IUST
Iran University of Science and Technology

Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Ultra-high Frequency Sensor for Partial Discharges Detection in High Voltage Substation

Sharulnizam Mohd Mukhtar *, Muzamir Isa*(C.A.) and Azremi Abdullah Al-Hadi*.

Abstract: The development of advanced diagnostic tools is critical for the effective monitoring and management of electrical insulation systems. This paper presents the development of an Ultra High Frequency (UHF) sensor designed for the detection of partial discharges (PD) within high-voltage substations. The study focuses on the sensor's technical development, encompassing design considerations, fabrication processes, and initial performance evaluations in laboratory settings. The engineering principles underlying the sensor design are detailed, including the selection of innovative materials that enhance sensitivity and frequency response. The sensor configuration is tailored to optimize the detection of PD signals, with adjustments made based on simulated PD scenarios. Initial testing results demonstrate the sensor's capability to detect a range of PD activities, showcasing its potential effectiveness in real-world applications. The sensor's performance is analyzed through a series of controlled lab experiments, which confirm its high sensitivity and broad operational frequency range. This paper not only illustrates the technical specifications and capabilities of the newly developed UHF sensor but also discusses its practical implications for improving the reliability and efficiency of PD monitoring systems in electrical substations.

Keywords: Partial Discharge; UHF Sensor; Antipodal Vivaldi Antenna.

1 Introduction

DETECTING and managing partial discharges (PD) is crucial for ensuring the reliability and safety of high voltage substations. PDs are localized electrical discharges that occur within insulation systems of equipment, indicating potential insulation defects that could lead to equipment failure and disruptions in power supply. Traditional methods of PD detection, such as acoustic, electrical, and optical techniques, have limitations in terms of sensitivity and accuracy, particularly in complex substation environments where electromagnetic interference (EMI) is prevalent [1].

Electrical methods are foundational in PD detection, utilizing sensors to measure the discharge currents directly or indirectly. These methods can capture the fast transient currents associated with PD events through the use of high-frequency current transformers (HFCTs). For instance, a comprehensive analysis by Uwiringiyimana et al., [2] showcased how HFCTs were utilized to detect PD in power cables under varying environmental conditions, demonstrating their robustness and reliability across a spectrum of operational scenarios.

Acoustic methods detect the sound waves produced by PD events [3]. These waves are typically captured using highly sensitive microphones or ultrasonic detectors positioned near or around the insulation system. A study by Xie et al., [4] utilized an array of ultrasonic sensors to pinpoint the location of PDs within transformer systems. Their approach effectively mapped the PD source by

Iranian Journal of Electrical & Electronic Engineering, 2025.
Paper first received 25 Dec. 2024 and accepted 22 Feb. 2025.
* The author is with Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau Perlis, Malaysia.
E-mails: sharul@unimap.edu.my, muzamir@unimap.edu.my, azremi@unimap.edu.my.
Corresponding Author: Muzamir Isa.

analyzing the time delay between sensor activations, illustrating the technique's potential in complex industrial settings.

Optical methods involve detecting the light emissions produced during PD events. Photomultiplier tubes, charged-coupled devices (CCDs), or newer technologies like optical fibers are employed to capture these emissions. A novel fiber-optic PD sensor, as reported by Liu et al., [5] enhances detection capabilities by converting high-energy photons into visible light, which is easier to detect and analyze. Their experiments showed promising results in detecting PD in underground high-voltage cables.

Chemical detection analyzes the composition of gases released during PD events in insulation oil. Techniques like Gas Chromatography-Mass Spectrometry (GC-MS) are utilized to detect gases like hydrogen and methane, which are by-products of PD. A notable example by Mehmood et al., [6] demonstrated how GC-MS could effectively predict insulation degradation in transformers, providing a preventive tool for maintenance before catastrophic failures occur.

UHF sensors detect the electromagnetic emissions produced by PD within the UHF spectrum. This method is particularly useful in enclosed systems like gas-insulated switchgear (GIS). A key study by Liang et al., [7] highlighted the use of UHF sensors in a GIS setup, combining sensor data with machine learning algorithms to improve the accuracy of PD prediction and localization.

Recent advancements in ultra-high frequency (UHF) sensor technology offer promising solutions to overcome these challenges. UHF sensors operate within the frequency range of 300 MHz to 3 GHz, where PD signals exhibit distinct electromagnetic characteristics that can be effectively detected and analyzed [8]. Unlike traditional methods, UHF sensors can penetrate insulation materials with minimal attenuation, allowing for precise localization and characterization of PD activity across various substation components as reports by Álvarez et al., [9]. The effectiveness of UHF sensors lies in their ability to capture and interpret electromagnetic waves emitted during PD events. These sensors typically employ compact antennas and sophisticated signal processing algorithms to distinguish PD signals from background noise and other electromagnetic interferences present in substations [10]. By leveraging advancements in antenna design and signal processing techniques, UHF sensors can offer enhanced sensitivity and reliability in detecting early signs of insulation degradation, thereby facilitating proactive maintenance and reducing the risk of unexpected failures [11].

