

# Impact of Pollution on Leakage Current in Polymeric Insulators: Time and Frequency Domain Analysis

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## Abstract

Insulators are used to provide mechanical support as well as prevent the flow of electricity that is not required for the transmission of high voltage electricity. Silicon rubber insulators are the commonly used insulating materials and are thus used in the highly polluted environment. Composite insulators are known to outperform the ceramic insulators. The Mechanical and reliability of polymeric insulators are critical for the high-performance voltage transmission lines and since most high voltage electricity transformation is done using the overhead lines safety and performance of the composite insulators used must be considered. This paper aims to analysis of the leakage current in time and frequency domain, particularly completed for polluted polymeric insulator surfaces.

The results indicate that significantly enhance the performance of polymeric insulator, the analysis of LC behaviors under different conditions can be monitored. In order to get an accurate picture of the insulator performance and surface activity, field measurement is required.

## خلاصة البحث

العوازل تُستخدم لتوفير الدعم الميكانيكي وكذلك لمنع تدفق الكهرباء غير الضروري لنقل الكهرباء عالية الجهد. تُستخدم عوازل مطاط السيليكون بشكل شائع كمادة عازلة، ولذلك فهي تُستخدم في البيئات الملوثة بشدة. من المعروف أن العوازل المركبة تتفوق على العوازل الخزفية. الأداء الميكانيكي والموثوقية للعوازل البوليمرية أمران حاسمان لخطوط نقل الجهد العالي ذات الأداء العالي، وبما أن معظم تحويل الكهرباء عالية الجهد يتم باستخدام الخطوط الهوائية، يجب النظر في سلامة وأداء العوازل المركبة المستخدمة. تهدف هذه الورقة إلى تحليل تيار التسرب في مجال الزمن والتردد، وخاصةً تلك التي يتم إجراؤها على أسطح العوازل البوليمرية الملوثة. تشير النتائج إلى أن تحليل سلوك تيار التسرب تحت ظروف مختلفة يمكن أن يُحسن بشكل ملحوظ من أداء عازل البوليمر. للحصول على صورة دقيقة لأداء العازل ونشاط سطحه، يلزم إجراء قياسات ميدانية.

**Keywords:** Leakage Current, Polymeric Insulator, High Voltage Transmission, Time Domain Analysis, Frequency Domain Analysis, polluted polymeric insulator surfaces

## 1. Introduction

Nowadays, in both distribution and transmission of high voltages ranges, polymeric insulators are widely used. They are steadily gaining a larger share of the market. In the applications of polymeric insulators, this incredible growth is because of their benefits over glass and porcelain insulators. These benefits include the low surface energy, higher mechanical strength to weight ratio, lightweight, resistance to vandalism and their optimal performance even in the presence of contamination and wet [1,2]. To perform as a high voltage insulator, their long-term ability is due to the fact of design test, which include normal aging test and accelerated test [3]. Many techniques are available for testing the performance of polymeric insulators which can be such as the surveilliance and diagnostics of the insulators. The provided equivalent deposit salt density, the leakage current, the surface conductance, non-soluble

deposit density, air pollution measurements and optical measurements are the commonly used techniques in order to monitor the insulator's performance [4]. The material aging and hydrophobicity are the most prominent factors that affect the polymeric insulators performance under environmental and electrical stresses. Because of the discharges and leakage currents, the degradation process can significantly develop the polymeric insulator material surface [5,6]. To assess the performance and degree of aging of polymeric insulators, the measurements of LC are frequently performed in field studies as well as in laboratories. Several test methods are currently being employed for testing the polymeric insulator performance. To understand the surface condition of the polymeric insulation materials, the leakage current analysis is very much important.

