Electrical Equivalent Circuit of Ceramic Insulators with RTV Silicone Rubber Coating and Computer Simulation of Leakage Currents

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Abstract: - During operation, high voltage insulators may severe a certain degree of pollution which may reduce their performances. RTV silicone rubber coating was proposed to improve the performances of outdoor ceramic insulators especially in highly polluted areas. This paper reports experimental results on the leakage current (LC) on RTV silicone rubber-coated ceramic insulators. The samples used were 20 kV post-pin ceramic insulators. The samples were coated by RTV silicone rubber from Dow Corning. There were 2 kinds of samples. The first one is clean and the second one is kaolin-salt polluted. The sample was put in a climate chamber under certain condition of fog. AC voltage of 50 Hz was applied to the sample and the leakage current flowed on the insulator surface was measured by measuring the voltage across a series resistance using a Digital Oscilloscope with sampling rate of 1 GS/s. The digital data was transferred to a personal computer trough a GPIB for further analysis. The experimental results showed that LC waveforms of RTV-coated insulators in general are distorted from sinusoidal applied voltage. The LC waveforms are symmetrical for positive and negative half cycles and no flashover was observed for applied voltage up to 60 kV. The THD as well as magnitude of the LC increased with applied voltage for both clean and kaolin-salt polluted samples.. From the experimental results, electrical equivalent circuit models are proposed. Using the proposed model computer simulation of leakage current waveforms was done using APT/EMTP under various conditions and applied voltages. The simulation was done by choosing appropriate values of capacitances, non linearity and arc models. The simulated LC waveforms were compared to those obtained from experiment. The similarity of the LC waveforms was determined by comparing the LC magnitude, THD, dominant harmonic components and symmetry. The results indicated that simulated leakage current waveforms were similar to those obtained from experiment. These revealed the validity of the proposed model.

Key-Words: - ceramic insulator, RTV coating, equivalent circuit, leakage current, harmonics, computer simulation

1 Introduction

Ceramic insulators are widely used in power system since long time ago. At present time ceramic insulators are still widely being used. Ceramic insulator has good mechanical and electrical properties and less expensive. Nevertheless, as outdoor insulator it has some weaknesses especially under certain environmental factors such as humidity, rainy season and pollution which may reduce their surface resistance. The reduction of surface resistance may enhance the leakage current(LC) to flow on the surface [1-2]. Leakage current with large magnitude flow on the surface for long period may cause degradation of the insulator surface [3]. Leakage current waveforms on outdoor insulator surfaces have been measured and reported[4-6]. It was also reported that the LC waveforms were useful for diagnosis of insulator condition[7-9]. Application of Room Temperature Vulcanized (RTV) Silicone Rubber on ceramic insulator surface has been proposed to improve the performances of ceramic insulators[10-12]. They showed great improvements of the insulators caused by the RTV coatings. However, there is no report concerning the electrical equivalent circuit models of ceramic insulators derived from experimental leakage current waveforms and using the model to conduct a computer simulation of the leakage current.

This paper reports the experimental results on the LC waveforms of RTV coated ceramic insulators under clean fog condition. This paper also proposes electrical equivalent circuit models of ceramic insulators derived from experimental leakage current waveforms. Based on the proposed model , computer simulation of LC was done using Alternative Transient Program/ Electromagnetic transient Program (ATP/EMTP) software package. The simulation results are presented in this paper. Comparison between experimental and simulated

LC waveforms is discussed in this paper based on the similarity of the LC waveforms indicated by their magnitude, total harmonic distortion (THD), dominant harmonic components and positive-negative symmetrical behaviour.

2 Experiment

2.1. Sample

The samples used in this experiment were post-pin ceramic outdoor insulators with nominal voltage of 20 kV which widely used in Indonesian electric power system. The insulators were coated with RTV silicone rubber made by Dow Corning using a high pressure nozzle with a thickness of about 0.3 mm. The pictures of the samples before and after RTV application are shown in figure 1.