Furthermore, UHF sensors enable non-intrusive monitoring of high voltage equipment, minimizing the need for physical contact during inspections and enhancing the safety of maintenance personnel [12]. Real-time data acquisition and analysis capabilities of UHF sensors also support continuous monitoring of substation assets, providing actionable insights for optimizing maintenance schedules and extending the operational lifespan of critical infrastructure [13]. The development and deployment of UHF sensors represents a significant advancement in the field of PD detection for high voltage substations. As the demand for reliable and efficient power supply continues to grow, the role of UHF sensors in enhancing substation reliability and reducing operational risks becomes increasingly indispensable [14].

Despite these advantages, existing UHF sensor technologies often face challenges related to sensitivity, specificity, and adaptability to diverse operational environments [15]. The development of a UHF sensor with enhanced sensitivity and broader frequency range could significantly improve the effectiveness of PD detection systems, providing earlier warnings of insulation failures and reducing the risk of unexpected maintenance issues [16]. A real-time UHF PD monitoring system, as documented by [17] has demonstrated significant improvements in operational efficiency and safety in various high-voltage applications. Safety improvements in UHF PD monitoring have also been documented by [18] showing reductions in maintenance-related accidents and enhanced detection accuracy. Continuous monitoring of substation assets using UHF sensors, as researched by [19] has been shown to optimize maintenance schedules and reduce operational costs. Moreover, optimizing maintenance schedules with UHF sensors has extended the operational lifespan of critical infrastructure, demonstrating the practical benefits of these advanced detection systems.

This article reports on the design, development, and testing of a new UHF sensor specifically engineered to address these challenges. By leveraging advanced materials and innovative design strategies, this sensor aims to surpass the performance of current market offerings in terms of sensitivity and detection capabilities. The objective of this research was not only to develop a sensor that can reliably detect PDs under various conditions but also to characterize its performance in a controlled environment to validate its potential for broader application in real-world high-voltage substations.

2 Methodology

The methodology began with the development of an Ultra High-Frequency (UHF) sensor for Partial

Discharge (PD) detection, encompassing both the design and simulation phases. The initial design and modeling tasks were carried out using Antenna Magus, a commercial software tool that streamlined the efficient creation and simulation of UHF sensors. CST Studio Suite® was subsequently employed to simulate the validated and loaded UHF sensor model. Following the simulation and analysis of the results, the prototyping phase of the UHF sensor was initiated.

The validation process for the UHF sensor involved a comparative analysis between the experimental data and the modeling results. Following this, a filter and amplifier circuit were constructed. Prior to fabrication, the circuits compatible with the UHF sensors were modeled using PSIM software. The analysis phase included a comparison between the simulation results and those obtained from the actual circuit.

Finally, the performance of the UHF sensor was rigorously assessed and analyzed to achieve the primary objectives of the study. The capabilities of the UHF sensor were benchmarked against other sensor models to identify the presence of PD. The proposed UHF sensor underwent several modifications to enhance detection accuracy.

2.1 UHF Sensor Design and Development

There are two primary methods to achieve the desired sensor design. The first method involves directly designing the sensor within the CST software. The second method utilizes computer-aided design (CAD) software to create sensor design, which is then imported into CST software. Figure 1 illustrates the modeling of a UHF sensor using CST software.

