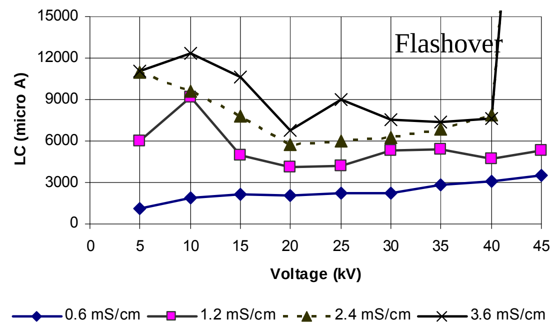


Fig. 8 Dependency of LC magnitude on applied voltage and fog conductivity

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 9 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 components.

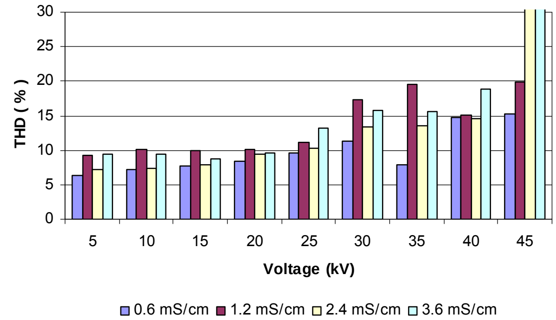
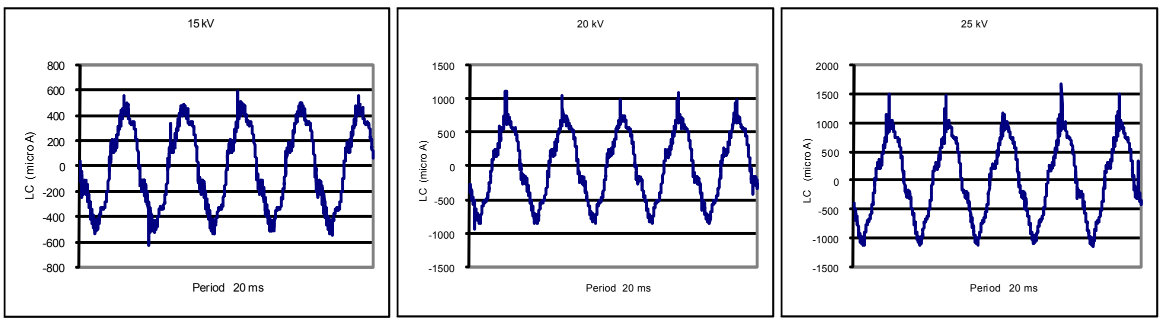


Fig. 9 LC magnitude as function of applied voltage and conductivity

3.2.2 Effects of Humidity and fog conductivity on LC waveforms



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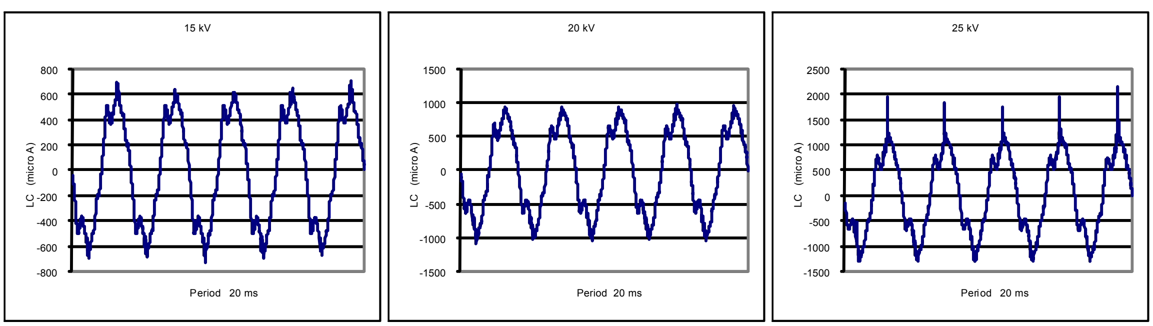

