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# UHF Partial Discharge Detection for Power Transformer Based on Hilbert Fractal Antenna with Different Feeding Techniques

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**ABSTRACT**

In power transformer, Partial Discharge (PD) can cause a major equipment risk and lead to further accidents. One of the PD detection techniques is Ultra-High Frequency (UHF) antenna. UHF antenna have a major advantage which is it immune to external interference. However, the choice of feeding technique used to connect the antenna to the transmission line can limit the performance of UHF antenna. This paper was conducted by comparing microstrip line feed and coaxial feed for Ultra-High Frequency (UHF) PD detection. The antenna is aimed to operate in the PD frequency range (300 – 3000 MHz) and there is no specific frequency band that PD radiate in a measurement. The frequency of UHF PD measurements in power transformers varies based on the individual case and is impacted by several factors, including the PD source and locations of PD in the transformer. In this work, 4$^{th}$ order Hilbert fractal antenna are selected as patch antenna for UHF PD detection. The proposed design for the antenna based on the appropriate size for internal installation in the power transformer. All these results showed that either microstrip line feed or coaxial feed technique are able to capture the PD in the range of UHF for the power transformer. However, the coaxial feed antenna is preferable as it shows that the fabricated measurement is consistent with the simulation and had a higher number of resonant frequencies.

***Keywords:***

Hilbert fractal antenna; Coaxial feed; Microstrip line feed; Partial discharge power transformer

## 1. Introduction

PD is a source of insulation breakdown and can result in power transformer failure. The research must be conducted to determine the PD signals as an initial step before serious damage to the power transformer occurs. The main issue when measuring PD is the accuracy of PD detection.

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The first step in managing partial discharge problems is to determine their causes, which requires a thorough inspection of the electrical system and its components with the common causes include mechanical strains, surface contaminants, and insulation defects [1]. There are several methods of detecting PD which are classified as the optical-based method, chemical detection, electrical detection, electromagnetic detection and acoustic emission are based on their physical characteristics [2-4].

The use of UHF detecting methods has widely increased in the field of power transformer monitoring due to its ability to provide high sensitivity for detecting PD signals while rejecting noise. This technique employs UHF sensors that are capable of detecting electromagnetic waves emitted by PD inside an oil-filled power transformer [5] . Power transformers typically use mineral oil as insulation which has a good dielectric property to ensure appropriate electrical insulation and heat dissipation during operation [6].

Patch antenna is one type of UHF sensors that have emerged as an effective alternative to conventional large antennas and are currently being utilized in various applications such as mobile phones, defence instruments, and wireless wearables [7]. Patch antennas offer more benefits and supply better results which are lightweight, flexible, simple to manufacture, can operate at multiple frequencies and are smaller in size. Several antenna parameters such as return loss, radiation pattern, and radiation gain are evaluated to determine the antenna matching properties, with return loss is measured using a vector network analyser (VNA) [8].

Thus, two types of feeding techniques for the Hilbert Fractal antenna are simulated and fabricated in this paper. Besides, the antennas performances are compared to select the optimum design of the antenna for PD detection in a power transformer.

## 2. Principle of Feeding Technique

There are several feeding techniques that can be used with patch antenna which are microstrip line feed, coaxial feed, aperture coupled feed, branch line feed and proximity couple feed. These techniques can be sorted into two categories which are contacting and non-contacting. In contacting techniques, the radiating patch is supplied with RF power directly through connecting components, while in a non-contacting technique, the electromagnetic coupling is used to transfer power from the feed line to the path [9].

Two types of feeding techniques which are coaxial feed and microstrip line feed have advantage which gives good impedance matching and is easy to fabricate for the patch antenna. In contrast, aperture coupled and proximity coupled feeds require multilayer fabrication, whereas branch line feeds require to adjust the patch antenna dimensions for optimal impedance matching.

The Hilbert fractal antenna has become increasingly common recently for detecting PD signals using UHF methods [10,11]. Normally the coaxial feed technique will be used for the Hilbert fractal antenna [12,13]. However, research conducted by M. V. Mokal *et al.,* [14] used microstrip line feed for the Hilbert Fractal antenna in his research for wireless communications applications. Thus, this paper selects and compares two types of feeding techniques which are the coaxial feed and microstrip line feed technique to analyse the best results of the feeding technique for the Hilbert Fractal antenna as PD detection sensor.