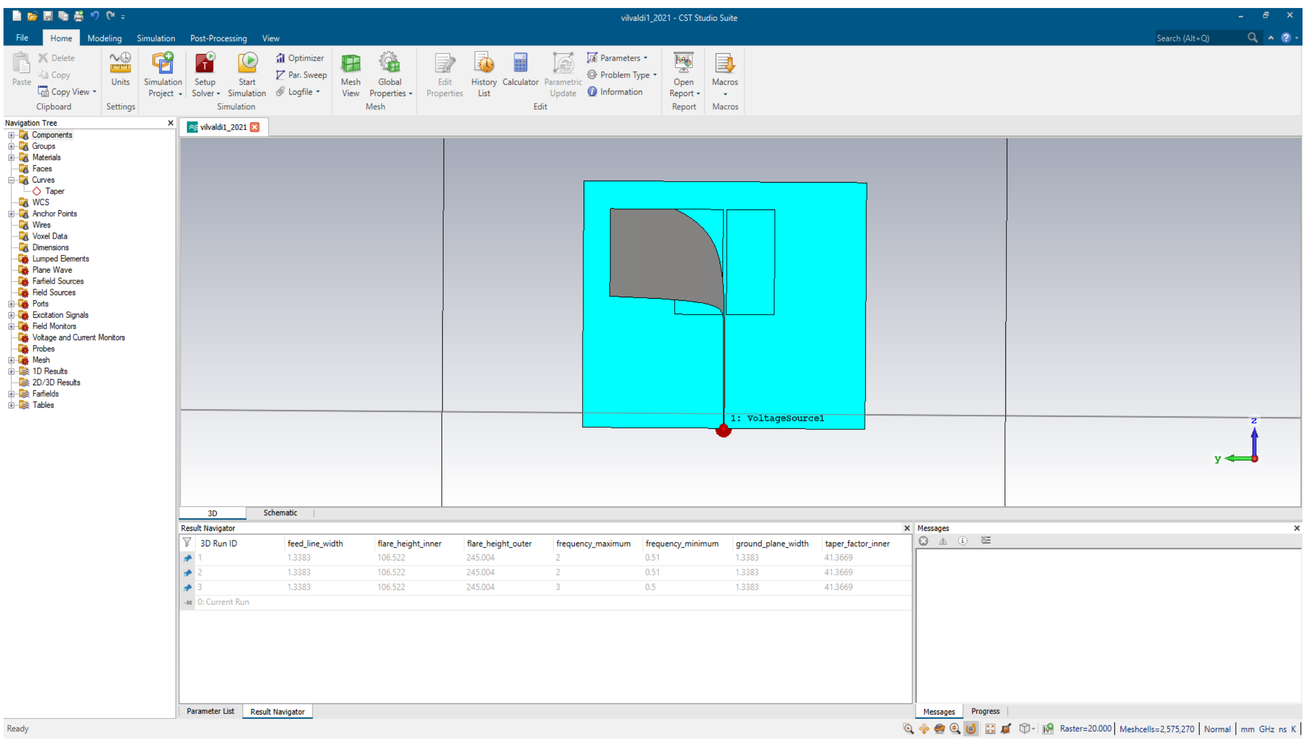


Fig 1. CST Design Studio® software design environment.

Upon completing the simulation process, various results can be obtained in the post-processing stage. The predefined parameters for the sensor can be directly modified within the CST software, allowing for immediate comparison of the results. This facilitates effective optimization of the sensor design.

In Ultra High-Frequency (UHF) networks, the accuracy of partial discharge (PD) detection is often compromised by interference from digital radios, televisions, telecommunications signals, and periodic pulses from switching operations.

To mitigate these disturbances, there is a need for a UHF sensor that possesses a wide bandwidth yet has the capability to selectively reduce interference at specific frequencies, such as those associated with mobile phone networks. Consequently, this study proposes the use of a Vivaldi design antenna, which is known for its wideband and high-gain characteristics, as the UHF sensor.

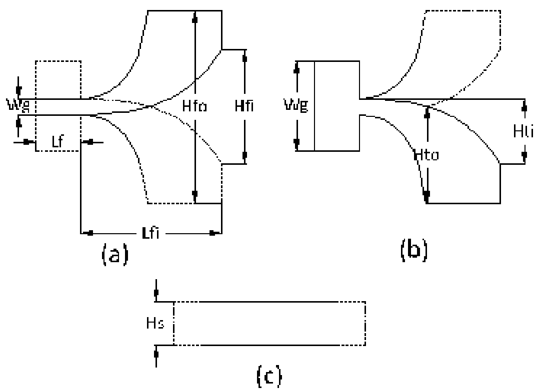


Fig 2. (a) Geometry of a top view of the UHF sensor (b) Geometry of a bottom view of the UHF sensor (c) Geometry of a side view of the UHF sensor

The antipodal Vivaldi antenna (AVA), also referred to as the dual exponentially tapered slot antenna (DETSA), belongs to the category of end-fire tapered slot antennas (TSAs) [20]. This category includes antennas with constant width (CWSA), linear tapering (LTSA), and exponential tapering (ETSA), the latter being commonly known as Vivaldi antennas. Vivaldi antennas are extensively utilized in wireless and radar applications due to their wide bandwidth, low cross-polarization, and highly directive radiation patterns. The geometry of a UHF sensor is illustrated in Figure 2.