It is an important fact that the status of insulator must be known in order to cater the problems associated with it. As well as for maintenance purpose, it is necessary to determine the outdoor insulator's insulation condition. To find out the condition of the insulators, it is mandatory to measure or identify signals to be used as an indicator. When the polymeric insulator is in operation, the flow of leakage current usually happens on the insulator surface [7] and it is usually used to analyze the condition of insulators [8,9]. To diagnose the insulator, several methods may be employed. Acoustic emission (AE), infra-red for hot spot detection, radio wave detection, ultrasonic detection, LC magnitude and waveforms, and harmonic contents are those methods [10]. So, it can be said that a healthy outdoor insulator must be having a small magnitude of LC and low harmonic content. If large magnitude of LC and high harmonic content in it, then it means the insulator flows on severe condition. In this report, the application of LC magnitude and harmonic content is being used to diagnose the condition of polymeric insulators.

## 2. Background:

On describing the state of contaminated insulator, the LC, which is usually driven by the voltage at the source and collected at the ground site of contaminated insulator provide useful information. The LC is usually capacitive in character when the insulator surface is hydrophobic in nature and the waveform is supposed to be sinusoidal. The LC becomes more resistive as the surface loses its hydrophobicity. The appearance of spikes on the LC signal crest is caused by dry-band discharges, leading to the deformation of the current waveform and an increase in harmonic content. The transition of LC waveforms until flashover can be classified into different stages. The likelihood of flashover increases as the harmonic content and magnitudes exceed a particular range. This discharging surface activity leads to deterioration of the electrical and mechanical properties of the material because of the chemical reactions. The degradation modes are the tracking formation, cracking as well as progressive material weight loss. In polymeric insulators, the changes in the surface condition affect the shape and magnitude of the leakage current. A non-linear relationship has been observed between LC time variation, arc length and surface discharge. If the surface discharge extension is beyond the air breakdown electrical stress, the arc will take place. It results in the magnitude changing and also in the shape of the leakage current. To the surface condition, the peak and rms currents are not sufficient. It results in the frequency content analysis of the leakage current waveform [11].

### 2.1. Glass vs polymer insulators for outdoors

Glass and ceramic insulators have been used for a long time for high-voltage insulation and lightning arrestors. This was because of their resistance to deterioration from outdoor exposure and electrical stress. Despite the fact that they perform appreciably in this regard especially in

general applications, the disadvantages are more significant when considering application in an all-weather or special weather conditions. Outdoor electrification is a subject that considers various environments; it is non-specific to a particular type of climate, temperature, or humidity fluctuations. Glass insulators are poor when it comes to hydrophobicity [12]. It offers a surface where moisture from the air can condense, leading to the accumulation of dust. In this regard, it alters the dielectric properties of the electrical system thus creating an imbalance that causes leakage of current from the distribution lines. Also, glass insulators have a voltage limit in their application, and thus, cannot be used for high voltage distribution. The reason for this limit is that glass can hardly be cast into irregular shapes that are required due to the non-uniform cooling that causes internal strains [13].

Glass is distinguished by its high dielectric strength and resistivity, as well as its low thermal expansion coefficient. It also has high tensile strength and hardly heats up due to its transparency. In addition, it non-porous and hardly contains any impurities. However, its low seismic sustainability, susceptibility to vandalism, and relatively high installation costs in addition to other disadvantages created the need for the development of a cheaper yet effective insulator.

Polymers have replaced most of the other material types used in the manufacture of insulators. Its application environment is wide and can be used in high voltage insulation. A polymer insulator is made up of two parts –EPDM (Ethylene propylene Diene Monomer) or silicon rubber and epoxy resins rod-shaped core that is reinforced with glass fiber [14]. Its composition gives it the name composite insulator. It is lightweight with high seismic sustainability and hydrophobicity. It is also less susceptible to breakage and contamination as compared to glass [15]. These qualities make it more suitable for outdoor use compared to glass insulators.

