Surface Discharge Detection with Ultra High Frequency Loop Antenna Sensor

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Abstract: UHF loop antenna sensors have been widely used for detecting partial discharges (PD) in high-voltage (HV) systems, their application in detecting surface discharges (SD) remains underexplored. Current technologies primarily focus on detecting bulk discharge events, leaving a significant gap in understanding the effectiveness of loop antennas for surface discharge detection. Surface discharges exhibit distinct electromagnetic characteristics that require optimized detection methods. This study investigates the use of loop antennas as Ultra High Frequency (UHF) sensors for detecting surface discharges on glass-type outdoor insulators. It delves into the design, development, and evaluation of the loop antenna, focusing on its performance in identifying dominant frequencies associated with SD events. Experimental results demonstrate the antenna's effectiveness at its resonant frequencies and its capability to detect SD over varying distances. These findings suggest that loop antennas are highly sensitive and cost-effective solutions for real-time monitoring of SD activities, improving maintenance strategies and increasing the reliability of high-voltage (HV) power transmission systems.

Keywords: Surface discharge; high voltage; UHF sensor; leakage current; insulator

1. Introduction

Power systems rely on effective insulation to ensure the consistent and safe transmission of electrical energy [1]. Outdoor insulators are critical to the reliability of power networks. However, surface discharges (SD) on these insulators can gradually affect the material, resulting in probable failures and decreased reliability. Timely detection of SD is essential to prevent unexpected equipment failures and improving the overall safety and durability of high-voltage (HV) systems.

Environmental factors, such as pollution and moisture, can lead to the formation of surface discharge on insulators [2, 3]. These surface discharges can degrade the insulating material, leading to increased risk of insulation failure and flashover, which can disrupt power transmission. Over time, surface discharge can cause significant damage to insulators, reducing their efficiency and lifespan. There has been extensive research into the performance of outdoor high voltage insulator in high polluted environments.

SD poses a significant threat to the insulation system's performance and longevity. SD is characterized by localized breakdowns occurring at or near the surface of the insulating material. It is often associated with leakage currents that result from the accumulation of contaminants on the insulator's surface [4].

Conventional methods for detecting SD on outdoor insulators have limitations in terms of sensitivity and real-time monitoring capabilities [5, 6]. The IEC 60270:2000 defines standard conventional method for detecting PD which requires an electrical connection through a coupling capacitor connected in parallel with the monitored equipment [7]. These methods are restricted by large physical dimensions for high voltage applications and impracticality for continuous monitoring due to their invasive nature [8].

UHF signals are known to be generated during PD events [9]. Research has discussed on the development of UHF sensor for detecting PD in high voltage equipment focusing on various UHF antennas and their suitability for PD diagnostics [10-12]. Factors such as detection range, directional characteristics, and ease of fabrication are considered. The UHF technique utilizes the electromagnetic signals emitted during surface discharge events with frequencies ranging from hundreds of megahertz to gigahertz and can be captured using suitable sensors and

Received: April 10th, 2025. Accepted: June 7th, 2025
DOI: 10.15676/ijeei.2025.17.2.7

instrumentation [13]. This method offers several advantages, including real-time monitoring, enabling prompt detection of incipient discharge events [14]. Additionally, the non-intrusive nature of the UHF monitoring minimizes the impact on the insulator's normal operation [15, 16]. This research contributes to the development of effective diagnostic tools for the proactive management of outdoor insulators, helping to prevent catastrophic failures and improving the reliability of power systems[17, 18]. A comparative analysis of shunt resistor, IMC and loop antenna techniques under varying voltages conditions is presented, providing insights by quantitatively correlating frequency shifts and bandwidth variations to discharge intensity and sensor sensitivity to improve UHF-based SD detection accuracy.