To optimize the efficiency of the UHF sensor, this study will meticulously examine the effects of various antenna parameters, such as dimensions and the thickness of printed circuit boards, using CST Design Studio® software. This parametric investigation aims to identify the optimal antenna parameters for future implementations. The UHF sensor comprises a substrate with copper layers on both sides, divided into the balun and radiation sections. The dielectric substrates are metalized, and the flares on both sides of the substrate taper exponentially. The equations defining the inner and outer profiles of the antenna are as follows:

$$y = C_1 e^{ax} + C_2 \qquad (1)$$

were

$$C_1 = \frac{y_2 + y_1}{e^{ax_2} - e^{ax_1}} \mathrm{e} \qquad (2)$$

and

$$C_2 = \frac{y_2 e^{ax_2} - y_1 e^{ax_1}}{e^{ax_2} - e^{ax_1}} \qquad (3)$$

where x1, x2, y1, y2 represent the initial and final x and y coordinates of the taper profiles, whereas C denotes the speed of light. The parameter values for the UHF sensor, obtained through optimization and based on the information described above and Equation (1), are provided in Table 1.

Table 1 Design parameters of the UHF Sensor.

Modeling parameters	Dimensions (mm)
Inner flare height, Hfi	106.5
Outer flare height, Hfo	245.0
Inner flare length, Lfi	210.0
Outer flare length, Lfo	120.0
Ground plane width, Wf	1.338
Feed line width, Wg	1.338

2.2 Fabrication of the UHF Sensor

Several antenna designs using various sets of parameters were produced using FR4 type printed circuit board (PCB). This process involved antenna design using computer-aided design (CAD) software, film production for PCB fabrication, and etching processes. Figure 3 depicts a flow chart illustrating the various procedures employed in the manufacture of UHF sensors. A mask was first produced to create a PCB with a UHF sensor. The circuit was then designed accurately using CAD software to produce an accurate mask. Two patents were required, one for each side of the PCB. Additionally, a marker was included in the design to ensure that the two masks were aligned. Later in the etching process, these markings were eliminated.

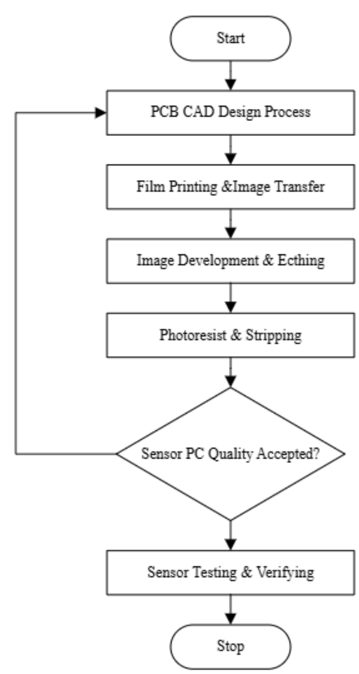


Fig 3. Flowchart of UHF sensor fabrication

Finally, two layouts were printed on top of the waterproof inkjet film AccuBlack™ 100P. These films were created exclusively to manufacture high-quality film positives and negatives, making them the ideal choice for the development of artwork photo tools for graphics and PCB production. The coating on the film enabled the production of a dense image without the ink bleeding. Additionally, the film was compatible with inkjet printers that employed dye-based ink.

The following procedure was the image transfer from printed film to a double-sided printed circuit board. This procedure consisted of three steps: applying the photoresist, exposing it, and developing it. Photoresists were applied to the PCB surface using heat and pressure. This procedure could be carried out using either a hot roll or a cut sheet laminator. Then, using a screen-printing process, the PCB and PCB films were aligned and exposed to high-intensity UV light for 30 seconds for each negative and positive print. The PCB film's clear portions or exposed areas let light flow through and polymerize (harden) the film resist, resulting in an image of the circuit panel (similar to a negative of a photograph). After holding the exposed PCBs for 15-20 minutes, they were developed in a conveyorized development process.

Following that, image development was carried out in a developer solution. The developer dissolved the resist in exposed places (those beneath the opaque PCB covering), exposing the copper layer beneath. In comparison, the polymerized portions that were exposed (clear parts) retained their integrity. The board was then cleaned thoroughly with water, dipped in 10% sulfuric acid, and rinsed thoroughly with water.

Following that, the etching procedure began. Etching was a critical stage in the subtractive PCB process's chemical processing. The final copper pattern (signal trace) was created using this method by selectively removing any undesirable copper (areas not covered by the dry film resist) while retaining the appropriate antenna patterns. Etching eliminated copper that was not covered by an etch resist. Etching was commonly carried out using conveyorized equipment that consisted of a primary spray chamber, an etchant flood rinse, and numerous cascading water rinses. The conveyor speed was designed so that the entire etching process could be completed in a single feed. The free rotation of rollers and the presence of blocked nozzles were verified. A sufficient amount of water was sprayed. Etchant (ferric chloride solution) sprayed across the panel's surface dissolved the visible copper but not the copper beneath the resist. This etching resulted in the formation of a copper circuit. The etching was consistent across the entire circuit board. Any copper that had been taken from the edges was removed by hand etching. After that, the boards were carefully cleansed under running water.

