The Study on Leakage Current Characteristics and Electrical Properties of Uncoated Ceramic, RTV Silicon Rubber Coated Ceramic, and Semiconducting Glazed Outdoor Insulators

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Abstract: Insulator is one of the most important equipments in an electric power system. Failure of insulator may interrupt the electric energy delivery. The system reliability is greatly affected by the performance of the insulator. Therefore, ensuring the high performance of insulators has become indispensable. There are many methods to increase the performance of the outdoor insulator that are exposed to environmental conditions, such as temperature, humidity, and the presence of pollutants. Among the methods, applying room temperature vulcanized (RTV) silicone rubber coating and semiconducting glaze on the insulator surface are often used. This paper discusses the performance of uncoated ceramic insulator, RTV silicone rubber coated insulator, and semiconducting glazed insulator (SGI), as well as the comparison result among them. The performance is indicated by measuring leakage current (LC), surface temperature, and hydrophobicity. In addition, computer simulation on outdoor insulators using ATPDraw software is also conducted for LC waveform resulted by each type of insulator in order to study the electrical properties of each insulator. In the simulation, an outdoor insulator is represented by an electrical circuit model consisting of capacitors, nonlinear resistors, and number of arc models. AC voltage is applied to the model and the current is monitored. Hence, some key parameters of LC waveform are required to determine the similarity between measured LC waveform and simulated LC waveform, which are LC magnitude, Total Harmonic Distortion (THD), and dominant harmonic number. Experiment results showed that LC waveform and magnitude are strongly affected by the applied voltage, environmental condition, and the condition of the insulator surface itself. Specifically for SGI, LC waveforms are generally similar with the sinusoidal applied voltage. The LC waveforms are also symmetrical for positive and negative half cycles and no flashover was observed for applied voltage up to 40 kV. The hydrophobicity of insulator surface decreases after the experiments, with the pollutant presence and salt fog condition cause higher reduction compared to the clean samples and in clean fog environment. SGI has higher hydrophobicity compared to ceramic insulator. Field-aged RTV silicone rubber coated insulator shows higher hydrophobicity compared to field-aged uncoated ceramic insulator. At the end of the 6th year, the difference of contact angle between the two types of insulators can reach up to 50 – 60°. This proves that less pollutant is likely to stick on coated insulators for long time.

The LC waveforms obtained from all experiments both in the laboratory or in the field have been successfully simulated through computer simulation. The simulation indicated that SGI is more capacitive than normal ceramic insulator and has lower values of piecewise resistance of the nonlinear resistance, resulting LC flow on the insulator surface also much higher. Despite the increased applied voltage, SGI shows very little discharge on its LC waveform, hence it has only 2 arc models, while at higher applied voltage, ceramic insulator has many discharges occur along the LC waveform, hence the arc models for this insulator can reach up to 9 arc models.

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1. Introduction

Failed insulators can disturb the electrical power distribution and cause greater damage to the whole power transmission system. Many failed insulator cases happened to outdoor insulators, where environmental elements, such as humidity, temperature, and pollution can affect the performance of insulators. On polluted insulator surface, flashover is initiated by the presence of conductive layer that is formed and causing increased leakage current, especially in humid atmosphere.

Ceramic insulators are beneficial as outdoor insulators to be installed in such industrial area or coastal area. Apart from being economical, it has good electrical properties, such as thermal resistance and resistance to surface degradation (corrosion), as well as good mechanical properties [1]-[4]. In addition, this ceramic insulator has a glass-like layer that allows the insulator to perform self-cleaning process with the help of rain water. In Indonesia, especially in Bali, ceramic insulators have been the most widely used type of insulators for transmission and distribution systems for a long time. Nevertheless, with the constant stress along the years, surface resistance of outdoor ceramic insulators can easily decrease due to the environmental factors, most of all is the pollutant and eventually leads to complete failure [4].

Many alternative solutions have been offered to overcome this situation, such as applying RTV silicone rubber coating or semiconducting glazed layer on the insulator surface. RTV silicone rubber coating has been proven that it can reduce LC magnitude. Hence, the aging effect on insulators performance can be reduced. Another type of coating material, semiconducting glazed insulator (SGI) has been proven to have higher flashover voltages compared to normal glazed porcelain or glass insulator, mainly due to the surface drying effect by LC flow on the glazed layer [5]. The special glazing can prevent dry band formation and therefore dry band arcing which often causes the flashover of the insulator [6]. High temperature of insulator surface that is caused from leakage current on semiconducting glazed layer prevent condensation and humidity effect [7].

This paper discusses the experiment results of ceramic insulators and SGI under artificial condition in laboratory that is made resembling to environmental condition in Bali. Another experiment result which is carried on at the field of coastal area at Pangandaran (southern of West Java island) is also reported, consisting of LC measurement result on field-aged RTV silicone rubber coated and uncoated insulators, including LC magnitude, Total Harmonic Distortion (THD), and dominant harmonic of each waveform, in which these parameters become the key for further simulation.

2. Experiment and Simulation

A. Laboratory Test for Ceramic and Semiconducting Glazed Insulators(SGI)

Both ceramic insulator and SGI used in this research are suspension-type insulators that have been used in Indonesia 150 kV transmission lines. For each type, there are two samples used in this experiment, where one has clean surface and the other one has polluted surface as shown in = 1.

(a) Clean surface – Ceramic insulator

(b) Polluted surface – Ceramic insulator

(c) Clean surface – SGI

(d) Polluted surface – SGI

Figure 1. Samples Used for Laboratory Testing

These samples are subjected to tests under artificial tropical condition, along with clean fog and salt fog (of 20 mS conductivity) condition in a chamber with size of (1.2 x 1.2 x 1.5) m, according to IEC 60-1 (1989) [9]. The temperature control is installed in the chamber while the humidity is adjusted through an external humidifier. Artificial pollution was applied according to IEC 507, where 40 g of kaolin was dissolved in 1 litre of water resulting pollutant solutions with conductivity of 3,6 mS. Then 12g/L of NaCl was added to the solution to get the varied desirable value of conductivity. For test, a 50 Hz AC voltage with range 5 to 20 kV was applied to the sample under various environmental conditions as shown in Table 1.

Table 1. Environmental Condition for Each Tests

No.	Sample	Chamber Condition	Room Temperature	Room Humidity	Applied Voltage
(a)	Clean	Clean Fog	28 – 32 °C	90 – 95 %	5 – 40 kV
(b)	Polluted (Kaolin-Salt 5 mS)				
(c)	Clean	Salt Fog (20 mS)			
(d)	Polluted (Kaolin-Salt 5 mS)				

The test is carried through an experimental circuit as shown in Figure 2.

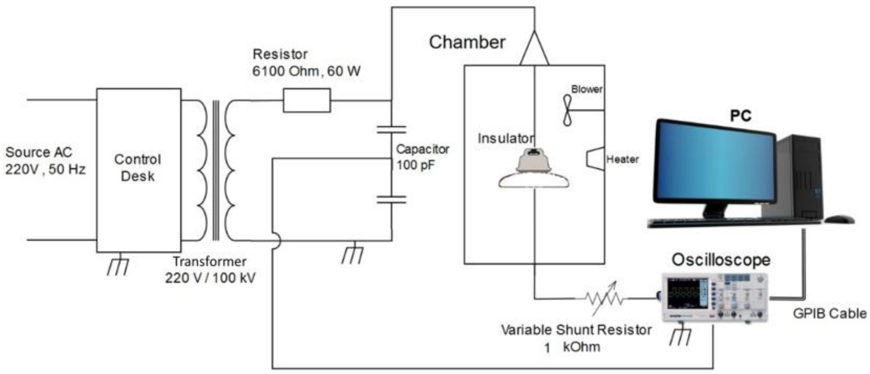


Figure 2. Experimental Setup Circuit for Laboratory Test

The data measured from each tests are leakage current and surface temperature. There are four parameters that were observed from leakage current output data which are LC magnitude, THD value, dominant harmonic, and the waveform itself. As for surface temperature, it was measured and captured using FLIR camera.