2. Methodology

A. Development of loop antenna as UHF sensor

Antenna is used as a sensor to detect EM waves radiated by the discharge source. Fig. 1 shows the completed wired loop antenna. The materials required for this construction of wired loop antenna include a 1-meter length of coaxial cable (such as RG-58), a ferrite core for the balun, enamel-coated copper wire suitable for high-frequency applications, a soldering iron and solder, heat shrink tubing, BNC connector, and wire strippers and cutters.

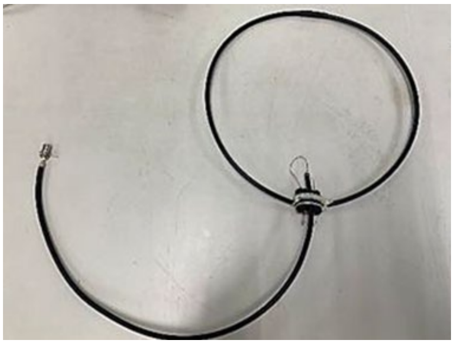


Figure 1. A wired loop antenna

For a loop antenna, the resonant frequency is related to the circumference of the loop, which is the total length of the wire forming the loop. The fundamental resonant frequency occurs when the circumference of the loop is approximately equal to one wavelength of the signal. The circumference, C of a circular loop is related to its diameter, D by the formula $C = \pi D$. Therefore, the resonant frequency can be expressed in terms of the diameter.

Given:

- Circumference of loop antenna, $C = 1$ m

  The relationship between the circumference, C=1 m and the diameter, D of a circle is given by:

$$C = \pi D \tag{1}$$

$$D = \frac{C}{\pi} \tag{2}$$

$$D = 0.318m$$

Given:

- Diameter of loop antenna, $D = 0.318$ m
- Speed of light, $c \approx 3 \times 10^8$ meters per second. The resonant frequency, f is given by:

$$f = \frac{c}{\pi D} \tag{3}$$

$$f = \frac{3 \times 10^8}{\pi \times 0.318}$$

$$f \approx 3 \times 10^8 \approx 300\ MHz$$

Therefore, the resonant frequency of a loop antenna with a diameter of 0.318 m is approximately 300 MHz.

B. Evaluation on frequency range of developed loop antenna

Fig. 2 illustrates the measured S11 parameters(magnitude in dB) of a loop antenna design obtained using a network analyzer. The S11 parameter, also known as the reflection coefficient, reveals how much power is reflected back from the antenna, a critical factor for determining its impedance matching and overall efficiency. The plot displays the amplitude of the S11 parameter across a frequency range from 10 MHz to 1 GHz.

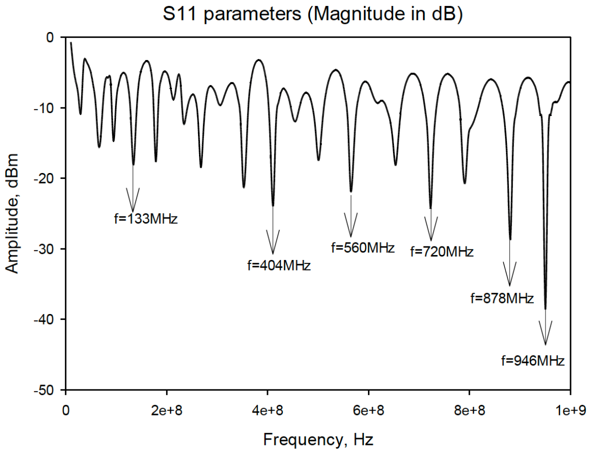


Figure 2. S11 results from measurement of loop antenna

From the results of S11 parameters shown in Fig. 2, the deepest dip on the graph is at 946 MHz, indicating the frequency at which the antenna has the best impedance match. At this frequency, reflection is minimized, suggesting that most of the power is transmitted rather than reflected, making 946 MHz the optimal operating frequency for this loop antenna design. SD events that occur at this frequency can be effectively detected by the antenna.