(a) (b)

Figure 1. Post-pin ceramic insulator samples
(a) Non-coated (b) RTV-coated

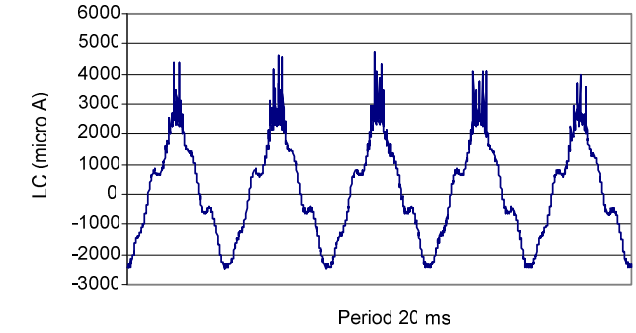
A test chamber made from aluminium panel with size of 90 cm x 90 cm x 120 cm was used to simulate fog exposed to the samples. The front opening of the test chamber was made from acrylic to facilitate the observation of the sample surface. Artificial pollution was applied in accordance with IEC Standard No. 507 1991[13]. Kaolin of 40 g was used in every 1 lt water and NaCl was added to the solution to get the desirable conductivity.

2.2 Leakage Current measurement.

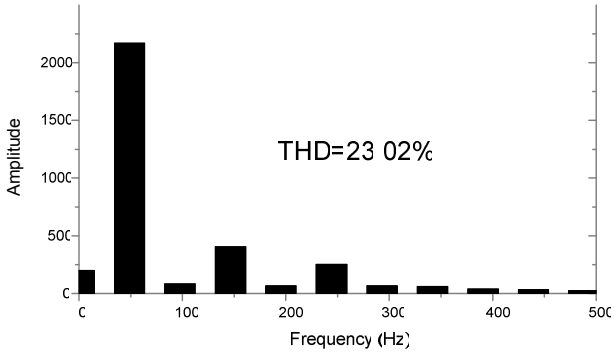
An AC high voltage of 50 Hz was applied to the insulators. The AC voltage was applied on the upper side of the insulators. The leakage current flowed on the insulator surface was measured by measuring the voltage across a series resistance using a Digital Oscilloscope with digitizer of 8 bit, bandwidth 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).

3. Modelling and Electrical equivalent circuit of outdoor insulator

Figure 2 shows typical LC waveform (a) and the corresponding harmonic components (b) for polluted non-coated ceramic insulator[14].



(a)



(b)

Figure 2. typical LC waveform (a) and the corresponding harmonic components (b).

It is seen that LC waveform is distorted from sinusoidal due to the appearance of harmonic components. THD of about 23 % indicated a strong distortion of the LC from its sinusoidal AC voltage. In order to well explain the insulator behaviour, electrical equivalent circuits are proposed based on the experimental leakage current waveforms. The proposed equivalent circuit of outdoor insulator is realized using ATPdraw/EMTP [15]. There are 3 kinds of electrical equivalent circuit models. The basic model was proposed in[16].

Model I

Figure 3 shows the basic electrical equivalent circuit of outdoor insulator (model I). It consists of capacitor(s) and nonlinear resistor(s). Those element purely depend on the insulator surface characteristics and the applied voltages. The levels of insulator leakage current were in order μA (microampere). Model I, in general can be used to represent clean insulator at low or moderate applied voltage.

Model II

Figure 4 shows a proposed equivalent circuit of outdoor insulator with discharges on the sample surface (model II). It consists of capacitor(s), non-linear resistor(s), and arcing circuit(s). The capacitor and nonlinear resistor connected in parallel, while the arcing circuit connected series with the nonlinear resistor. The presented circuit is a modification of precious one by adding arc model in parallel, as representation of discharge condition. Arc model is used to simulate surface discharges by controlling the spark voltage of arc model switch. This equivalent circuit can be used to simulate leakage current with symmetrical waveforms at both polarity (positive and negative cycle have the same leakage current waveforms).

Model III

Figure 5 shows a proposed equivalent circuit of outdoor insulator with discharges on the sample surface and additional circuit to simulate the asymmetrical positive and negative half cycle of the leakage current waveforms (model III). The asymmetrical behaviour of LC indicated different response of the insulator surface during positive and negative half cycles. These conditions can be simulated by adding diode. The idea is to divide the circuit into two parts. The upper part of equivalent circuit is to simulate the positive half cycle while the lower part is to simulate the negative half cycle. To simulate the distorted sinusoidal LC waveforms due to presence of surface discharges, additional arc model is required.

