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Analysis of Array UHF Sensor for Partial Discharge Detection in Power Transformer

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ABSTRACT

Partial discharges (PD) are small electrical discharges that occur within insulation materials and can lead to equipment failure and safety hazards. The Ultra High Frequency (UHF) sensor consists of a broadband antenna and a UHF receiver, which are designed to detect and analyse the electromagnetic emissions from partial discharges. This paper presents the design and characterization of the 4th order Hilbert fractal UHF sensor for PD detection in power transformer. The sensor is designed to operate in the frequency range of 300 MHz to 3 GHz and is optimized for high gain and directivity. The performance of the sensor is evaluated using simulation and measurement techniques. Simulation results show that the sensor has directivity of 7.9 dBi and reflection coefficient below -10 dB with VSWR ≤ 5.

1. Introduction

Power transformers are critical components in power systems, and their failure can lead to expensive maintenance and operation costs. Transformer failures can be attributed to both internal and external factors as mentioned by the previous studies [1-4]. In oil-filled transformers, internal factors may include insulation issues, overheating, corrosion, solid infection in the liquid and high moisture and oxygen level. External factors such as lightning strikes and exchange processes can also contribute to transformer failures. Partial discharge (PD) is a key factor in the degradation of insulating materials within power transformers, and it represents an initial fault that occurs in high voltage (HV) equipment as taken from the previous studies [1,4-6]. Numerous studies have focused on identifying the mechanisms of PD, techniques for detecting PD, the link between PD and the

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causes of insulating material and system damage, the identification of PD sources, and the prevention of external interference by authors [4,7-9]. The insulation condition has a significant influence on the efficiency of power transformers, and early detection of any signs of impending failure is crucial.

Early detection of PD is essential to prevent further damage to high-voltage equipment. Several methods can be utilized for PD detection, including electrical, chemical, acoustic, UHF, and optical techniques. Electrical PD detection systems use conventional PD measurement circuits and instruments to test the apparent charge quantity, with an effective frequency bandwidth of less than 500 kHz by authors [5,6]. On the other hand, acoustic methods utilize an acoustic sensor to detect the acoustic emission of PD from high-voltage equipment, requiring non-conventional PD detection techniques was also introduced by [10-12].

The PD detection using UHF sensor is frequently used due to its high sensitivity and ability to tolerate external electromagnetic interference, resulting in a high signal-to-noise ratio. Consequently, the UHF sensor is a favourable option for on-site testing by U. Khayam *et al.,* [13]. The UHF technique is essential to detect, locate, and classify various types of PD to estimate the power transformer's insulation status. The UHF sensor is highly sensitive to PD signals, as its fast electrical discharge produces electromagnetic emissions within a range of UHF frequencies from 300 MHz to 3 GHz by N. D. Roslizan *et al.,* [10], and A. H. Zahed *et al.,* [14]. The UHF sensors have been developed and tested on HV power transformers for PD detection under online conditions. Previous publications [15-17] have used a UHF Hilbert fractal sensor to detect different types of PD in an oil paper insulated system. The UHF sensor has also been employed in detecting different types of PD signals in power transformers in a prior study [20,21]. This sensor is favoured due to its size and frequency range; however, it has some limitations such as low gain, narrow bandwidth, and suboptimal performance. To overcome these limitations, an array of UHF sensors has been analysed in this paper. The design of the sensor considers two key parameters: size and operating frequency band. This paper presents details of the sensor design and simulation results.

2. Design and Analysis

Hilbert fractal sensor that is optimized for detecting PD signals in power transformers through UHF frequencies in this section. To achieve this goal, the sensor was modelled using CST software and fabricated, and its performance was evaluated through analysis and simulation. A Hilbert fractal sensor can detect electromagnetic emissions from various sources, including PD. Designing a Hilbert fractal sensor specifically for PD detection requires ensuring that its operating frequency range falls within the range of electromagnetic emissions generated by PD, making these two factors critical in the sensor's design as mentioned by Roslizan *et al.,* [10], and Khayam *et al.,* [13]. In publication Roslizan *et al.,* [22] has provided a detailed explanation of the design of the 4th order Hilbert fractal. In this paper, the UHF sensor has been classified into three designs, namely, a single design, an array design, and an array design with partial ground.