### *2.1 Coaxial Feed Technique*

The coaxial feed technique consists of a coaxial connector which is connected perpendicular to the patch antenna with a specific feed point. The outer conductor of the coaxial connector is connected to the ground plane and the inner conductor is connected to the patch through the substrate as shown in Figure 1.

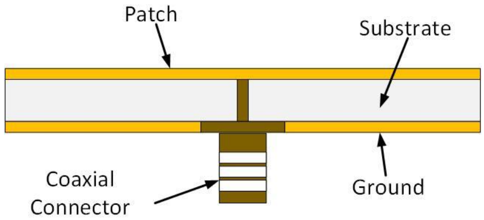



**Fig. 1.** Microstrip line feed

*2.2 Microstrip Line Feed Technique*

The microstrip line feed technique consists of one microstrip line which is connected to the patch of the antenna as shown in Figure 2. In this feed technique, the impedance of the microstrip line must be 50 ohms [15]. The impedance can be set by calculating the width of the feed line.

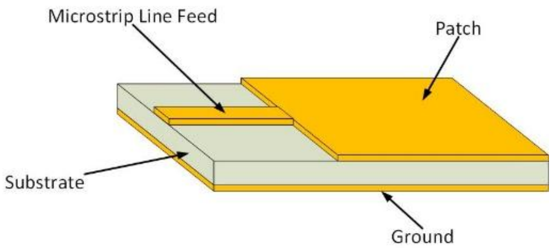



**Fig. 2.** Coaxial feed

## 3. Design of Hilbert Fractal Antenna

Several studies have examined the types of fractal antenna used for partial discharge detection and the material used for the antenna [16,17] . In this study, the researcher intends to study the feed line of the Hilbert fractal antenna with FR-4 as the material of PCB. Figure 3 shows examples of Hilbert fractal antennas of varying orders that can be used in PD detection applications. In this research, two types of feed techniques are designed for Hilbert fractal antenna.

Hilbert fractal antenna can detect electromagnetic waves that are released by PD within the power transformer system, which enables early detection as well as maintenance. Hilbert curve has an advantage in space-filling the long length of the wire in a minimum size of the antenna. The Hilbert fractal antenna provides a minimum size antenna which can be placed in the power transformer tank.

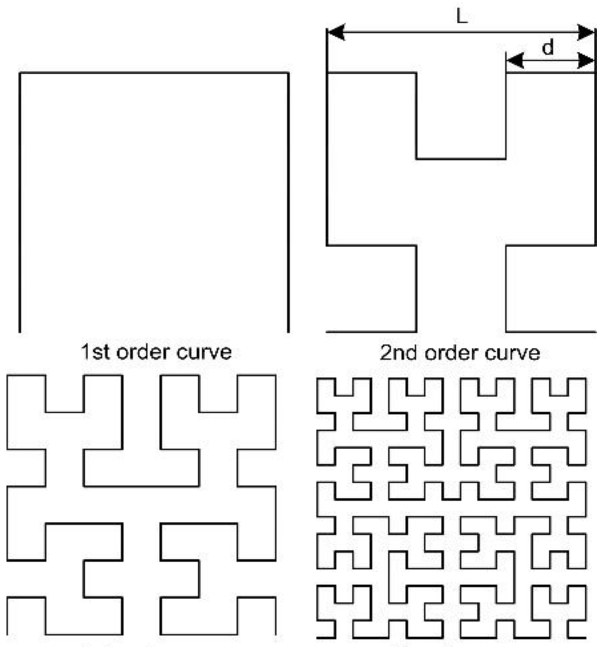



**Fig. 3.** Hilbert fractal curve at different order [18]

The expression for determining the length of each line segment, *d*, can be represented as Eq. (1), and the total length of the line segment, *S*, can be determined by utilizing Eq. (2). Where *n* is the number of orders of the antenna, and *L* is the outer dimension of the antenna.

$$d = \frac{L}{2^n - 1} \quad (1)$$

$$S = (2^n + 1)L \quad (2)$$

There are several types of PCB can be used as patch antenna such as RT/Duroid 5880, FR-4 and RO3003 [19]. Compared to other PCB types, many researchers have utilized FR-4 as PCB material because it is the most adaptable and cost-effective. FR-4 is usually fabricated of woven fibreglass that has been reinforced with epoxy for strength and fire resistance [20]. Figure 4 displays the layer structure of the FR-4 PCB patch antenna which consists of a copper patch conductor at the top, FR-4 epoxy substrate at the middle and copper ground at the bottom layer of the PCB.