B. LC Measurement for Field-Aged RTV Silicone Rubber Coated Insulator

Another experiment that was carried in the field are LC measurement comparison of uncoated and RTV silicone rubber coated insulators. The experiment was performed on 12 post-pin type outdoor ceramic insulators that have been installed in a substation in Pangandaran coastal area since 2011. The LC measurements were taken every 1-2 years until the last measurement that was in July 2017. Half of the insulators are coated with RTV silicone rubber and the others are not, as shown in Figure 3.

(a) (b) (c)

Figure 3. Samples for Field Experiment: (a) Uncoated Insulator, (b) Coated Insulator, and (c) Installation of Uncoated & Coated Insulators in field

An 11 kV rms voltage supply was constantly applied to the insulators. Each measurement was carried out in the afternoon where the temperature was the highest (35.5 - 40 ^{0}C) and the humidity was relatively low (42 - 53%) compared to the other times of the day.

C. Simulation on Outdoor Insulator

With aim of being capable to diagnose the condition of insulators before flashover, computer simulation is conducted to obtain electrical properties of LC waveform in various conditions. The simulation was performed on electrical equivalent circuit of outdoor insulator using ATPDraw software to get similar waveforms of each type resulted from the experiments. By changing electrical equivalent circuit parameters, such as capacitance, nonlinear resistance, and number of arc models, similar waveforms can be obtained. The electrical equivalent circuit model that is used in this simulation is Suwarno model, as shown in Figure. 4 [1].

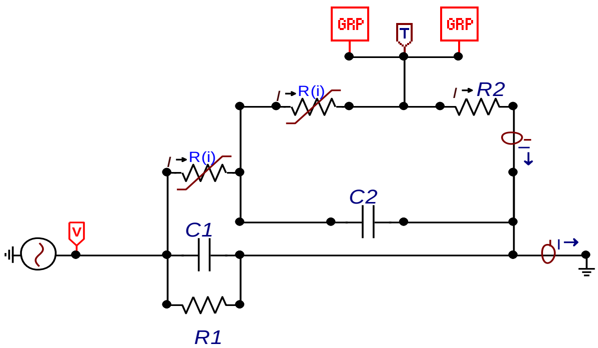


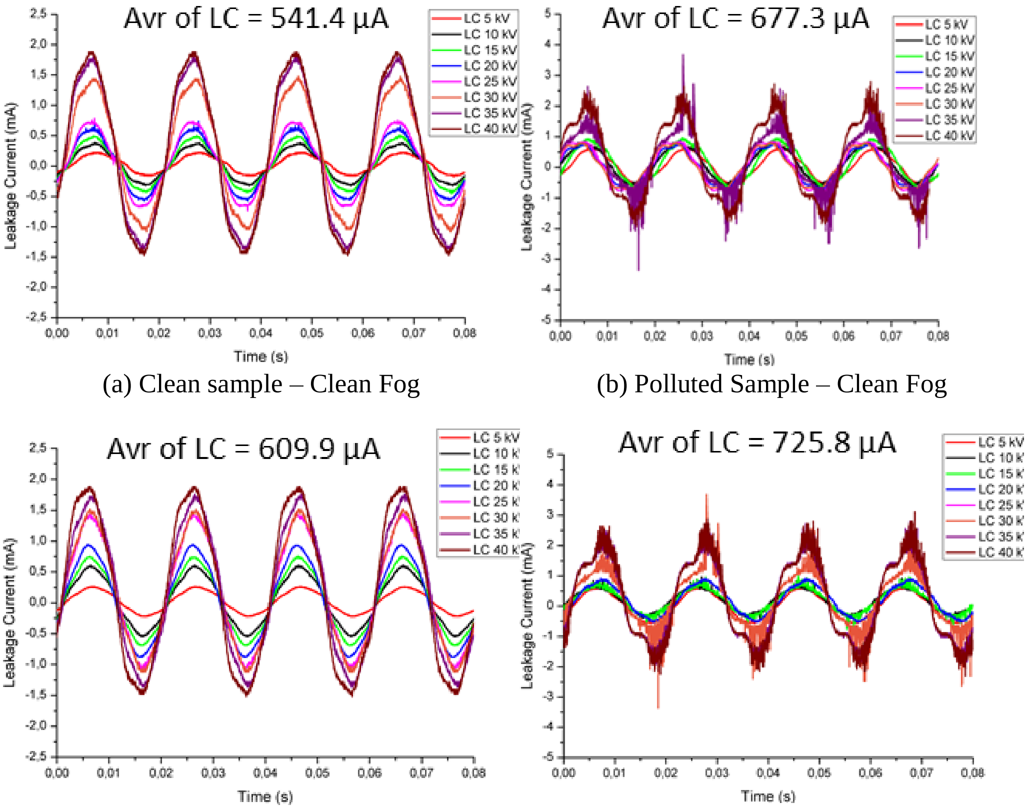
Figure 4. Electrical equivalent circuit of outdoor insulator (Suwarno model) [2]

3. Experiment and Simulation Result

A. Leakage Current Measurement

1. Laboratory Test for Ceramic and Semiconducting Glazed Insulators(SGI)

LC waveforms for each ceramic insulator and SGI under various environmental condition are shown in Figure 5 and Figure 6 respectively. From Figure 5, it can be seen that for ceramic insulator, the LC waveforms are mostly different toward the condition of insulator surface. Clean samples in either clean or salt fog condition tend to have only slightly distorted waveform on the peaks started from 25 – 30 kV applied voltage. Meanwhile polluted samples already have slightly distorted waveform on the peaks at 5 kV applied voltage, and the distortion is getting larger at 25 kV (under salt fog condition) and 35 kV (under clean fog condition) applied voltage.