The 4th order Hilbert fractal sensor has several advantages for PD detection which are the sensor can operate over a wide range of frequencies (0.3 – 3 GHz) which is important for detecting PD signals that occur at different frequencies. In addition, the sensor also operates at multiple frequencies simultaneously where it is useful for PD detection in transformer that require the ability to transmit and receive signals across different frequency bands. Hilbert fractal sensor have an omnidirectional radiation pattern, which means its transmit and receive PD signals in all directions during PD detection. Figure 1 show the single 4th order Hilbert fractal sensor with the parameter length, L, width, W, thickness, b, of the sensor which has been described by Roslizan *et al.,* [22].

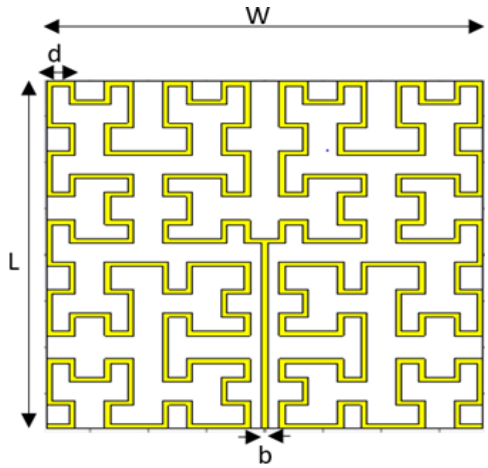

Fig. 1. Single design UHF sensor model

The efficiency of the antenna in terms of return loss, is reliant on the impedance matching between the patch and transmission feed line as explained by Li *et al.,* [19]. An array UHF sensor has demonstrated high efficiency when there is perfect impedance matching between the transmission feed and patch. However, microstrip antennas have certain limitations, including a narrow frequency range and inability to operate at high power levels in coaxial cables, waveguides, and strip lines. To overcome these limitations, an array of Hilbert fractal sensors has been developed in this study to increase the bandwidth and gain, resulting in higher efficiency as illustrated in Figure 2. The distribution of voltages across the array elements is determined by the power supply network, and all induced voltages are gathered at a single point through an efficient feeding network.

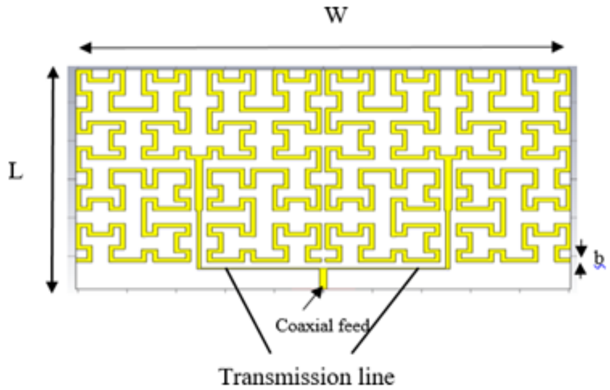

Fig. 2. An array design of UHF sensor model

Reducing the ground plane is proposed to enhance the characteristics of an antenna. This approach has been employed to improve performance, enhance impedance matching, increase the front-to-back ratio, and expand the bandwidth of UHF antennas as mentioned by the previous studies [19,22]. However, in transformer partial discharges can occur at relatively low voltages which the partial ground sensor cannot be detect at the early UHF frequency range because based on the result and discussion part below the sensor cover from the high frequency only.