The 3 models in general can be used to represent outdoor insulator under various condition. Using the models, computer simulation of LC waveforms was done using ATP/EMTP.

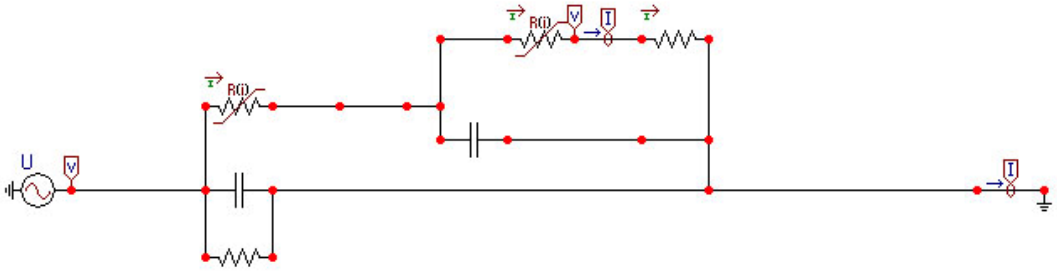


Figure 3. Basic electrical equivalent circuit of outdoor insulator with non-linear resistance (model I)

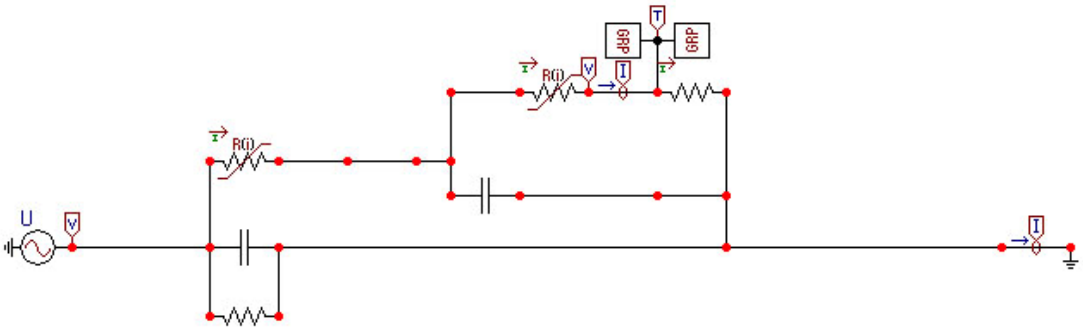


Figure 4: The proposed electrical equivalent circuit of outdoor insulator with symmetrical LC waveforms and discharge (Model II)

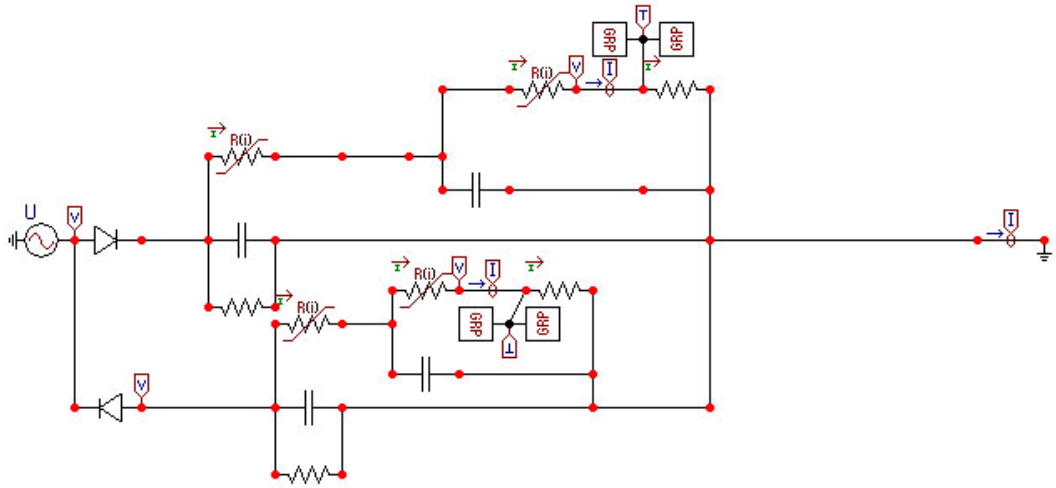


Figure 5. The proposed electrical equivalent circuit of outdoor insulator with asymmetrical LC waveforms and discharge (Model III)