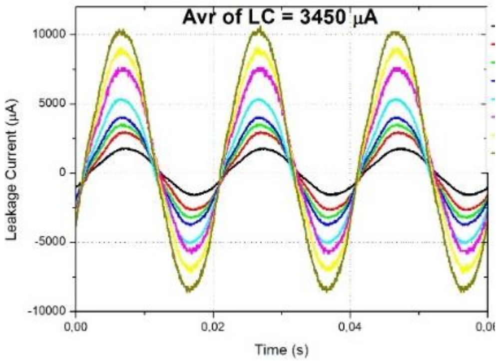


(a) Clean sample – Clean Fog (b) Polluted Sample – Clean Fog

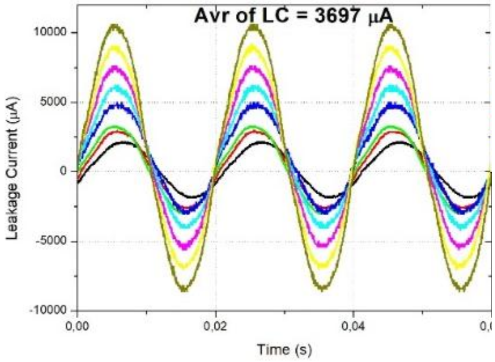
(c) Clean Sample – Salt Fog (d) Polluted Sample – Salt Fog

Figure 5. LC waveform measurement result for ceramic insulator under various environmental condition

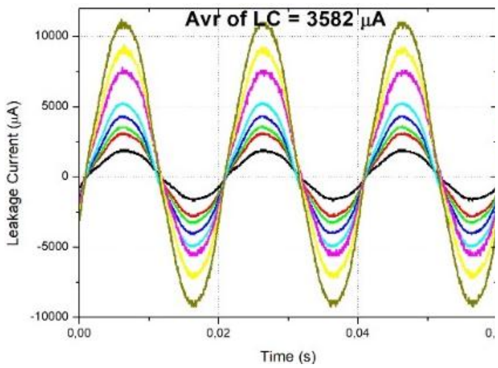
On the other side, as seen from Figure 6, despite the difference in the LC magnitude, the sinusoidal LC waveform of SGI remain unchanged under any environmental condition. For both types of insulator, the average of LC magnitude goes from the smallest to the largest with the following order: clean sample under clean fog condition, clean sample under salt fog condition, polluted sample under clean fog condition, and polluted sample under salt fog condition. This result has shown that the pollutants that lay on the insulator surface have more impact to the LC flow than the pollutants in the surrounding atmosphere.



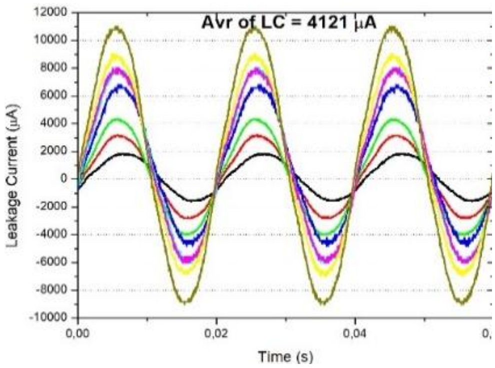
(a) Clean sample – Clean Fog



(b) Polluted Sample – Clean Fog



(c) Clean Sample – Salt Fog

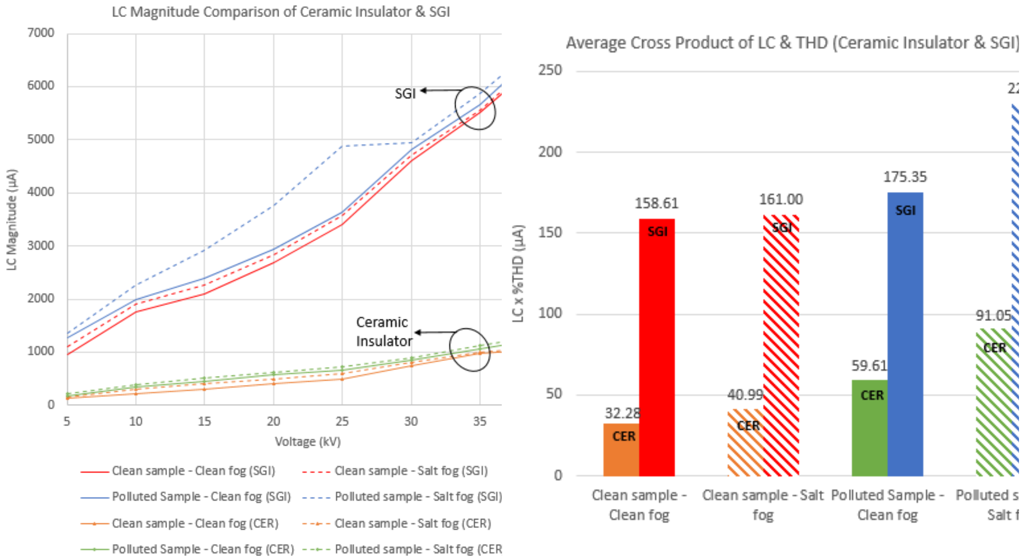


(d) Polluted Sample – Salt Fog

Figure 6. LC waveform measurement result for SGI under various environmental condition

Another parameter for comparison is the cross product between LC magnitude and THD value. Contrary to the magnitude, THD value usually tends to decrease against the LC magnitude. This is because the fundamental components increase faster than the increase in harmonics components so that THD value shrinks when there is a great increase of leakage current, and vice versa. However, when pollutant distribution among samples are not uniform, which are more likely to happen, combined by humidity factor, THD value could quite fluctuate. Thus, it is more reliable to see the LC characteristics from the cross product of LC magnitude and THD. This parameter has shown a better correlation to the insulator conditions in the past research due to the distribution of artificial pollutant can be quite varied which means fluctuated THD [10].

The LC magnitude and the average cross product of LC Magnitude and THD comparison between ceramic insulator and SGI under each environmental condition are shown in Figure 7. Figure 7 clearly shows that LC magnitude increase along with increased apply voltage for any samples under any environmental condition. Moreover, the Figure above pointed out that the range of LC magnitude for ceramic insulator and SGI is obviously different, where the maximum LC of SGI can reach up to seven times of LC of ceramic insulator. With applied voltage ranging from 5 to 40 kV, ceramic insulator has LC magnitude of 130 – 1300 µA, while SGI has LC magnitude of 950 – 7000 µA. This is caused by the characteristic of semiconducting glazed layer that is more conductive than ceramic material, allowing larger LC flow on the insulator surface.



a) (b)

Figure 7. LC Magnitude comparison of ceramic insulator & SGI:
(a) LC Magnitude, (b) Average cross product of LC Magnitude & THD

For each type of insulator, both the LC magnitude only and the average cross product of LC magnitude and THD shows the same trend. Their values from clean samples are smaller than of polluted samples. Those parameter values of both samples under clean fog condition are also smaller than under salt fog condition. The largest LC magnitude is found for polluted sample under salt fog condition, while the smallest is found for clean sample under clean fog condition. It is consistent with the result from Figure 5 and 6, where the pollutant stick on the insulator surface causes larger LC flow on the insulator surface. Humidity especially with air pollution also causes large LC flow, but the impact is not as high as the pollutant that have direct contact to the insulator surface. The largest LC flow is surely found on the combination of both condition, which is polluted sample under salt fog condition.

The polluted samples contain many harmonic components and even discharge. The amount of kaolin-salt pollution has increased the surface conductivity and reduced the hydrophobicity. As a result, the cement that traps water forms a conductive layer, hence larger LC flow occured on the insulator surface. When this continuously happens, continuous dry band is started forming which leads to discharge. The process of discharge is characterized by the formed pulses in the LC waveform. This also causes harmonic components other than the fundamental appear. Salt fog conductivity also affects the magnitude of LC since the magnitude of LC under salt fog condition is higher than clean fog condition.

2. LC Measurement for Field-Aged RTV Silicone Rubber Coated Insulator

The LC measurement for field-aged RTV silicone rubber coated and uncoated ceramic insulator has been carried out from the year of 2012 to 2017, with result as shown in Figure 8. The values stated in the graph are taken from the average LC magnitude from all pairs of coated and uncoated insulators. The result shows that LC magnitude tends to increase along the aging which shows the performance of insulators are unavoidably decreasing, except in the 5th year where the LC magnitude is lower than the previous year. When measurement in the 5th year was conducted, the environmental condition was cleaner due to rain in the previous night. Rain as one of the natural self-cleaning ways for insulator may cause the decrease in leakage current.