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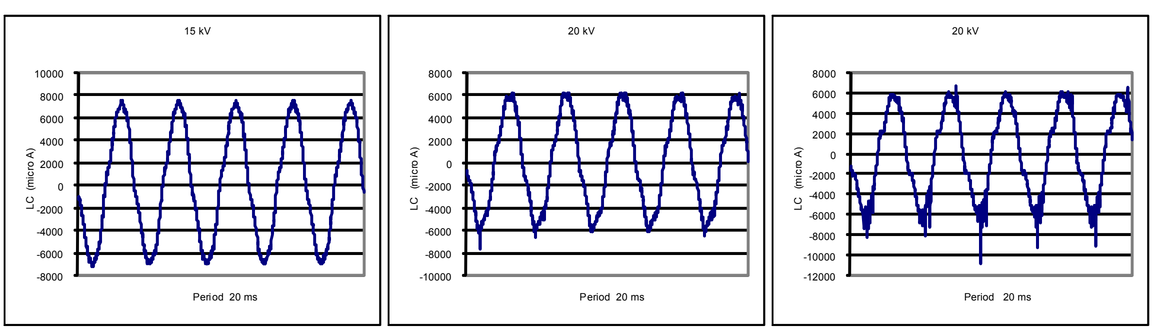

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Fig. 10 LC waveforms of lean sample under salt fog of 1.2 mS/cm at various humidity at applied voltage of 15, 20 and 25 kV

Figure 10 shows typical LC waveforms of clean sample under salt fog of 1.2 mS/cm at various humidity. The figure clearly indicates that LC amplitude increases with applied voltage and RH. At low RH positive discharges started to grow at applied voltage of about 20 kV. The positive discharges became large at higher applied voltages. The appearance of positive discharges can be explain in term of the initial electrons which initiated the discharge process. At low RH the initial electrons were ejected from the fog side. At medium RH the positive discharges started to appear at applied voltage of about 25 kV. At high RH larger distortion of LC waveforms were observed at negative half cycles. This means that the discharges were initiated from sample side. The discharges contribute to the harmonic especially the 3rd component. The amplitude of the LC increases with the applied voltage. However, the THD decreases with the increase of RH since the increase of harmonic components are smaller than fundamental as shown in figure 11.