## 2.2. Conductors used in overhead lines

The demand for reliable and efficient electrical power transmission has never been greater, driven by the increasing energy consumption of modern societies and the integration of renewable energy sources. Overhead line conductors play a pivotal role in this infrastructure, serving as the medium through which electricity travels from power plants to substations and, ultimately, to consumers. These conductors are subject to a range of environmental and operational challenges that can impact their performance and longevity. The demand for reliable and efficient electrical power transmission has never been greater, driven by the increasing energy consumption of modern societies and the integration of renewable energy sources. Overhead line conductors play a pivotal role in this infrastructure, serving as the medium through which electricity travels from power plants to substations and, ultimately, to consumers. These conductors are subject to a range of environmental and operational challenges that can impact their performance and longevity.

Traditionally, conductors such as Aluminum Conductor Steel Reinforced (ACSR) have been widely used due to their strength and cost-effectiveness [16]. However, the evolving needs of the power industry have led to the development of advanced conductor types, such as All-Aluminum Alloy Conductor (AAAC) and Aluminum Conductor Composite Core (ACCC), which offer enhanced performance characteristics [17]. The choice of conductor material and design significantly influences the efficiency of power transmission and the overall reliability of the grid [18]. Overhead line conductors are critical components in electrical power transmission systems, responsible for carrying high-voltage electricity across vast distances. These conductors, often made of aluminum or aluminum alloys, are designed to withstand environmental stresses such as wind, ice, and extreme temperatures [19]. Here, we will discuss some materials, construction, and performance characteristics of various types of overhead line

conductors, including Aluminum Conductor Steel Reinforced (ACSR), All-Aluminum Alloy Conductor (AAAC), and Aluminum Conductor Composite Core (ACCC) [20]. Understanding these aspects is crucial for optimizing the design and operation of power transmission networks, ensuring stability, and meeting increasing energy demands. By understanding these elements, engineers and grid operators can make informed decisions to enhance the sustainability and resilience of power transmission systems [21,22]. Some commonly used types of conductors in overhead lines:

- 1) Splice Connectors: Used to join two conductors end-to-end. These can be compression splices or mechanical splices.
  - a) Compression Splices: Use a hydraulic press to compress the connector onto the conductor, forming a secure connection.
  - b) Mechanical Splices: Utilize bolts or other mechanical means to secure the connection without the need for special tools.
- 2) Tension Clamps: Used to grip and hold conductors under tension. They are often used at the end of a span or for dead-ending.
  - a) Dead-end Clamps: Specifically designed to anchor the conductor at the end of a line.
- 3) Suspension Clamps: Support conductors and allow them to hang freely while maintaining the correct sag and tension.
- 4) Tap Connectors: Allow for the branching off of a main conductor to a secondary line or equipment.
  - a) Parallel Groove Clamps: Commonly used for tap connections; they clamp onto the main conductor and the tap conductor simultaneously.
- 5) Line Post Insulators Support and insulate conductors from pole or tower structures.
- 6) Armor Rods: Provide additional protection and support to conductors at points where they are subject to mechanical strain, such as near connectors or clamps.
- 7) Vibration Dampers: Used to reduce the amplitude of vibration in conductors caused by wind or other environmental factors, thus preventing damage.
- 8) Jumper Assemblies: Allow for flexibility in the connection between two conductors, often used in switching and protection setups.
- 9) Wedge Connectors: Utilize a wedge mechanism to create a secure connection, often used for grounding applications.

These connectors are typically made from materials like aluminum, copper, or a combination, to match the conductivity and mechanical strength requirements of the conductors they connect.

### 3. Methodology

The analysis of the leakage current in both time and frequency domain has done in this paper; particularly completed for clean and polluted polymeric insulator surfaces. The LC waveforms characteristic parameters up to flashover namely the phase shift, peak value, the total harmonic distortion and the harmonic content are investigated. However, it is observed that the LC peak value and the phase shift cannot be a true indication of the surface activity related to the waveform types and partial discharges, but the harmonic content can be correlated well with the LC distortions. In the early stages, it is observed that the fifth and seventh harmonic contribution to the LC distortion is the most significant among all. A time–frequency analysis is also carried out to better understand the LC behavior. Different stages of LC activity spectrogram is computed using PROTEUS toolbox. It leads to an observation that time–frequency analysis can be used as a tool for LC classification and for patterns recognition.