Finally, following etching, the photoresist was stripped. The stripping was carried out in batches in a stripping tank. For 5-10 minutes, the etched boards were immersed in a sodium hydroxide solution. After removing the boards, they were cleaned and dried with water. The finished constructed PCB was next rigorously scrutinized for cuts, shorts, and under or over-etching.

2.3 Experiment Setup

In this experiment, the Partial Discharge (PD) calibrator CAL 542 from Omicron served as the PD source. This tool acts as a test setup calibration to ensure IEC 60270 compliant PD measurements on various electrical assets. This PD source was connected to the terminal of a 240 mm² XLPE-type power cable, and the Ultra High-Frequency (UHF) sensor was mounted on a tripod and positioned at a distance of 10 cm from the cable, as depicted in Figure 4.

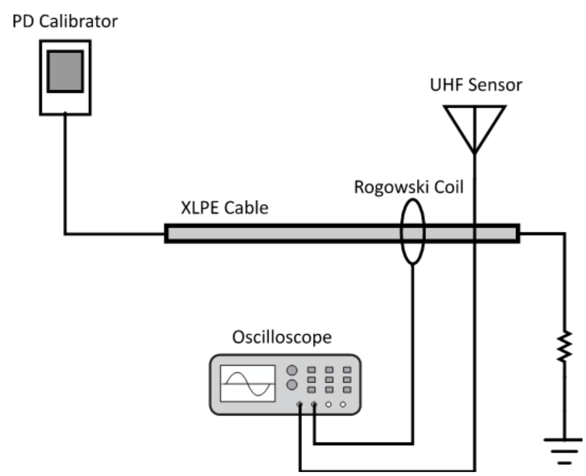


Fig 4. Experiment setup for UHF sensor

To establish a correlation between the electromagnetic (EM) signal detected by the UHF sensor and the PD phenomenon, the signals from both the UHF sensor and the Rogowski coil sensor were concurrently recorded using a digital oscilloscope (Teledyne Lecroy Wavesuffer 3024) with a sampling rate of 4 GS/s. To assess the efficacy of the newly designed UHF sensor, its performance in detecting PD was compared with Rogowski coil sensor and evaluated across seven different PD range of pico-coulombs (pC).

3 Result

The performance of the proposed UHF sensor was evaluated through a series of measurements, as illustrated in Figures 5 through 8. The Voltage Standing Wave Ratio (VSWR), a measure of how much power is reflected by the antenna, should be less than 2 to meet the bandwidth requirements. As shown in Figure 5, the VSWR value for the proposed UHF sensor is below 2 across the entire frequency band, except for the range between 825 MHz and 950 MHz. Within this exception range, the VSWR slightly exceeds 2, whereas for other frequencies, the VSWR varies between 1 and 1.9.

The Reflection Coefficient (S11) parameter, indicating return loss or the amount of power reflected from the antenna, was also measured. As depicted in Figure 6, the S11 value for the proposed UHF sensor remains below -10 dB, except within the frequency range of 825 MHz to 950 MHz. This indicates efficient power transmission and minimal reflection for most of the operating frequencies.

The Gain Over Frequency of the UHF sensor was observed to increase with frequency, reaching a maximum value at 2.82 GHz before decreasing at higher frequencies, as shown in Figure 7. Despite a lower gain of approximately 2.3 dB at the lower frequency range, the antenna maintains its ability to radiate effectively. The radiation pattern of the UHF sensor at various frequencies is presented in Figure 8. The solid line represents the H plane, while the dotted line represents the E plane. The sensor exhibits good directivity at frequencies of 3 GHz, 2 GHz, and 1.5 GHz. However, at 0.5 GHz, the pattern indicates an omnidirectional radiation characteristic.