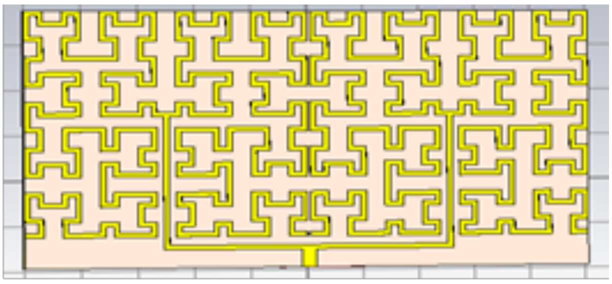

Fig. 3. Front view

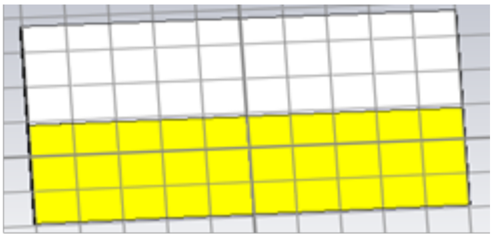

Fig. 4. Back view

3. Results and Discussion

This section aims to provide a detailed explanation of the simulation and measurement results of the Hilbert fractal UHF sensor. It is divided into three subsections that cover the analysis of the S parameter, the 2D radiation pattern results, and the Voltage Standing Wave Ratio (VSWR).

3.1 Simulation and Measurement Result of S Parameter

The performance of the array 4th order Hilbert fractal sensor array for detecting partial discharge (PD) in power transformers was evaluated, and it was found to have the best performance. The results of simulations and measurements using a single sensor, an array, and a partially grounded sensor were discussed. Figures 5, 6, and 7 illustrate the coefficient of reflection and S parameter curves of the sensor.

The S parameter curves in Figures 5, 6, and 7 exhibit some differences, which could be attributed to inconsistencies in coupling between the SMA and radiating element, fabrication tolerances, or interference from the surrounding environment and other components of the sensor. The impedance matching measurement of the sensor was carried out using the Agilent E5071C vector network analyser. From the result as shown in Figure 5, there was multiple operating bands can be seen at the early stage which from 0.41 GHz - 1.78 GHz and the resonance frequency, 1.64 GHz at -47 dB and 1.91 GHz at -36 dB.

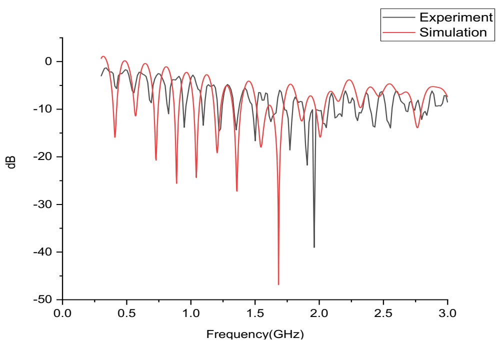

Fig. 5. Single design UHF sensor

The comparing result of the simulated and measured at Figure 6 shows that the sensor was well operating from the frequency 0.3- 0.4 GHz and from 1.2- 2.3 GHz. The resonance frequency for an array Hilbert sensor was at the 1.57 GHz with -49 dB while the experiment result was at 1.69 GHz with -40 dB in less than -10 dB.

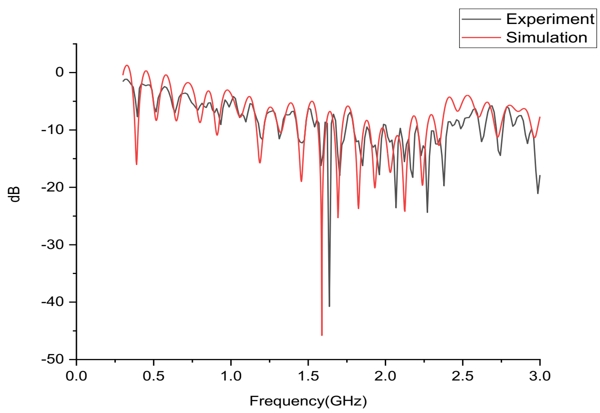

Fig. 6. An array design UHF sensor

Figure 7 shows the three-operating band at 1.3 - 1.45 GHz, 1.52 - 1.55 GHz and 2.12 - 2.26 GHz and the resonance frequency at 2.2 GHz with -28 dB while for the measured result, the sensor was operating at high frequency which from 1.26 - 1.35 GHz and 2.18 – 2.36 GHz and resonance at 2.25 GHz with -37 dB. The S11 response of the partial ground sensor is a measure of how well the sensor is matched to the system being measured and form the result, the partial ground sensor was detected only at the high frequency.