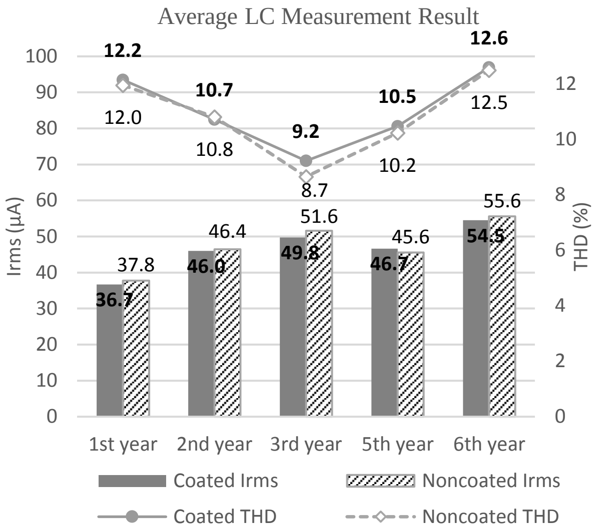


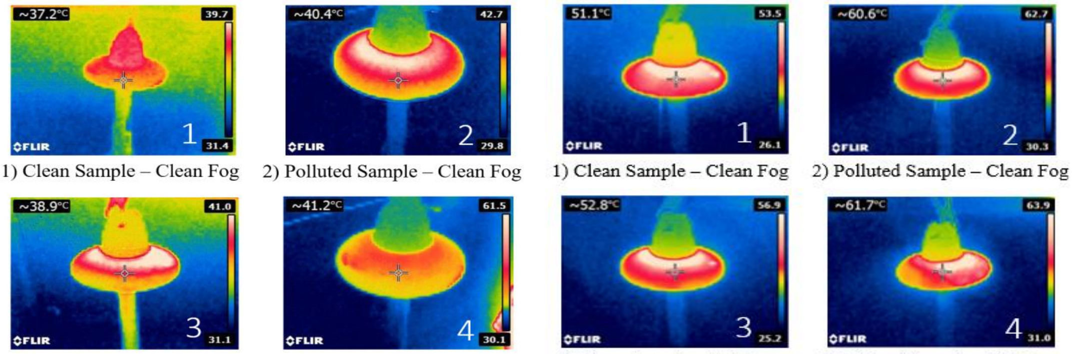
Figure 8. LC Measurement Result on Field-Aged Insulators

As for THD, from the 1st to 3rd year the value constantly decreasing but then increase from the 3rd to 5th. This could happen because higher LC magnitude would cause the fundamental harmonic higher as well, resulting the ratio between total sum of all harmonics and its fundamental smaller, which means the THD value becomes smaller. However, in the 6th year, where the LC magnitude went back up than the previous years, the THD value increase as well. This is caused by the pollutant distribution on the insulators' surface that is denser than before, that also indicates the assured degradation of the insulators' performance.

From Figure 8, it can be clearly seen as well, the comparison of RTV silicon rubber coated and uncoated insulators' performance, where both magnitude and THD value of coated insulators are constantly lower than uncoated insulators from year to year. The exception result is in the 5th year, where the rain caused the pollutant distribution between coated and uncoated insulators differed. This could be the cause the difference in LC magnitude as well. The change in LC magnitude and THD is affected by humidity level and pollutant distribution on the insulators' surfaces [11]-[12]. This deranged pollutant distribution can be caused by rain and wind along the aging. Therefore, the unexpected results of LC measurement can occur along the aging and is strongly related to the environmental condition during the experiments.

B. Surface Temperature

Aside from leakage current, surface temperature is also another parameter that is investigated in this study. The measurement result using FLIR camera is captured and sample at 40 kV supplied voltage are taken and shown in Figure 9. It shows that at 40 kV applied voltage, which is the highest supply voltage applied in this experiment, for both types of insulator, the same as leakage current trend, the temperature characteristic according to various environmental condition goes from the largest to the lowest value with following order: polluted sample under salt fog condition, polluted sample under clean fog condition, clean sample under salt fog condition, and clean sample under clean fog condition. This is because the surface temperature is affected directly by the leakage current flow on insulator surface.



1) Clean Sample – Clean Fog 2) Polluted Sample – Clean Fog 1) Clean Sample – Clean Fog 2) Polluted Sample – Clean Fog

3) Clean Sample – Salt Fog 4) Polluted Sample – Salt Fog 3) Clean Sample – Salt Fog 4) Polluted Sample – Salt Fog

(a) Ceramic insulator (b) SGI

Figure 9. FLIR Camera result at 40 kV applied voltage

Figure 10 shows the surface temperature characteristic against increased supply voltage for ceramic insulator and SGI. The temperature clearly increase along with increased applied voltage as well as leakage current magnitude. Compared to ceramic insulator, the range of temperature under various environmental condition of SGI is higher than of ceramic insulator by about 10 – 20°C. This phenomenon is caused by the LC flow in the semiconducting glazed layer that prevents condensation and humidity effect, so the larger LC magnitude flow on the surface, the higher temperature it reaches.

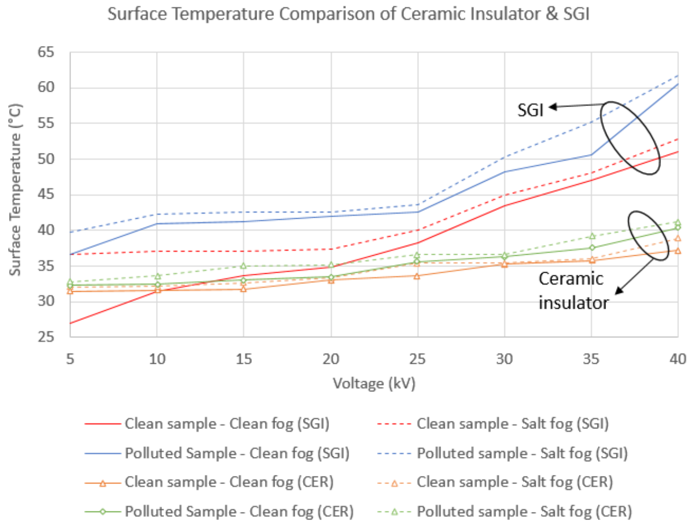


Figure 10. Surface temperature characteristic of ceramic insulator and SGI

Regarding field experiment of RTV silicone rubber coated and uncoated insulators, the actual environmental condition had real impact to the measurement result, since the weather actually caused heating and cooling process on the insulator surface. The insulator surface condition would further affect the insulator thermal characteristic [25]. The insulator thermal characteristic in this experiment is shown in Figure 11.