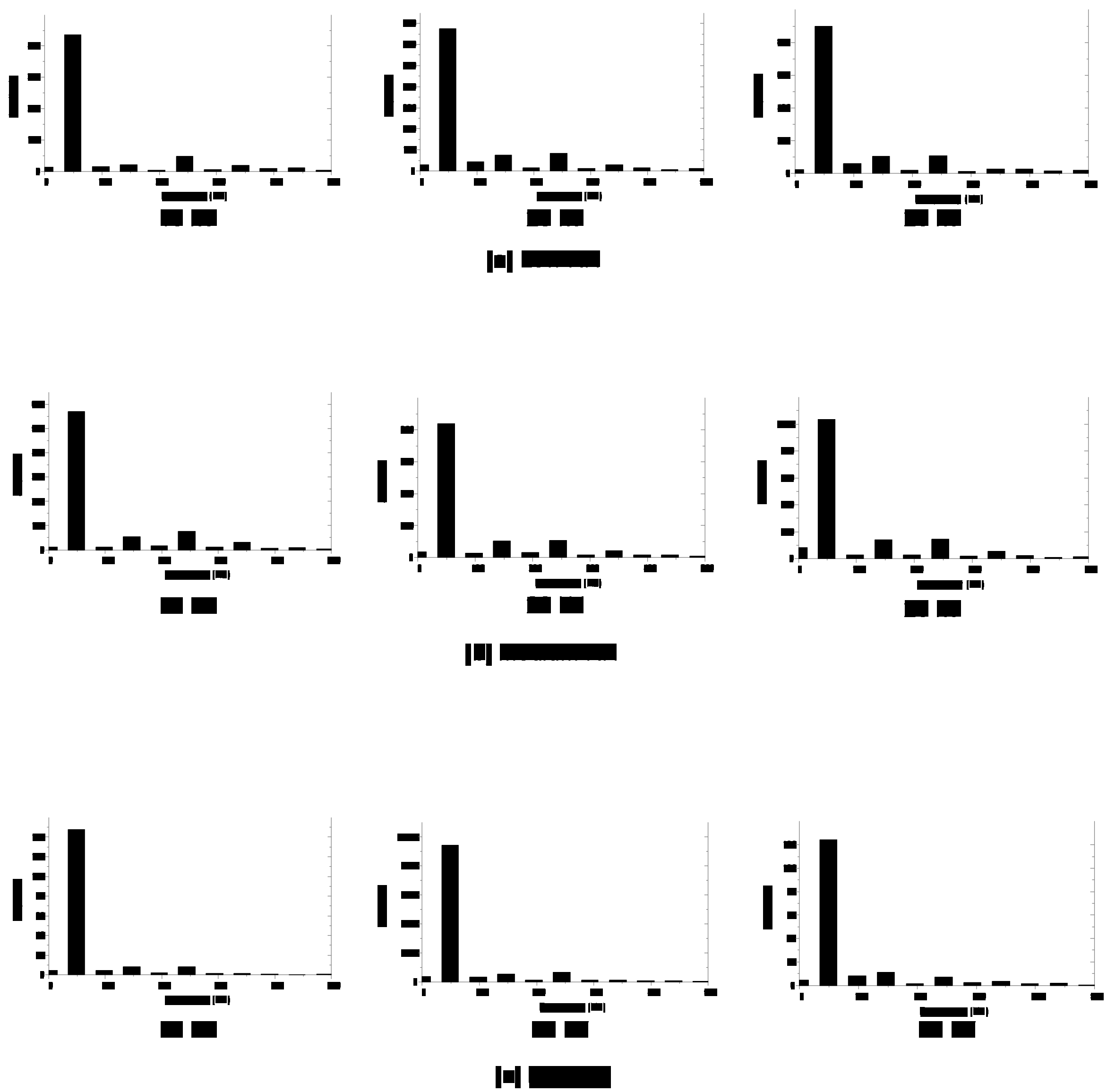
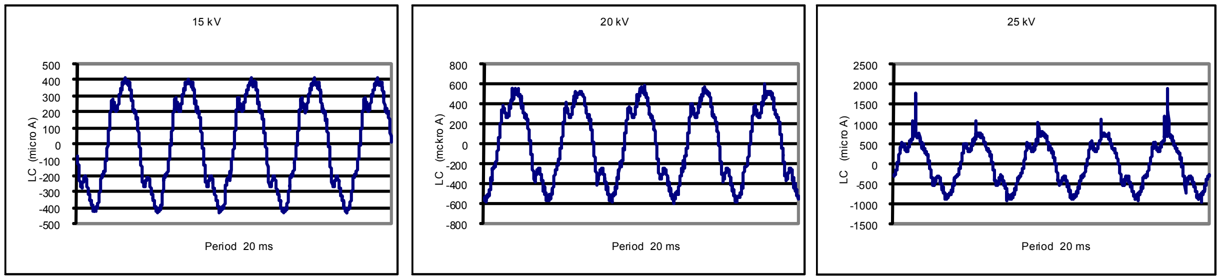
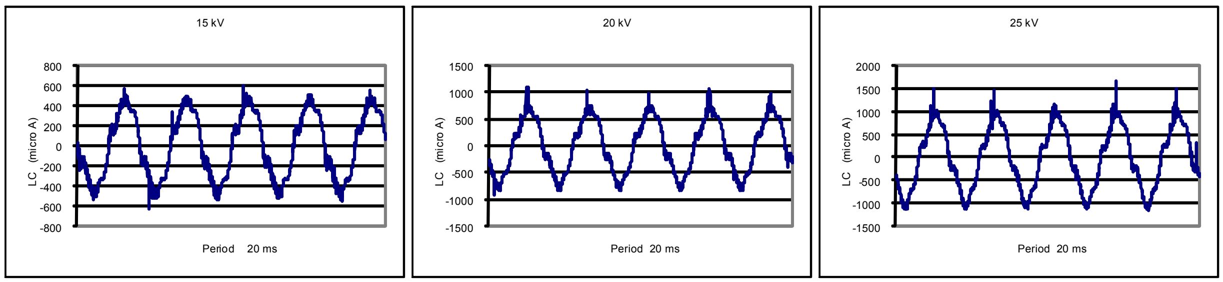


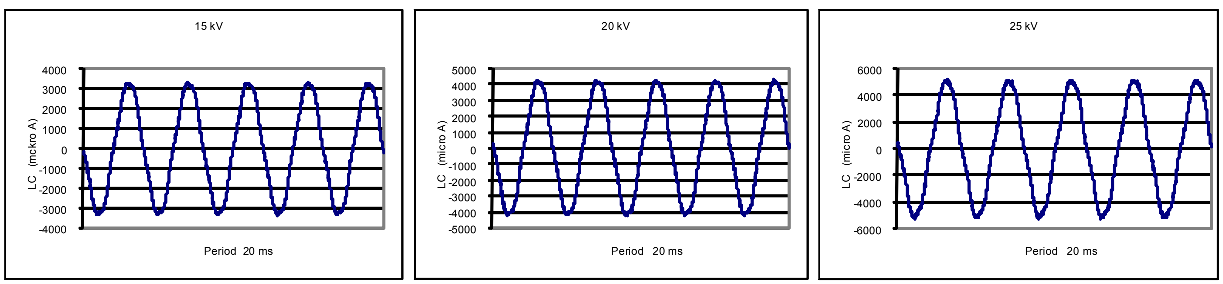
Fig. 11 Harmonic components of LC under fog of 1.2 mS/cm at low, medium and high RH at applied voltage of 15, 20 and 25 kV