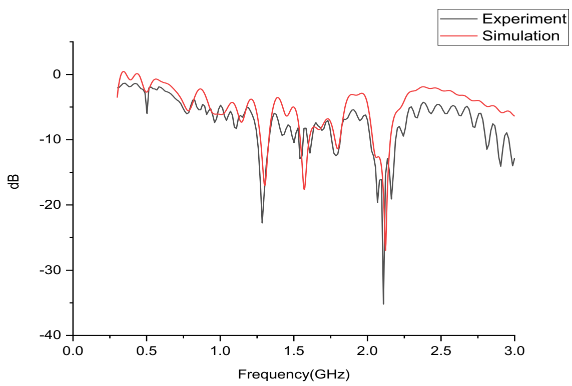

Fig. 7. Partial ground design UHF sensor

The frequency range of operation of a sensor is limited by its physical structure and the materials used to construct it. The sensor's ability to efficiently radiate or receive electromagnetic waves decreases as the frequency deviates from its resonant frequency. This means that sensor designed for a specific frequency range will have limited performance outside that range as mentioned by Roslizan *et al.,* [22].

3.2 2D Radiation pattern

In addition to analysing the reflection coefficient result, it is also important to examine the 2D radiation pattern of the sensor. The sensor pattern refers to the spatial distribution of the field strengths emitted by the sensor. This parameter is discussed in previous research papers Roslizan *et al.,* [22].

Figures 8, 9, and 10 depict the 2D radiation pattern simulation results of the sensor at different frequencies, including a single 4th order Hilbert fractal, an array, and a partial ground configuration. In CST farfield diagrams, the colours red, green, and blue are used to represent different components of the electromagnetic fields. Specifically, the red line represents the electric field component in the x-direction, the green line represents the electric field component in the y-direction, and the blue line represents the electric field component in the z-direction.

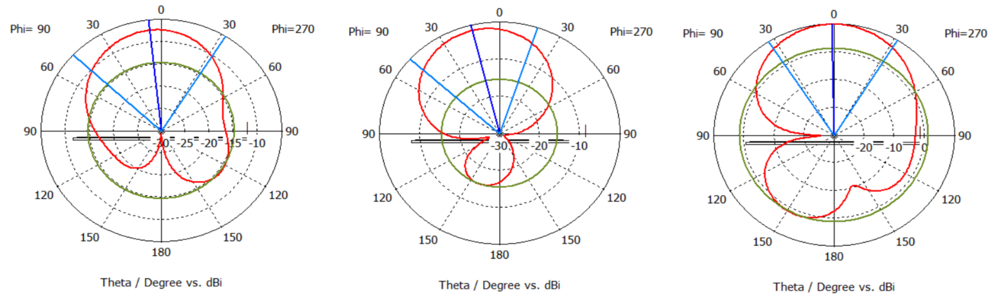

Fig. 8. Single design UHF sensor 2D Radiation Pattern (a) 0.73, (b) 0.89, (c) 1.68 GHz

These results show that the radiation pattern of the array 4th order Hilbert fractal sensor is almost hemispherical in shape at frequencies 1.59, 1.69, and 1.82 GHz. In summary, even though Figure 10 the partial ground shown more too hemispherical shape compared with the Figure 9, the performance of both s11 response and radiation pattern need to be carefully considered to ensure the best possible performance for partial discharge detection. Moreover, the variation in gain across these frequencies is relatively consistent.