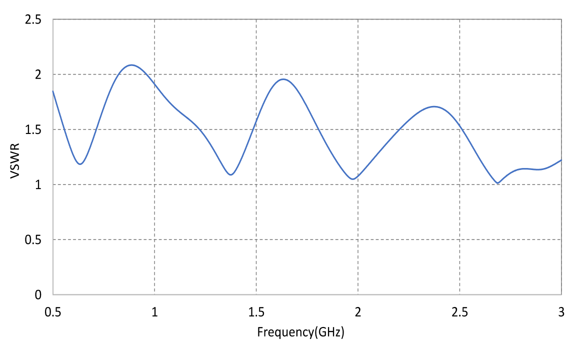


Fig 5. Voltage standing-wave ratio (VSWR) of the UHF sensor

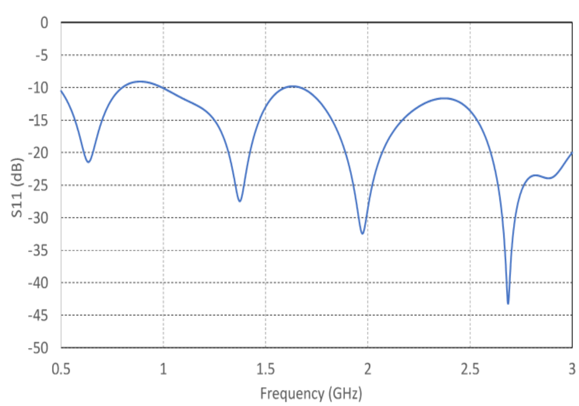


Fig 6. .S11 parameter result of the UHF sensor

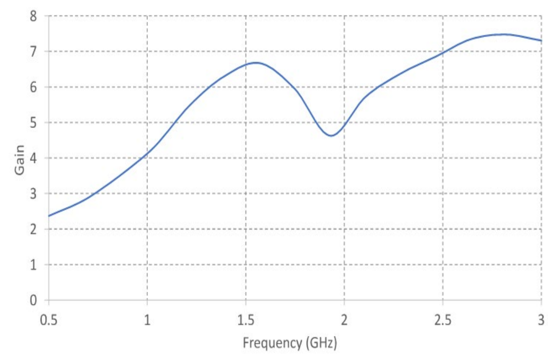


Fig 7. Result of Gain versus frequency of the UHF sensor

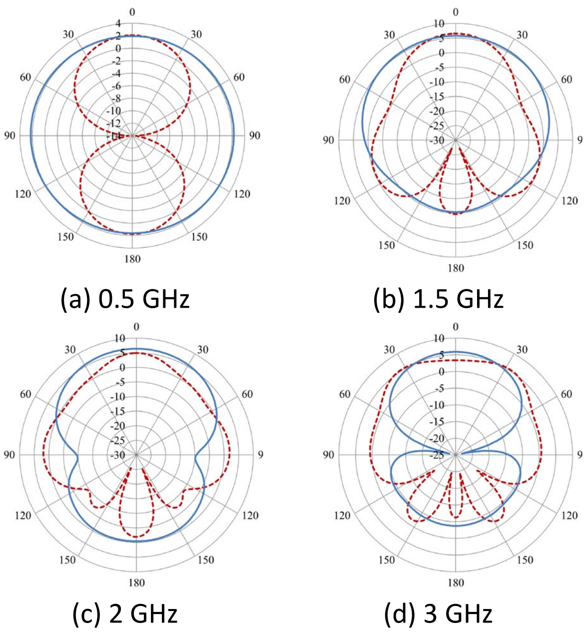


Fig 8. Result of the radiation pattern of the UHF sensor at different frequencies

Figure 9 shows the typical PD signal at 50 pC captured by both the Rogowski coil and the UHF sensor. The captured waveforms demonstrate the ability of both sensors to detect PD impulses. The Rogowski coil signal serves as a reference to pinpoint the occurrence of the PD event. The similarity between the waveforms captured by the different sensors indicates the high sensitivity of the UHF sensor.

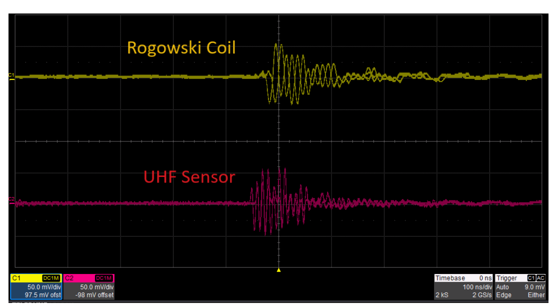


Fig 9. PD signal captured by UHF sensor and Rogowski coil sensor at 50 pC

4 Conclusion

The development and deployment of the new Ultra High-Frequency (UHF) sensor for partial discharge (PD) detection in high voltage substations marks a significant advancement in the field of electrical engineering. This research addressed the limitations of traditional PD detection methods by leveraging the distinct electromagnetic characteristics of PD signals within the UHF spectrum. The UHF sensor demonstrated superior sensitivity and reliability in detecting and localizing PD activities, thanks to its advanced design, sophisticated signal processing algorithms, and non-intrusive monitoring capabilities.

The methodology employed in this study—from sensor design and simulation using CST Studio Suite® and Antenna Magus, to the construction and validation phases—proved effective in developing a sensor with enhanced performance. The innovative use of the Vivaldi design antenna, characterized by its wide bandwidth and high-gain properties, enabled the UHF sensor to mitigate interference from various external sources, such as digital radios and mobile phone networks. This capability is crucial for ensuring accurate PD detection in complex substation environments. Experimental results showcased the UHF sensor's excellent performance across various metrics, including Voltage Standing Wave Ratio (VSWR), Reflection Coefficient (S11), Gain Over Frequency, and radiation patterns. The sensor maintained a VSWR below 2 across most of the frequency bands, except for a slight increase between 825 MHz and 950 MHz. Additionally, the S11 values indicated efficient power transmission, while the gain and radiation pattern results confirmed the sensor's ability to radiate effectively and exhibit good directivity. Comparative analysis with the Rogowski coil sensor further validated the UHF sensor's high sensitivity and accuracy in detecting PD impulses. The waveforms captured by both sensors at 50 pC demonstrated the UHF sensor's capability to detect PD events reliably, thus confirming its potential for broader application in real-world high-voltage substations.