The minimum frequency of the antenna requires more than or equal to 100 MHz in order to prevent external noise and intends to reach as close to 100 MHz as possible in order to obtain greater discharge signal [21]. The antenna selected for this study was 100 × 100 mm in dimension and 1.6 mm in thickness, which makes it suitable for internal placement in power transformers [22]. The antenna has an ultra-high frequency range from 300 MHz to 3000 MHz.

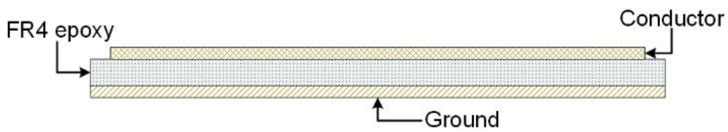



**Fig. 4.** Layers structure of the patch antenna

Several factors were considered when designing the Hilbert fractal antenna, as indicated in Table 1. The CST Studio Suite software was used to evaluate the design parameters and ensure that the antenna could function with acceptable performance in the specified frequency range.

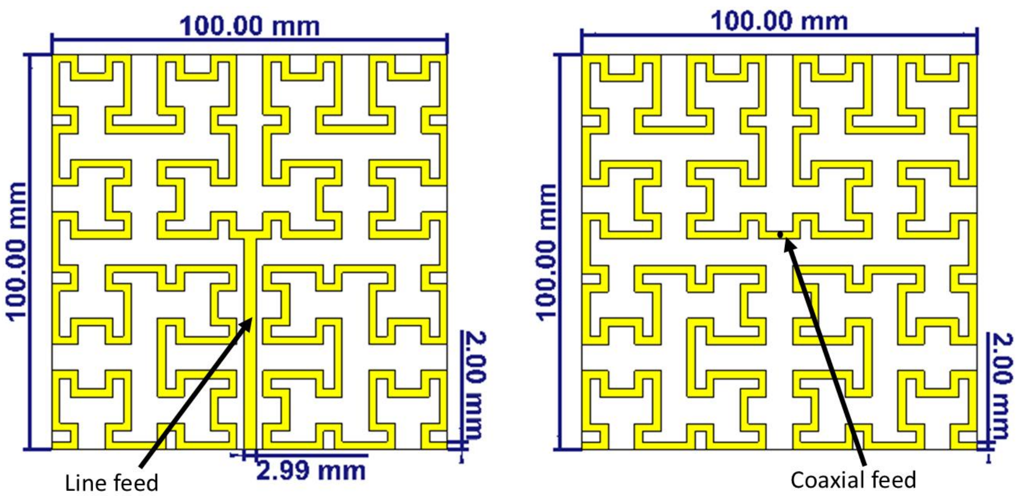
**Table 1**
Dimension of the antenna

| Parameter | Value |
|---|---|
| Side dimension, *L* | 100 mm |
| Width of conductor, *c* | 2 mm |
| Thickness of substrate | 1.6 mm |
| Thickness of ground layer | 0.035 mm |
| Thickness of patch conductor | 0.035 mm |
| Dielectric constant of FR-4 substrate ($\varepsilon_r$) | 4.3 |
| Coaxial feeding technique (Ω) | 50 Ω |
| Microstrip feed line thickness for 50 Ω | 2.99 mm |

The feeding point was determined to be in the centre of the antenna which provides symmetrical positioning regarding both the left and right sides of the antenna. Microstrip line feed was drawn and connected with the Hilbert patch on the top conductor surface as shown in Figure 5(a). To ensure the microstrip line feed was compatible with the coaxial cable that was used for external connections, it was calculated to have a specific impedance of 50 ohm.

On the other hand, the placement of the coaxial feed is shown in Figure 5(b), which shows where it was attached through the FR-4 PCB. The inner conductor of the coaxial cable was connected to the Hilbert patch at the top layer of the antenna, while the outer conductor was grounded to the ground layer of the antenna. This technique has the potential to provide advantages such as decreased interference and increased isolation between the antenna and the external system.

After determining the location of feeding points, the performance parameters of the Hilbert fractal antenna were analysed considering both feeding techniques. For each technique, the results of antenna gain, return loss, and radiation pattern are analysed to see if they match the requirements of partial discharge detection.