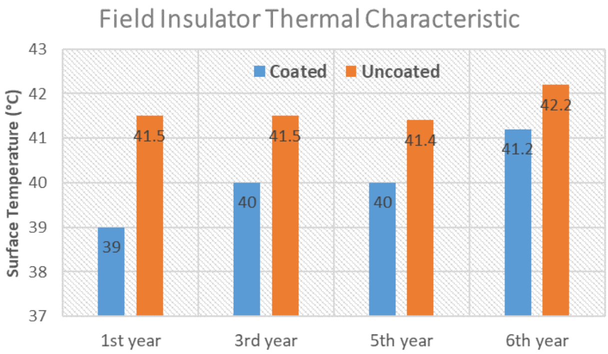


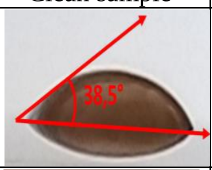
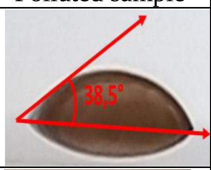
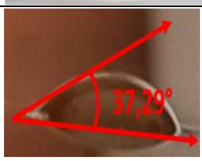
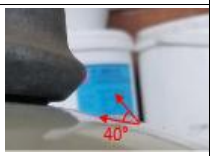
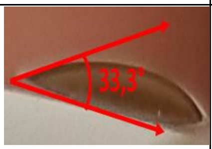
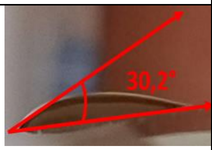
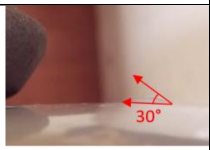
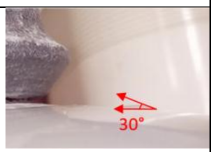
Figure 11. Thermal measurement result of field-aged RTV silicone rubber coated and uncoated insulators

From the above Figure, the RTV silicone rubber coated insulators successfully maintains about 1 – 2.5°C lower surface temperature than uncoated insulators from time to time, although it is also undeniable that the surface temperature of the insulator themselves are increasing along with the aging. This is proportional to the increase trend of LC on insulators surface during the aging process due to the degradation of insulator surface, hence the older the insulators get, the higher the temperature each of the insulator reaches.

C. Hydrophobicity

Hydrophobicity is another characteristic that can be measured on an insulator surface through parameter of contact angle. The hydrophobicity on an insulator surface affects the water content on the insulator surface that can cause a change on surface conductivity, hence it influences the LC magnitude. The hydrophobicity measurement results are shown in Table 2.

Table 2. Contact angle measurement result of ceramic insulator and SGI

Condition	Ceramic Insulator		SGI	
	Clean sample	Polluted sample	Clean sample	Polluted sample
Before LC Experiment				
After LC Experiment (Clean fog)	 $\Delta\angle = 1.21°$	 $\Delta\angle = 7.66°$	 $\Delta\angle = 5°$	 $\Delta\angle = 15°$
After LC Experiment (Salt fog)	 $\Delta\angle = 5.2°$	 $\Delta\angle = 8.3°$	 $\Delta\angle = 10°$	 $\Delta\angle = 5°$

Both types of insulators show that contact angle in any condition is below 90°, which shows that both insulators have more characteristic of hydrophilic, and seen from the initial condition, the SGI is more hydrophobic than the ceramic insulator. The changes (delta) of contact angle before and after LC test result show that the presence of pollutants on the insulator surface can cause the reduction of hydrophobicity up to 8.3° for ceramic insulator and 15° for SGI. For salt fog experiments, the change of contact angle is larger than clean fog experiments, except for SGI with polluted surface whose result is the opposite. This shows that both pollutant presence in the surrounding air and on the insulator surface have effects in reducing the hydrophobicity of insulator surface.

For field-aged insulator experiments, the contact angle measurement result along the aging process is shown in Table 3.

Table 3. Contact angle measurement result of field-aged RTV silicone rubber coated and uncoated insulators

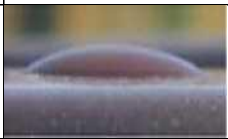
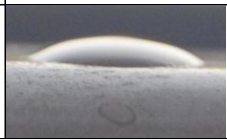
Aging Period	1st Year	3rd Year	5th Year	6th Year
Coated insulator				
Cont. Angle	90 – 100°	76 – 90°	57 – 80°	51 – 67°
Uncoated insulator				
Cont. Angle	30 – 35°	25 – 30°	5 – 22°	0 – 7°

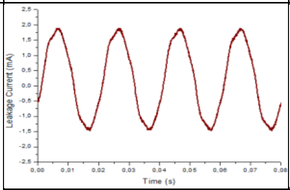
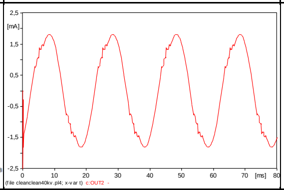
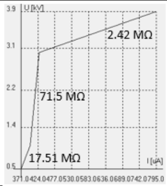
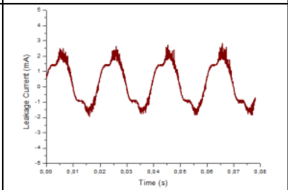
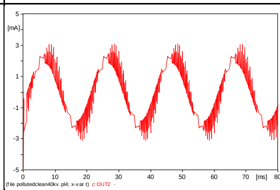
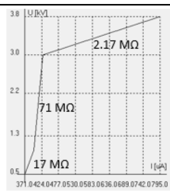
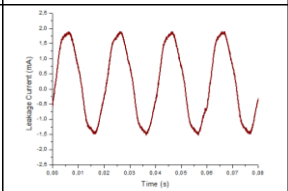
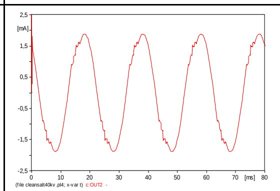
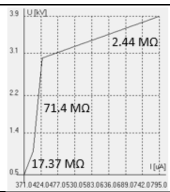
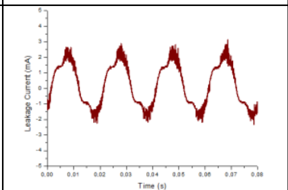
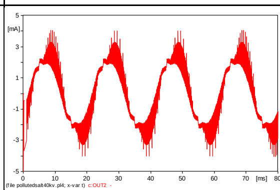
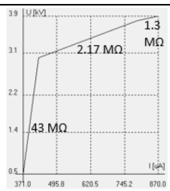
Table 3 shows that the field-aging process with constant charged voltage as well as constant high temperature and humidity weather have obviously great impact on hydrophobicity reduction of the insulator surface. It also shows that how much improvement on insulator performance when RTV silicone rubber coating is applied to an insulator surface, especially in the first year where the coated insulator was clearly hydrophobic. Up until the 6th year, coated insulator also still shows higher hydrophobicity with contact angle of 51 - 67°, whereas uncoated insulators already turned into completely hydrophilic with contact angle of 0 - 7°. Coated insulator surface has hydrophobic layer that can reduce water content on the insulator surface so that the pollutant that falls on the insulator surface can be easily carried by the water through natural self-cleaning process of the insulator. In high humidity weather, the water content on the insulator surface is quite high as well that it increases surface conductivity. Since the aged uncoated insulator is already hydrophilic, the water is easily absorbed, hence when the insulator is charged, leakage current flows and form dry bands. Meanwhile, coated insulator is more hydrophobic, thus the leakage current flow is also smaller. After the humidity turns back to normal, the coated insulator surface becomes dryer than the uncoated ones, resulting lesser LC flow. Therefore, eventually at the end of the aging process, coated insulator successfully maintained its high hydrophobicity level of the insulator surface.