The circuit setup comprises of a high voltage transformer up to (50 kVA, 50 Hz), a current probe, a voltage divider, insulator models and a monitoring system (Fig.1). A non-inductive resistor of 10 K ohm is placed in between the ground and the insulator sample which is consisted by the current probe [23]. Data acquisition card can be used to recover the LC data.

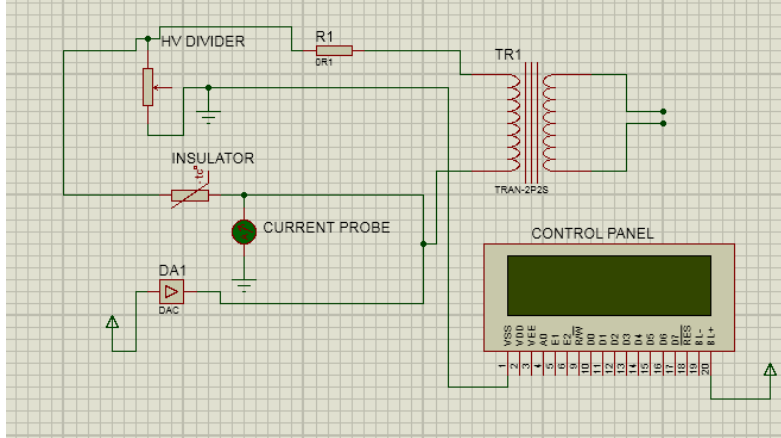


Figure1: Proteus Model

To visualize clearly the current transitions during arcing phenomena, the sampling frequency is fixed at 125 kHz. In this a polymeric insulator is used for model purpose because of ease of realization. Connection is made to both high voltage and ground bounds by two aluminum electrodes. The leakage path is represented by the distance between two electrodes. The observations were made for clean insulator. In order to collect the maximum information about the surface condition, the computation of phase shift and current peak of the LC were done. The insulator surfaces must be washed with alcohol and rinsed with distilled water in order to remove any dust trace and grease. For different trials, different samples of the same type were used. The values observed during this are the averaged values of three measurements in order to make sure the accuracy [24]. The frequency characteristics of the LC was also extracted as these values are handy in terms of investigating the behavior of insulator under stress conditions. To analyze all the characteristics parameter, Fourier transform is then used. It is used for the transformation from time-domain to its frequency domain. Suppose  $s(t)$  is the time-domain representation of a signal 's';  $S(f)$  is then used to represent the frequency domain signal. The formula for  $S(f)$  is given below:

$$S(f) = \int_{-\infty}^{\infty} s(t)e^{-j2\pi ft} dt \text{ --- (1)}$$

For Fourier transform computation, using the DFT formula:

$$S_k = \sum_{n=0}^{N-1} s_n e^{-j2\pi fn/N}, k = 1, 2, \dots, N \text{ --- (2)}$$

For analyzing the "Thermal Harmonic Distortion", using the formula:

$$THD = \frac{\sqrt{\sum_{k=2}^{\infty} H_k^2}}{H} \text{ --- (3)}$$

Where,

$$H^2 = \sum_{k=1}^{\infty} H_k^2$$

#### 4. Observations

The evolution of the LC waveform and its Fourier transform (FFT) are shown in Figures. 2 a, b and c. It is observed that the more distortion in LC waveform is occurred as the applied voltage is increased. Partial discharges are indicated due to the presence of some pulses. From those observations, it is possible to create a correlation between the events of surface condition that is: the higher the non-fundamental frequency component, the higher the signal distortion. Moreover, the current spectra indicate an increase in the odd number harmonics amplitude which directly related to the distortion of the LC waveform with the increase in the electric stress level. Due to the intensity of the electric field, these distortions are practically appeared but only if it reaches to the breakdown dielectric strength. This results on the appearance of discharges on the surface of an insulator which leads towards the decrease of surface resistance of insulator and increasing the odd harmonics in LC. Furthermore, these harmonics can be characterized by the low energy magnitudes.