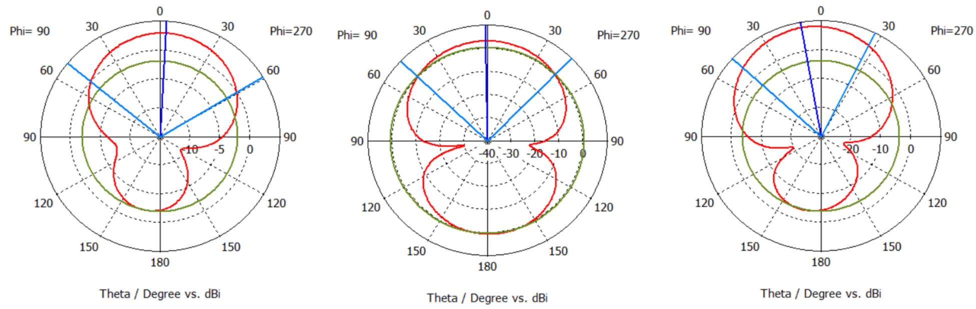

Fig. 9. An array design 2D radiation pattern (a) 1.59, (b) 1.69, (c) 1.82 GHz

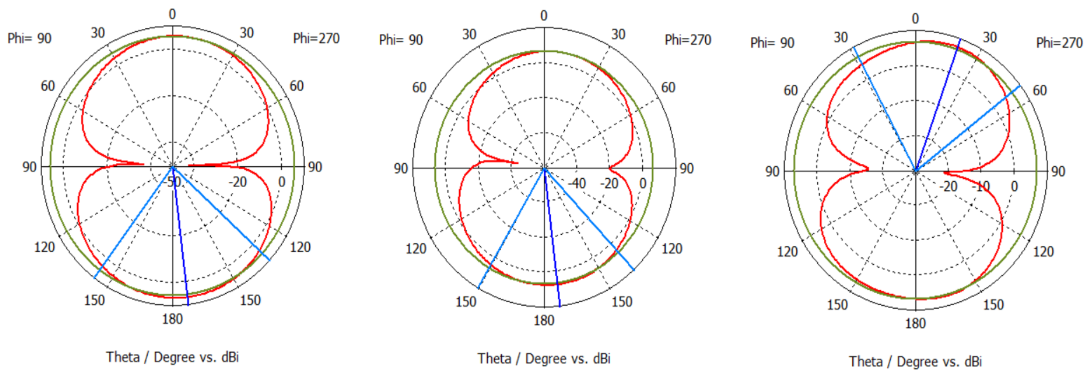

Fig. 10. Partial ground design UHF sensor 2D radiation pattern (a) 1.31, (b) 1.57, (c) 2.12 GHz

The sensitivity of a sensor in different directions can be assessed by analysing its radiation pattern, which can also aid in determining the optimal orientation for achieving desired performance as shown by Li, T. Jiang *et al.,* [19]. Based on the obtained radiation patterns, it can be inferred that most of the energy is emitted towards the direction of the PD source. Simulation results reveal that the sensor is compatible with a 50 Ω coaxial cable within the pass band. These results indicate that the array 4th order Hilbert fractal sensor array technique satisfies some of the necessary criteria for a UHF sensor.

3.3 Voltage Standing Wave Ratio

The performance of the sensor can be described by the voltage standing wave ratio (VSWR), which is depicted in Figures 11, 12, and 13. VSWR is a real and positive number that indicates the sensor's matching capability. A lower VSWR value is indicative of better output from the transmission line-matched sensor, according to antenna principles as mention from the previous studies [16-18]. The ideal sensor has a VSWR value of 1, indicating that no power is reflected from the sensor by Khayam *et al.,* [13]. According to simulation results, the sensor has a VSWR value of VSWR ≤ 5 at the resonance frequency, indicating that the sensor is still functional. A VSWR value greater than 5 suggests that the sensor is unsuitable for production as mention by Li, T. Jiang *et al.,* [19, 22-24].