SD events typically generate electromagnetic emissions that span a range of frequencies. An antenna operating at its resonant frequency is most sensitive to signals at that frequency. Therefore, if the resonant frequency of the loop antenna aligns with the frequency spectrum of SD events, the antenna will efficiently detect these events. Furthermore, the presence of multiple resonant frequencies enhances the antenna's ability to cover a broader frequency spectrum, making it suitable for detecting a wider range of SD events and their harmonics. The network analyzer's measurements illustrate the antenna's performance characteristics across the specified frequency range, demonstrating its capability to detect surface discharge events at these optimal frequencies.

C. Verification of frequency transmission-loop antenna (receiver) and S11 parameter analysis

A signal generator was connected to the transmitter antenna to inject a specified frequency. The transmitter antenna then transmitted this frequency to the receiver antenna, which was positioned at a measured distance. In this project, a loop antenna was used as the receiver antenna. The loop antenna received the transmitted signal and was connected to a signal analyzer to verify the received frequency. Fig. 3 depicts the setup for frequency injection from transmitter to receiver antenna.

The verification process involved comparing the frequency value displayed on the signal analyzer with the injected frequency from the signal generator. A match between these frequencies confirmed that the loop antenna successfully received the transmitted frequency.

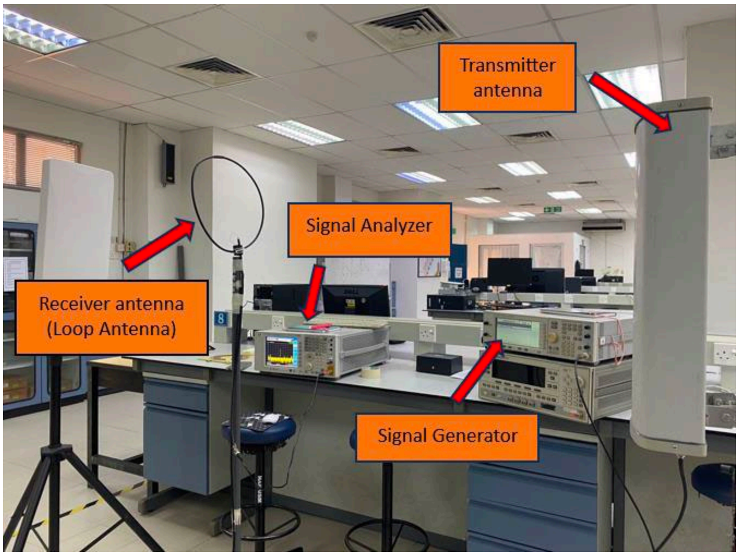
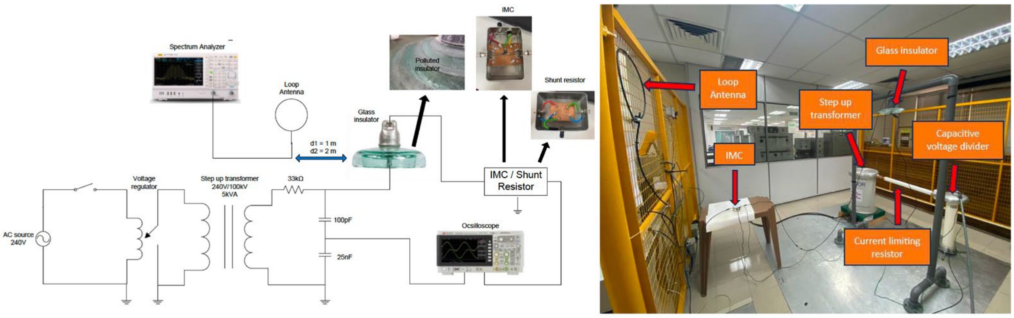


Figure 3. Setup for frequency injection from transmitter to receiver antenna

D. Experimental setup

Fig. 4(a) illustrates the schematic circuit diagram of the experimental setup, whereas Fig. 4(b) depicts the SD experiment configuration within the HV laboratory. A 240V, 50Hz input voltage was fed to a voltage regulator, with a circuit breaker in between to protect against overload or short circuit. A 5kVA step-up transformer is used to increase the voltage source. The voltage regulator controlled the voltage supplied to the transformer. In the experiment, the applied voltage was 4.5kV and a 33kΩ current limiting resistor was used to keep the current below 0.1A, limiting potential short circuit currents [19, 20] .