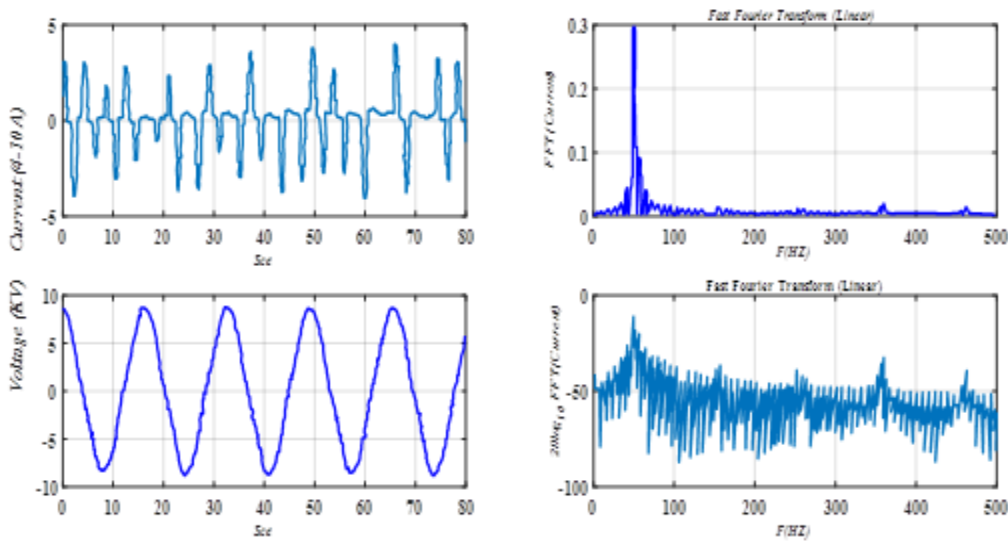


Figure 2 (a): LC waveform and FFT values at 6kVrms for polluted polymeric insulator

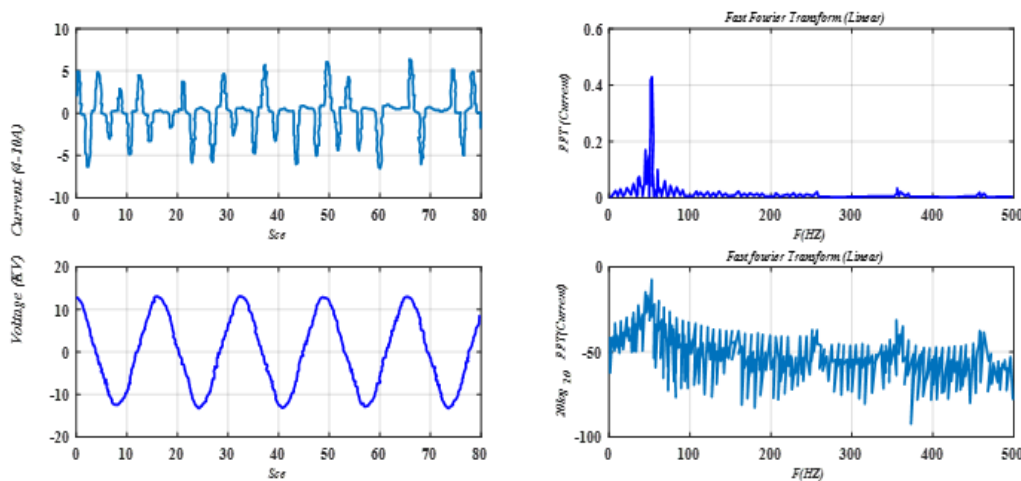


Figure 2 (b): LC waveform and FFT values at 8kVrms for polluted polymeric insulator