(a) Conductivity 0. 6 mS/cm



(b) Conductivity 1.2mS/cm



(c) Conductivity 3.6mS/cm

Fig 12 LC waveforms under salt fog with various conductivity at low RH under fog with conductivity of 0.6, 1.2 and 2.4 mS/cm at applied voltage of 15 , 20 and 25 kV

Figure 12 shows the typical LC waveforms 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 significantly decreased with the salt fog conductivity resulting in smaller THD. 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 12(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 at low RH as depicted in figure 4(a). The electric discharges ceased under salt fog conductivity of 3.6 mS/cm as showed at figure 11(c). 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.

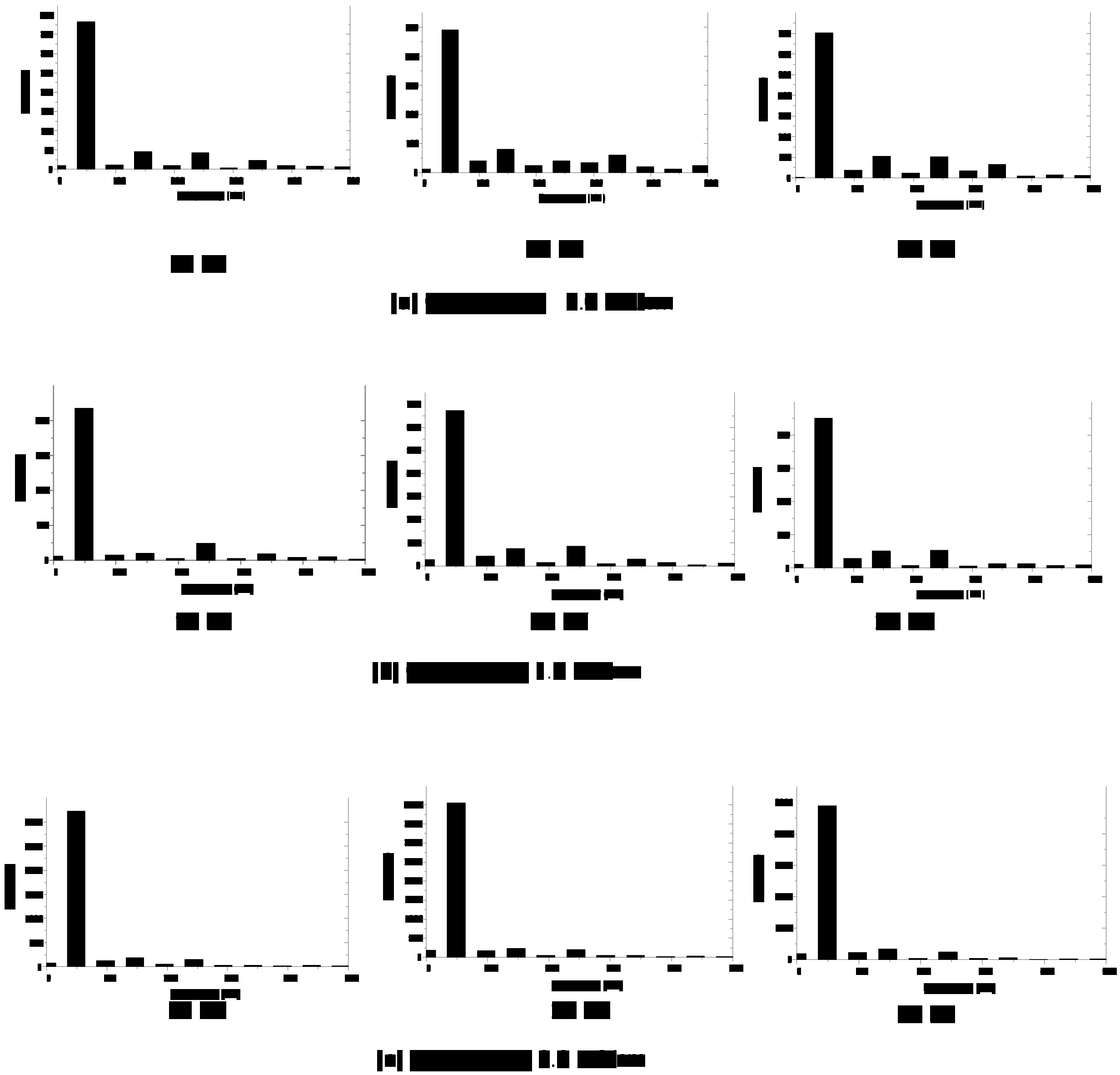


Fig. 13 Harmonic components of LC under fog of 1.2 mS/cm at low, medium and high RH at applied voltage of 15, 20 and 25 kV

Figure 13 shows the dependence of harmonic components of LC on salt fog conductivity and applied voltage. In general, at applied voltage in the range of 15 – 25 kV the harmonic components increase with applied voltage at all fog conductivity. At given applied voltage the harmonic components decrease with the increase of fog conductivity.

The fundamental component increases significantly. At applied voltage of 15 kV, the fundamental increases from 375 μA at fog conductivity of 0.6 mS/cm to 450 μA at fog conductivity of 2.4 mS/cm and to 3200 μA at fog conductivity of 3.6 mS/cm. At applied voltage of 25 kV, the fundamental component increases from 700 μA under 0.6 mS/cm to 900 μA under 1.2 mS/cm and to 4900 mA under fog conductivity of 3.6 mS/cm.

Figure 13 shows that the dominant harmonic components are 3^{rd} and 5^{th} except fog fog conductivity of 0.6 mS/cm, the LC waveforms contain the 7^{th} harmonic component with considerable large amplitude.

4 Conclusion

Leakage current and its waveform of ceramic insulator have been investigated under clean and salt fog conditions. The effects of humidity and fog conductivity on the LC magnitude and its waveform were elaborated. The experimental results indicated that under clean fog, LC magnitude almost linearly increased with applied voltage at low