D. Simulation of Leakage Current Waveform

1. Ceramic insulator under various environmental condition

From the whole experiment results, some samples of LC waveform are simulated using ATPDraw software to get the electrical equivalent circuit parameters and study on the characteristics. For ceramic insulator, the LC waveforms at 40 kV applied voltage are taken into simulation, with results as shown in Table 4. The similarity of the simulated and experimental leakage currents was indicated in the magnitude, THD and dominant harmonic components.

Table 4. Simulated LC waveform of ceramic insulator at 40 kV applied voltage

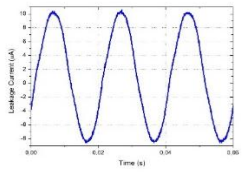
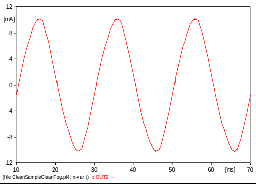
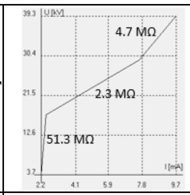
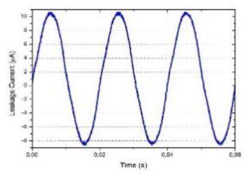
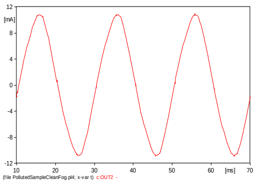
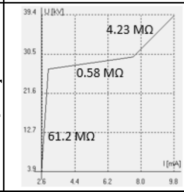
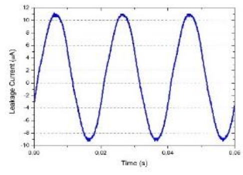
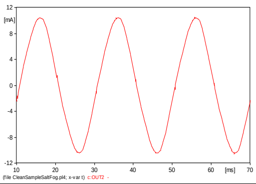
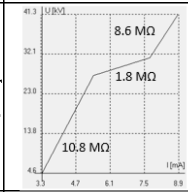
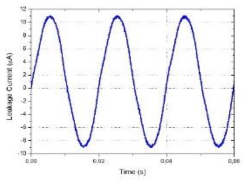
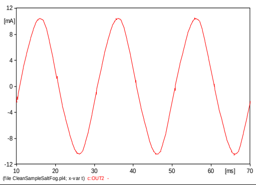
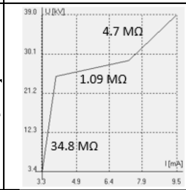
<table>
<tr><th>Condition</th><th>Experimented LC Waveform</th><th>Simulated LC Waveform</th><th colspan="2">Electrical Properties</th></tr>
<tr><td rowspan="4">Clean sample – Clean fog</td><td></td><td></td><td>Nonlinear resistance</td><td>
</td></tr>
<tr><td>Amplitude = 1800 μA</td><td>Amplitude = 1800 μA</td><td>C1</td><td>215.7 pF</td></tr>
<tr><td>THD = 8.32 %</td><td>THD = 8.32 %</td><td>C2</td><td>50 pF</td></tr>
<tr><td>Dominant Harmonic = 3rd & 5th</td><td>Dominant Harmonic = 3rd</td><td>Arc models</td><td>2</td></tr>
<tr><td rowspan="4">Polluted sample – Clean fog</td><td></td><td></td><td>Nonlinear resistance</td><td>
</td></tr>
<tr><td>Amplitude = 2100 μA</td><td>Amplitude = 2100 μA</td><td>C1</td><td>375 pF</td></tr>
<tr><td>THD = 9.01 %</td><td>THD = 9.01 %</td><td>C2</td><td>0.7 pF</td></tr>
<tr><td>Dominant Harmonic = 5th</td><td>Dominant Harmonic = 5th</td><td>Arc models</td><td>9</td></tr>
<tr><td rowspan="4">Clean sample – Salt fog</td><td></td><td></td><td>Nonlinear resistance</td><td>
</td></tr>
<tr><td>Amplitude = 1900 μA</td><td>Amplitude = 1900 μA</td><td>C1</td><td>250 pF</td></tr>
<tr><td>THD = 7.82 %</td><td>THD = 7.82 %</td><td>C2</td><td>50 pF</td></tr>
<tr><td>Dominant Harmonic = 5th</td><td>Dominant Harmonic = 5th</td><td>Arc models</td><td>2</td></tr>
<tr><td rowspan="4">Polluted sample – Salt fog</td><td></td><td></td><td>Nonlinear resistance</td><td>
</td></tr>
<tr><td>Amplitude = 2600 μA</td><td>Amplitude = 2600 μA</td><td>C1</td><td>375 pF</td></tr>
<tr><td>THD = 12.6 %</td><td>THD = 12.6 %</td><td>C2</td><td>0.7 pF</td></tr>
<tr><td>Dominant Harmonic = 3rd</td><td>Dominant Harmonic = 3rd</td><td>Arc models</td><td>9</td></tr>
</table>

The table shows that on the highest supplied voltage of 40 kV, the experiment of polluted samples which shows higher LC magnitude and THD value, have lower piecewise resistances than the clean samples with higher insulator capacitance, allowing larger magnitude of LC flow on the insulator surface. Meanwhile, the frequent arcs that occur on LC waveform of polluted samples are represented by 9 arc models and dry band capacitance of 0.7 pF. On the other side, LC waveforms of clean samples at the same applied voltage only have slight discharge on the peak of the waveform, hence represented only by 2 arc models with dry band capacitance of 50 pF.

2. Semiconducting glazed insulator under various environmental condition

Simulated LC waveforms of SGI are shown in Table 5 below.

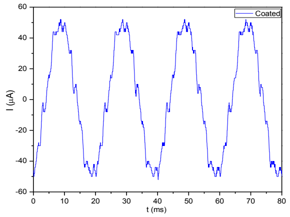
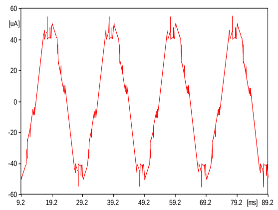
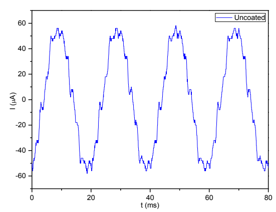
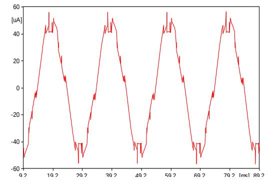
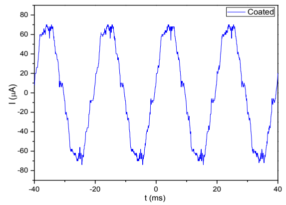
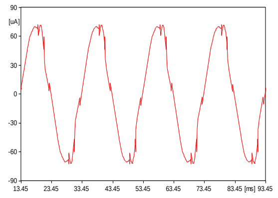
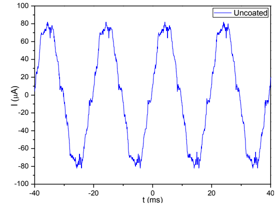
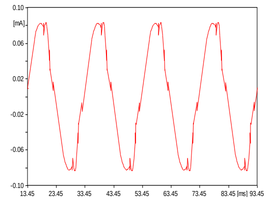
Table 5. Simulated LC waveform of SGI at 40 kV applied voltage