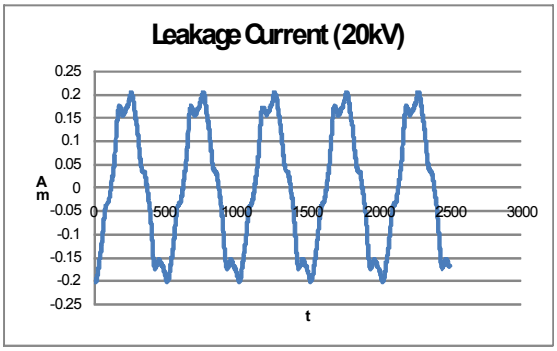
4. Experimental and Computer Simulation Results

4.1 Leakage Current waveforms for clean sample under clean fog condition

Figure 6 shows typical experimental leakage current waveforms for clean RTV coated insulator under clean fog at applied voltage of (a) 20 kV, (b) 40 kV and (c) 60 kV. The LC waveforms are symmetrical at positive and negative half cycles. The amplitude of the LC increased almost linearly from about 0.2 mA with THD of 14.2 % at 20 kV to about 0.4 mA with THD of 18.34 % at applied voltage of 40 kV and 0.6 mA with THD of 21.63 at applied voltage of 60 kV. The LC waveforms were slightly distorted from their sinusoidal due to the presence of harmonic components especially 5^{th} component. The results also showed that THD of LC increased with the applied voltage at the present conditions. However, no flashover was observed up to 60 kV applied voltage. This result indicated that RTV coating greatly increased the flashover of outdoor insulators since non-coated insulators typically flashover at applied voltage of less than 50 kV.

Figure 7 shows the typical computer simulated leakage currents with the same applied voltage. Model II was used to simulate the LC. The resistance value is assumed to be 4421 MΩ. This value is chosen in order to obtain the leakage current of the order of microamperes. The LC waveforms were obtained by choosing combination of the three parameters in the electrical equivalent circuit for each applied voltage as tabulated in table 1. Table 1 shows the change of the non-linear characteristics for each voltage applied. At 20 kV, short burst of leakage current was observed. The LC waveforms were slightly changed at 40 kV and 60 kV.

The waveforms are similar to the typical leakage current waveforms in fig 6. Simulation results shows that at applied voltage of 20 kV the LC amplitude was about 0.2 mA and the THD 13.2%. At applied voltage of 40kV the amplitude of LC was about 0.4 mA with THD of 18.2 % while at applied voltage of 60kV the amplitude of LC was about 0.6 mA with THD of 21.27 %.



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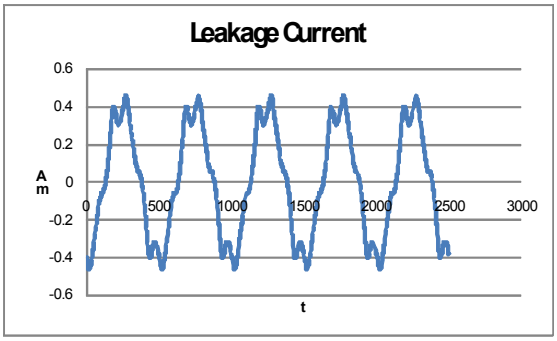

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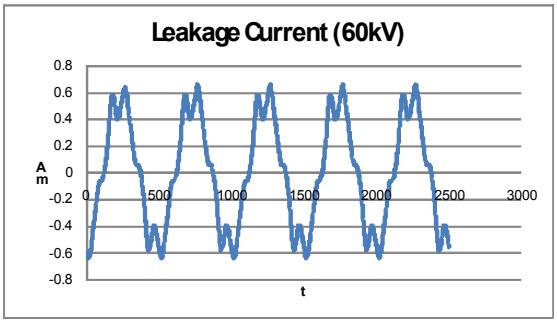