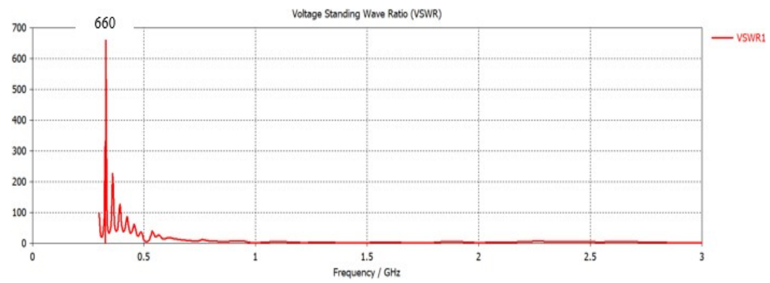

Fig. 11. Single 4th order Hilbert sensor

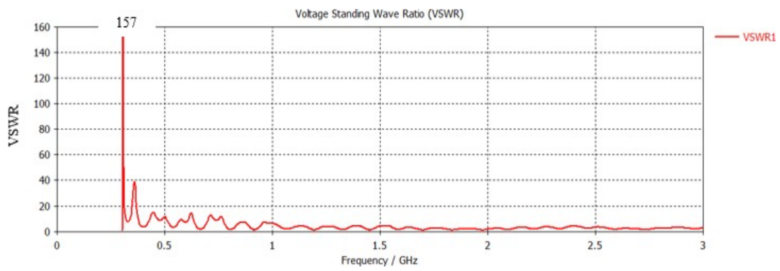

Fig. 12. An array 4th order Hilbert sensor

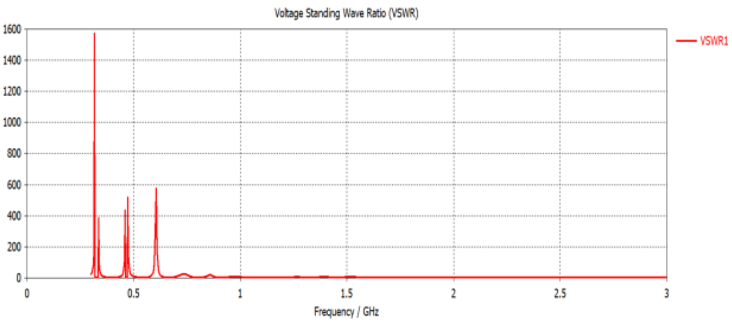

Fig. 13. Partial ground 4th order Hilbert sensor

According to the simulation results, it can be inferred that the sensor performs optimally with a VSWR value of less than 5. This VSWR value is observed in the frequency range of 0.3 GHz to 2.3 GHz, with a VSWR value of 1.0415 at 1.57 GHz, which is close to 1. This indicates excellent performance of the sensor at this frequency [25,26].

4. Conclusion

The primary objective of this study was to introduce a novel UHF PD sensor, specifically an array 4th order Hilbert fractal sensor, that could effectively detect PD signals in power transformers. The design of this sensor was based on the 4th order Hilbert fractal curve principle and exhibited excellent performance characteristics, meeting the size and bandwidth requirements for effective PD detection in the frequency range of 0.3 to 3 GHz. After experimentation, the optimal configuration for the sensor was found to be an array of 4th order Hilbert fractal curves, with a side dimension of 200 mm x 200 mm, a width of 2 mm, and a thickness of 1.6 mm, and a dielectric constant of 4.4. Simulation results showed that the sensor could detect electromagnetic waves generated by PD in a frequency band exceeding 300 MHz, demonstrating robust anti-interference capabilities. The radiation patterns and VSWR values indicated that the sensor could capture electromagnetic waves from the front of the sensor and operate in all directions within the transformer tank. Furthermore, the gain variations of this sensor at three frequencies were found to be relatively stable, indicating good compatibility with a 50 Ω coaxial cable in the pass band. Compared to the experimental results, simulation results demonstrated that an array of 4th order Hilbert fractal sensors provided a higher bandwidth.

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References

[1] Nobrega, Luiz AMM, George VR Xavier, Marcus VD Aquino, Alexandre JR Serres, Camila CR Albuquerque, and Edson G. Costa. "Design and development of a bio-inspired UHF sensor for partial discharge detection in power transformers." *Sensors* 19, no. 3 (2019): 653. https://doi.org/10.3390/s19030653

[2] Abdullah, A. Z., M. N. K. H. Rohani, M. Isa, H. Hamid, S. N. M. Arshad, and M. Othman. "Real on-site partial discharge measurement technique in medium voltage power cable." In *2018 IEEE 7th International Conference on Power and Energy (PECon)*, pp. 405-408. IEEE, 2018. https://doi.org/10.1109/PECON.2018.8684134

[3] Roslizan, N. D., M. N. K. H. Rohani, A. S. Rosmi, B. Ismail, M. A. Jamlos, and M. Z. Aihsan. "Multiband Frequency of 4 th Order Hilbert Fractal UHF Sensor Modelling for Partial Discharge Detection in Power Transformer." In *2021 IEEE Industrial Electronics and Applications Conference (IEACon)*, pp. 286-291. IEEE, 2021. https://doi.org/10.1109/IEACon51066.2021.9654524