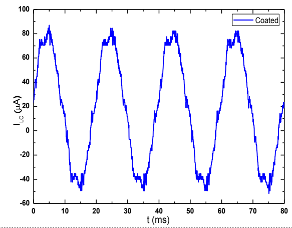
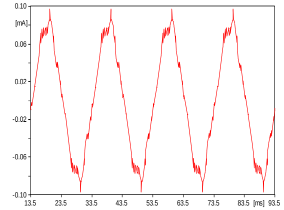
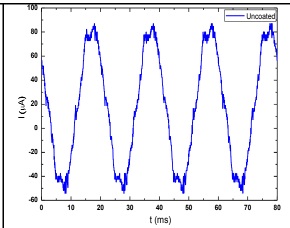
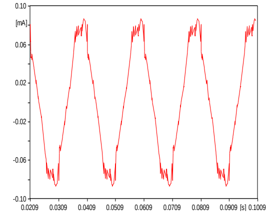
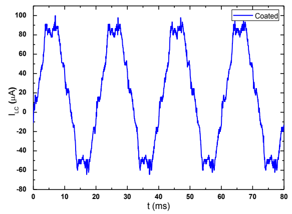
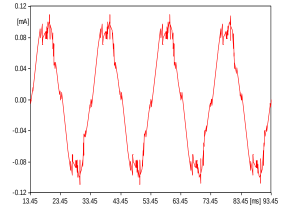
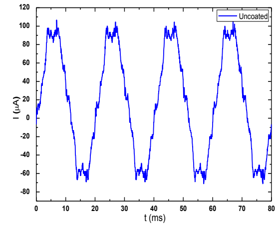
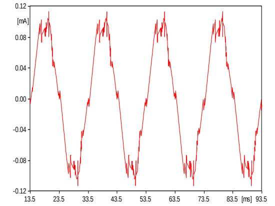
Condition	Experimented LC Waveform	Simulated LC Waveform	Electrical Properties	
Clean sample – Clean fog			Nonlinear resistance	
	Amplitude = 6600 μA	Amplitude = 6600 μA	C1	1990 pF
	THD = 3.98 %	THD = 3.98 %	C2	0.5 pF
	Dominant Harmonic = 5^{th} & 3^{rd}	Dominant Harmonic = 3^{rd}	Arc models	2
Polluted sample – Clean fog			Nonlinear resistance	
	Amplitude = 6850 μA	Amplitude = 6850 μA	C1	2100 pF
	THD = 4.33 %	THD = 4.33 %	C2	0.5 pF
	Dominant Harmonic = 5^{th} & 3^{rd}	Dominant Harmonic = 3^{rd}	Arc models	2
Clean sample – Salt fog			Nonlinear resistance	
	Amplitude = 6700 μA	Amplitude = 6700 μA	C1	2000 pF
	THD = 4.13 %	THD = 4.13 %	C2	0.5 pF
	Dominant Harmonic = 5^{th} & 3^{rd}	Dominant Harmonic = 3^{rd}	Arc models	2
Polluted sample – Salt fog			Nonlinear resistance	
	Amplitude = 6950 μA	Amplitude = 6950 μA	C1	2300 pF
	THD = 5.68 %	THD = 5.68 %	C2	0.5 pF
	Dominant Harmonic = 5^{th} & 3^{rd}	Dominant Harmonic = 5^{th} & 3^{rd}	Arc models	2

From the table, it is known that the sinusoidal LC waveform of SGI can be recreated through simulation with the exact same value for parameters such as amplitude, THD, and dominant harmonic. This sinusoidal LC waveforms have large magnitude and very small THD value (with range 4 to 6% only), which is here formed by smaller value of piecewise nonlinear insulator resistance (R = 10 – 50 MΩ), higher insulator capacitance (C1 = 1900 – 2300 pF) and few arc models (only 2 arc models required), compared to ceramic insulator (R = 40 – 70 Ω ; C1 = 200 – 400 pF). Despite the difference in magnitude, the LC waveforms under every environmental conditiona are similar, thus the insulator surface resistance nonlinearity and number of arc models are all similar as well.

3. Field-aged RTV silicone rubber coated and uncoated ceramic insulator

Table 6. The comparison of LC waveform from experiments and simulation result

Aging Period	**Coated Insulator**		**Uncoated Insulator**	
	Experiment	**Simulation**	**Experiment**	**Simulation**
1st year				
Amplitude	52 µA	52 µA	56 µA	56 µA
THD	11.581 %	11.581 %	11.394 %	11.394 %
Dominant Harmonic	5th & 11th	5th & 13th	5th & 11th	5th & 7th
3rd year				
Amplitude	70 µA	70 µA	82 µA	82 µA
THD	10.543 %	10.543 %	10.608 %	10.608 %
Dominant Harmonic	5th	5th	5th	5th

5^{th} year				
Amplitude	87 μA	87 μA	87 μA	87 μA
THD	9.924 %	9.924 %	9.778 %	9.778 %
Dominant Harmonic	5^{th} & 7^{th}	5^{th} & 7^{th}	5^{th} & 7^{th}	5^{th} & 7^{th}
6^{th} year				
Amplitude	99.5 μA	100 μA	104.3 μA	104.3 μA
THD	12.517 %	12.517 %	12.385 %	12.385 %
Dominant Harmonic	5^{th} & 7^{th}	5^{th} & 7^{th}	5^{th} & 7^{th}	5^{th} & 7^{th}

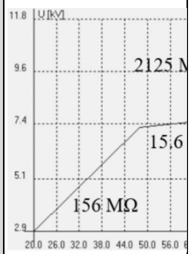
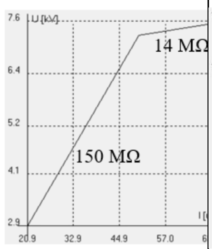
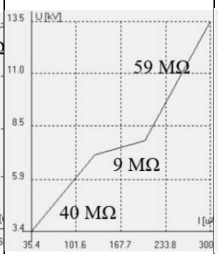
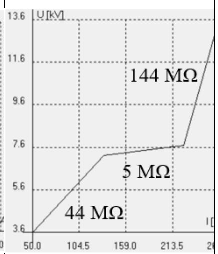
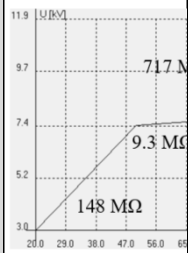
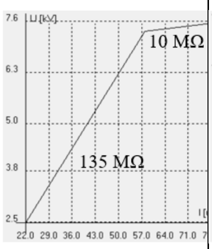
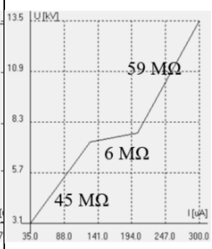
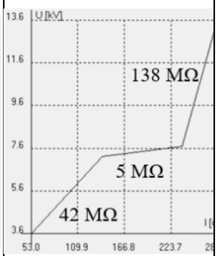
Among six pairs of coated and uncoated insulators experiment result, a pair of them is taken from each year as samples for computer simulation. Hence there are total of eight samples of LC waveforms which were reconstructed using electrical equivalent circuit of outdoor insulator with different parameters of the capacitance, nonlinear resistance, and number of arc models. The results of this simulation are shown in Table 6, along with each of original waveforms obtained from the experiments. The monitored parameters value that determine how much the simulated waveforms resemble the experiments waveform are LC magnitude, THD, and dominant harmonic numbers, while Table 7 shows the electrical parameters that resulting the respected waveforms.

From Table 6, it can be seen that the LC waveforms become more distorted from time to time. This distortion level on the peak of the waveform are determined by the number of arc used in simulation. In the 1st and the 3rd year, where the waveforms are slightly distorted, there only required 1 to 2 arc models connected to the main circuit, meanwhile in the 5th and the 6th year where the insulators have aged, 5 arc models are required to shape that kind of distortion.