(a) (b)

**Fig. 5.** The placement of feeding technique (a) Microstrip line feed (b) coaxial feed

Next, the simulation of the coaxial feed Hilbert fractal antenna is repeated with varying feed points to evaluate the effect that differences in feed point affect the antenna performance. The coaxial feed is defined by a set of analyses and simulations at each point from point 1 to point 8 as shown in the Figure 6. The feed point is selected randomly in the bottom left side of the antenna because of Hilbert fractal curve is symmetrical, self-similarity and reflected along its axis of symmetry without changing its overall shape [18,23] . The side dimensions of the antenna have remained the same at 100 x 100 mm for the whole simulation. This study is focused on clarifying the effect of feed point variation on the antenna performance by analysing the results. This will provide the results that can be used to improve the design of Hilbert fractal antennas for partial discharge detection.

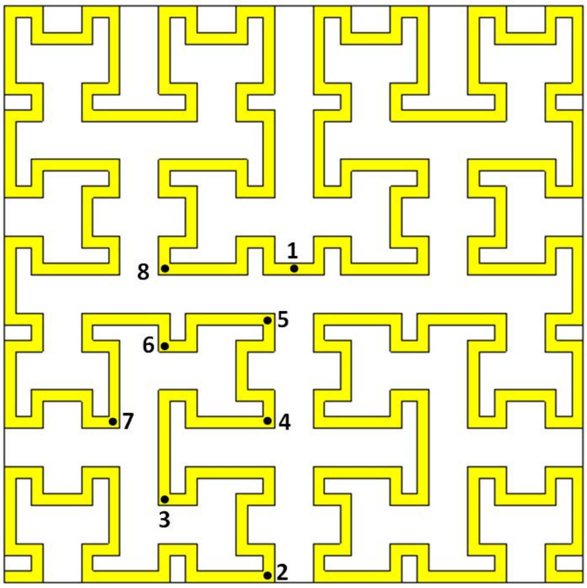


**Fig. 6.** Multiple points for coaxial feed technique

## 4. Result and Discussion

Two types of feed techniques have been designed in this paper to measure and compare the effectiveness of the antenna to capture the partial discharge data. The results compared the differences of return loss results, VSWR results, radiation pattern and gain between microstrip line feed and coaxial feed. The analysis and discussion are based on the results simulated using CST Studio Suite software. This study investigated and compared the performance of the Hilbert fractal antenna with two different feeding techniques for measuring partial discharge. The microstrip line feed and the coaxial feed were selected as the feeding technique in this research.

### *4.1 Return Loss Results*

Return loss or S-parameters represent the amount of power reflected from the antenna. The reflectance value expresses the reflection in decibels (dB). The lower the return loss, the higher the efficiency of the antenna. Return loss is an important aspect to consider when designing and optimizing transmission lines because it directly affects signal transmission efficiency and reliability. A lower value of return loss in dB indicates that more signal is being lost or reflected back, while a higher value indicates less loss and better performance of the antenna. Figure 7 compares the results of the return loss of microstrip line feed and coaxial line feed.

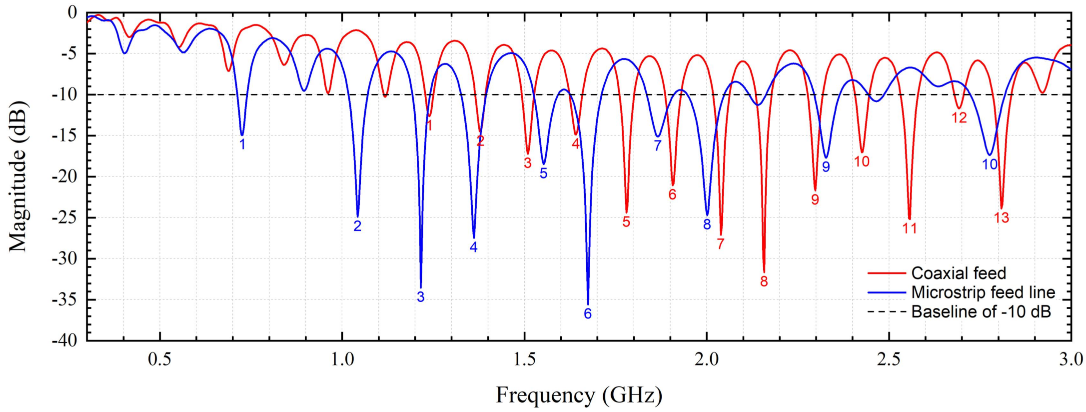



**Fig. 7.** Result of return loss for microstrip line feed and coaxial feed

The results of the return loss for the coaxial feed and line feed are compared in Table 2. This result shows that coaxial feed resulted in a greater number of resonant frequencies, which is 13 resonant frequencies compared to line feed with 10 resonant frequencies. The coaxial feed generated more resonant frequencies than the line feed indicating that it is more appropriate for partial discharge detection in power transformers that cover a larger frequency range.