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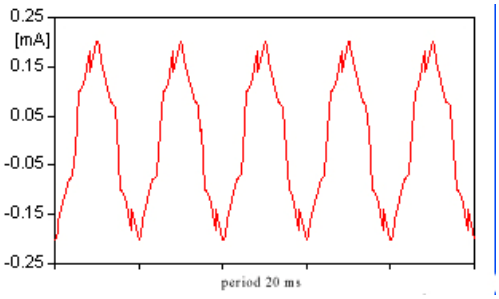
Figure 6: Experimental LC waveforms for clean samples under clean fog at (a) 20 kV, (b) 40 kV and (c) 60 kV



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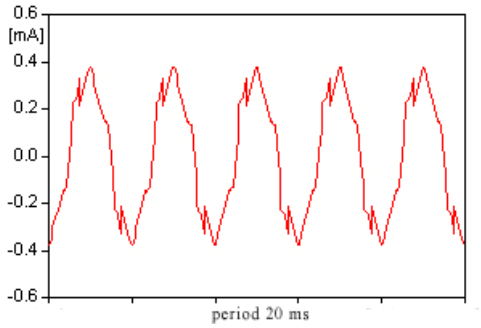

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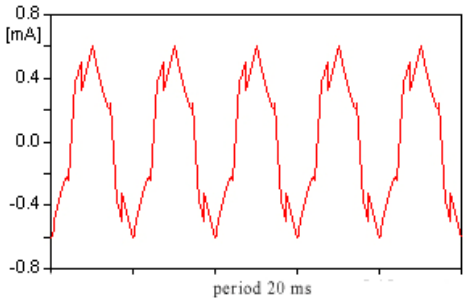


(c)

Figure 7: Computer-simulated LC waveforms for clean samples under clean fog at (a) 20 kV, (b) 40 kV and (c) 60 kV

Table 1. Equivalent Circuit Parameters for clean samples under clean fog

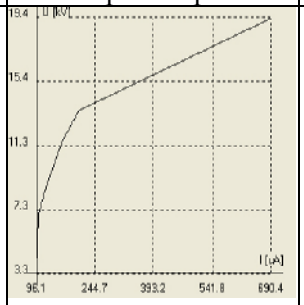
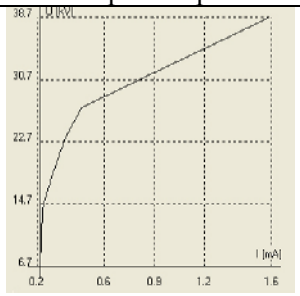
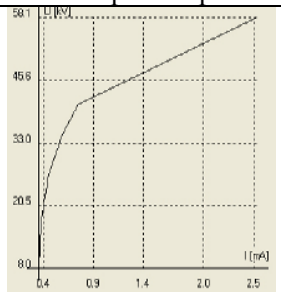
Parameters	**20 kV**	**40 kV**	**60 kV**
Capacitance	0.2 pF & 5 pF	0.11 pF & 5 pF	0.11 pF & 5 pF
Non-linear characteristics			
Arc model	-Negative half cycle: 1 arc model -Positive half cycle: 1 arc model -Both have same parameter	-Negative half cycle: 2 arc model -Positive half cycle: 2 arc model -Both have same parameters	-Negative half cycle: 2 arc model -Positive half cycle: 2 arc model -Both have same parameters

Table 2. Comparison between experimental and computer-simulated LC waveforms for clean sample under clean fog

	Experimen-tal LC	**Simulated LC**
20 kV		
- LC magnitude	0.2 mA	-0.2 mA
-Dominant harmonic	5	5
- THD	14.2 %	13.2 %
- symmetry	symmetrical	symmetrical
40 kV		
- LC magnitude	0.4 mA	0.4 mA
-Dominant harmonic	5	5
- THD	18.34 %	18.2%
-symmetry	symmetrical	symmetrical
60 kV		
- LC magnitude	0.6 mA	0.6 mA
-Dominant harmonic	5	5
- THD	21.63 %	21.27 %
- symmetry	symmetrical	symmetrical