[4] Li, Jian, Tianyan Jiang, Caisheng Wang, and Changkui Cheng. "Optimization of UHF Hilbert antenna for partial discharge detection of transformers." *IEEE Transactions on Antennas and Propagation* 60, no. 5 (2012): 2536-2540. https://doi.org/10.1109/TAP.2012.2189929

[5] Roslizan, N. D., M. N. K. H. Rohani, C. L. Wooi, M. Isa, B. Ismail, A. S. Rosmi, and W. A. Mustafa. "A review: Partial discharge detection using UHF sensor on high voltage equipment." In *Journal of Physics: Conference Series*, vol. 1432, no. 1, p. 012003. IOP Publishing, 2020. https://doi.org/10.1088/1742-6596/1432/1/012003

[6] Hamadi, S. H. K., M. Isa, L. M. Ishak, M. N. K. H. Rohani, C. C. Yii, B. Ismailf, and M. Shafiq. "Modelling of partial discharge signal and noise interference using labview." In *2017 IEEE 15th Student Conference on Research and Development (SCOReD)*, pp. 451-455. IEEE, 2017. https://doi.org/10.1109/SCORED.2017.8305441

[7] Jahangir, H., A. Akbari, Peter Werle, and J. Szczechowski. "UHF PD measurements on power transformers-advantages and limitations." *IEEE Transactions on Dielectrics and Electrical Insulation* 24, no. 6 (2017): 3933-3940. https://doi.org/10.1109/TDEI.2017.006149

[8] Nanyan, Ayob Nazmy, Muzamir Isa, Haziah Abdul Hamid, Mohamad Nur Khairul Hafizi Rohani, and Baharuddin Ismail. "The rogowski coil sensor in high current application: A review." In *IOP Conference Series: Materials Science and Engineering*, vol. 318, no. 1, p. 012054. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/318/1/012054

[9] Chen, Guang, Jiagui Tao, Yong Ma, H. U. I. Fu, Yang Liu, Zhicheng Zhou, Chengjun Huang, and Canxin Guo. "On-site portable partial discharge detection applied to power cables using HFCT and UHF methods." *WSEAS Trans. Circuits Syst* 15 (2016): 83-90.

[10] Mukhtaruddin, A., and Sungai Besi Camp. "Hilbert Fractal UHF Sensor based on Partial Discharge Detection Signal for On-line Condition Monitoring in Power Transformer."

[11] Dukanac, Djordje. "Application of UHF method for partial discharge source location in power transformers." *IEEE Transactions on Dielectrics and Electrical Insulation* 25, no. 6 (2018): 2266-2278. https://doi.org/10.1109/TDEI.2018.006996

[12] Rosmi, A. S., M. Isa, B. Ismail, M. N. K. H. Rohani, and Y. Wahab. "An optimization of electrical output power for piezoelectric energy harvester using different micro-cantilever beam geometries." In *Journal of Physics: Conference Series*, vol. 1019, no. 1, p. 012033. IOP Publishing, 2018. https://doi.org/10.1088/1742-6596/1019/1/012033

[13] Khayam, Umar, and Fakih Alfaruq. "Design of Hilbert antenna as partial discharge sensor." In *2016 2nd International Conference of Industrial, Mechanical, Electrical, and Chemical Engineering (ICIMECE)*, pp. 84-88. IEEE, 2016. https://doi.org/10.1109/ICIMECE.2016.7910419

[14] Zahed, Abdalmonam H., Mustafa M. Harbaji, Shahed A. Habboub, Maryam A. AlMajidi, Mustafa J. Assaf, Ayman H. El-Hag, and Nasser N. Qaddoumi. "Design of hilbert fractal antenna for partial discharge detection and classification." In *2015 4th International Conference on Electric Power and Energy Conversion Systems (EPECS)*, pp. 1-4. IEEE, 2015. https://doi.org/10.1109/EPECS.2015.7368499

[15] Darmawan, Muhammad Anung, and Umar Khayam. "Design, simulation, and fabrication of second, third, and forth order Hilbert antennas as ultra high frequency partial discharge sensor." In *Proceedings of the Joint International Conference on Electric Vehicular Technology and Industrial, Mechanical, Electrical and Chemical Engineering (ICEVT & IMECE)*, pp. 319-322. IEEE, 2015. https://doi.org/10.1109/ICEVTIMECE.2015.7496707

[16] Samsudin, Muhammad Syazwan Nizam, Md Mizanur Rahman, and Muhamad Azhari Wahid. "Sustainable power generation pathways in Malaysia: Development of long-range scenarios." *Journal of Advanced Research in Applied Mechanics* 24, no. 1 (2016): 22-38.