(a) (b)

Figure 4. (a) Schematic circuit diagram and (b) SD experiment in HV laboratory

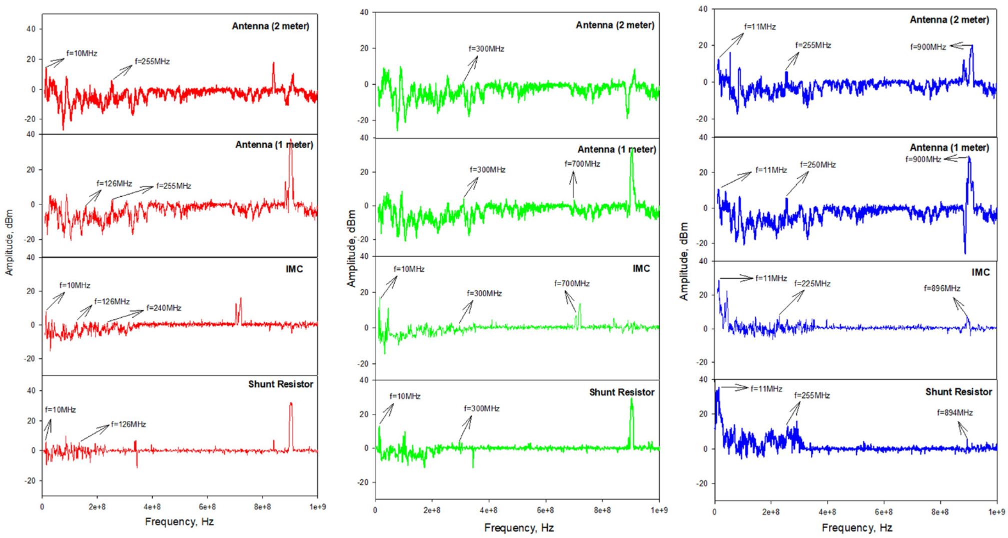
A capacitive voltage divider, with a ratio of 1000:1, scale down the high voltage signals for safe measurement by an oscilloscope, which has a voltage input limit of 400V. The high voltage from the transformer's secondary winding was connected to the pin end of the glass insulators, designed to support high voltage cables. The cap end of the insulator was connected to the grounding system for safety, providing a controlled path to the ground for any fault current or induced voltages.

A NaCl solution with an ESDD level of 0.5 mg/cm² was used to create leakage current on the insulator by spraying it on the surface of glass insulator based on IEC 60507:2013 [21]. The shunt resistor and IMC are used as SD detection devices, measured by an oscilloscope and a spectrum analyzer, to observe the SD events. These methods serve as reference points for detecting SD events with the loop antenna. The antenna is connected with spectrum analyzer to record SD events emitted due to the occurrence of leakage current on glass insulator.

3. Results and discussion

Fig. 5(a)-(c) shows the frequency spectrum of SD events when tested with shunt resistor, IMC, and loop antenna at 5 kV, 13 kV and 17 kV applied voltages of respectively. Numerically, the loop antenna recorded the highest amplitude signals, with dominant frequencies shifting from approximately 255 MHz at 5 kV to 900 MHz at 17 kV, increasing by a factor of 3.5. In comparison, the shunt resistor and IMC serve as reference points for the loop antenna, showed frequency increases with voltage, but the loop antenna demonstrated greater sensitivity to higher frequency signals generated by more intense SD. The SD spectra results shown in the figures after the filtration of background noise.