and medium RH. At high RH, LC magnitude drastically increased compared to those of low RH. At low RH the waveform distortion was observed at positive half cycles at applied voltage of higher than 20 kV. The LC waveform distortion drastically reduced at high RH and LC waveforms almost sinusoidal. The results also clearly indicated that at given applied voltage THD of LC decreased with RH.

At low RH the dominant harmonics number are 5^{th} , 3 rd and 7^{th} with relatively large amplitude while at medium and high RH the dominant harmonic components of the LC waveforms are 5^{th} and 3^{rd} with smaller amplitude compared to it fundamentals resulting in smaller THD.

Under fog condition, LC magnitude increase with fog conductivity. 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 while at high fog conductivity the oscillation behaviour of LC magnitude dependence on applied voltage was observed due to the wetting effect of sample surface by the fog and drying effect caused by the higher LC. The THD of leakage current under salt fog increased with the applied voltage.

LC amplitude increases with applied voltage and RH. At low RH positive discharges started to grow at applied voltage of about 20 kV. The appearance of positive discharges can be explain in term of the initial electrons which initiated the discharge process. At medium RH the positive discharges started to appear at applied voltage of about 25 kV. At high RH larger distortion of LC waveforms were observed at negative half cycles. The discharges contribute to the harmonic especially the 3^{rd} component. THD reduces with the increase of RH since the increase of harmonic components are smaller than fundamental.

LC waveforms distortion significantly decreased with the salt fog conductivity resulting in smaller THD. In general, at applied voltage in the range of 15 – 25 kV the harmonic components increase with applied voltage at all fog conductivity. At given applied voltage the harmonic components decrease with the increase of fog conductivity.

References:

[1] R.E.T. Sharma, Kapal. Technical Article: Polymeric Insulators. 2001

[2] R.S.Gorur, E.A. Cherney, J.T. Burnham,Outdoor Insulators, Ravi S. Gorur, Inc, 1999.