[17] Albarracín, Ricardo, Jorge Alfredo Ardila-Rey, and Abdullahi Abubakar Mas' ud. "On the use of monopole antennas for determining the effect of the enclosure of a power transformer tank in partial discharges electromagnetic propagation." *Sensors* 16, no. 2 (2016): 148. https://doi.org/10.3390/s16020148

[18] Harbaji, Mustafa MO, Abdalmonam H. Zahed, Shahed A. Habboub, Maryam A. AlMajidi, Mustafa J. Assaf, Ayman H. El-Hag, and Nasser N. Qaddoumi. "Design of Hilbert fractal antenna for partial discharge classification in oil-paper insulated system." *IEEE Sensors Journal* 17, no. 4 (2016): 1037-1045. https://doi.org/10.1109/JSEN.2016.2638804

[19] Li, Jian, Tianyan Jiang, Changkui Cheng, and Caisheng Wang. "Hilbert fractal antenna for UHF detection of partial discharges in transformers." *IEEE transactions on dielectrics and electrical insulation* 20, no. 6 (2013): 2017-2025. https://doi.org/10.1109/TDEI.2013.6678849

[20] Mashaal, O. Ahmad, S. K. A. Rahim, A. Y. Abdulrahman, M. I. Sabran, M. S. A. Rani, and P. S. Hall. "A coplanar waveguide fed two arm Archimedean spiral slot antenna with improved bandwidth." *IEEE Transactions on Antennas and Propagation* 61, no. 2 (2012): 939-943. https://doi.org/10.1109/TAP.2012.2224831

[21] Viswanathan, Abishek, and Rajasi Desai. "Applying partial-ground technique to enhance bandwidth of a UWB circular microstrip patch antenna." *International Journal of Scientific & Engineering Research* 5, no. 10 (2014): 780-784.

[22] Roslizan, N. D., M. N. K. H. Rohani, A. S. Rosmi, B. Ismail, M. A. Jamlos, W. C. Leong, C. M. N. C. Isa, and M. A. A. Jalil. "Comparison Study of UHF Sensor Modelling Based on 4th Order Hilbert Fractal Category for Partial Discharge Detection in Power Transformer." In *2020 IEEE 8th Conference on Systems, Process and Control (ICSPC)*, pp. 196-201. IEEE, 2020. https://doi.org/10.1109/ICSPC50992.2020.9305753

[23] Nabil, Mohammed, Mohamed Helmy Megahed, and Mohamed Hassan Abdel Azeem. "Design and simulation of new one time pad (OTP) stream cipher encryption algorithm." *Journal of Advanced Research in Computing and Applications* 10, no. 1 (2018): 16-23.

[24] Zulkefli, M. H., KA Mohd Annuar, S. H. Johari, MR Mohamad Sapiee, and S. Ahmad. "Graphical user interface (GUI) controlled mobile robot." *Journal of Advanced Research in Computing and Applications* 1, no. 1 (2015).

[25] Kamarudin, Nurzatulshima, Nik Mawar Hanifah Nik Hassan, Mohd Mokhtar Muhamad, Othman Talib, Haryati Kamarudin, Norhafizan Abdul Wahab, Aidatul Shima Ismail, Haza Hafeez Borhan, and Nazihah Idris. "Unveiling

Collaborative Trends in Fuzzy Delphi Method (FDM) Research: A Co-Authorship Bibliometrics Study." *International Journal of Computational Thinking and Data Science* 2, no. 1 (2024): 1-20.

[26] SIvakumar, Renukka, Saidatul Norlyana Azemi, Lee Yeng Seng, Kok Yeow You, and Ping Jack Soh. "3-D Printed Antennas with Dielectric Lens for Free-Space Constitutive Parameters Measurement." *Semarak International Journal of Electronic System Engineering* 1, no. 1 (2024): 1-25.