The resonant frequencies generated by the coaxial feed ranged from 1.2396 GHz to 2.8083 GHz, while the resonant frequencies generated by the line feed ranged from 0.7266 GHz to 2.7759 GHz. In comparison to the line feed, the coaxial feed generated a return loss significantly greater in the resonant frequency range. This result simply a better performance of the coaxial feed in terms of its ability to capture UHF PD signal in power transformers.

**Table 2**
Comparison of return loss for the antenna

| No. of resonant frequency | Coaxial Feed | | Line Feed | |
|---|---|---|---|---|
| | Frequency (GHz) | Return loss (dB) | Frequency (GHz) | Return loss (dB) |
| 1 | 1.2396 | -12.64291 | 0.7266 | -14.9450 |
| 2 | 1.3800 | -14.51867 | 1.0425 | -24.8823 |
| 3 | 1.5096 | -17.23054 | 1.2153 | -33.5413 |
| 4 | 1.6419 | -14.87921 | 1.3611 | -27.4894 |
| 5 | 1.7796 | -24.39654 | 1.5528 | -18.4743 |
| 6 | 1.9065 | -21.06937 | 1.6743 | -35.5846 |
| 7 | 2.0388 | -27.08631 | 1.8660 | -15.1102 |
| 8 | 2.1576 | -31.67057 | 2.0010 | -24.7109 |
| 9 | 2.2980 | -21.69930 | 2.3277 | -17.7080 |
| 10 | 2.4249 | -17.02555 | 2.7759 | -17.3798 |
| 11 | 2.5572 | -25.16955 | | |
| 12 | 2.6922 | -11.67706 | | |
| 13 | 2.8083 | -23.88397 | | |

The next objective was to identify the optimal coaxial feed point for the Hilbert fractal antenna by comparing its performance with various feed positions. These studies are needed to select the best and efficient feeding point for coaxial feed technique.

The graphs for Points 2 to 7 showed similar patterns but were shifted relative to one another as shown in Figure 8. The return loss values for each of these points were within acceptable PD detection in the power transformer, but the graph shift indicated a change of the impedance. Besides, the graphs for Points 2 through Point 8 displayed a ripple in the values of the return loss.

The ripples in the return loss graph are caused by variations of the antenna impedance. The distance of the patch conductor in the Hilbert fractal antenna is too close resulting in changes of impedance.