In conclusion, the newly developed UHF sensor not only enhances the sensitivity and accuracy of PD detection but also offers significant advantages in terms of non-intrusive monitoring, safety, and real-time data acquisition. This research contributes to the ongoing efforts to improve the reliability and safety of high-voltage substations by providing a robust tool for early detection and proactive maintenance of insulation systems. Future work could focus on further optimizing the sensor design and exploring its applications in various operational environments to fully harness its potential in enhancing substation reliability and reducing operational risks.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

Sharulnizam Mohd Mukhtar: Research & Investigation, analysis and original draft preparation. Muzamir Isa: Supervision, revise and editing. Azremi Abdullah Al-Hadi: Supervision, revise and editing. Each author has read and agreed to the published version of the manuscript.

Funding

The authors acknowledge the financial support provided by the Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP) under FKTE research fund.

Acknowledgment

The authors wish to thank Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP). This work was supported in part by a grant FKTE research fund.

References

[1] Cichecki, Piotr, Edward Gulski, J.J. Smit, T. Hermans, R. Bodega, and P.P. Seitz. 2009. "Conventional and Unconventional Partial Discharges Detection in Power Cables Using Different AC Voltages." In 2009 IEEE Electrical Insulation Conference, 5–9. https://doi.org/10.1109/EIC.2009.5166316.

[2] Uwiringiyimana, Jean Pierre, Umar Khayam, Suwarno, and Gian Carlo Montanari. 2022. "Comparative Analysis of Partial Discharge Detection Features Using a UHF Antenna and Conventional HFCT Sensor." IEEE Access 10:107214–26. https://doi.org/10.1109/ACCESS.2022.3212746.

[3] Kalathiripi, Hussain, and Subrata Karmakar. 2017. "Partial Discharge Study in Transformer Oil Using Acoustic Emission Technique and UV-Visible Spectroscopy." In 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), 361–66. https://doi.org/10.1109/CATCON.2017.8280245.

[4] Xie, Qing, Shuyi Cheng, Fangcheng Fangcheng Lü, and Yanqing Li. 2013. "Location of Partial Discharge in Transformer Oil Using Circular Array of Ultrasonic Sensors." IEEE Transactions on Dielectrics and Electrical Insulation 20 (5): 1683–90. https://doi.org/10.1109/TDEI.2013.6633698.

[5] Liu, Zhiheng, Yongqing Wang, Xiao Chen, Xiaokai Meng, Xiuling Liu, and Jianquan Yao. 2021. "An Optical Fiber Sensing Method for Partial Discharge in the HVDC Cable System."

International Journal of Electrical Power & Energy Systems 128:106749. https://doi.org/10.1016/j.ijepes.2020.106749.

[6] Mehmood, Muhammad Ali, Jian Li, Huang Zhengyong, Feipeng Wang, M. Shoaib Bhutta, Xudong Li, and Jawad Ahmad. 2018. "Study of Field Aged Transformer Insulation Oil Properties Using GC-MS." In 2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE), 1–4. https://doi.org/10.1109/ICHVE.2018.8642174.

[7] Liang, Rui, Shenglei Wu, Peng Chi, Nan Peng, and Yi Li. 2019. "Optimal Placement of UHF Sensors for Accurate Localization of Partial Discharge Source in GIS" Energies 12, no. 6: 1173. https://doi.org/10.3390/en12061173.

[8] Jahangir, Hamid, Asghar Akbari, Peter Werle, Mohammad Akbari, and Janusz Szczechowski. 2017. "UHF Characteristics of Different Types of PD Sources in Power Transformers." In 2017 Iranian Conference on Electrical Engineering (ICEE), 1242–47. https://doi.org/10.1109/IranianCEE.2017.7985232.

[9] Álvarez, Fernando, Fernando Garnacho, Javier Ortego, and Miguel Ángel Sánchez-Urán. 2015. "Application of HFCT and UHF Sensors in On-Line Partial Discharge Measurements for Insulation Diagnosis of High Voltage Equipment" Sensors 15, no.4:7360-7387. https://doi.org/10.3390/s150407360.