The LC amplitude is noticeably increasing from time to time as the insulators performance degrade due to aging. It is also clear that coated insulator has lower LC amplitude than the uncoated insulator. This is consistent with the parameters that determine the LC magnitude, which is the nonlinear resistance shown in Table 7. The lower LC magnitude is resulted from higher piecewise resistance values. This applies for the difference LC magnitude along the aging as well as the difference LC magnitude between coated and uncoated insulators. However, despite the different magnitude, the waveform between coated and uncoated insulators are always similar in each year. Thus, the nonlinear resistance characteristic curve is also the same.

The capacitance C1 which represents insulator capacitance is 4 pF in the 1st and the 5th year, while the value is higher in the 3rd and the 6th year (8 pF and 7.8 pF). It affects the phase difference between the LC and the current resulted by arc. Hence, it affects the position of arc occurs on the LC waveforms. The capacitance C2 value which refers to dry band capacitance is almost the same for all waveforms, except in the 5th year. The humidity and pollutants on the insulator surface usually has an impact on dry band capacitance. However, the simulated waveforms are all taken from condition with relatively low humidity and pollution conditions, except in the 5th year. Therefore, the capacitance value is also the same, except for waveforms in the 5th year.

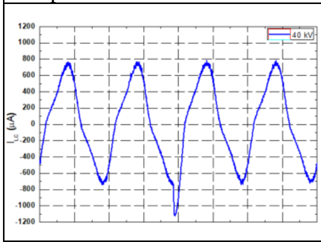
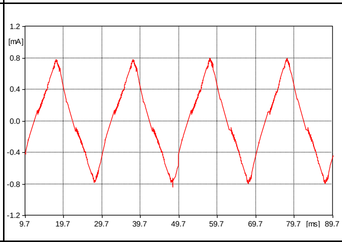
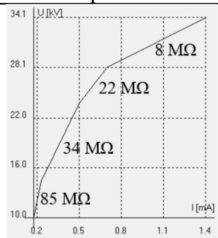
Table 7. Electrical equivalent circuit parameters for LC waveform of field-aged ceramic insulators

Year	Parameter	1st Year	3rd Year	5th Year	6th Year
Coated Insulator	C1 & C2	4 pF & 0.1 pF	8 pF & 0.1 pF	4 pF & 0.5 pF	7.8 pF & 0.1 pF
	Nonlinear Resistance				
	Number of arc models	2	1	5	5
Uncoated Insulator	C1 & C2	4 pF & 0.1 pF	9.9 pF & 0.1 pF	4 pF & 0.5 pF	7.8 pF & 0.1 pF
	Nonlinear Resistance				
	Number of arc models	2	1	5	5

The harmonic number has the 5th as the dominant harmonic for all waveforms, as it contributes significantly to the THD value [3]. The 2nd and 3rd dominant harmonic varies for each measurement, which are the 7th, 3rd, or 11th, but usually insignificant compared to the 5th harmonic. In the electrical equivalent circuit, this is affected by various combination of parameters among nonlinear resistance, capacitance, and arc models.

The long term goal of this LC simulation is to distinguish LC characteristics of each different insulators, under various conditions, and to get such an early warning for aging condition before flashover occurs. One of the field-aged insulators was tested in the laboratory by applying various voltage to represent the aging effect. At applied voltage 40 kV under salt fog condition, the LC waveform is unsymmetrical and started to show large discharge at one of the troughs. The simulation result and the electrical equivalent parameters that form the waveform is as shown in Table 8.

Table 8. Experiment and simulated LC waveform of insulator under salt fog condition at 40 kV applied voltage.

Experimented LC Waveform	Simulated LC Waveform	Electrical Properties	
		Nonlinear resistance	
Amplitude = 754 μA	Amplitude = 758 μA	C1	4 pF
THD = 18.94 %	THD = 18.94 %	C2	57 pF
Dominant Harmonic = 3rd	Dominant Harmonic = 3rd	Number of Arc models	6

Based on Table 8, when the insulator condition gets charged until flashover almost occurred, the dominant harmonic number is 3rd, instead of 5th, and many even harmonic numbers started to appear due to the unsymmetrical waveform. The insulator capacitance (C1) is normal, but the capacitance of dry band (C2) is much larger than in normal condition (operating voltage), representing the condition close to flashover, which also has impact in large THD value. The insulator nonlinear resistance shows increased nonlinearity properties than in normal condition as shown in the table. In order to create the unsymmetrical waveform and discharge on the trough, six arc models are required.

4. Conclusions

This study has shown that LC waveform and magnitude that flows on the insulator surface is strongly affected by the applied voltage, environmental condition, and the condition of the insulator surface itself. Both for ceramic insulator and SGI, along with the increased apply voltage, the LC magnitude and the cross product of LC magnitude and THD value increased with different environmental condition with the presence of pollutant stick on the insulator surface, which has higher impact, followed by the polluted atmosphere (in this case salt fog condition). Specifically for SGI, LC waveforms are generally similar with the sinusoidal applied voltage. The LC waveforms are also symmetrical for positive and negative half cycles and no flashover was observed for applied voltage up to 40 kV. Additionally, the surface temperature increases proportionally to the LC magnitude.

The hydrophobicity of insulator surface decrease after the experiments, with the pollutant presence and salt fog condition cause higher reduction compared to the clean samples and in clean fog environment. The observed SGI that has higher hydrophobicity compared to ceramic insulator has been proven as well. On the other hand, field-aged experiment result on RTV silicone rubber coated insulator shows much better result on maintaining its hydrophobicity characteristic compared to field-aged uncoated ceramic insulator. At the end of the 6th year, the difference of contact angle between the two types of insulators can reach up to 50 – 60°. This proves that less pollutant is likely to stick on coated insulators for long, hence preventing more dry bands to form and cause less leakage current flow on the insulator surface.

Experiment of LC measurement have been conducted on field-aged outdoor ceramic insulators with and without RTV silicon rubber coating in a coastal area. The LC characteristics along the five consecutive years are observed, and the result shows that coated insulators have consistently lower LC magnitude than the uncoated insulators. Quite the opposite, THD value of coated insulators are relatively higher than the uncoated ones, which is caused by the larger magnitude of leakage current has larger fundamental harmonic, resulting lower THD value.

The LC waveforms obtained from all experiments both in the laboratory or in the field have been successfully recreated through computer simulation using ATPDraw software with precise key parameters of LC amplitude, THD, and dominant harmonic. For lab experiments, it shows that SGI is more capacitive than normal ceramic insulator and has lower values of piecewise resistance of the nonlinear resistance, resulting LC flow on the insulator surface also much higher. Despite the increased applied voltage, SGI shows very little discharge on its LC waveform, hence it has only 2 arc models, while at higher applied voltage, ceramic insulator has many discharges occur along the LC waveform, hence the arc models for this insulator can reach up to 9 arc models.

As for LC waveform on field-aged insulators, the electrical equivalent circuit parameter shows that as the insulator aged, the nonlinearity of resistance characteristic increased but accompanied by decreased value of each piecewise resistance, resulting higher LC magnitude. Number of arc models also increased to obtain more distorted waveforms along the aging of insulator. Meanwhile the capacitance does not vary a lot due to environment and pollutant condition during experiments are relatively similar.

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