[3] T. Fujimura, The Evolution of Porcelain Insulator Technology in Japan, *Electrical Insulation Magazine,* Vol. 11, Issue 3, 1999, pp. 26-36

[4] R. Sudararajan, R.S. Gorur, Role of non-Soluble Contaminants on the Flashover Voltage of Porcelain Insulators, *IEEE Trans. DEI,* Vol. 3, Issue 1, 1998, pp. 113-118

[5] R.S. Gorur, D. Subramanian, Use of Surface Resistance for Asssessing Vulnerability of HV Outdoor Insulators to Contamination Flashover, *Annual Report, Conf. Electrical Insulation and Dielectric Phenomena,* 2003, pp. 406-409

[6] S. Venkataraman, R.S. Gorur, Flashover Voltage Prediction of Outdoor Insulators Subdjected to Road Salt Contamination, *Annual Report, Conf. Electrical Insulation and Dielectric Phenomena,* 2005, pp. 293-296

[7] F. Amarh, G. Karady, R. Sundararajan, Linear Stochastic Analysis of Polluted Insulator leakage Current, *IEEE Trans on Power Delivery,* Vol. 17, No. 4, 2002, pp. 1063-1069

[8] Jeong Ho Kim, Woo Chang Song, Jae Hyung Lee, Yong Kwan Park, Han Goo Cho, Yeong Sik Yoo, Kea Joon Yang, "Leakage Current Monitoring and Outdoor Degradation of SIR", *IEEE Trans. on Dielectrics and Electrical Insulation,* Vol. 8 No. 6, pp. 1108-1115, Dec. 2001.

[9] E. A. Cherney, B. Biglar, S. Jayaram, Salt Fog Testing of Polymer Housed Surge Arresters, *IEEE Trans. Power Delivery*, Vol. 10, No. 2, 2001, pp. 252-258.

[10] Y. Mizuo, H. Kusada, K. Naito, Effect of Climatic Conditions on Contamination Flashover Voltage of Insulators, *IEEE Trans. DEI*, Vol. 4 No. 3, 1997, pp. 286-289.

[11] O. Fujii, K. Hidaka, Y. Mizuno, K. Naito, Examination of Humidity Correction method Assessing Flashover Voltage of Insulators, *WSEAS Trans. On Circuits and Systems*, Issue 9, Vol. 4, 2005, pp. 1158-1165.

[12] K. Siderakis, D. Agoris, P. Eleftheria, E. Thalassinakis, Investigation of leakage Current on High Voltage Insulators- Field

Measurements, *WSEAS Trans. onCircuits and Systems*, Issue 5, Vol. 3, 2004, pp. 1188-1191

[13] K. Naito, Y. Mizuno, W. Naganawa, A Study on Probabilistic Assessment of Contamination Flashover of High Voltage Insulators, *IEEE Trans. Power Delivery*, Vol. 10, No. 3, 1995, pp. 1378-1383.

[14] Ayman H. El Hag, A New Technique to Detect Dry Band Arcing, *IEEE Trans on Power Delivery*, Vol. 20, No. 2, 2005, pp. 1202-1203

[15] Suda, T., Frequency Characteristics of Leakage Current Waveforms of a String of Suspension Insulators. *IEEE Transactions on Power Delivery*, Vol. 20, No. 1, 2005, pp 481-487

[16] A.A. Gialketsi, V.T. Kontargyri, I.F. Gonos, I.A. Stathopulos, Estimation of the Flashover Voltage on Insulator using Artificial Neural Networks, *WSEAS Trans. On Circuits and Systems*, Issue 5, Vol. 4, 2005, pp. 514-518.

[17] M. Otsubo, T. Hashiguchi, C. Honda, O. Takenouchi, Evaluation of Insulation Performance of Polymeric Surface Using a Novel Separation Technique of Leakage Current, *IEEE Trans.s on Dielectrics and Electrical Insulation*, Vol. 10, No. 6, 2003, pp. 1053-1060

[18] Suwarno, leakage Current Waveforms of Outdoor Polymeric Insulators and Possibility of Appalication for Diagnostics of Insulator Conditions, *KIEE Journal of Electrical Engineering and Technology*, Vol. 1, pp. 114-119, 2006.

[19] E. Fontana, S. Oliviera, F. Monte de Melo, R. Lima, J. Filho, Novel Sensor System for Leakage Current Detection on Insulator Strings of Overhead Transmission Lines, *IEEE Trans. Power Delivery*, Vol. 21, No. 4, 2006, pp. 2064-2070.

[20] Suwarno, S.K. Ardianto, Study on Leakage Current, Hydrophobicity and Flashover Characteristics of Epoxy Resin for Outdoor Insulators, *WSEAS Trans.on Power System*, Issue 8, Vol. 1, 2006, pp. 1499-1506.

[21] AH El Hag , S.H. Jayaram, E.A. Cherney, Fundamental and low Freq. components of LC as a diagnostic Tool to Study Aging of RTV and HTV SIR in Salt-Fog, *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol. 10, No. 1, 2003, pp. 128- 136, Feb. 2003.