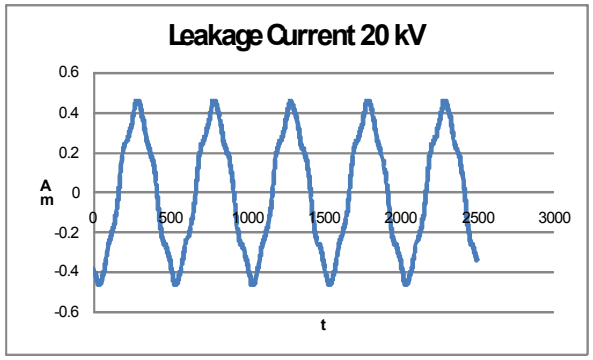
The similarity of the experimental and computer-simulated leakage current waveforms was assessed using 4 kinds of parameters. They are LC magnitude, dominant harmonic component, total harmonic distortion and symmetrical behaviour of the LC waveforms. The combination of the 4 parameters represent the shape of the LC waveform. The comparison of the parameters between experimental and computer-simulated LC waveforms are shown in table 2. Table 2 indicates that computer-simulated LC waveforms have great similarity with those obtained from experiment. These results show the validity of the proposed model.

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

Figure 8 shows LC waveforms for kaolin-salt polluted at conductivity of 3.6 mS/cm under clean fog for applied voltage of 20, 40 and 60 kV. All LC waveforms are symmetrical (i.e. similar distortion at positive and negative half cycles). Leakage current magnitude was slightly higher than those from clean sample. At applied voltage of 20 kV the amplitude was about 0.43 mA with THD of 9.51%. At applied voltage of 40 kV the amplitude was 1 mA and THD was 14.31 % while for 60 kV the amplitude was 1.2 mA and THD 17.32 %. These results showed that both LC magnitude as well as THD increase with the applied voltage. The increase of THD with the applied voltage can be seen clearly by the increase of the distortion of LC waveforms from 20 kV to 40 kV and 60 kV.

Compared to those LC from clean sample, the LC magnitude from kaolin-salt polluted samples was slightly higher but the THD was smaller. For non-coated ceramic insulator, for the same experimental condition, the leakage current magnitude was much larger. This is because the RTV silicone rubber coating suppressed the magnitude of leakage current, the harmonic content of leakage current and increased the flashover voltage under various artificially - simulated pollution. The low LC corresponds with high surface resistance which indicates high quality of insulator. The increase of surface resistance of the sample was caused by the application of RTV coating.

Figure 9 shows simulated LC waveforms at applied voltage of 20 , 40 and 60 kV respectively. The LC waveforms were obtained by utilizing model II and choosing the parameters values as tabulated in table 3. Model II was chosen in the simulation since the LC waveforms were symmetrical for this condition. The capacitances and V-I characteristics were similar for all applied voltages. However, arc model number increased with applied voltage in order to generate a higher distortion in the LC waveforms. The electrical equivalent circuit parameters are similar for positive and negative half cycles in order to generate symmetrical LC waveforms.



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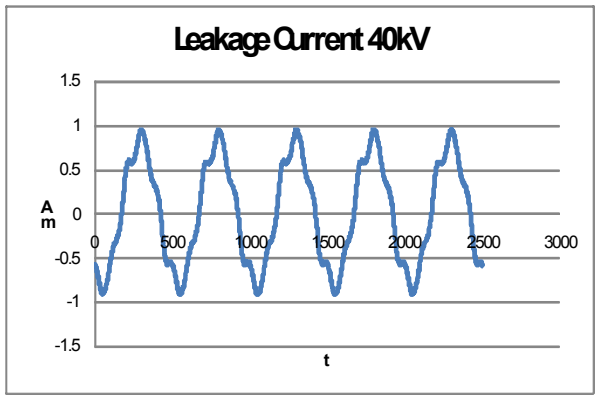