[10] Ma, Chenxi, Han Li, Wenjun Zhou, Jianhui Yu, Lingzhi Wang, Shuai Yang, and Shizhuo Hu. 2018. "Background Noise of Partial Discharge Detection and Its Suppression in Complex Electromagnetic Environment." In 2018 IEEE International Conference on High Voltage Engineering and Application(ICHVE),1–4. https://doi.org/10.1109/ICHVE.2018.8642084.

[11] Chai, Hua, B.T. Phung, and Steve Mitchell. 2019. "Application of UHF Sensors in Power System Equipment for Partial Discharge Detection: A Review" Sensors 19, no. 5: 1029. https://doi.org/10.3390/s19051029.

[12] Dennis, Graham, Miles Redfern, and Steve Pennock. 2006. "The Development of Non-Intrusive Techniques for Partial Discharge Detection on MV and EHV Switchgear." In Proceedings of the 41st International Universities Power Engineering Conference, 3:814–18. https://doi.org/10.1109/UPEC.2006.367593.

[13] Reid, Alistair. 2009. "Monitoring of Partial Discharge in Substation Equipment Using a Novel Multi-Sensor Cable Loop." In CIRED 2009 - The 20th International Conference and Exhibition on Electricity Distribution - Part 2, 1–18. https://doi.org/10.1049/cp.2009.1005.

[14] Kurrer, R., and K. Feser. 1998. "The Application of Ultra-High-Frequency Partial Discharge Measurements to Gas-Insulated Substations." IEEE Transactions on Power Delivery 13 (3): 777–82. https://doi.org/10.1109/61.686974.

[15] Pinpart, T., and M. D. Judd. 2009. "Experimental Comparison of UHF Sensor Types for PD Location Applications." In 2009 IEEE Electrical Insulation Conference, 26–30. https://doi.org/10.1109/EIC.2009.5166319.

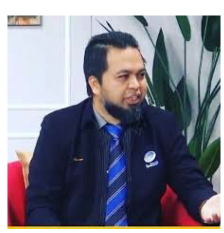
[16] Park, Seungyong, and Kyung-Young Jung. 2020. "Design of a Circularly-Polarized UHF Antenna for Partial Discharge Detection." IEEE Access 8:81644–50. https://doi.org/10.1109/ACCESS.2020.2991158.

[17] Pei, Yan, Zheng Qian, Jixi Lu, Fengtao Liu, and Xiaohu Zhao. 2015. "Development of UHF PD Monitoring System Based on FPGA." In 2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM),999–1002. https://doi.org/10.1109/ICPADM.2015.7295443.

[18] Sinaga, H. H., B. T. Phung, P. L. Ao, and T. R. Blackburn. 2011. "Partial Discharge Localization in Transformers Using UHF Sensors." In 2011 Electrical Insulation Conference (EIC)., 64–68. https://doi.org/10.1109/EIC.2011.5996117.

[19] Hu, Yue, Zijing Zeng, Jiangting Liu, Jianwen Wang, and Weidong Zhang. 2019. "Design of a Distributed UHF Sensor Array System for PD Detection and Location in Substation." IEEE Transactions on Instrumentation and Measurement 68(6):1844–51. https://doi.org/10.1109/TIM.2018.2890748.

[20] Dixit, Amruta S., and Sumit Kumar. 2020. "A Survey of Performance Enhancement Techniques of Antipodal Vivaldi Antenna." IEEE Access 8:45774–96. https://doi.org/10.1109/ACCESS.2020.2977167.



Muzamir Isa was born in Perlis, Malaysia, in 1979. He received the B.Eng. (Hons) degree in electrical engineering from University Technology Malaysia, Skudai, Johor, Malaysia, in 2001, the M.Eng. degree in electrical engineering from the Tun Hussein Onn University of Technology, Johor, in 2004, and the Ph.D. degree from Aalto University, Finland. He is currently working as Professor at University Malaysia Perlis. His research interests are partial discharge measurement, detection and location technique, and power system transient studies, including EMTP-ATP simulation.

Azremi Abdullah Al-Hadi was born on August 26 in Michigan, United States of America. He received the Master of Science degree in communication engineering from Birmingham University, United Kingdom in 2004 and the Doctor of Science in Technology degree from Aalto University, Finland in 2013. His current research interests include design and performance evaluation of multi-element antennas, mobile terminal antennas and their user interactions, and wireless propagation. He is currently working as Professor and holds position as Director at the Academic Management Centre, Universiti Malaysia Perlis.

Sharulnizam Mohd Mukhtar was born in Sabah, Malaysia, in 1976. He received the B.Eng. (Hons) degree in electrical engineering from University Putra Malaysia, Serdang, Selangor, Malaysia, in 2001, the M.Eng. degree in electrical engineering from Universiti Malaysia Perlis, Perlis, in 2012. His research interests are partial discharge measurement, detection and location techniques.