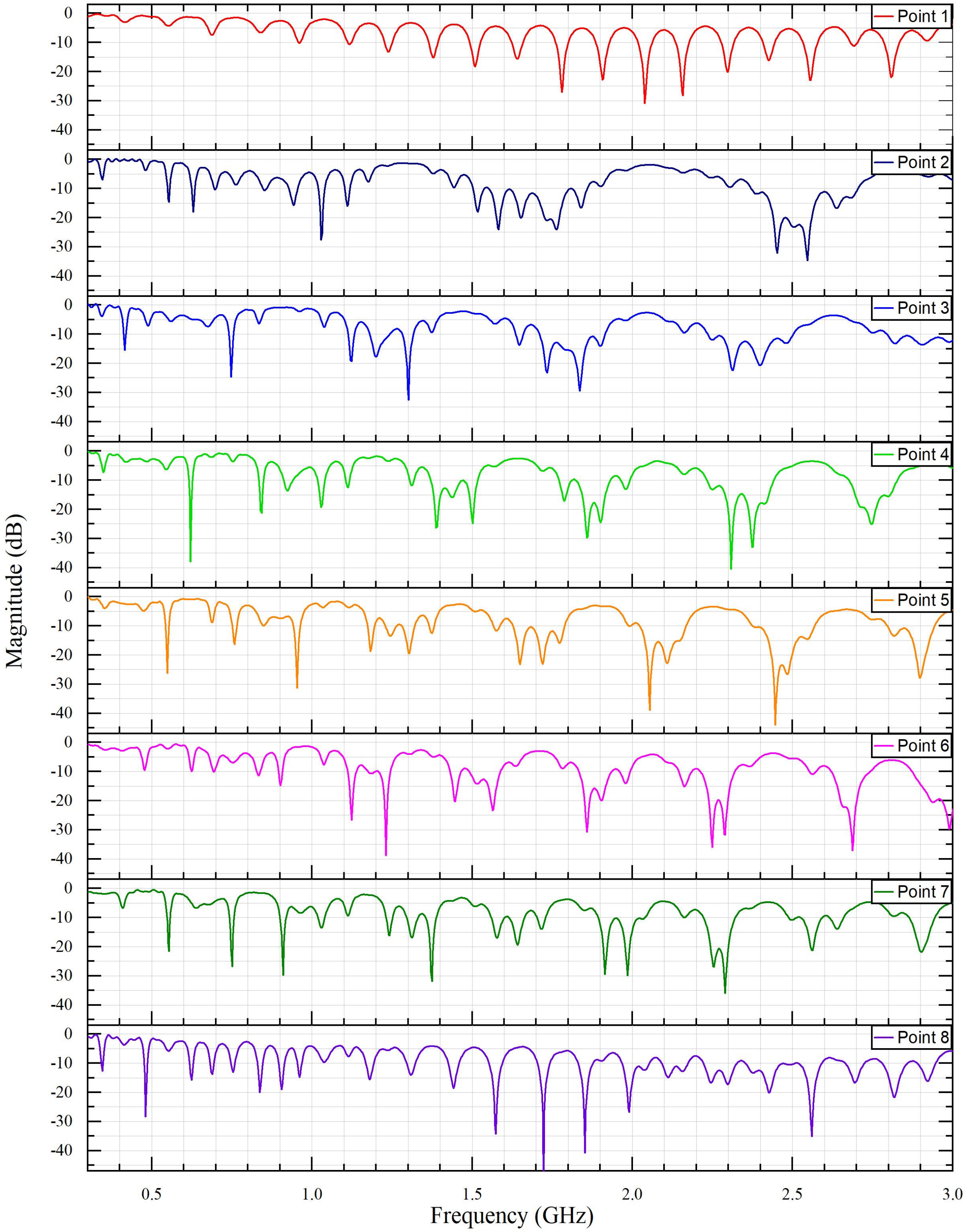



**Fig. 8.** Return loss of various point positions for coaxial feed technique

### *4.2 Voltage Wave Standing Ratio (VSWR)*

VSWR is the ratio of the voltage applied to the voltage reflected from the transmission line to the measuring device. It is similar to return loss but measured the standing wave ratio. The best value for the VSWR is one because it has slight differences. However, the value of VSWR is acceptable if below five. The results obtained from VSWR analysis of microstrip line feed and coaxial feed are presented in Figure 9.