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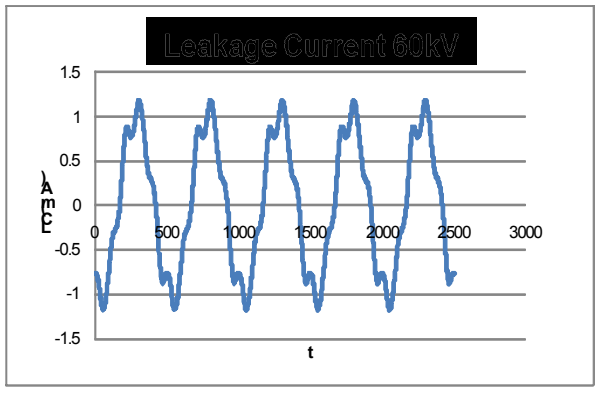
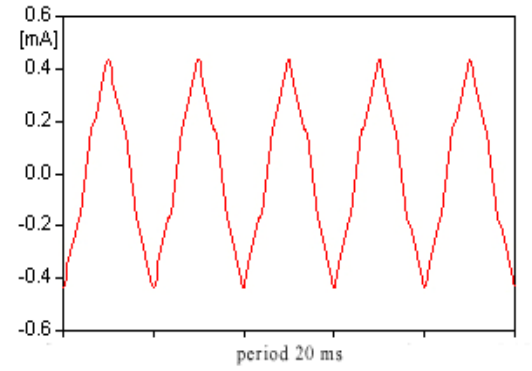


(c)

Figure 8: Typical LC waveforms for kaolin-salt polluted sample under clean fog at (a) 5 kV (b) 10 kV and (c) 20 kV



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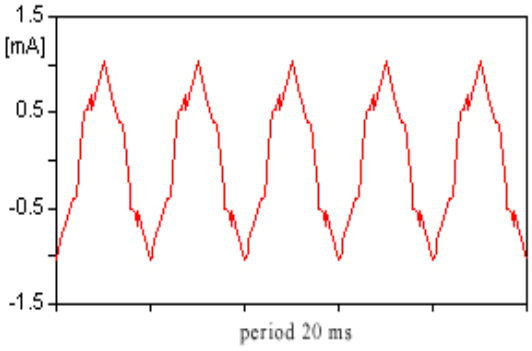

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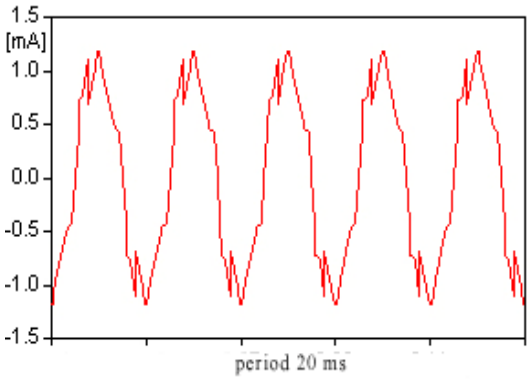


(c)

Figure 9: LC waveforms of the proposed equivalent circuit for kaolin-salt polluted sample under clean fog at (a) 5 kV, (b) 10 kV and (c) 20 kV

The simulated LC waveforms and magnitude are similar to the leakage current waveforms from experimental results in figure 8. Amplitude of LC increased with the applied voltage from 0.4 mA at 20 kV to almost 1.1 mA at 60 kV. The increase of leakage current flowed can be done by enlarge the non-linear V-I characteristic magnitude

The THD from the simulated LC waveforms were pretty much the same as the experiment. At 20 kV, the LC waveforms slightly distorted with THD of 9.51 %. The distortion kept increased with the applied voltage. At 40 kV the LC waveform from simulation had THD of % meanwhile the experiment is about 14.31%. The THD value of the leakage current waveforms is depend on the non-linear resistance characteristic, the number of arc model, and capacitance value.