Fig. 6 illustrates the frequency bandwidth at 17 kV applied voltage, comparing the calculated frequencies with the measured frequencies of SD events on polluted insulator. Based on Fig. 6, the frequency of 11 MHz is the only value that remains consistent across both calculated and measured frequency bandwidth. Additionally, the SD spectra at 11 MHz, 255 MHz, and 900 MHz were consistently detected by all SD measurement devices; shunt resistor, IMC and loop antenna. Nevertheless, these frequencies; 255 MHz and 900 MHz, were not detected by oscilloscope through rise time measurement. This is likely due to the small magnitude of SD events at these frequencies. Despite the discrepancy between measured and calculated value, the consistency of these frequencies across various measurement techniques confirms their accuracy as dominant frequencies of SD events.



(a) (b) (c)

Figure 5. (a)-(c): SD spectra at 5kV, 13kV, 17kV applied voltage

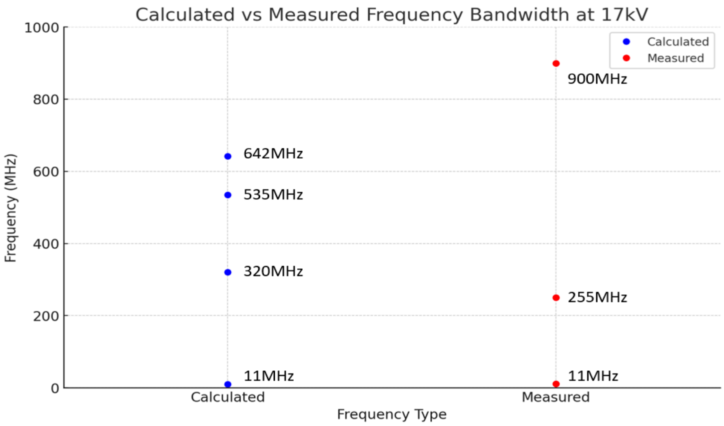


Figure 6. Frequency bandwidth at 17kV applied voltage

On the other hand, the calculated frequencies, while present in the spectrum, does not stand out as a dominant frequency. This is because, despite its association with high-magnitude SD events as observed with the oscilloscope, it occurs less frequently compared to lower- magnitude events. When analyzed with a spectrum analyzer, this frequency appears as a subtle signal rather than a prominent one, yet it remains relevant for a thorough understanding of SD events. Thus, the dominant frequencies of SD events are 11 MHz, 255 MHz, and 900 MHz.

Besides, those frequencies detected by loop antenna are close to its resonant frequencies, making it more effective at detecting SD events that occur around these resonant frequencies. Furthermore, the loop antenna's performance over a distance of 2 meters was also measured. We observe that even with the increased distance between the glass insulator and the loop antenna, the signal strength of SD events remained detectable. The antenna's ability to detect numerous SD events at its resonant frequencies, even over an increased distance, suggests that it is highly sensitive.

4. Conclusion

The optimized loop antenna shape significantly influences frequency response characteristics such as bandwidth, return loss and resonant frequency, enhancing SD detection across a broad frequency range and at extended distances through integration with multiple sensor techniques. The results show that the dominant frequencies of the SD spectra are 11 MHz, 255 MHz, and 900 MHz. Additionally, SD spectra tested with the loop antenna, which was simultaneously connected with the IMC and shunt resistor, not only captured a wide range of frequencies but also showed SD events radiated very effectively at the antenna's resonant frequency. The antenna continued to detect surface discharge (SD) events effectively at 2 meters, with minimal reduction in signal strength compared to measurements taken at 1 meter.

5. Acknowledgment

Appreciation and gratitude are to be given to the authority of the School of Electrical and Electronics Engineering University Sains Malaysia for providing the materials and guidance to complete the project. The research and implementation of the project would never be completed without the facilities provided by the school.

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