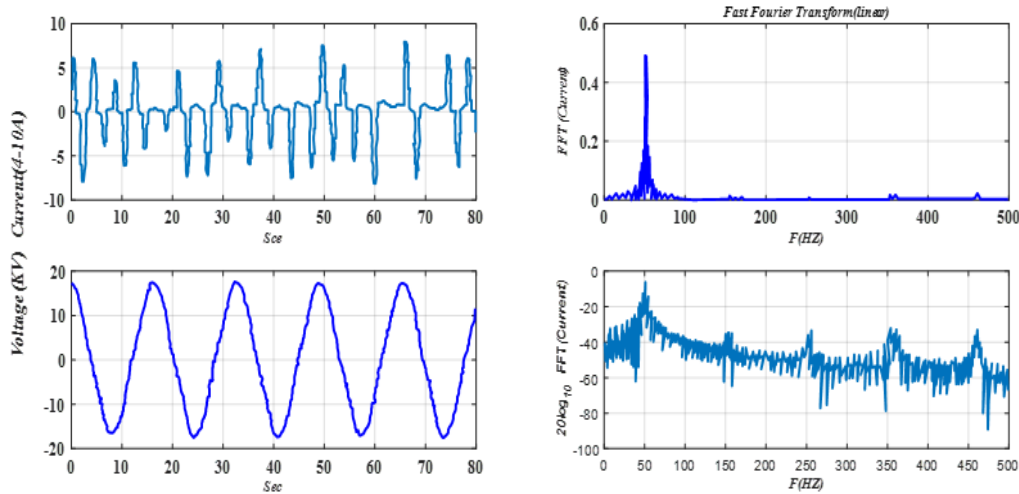


Figure 3 (c): LC waveform and FFT values at 10kVrms for polluted polymeric insulator

Other researchers also observed the same phenomena [25,26]. attributed the distortion in LC to the electric charges started in air in insulator proximity in case of the clean surface in which the initial electron is easier to be released from the air instead of that from the surface. For the quantification of the LC behavior, the computation of THD co-efficient, the magnitude of odd-harmonic and the peak value were done

## 5. Conclusion

In this paper, the variations of the LC of polymeric insulator versus the voltage and the other conductivities in terms of THD, the phase shift, the peak value and the spectrogram from time-frequency analysis. The main results are summarized in the below points:

- 1) LC waveforms are of several types representing the different stages of activity which are:
  - a) At the initial stage in which the insulator is still hydrophobic, the current is sinusoidal and capacitive, but a very small magnitude is observed.
  - b) Distorted sinusoidal waveforms are then observed corresponding to the intermediate stage which showed observable discharges activities due to water droplets related to the electric field distortion present on the hydrophobic surface that has a direct impact on the insulator's surface condition.
  - c) A non-linear waveform which corresponds towards the dry band activity in that the current is resistive resulting to the positive loss of hydrophobicity.
- 2) In the same waveform, different types of activities can coexist; the discharges behavior, like elongation, occurrence and extinction varies with the applied stress and pollution level.
- 3) The LC extracted characteristic parameters like phase shift, peak value and harmonic components are not always represent the condition of insulator and can sometime mislead it. Electric stress directly relates with the LC amplitude, whereas the harmonic component and phase shift can used as an indicator for the surface condition event. Moreover, the LC signal distortion severity will be indicated with the higher content.
- 4) To diagnose the insulator condition under uniform or non-uniform conditions, spectrogram distribution is performed in order to predict the flashover.

- 5) A spectrogram is used to display the frequency spectrum of failure for each evolution of LC. This technique is considered as easy to understand and use with a key parameter having low calculation time in the perspective of a real-time implementation in a dedicated microprocessor.
- 6) The correlation must be established among the LC magnitude, harmonic components, and waveforms. Through the analysis of the images, these findings are confirmed from the time-frequency analysis.

To significantly enhance the performance of polymeric insulator, the analysis of LC behaviors under different conditions can be monitored. In order to get an accurate picture of the insulator performance and surface activity, field measurement are required.

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