All simulated LC waveforms are symmetrical. For applied voltage of 20 and 40 kV, the dominant harmonic component is 5^{th} while for 60 kV applied voltage the dominant harmonic components are 5^{th} and 3^{rd}. The simulation results indicated that model II is suitable to be used for simulating leakage current on the kaolin-salt polluted RTV coated insulators. The proposed equivalent circuit to simulate insulator kaolin-salt polluted sample under clean fog condition is similar to the equivalent circuit for clean sample.

Table 4 shows comparison between the characteristics of LC waveforms from clean samples and kaolin-salt polluted samples. The values of LC magnitude, total harmonic distortion (THD), dominant harmonic component and symmetry were used to evaluate the similarity between the experimental and the simulated leakage current waveforms. From the table it can be seen that the values are similar. The results indicated that experimental LC waveforms were similar to those simulated by utilizing proposed model II using ATP/EMTP program.

Table 3. Equivalent Circuit Parameters for kaolin-salt polluted sample under clean fog

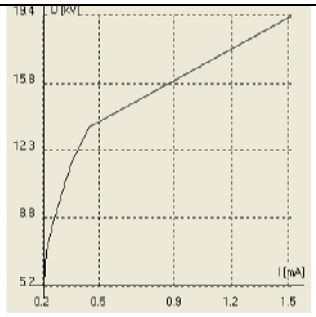
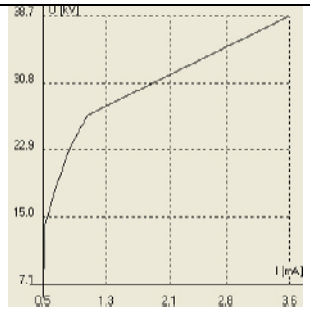
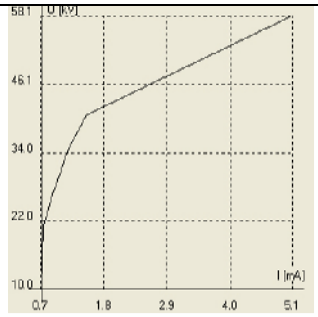
Parameters	**20 kV**	**40 kV**	**60 kV**
Capacitance	0.1 pF & 0.5 pF	0.1 pF & 0.5 pF	0.1 pF & 0.5 pF
Non-linear characteristcs			
Arc model	-Negative half cycle: 1 arc model Positive half cycle: 1 arc model	-Negative half cycle: 2 arc model -Positive half cycle: 2 arc model	-Negative half cycle: 2 arc model -Positive half cycle: 2 arc model

Table 4 Comparison between experimental and computer-simulated LC waveforms for kaolin-salt polluted sample under clean fog

	Experimental LC	**Simulated LC**
20 kV		
- LC magnitude -Dominant harmonic - THD - symmetry	0.43 mA 5 9.51 % symmetrical	0.43 mA 5 9.55 % symmetrical
40 kV		
- LC magnitude -Dominant harmonic - THD - symmetry	1 mA 5 14.31 % symmetrical	1 mA 5 14.6 % symmetrical
60 kV		
- LC magnitude -Dominant harmonic - THD - symmetry	1.2 mA 5, 3 17.32 % symmetrical	1.2 mA 5, 3 17.82 % symmetrical

5. Conclusion

We have investigated leakage current waveforms from RTV-coated ceramic insulators. From these experimental results following conclusions can be drawn. LC waveforms of RTV-coated insulators in general are distorted from sinusoidal applied voltage. The LC waveforms are symmetrical for positive and negative half cycles and no flashover was observed for applied voltage up to 60 kV. The THD as well as magnitude of the LC increased with applied voltage for both clean and kaolin-salt polluted samples. Particularly for kaolin-salt polluted samples, the LC magnitude was much lower than non-coated samples.

From the experimental results, electrical equivalent circuit models are proposed. Using the proposed model computer simulation of leakage current waveforms was done using APT/EMTP under various conditions and applied voltages.

The simulation was done by choosing appropriate values of capacitances, non linearity and arc models. The simulated LC waveforms

were compared to those obtained from experiment. The similarity of the LC waveforms was determined by comparing the LC magnitude, THD, dominant harmonic components and symmetry. The results indicated that simulated leakage current waveforms were similar to those obtained from experiment. These revealed the validity of the proposed model.

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