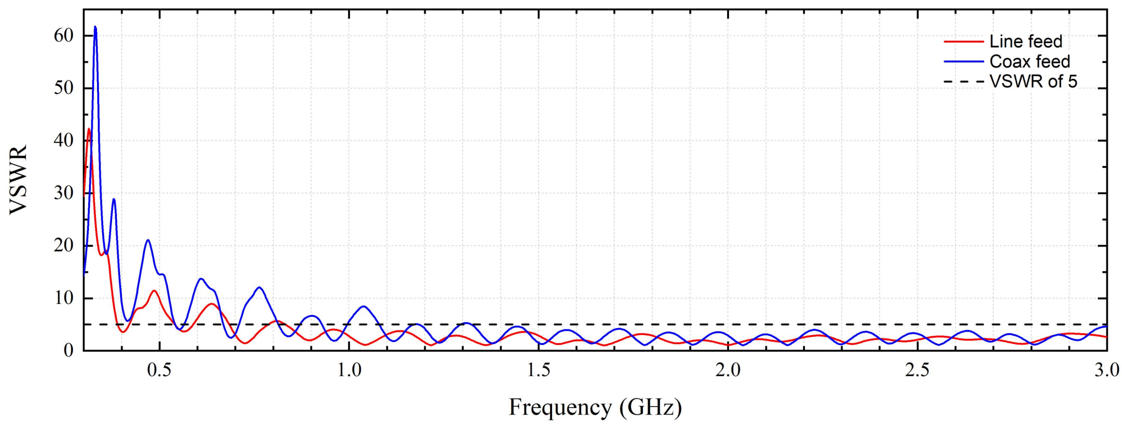



**Fig. 9.** Result of return loss for microstrip line feed and coaxial feed

From Figure 9 it can see that the VSWR for line feed is not significantly different compared to coaxial feed. At the resonance frequencies of the antenna, the VSWR for the line feed technique is similar to the coaxial feed technique with both of them having a value that is less than five. Signal transmission and receiver are more effective when the VSWR is under 5 because most of the power from the transmitter or receiver is transferred to the antenna. A VSWR under 5 also shows that there is less power reflection back towards the transmitter and receiver, which lowers the risk of damage to these components. These results indicate that both feeding techniques can be applied to fabricate the Hilbert fractal antenna.

### *4.3 Radiation Pattern*

The radiation pattern refers to the positional dependence of the electromagnetic field. The radiation pattern of an antenna is a graphical representation of the radiation characteristics of the antenna in the far field. The radiation pattern of these antennas is simulated based on each resonance frequency. The simulation results of radiation pattern and side lobe level for the microstrip feed line are shown in Figure 10, while coaxial feed technique is shown in Figure 11.

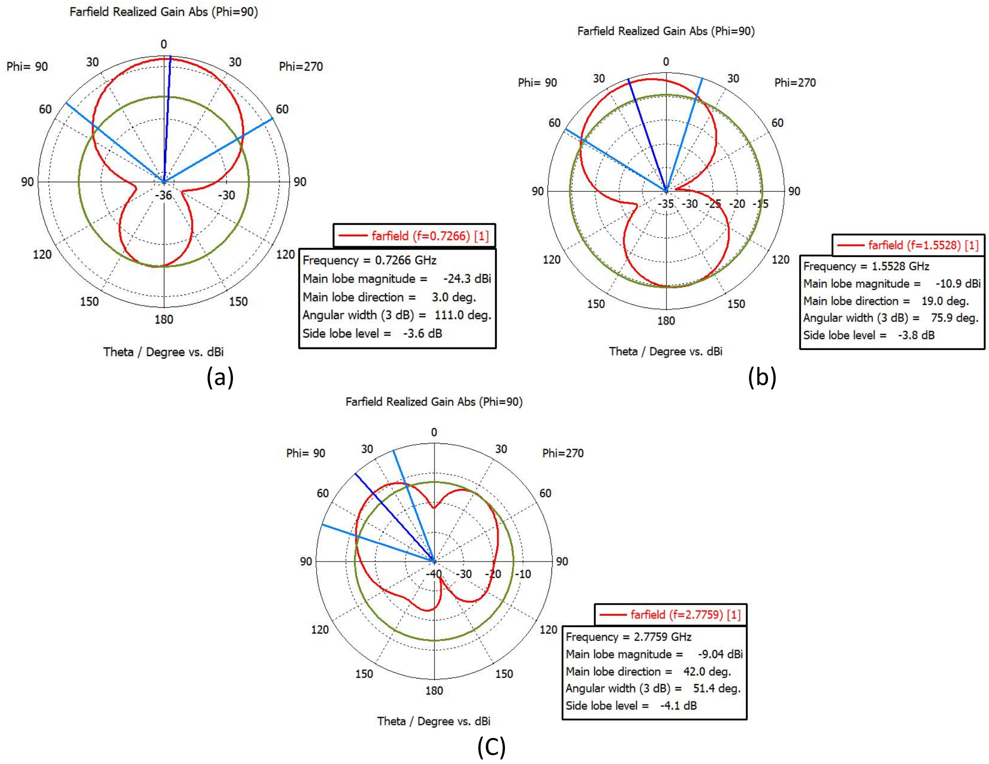



**Fig. 10.** Simulated radiation patterns of feedline technique at (a) 0.7266 GHz , (b) 1.5528 GHz, (c) 2.7759 GHz

The analysis shows that the radiation pattern is measured from three frequencies that were observed from the entire range of resonant frequencies. These frequencies collected from the lowest, middle, and highest frequencies. The results of the coaxial feed and line feed technique show that the antenna has an omnidirectional radiation pattern. These results indicate that both antennae are capable to detect and receiving PD signals from all directions [20].

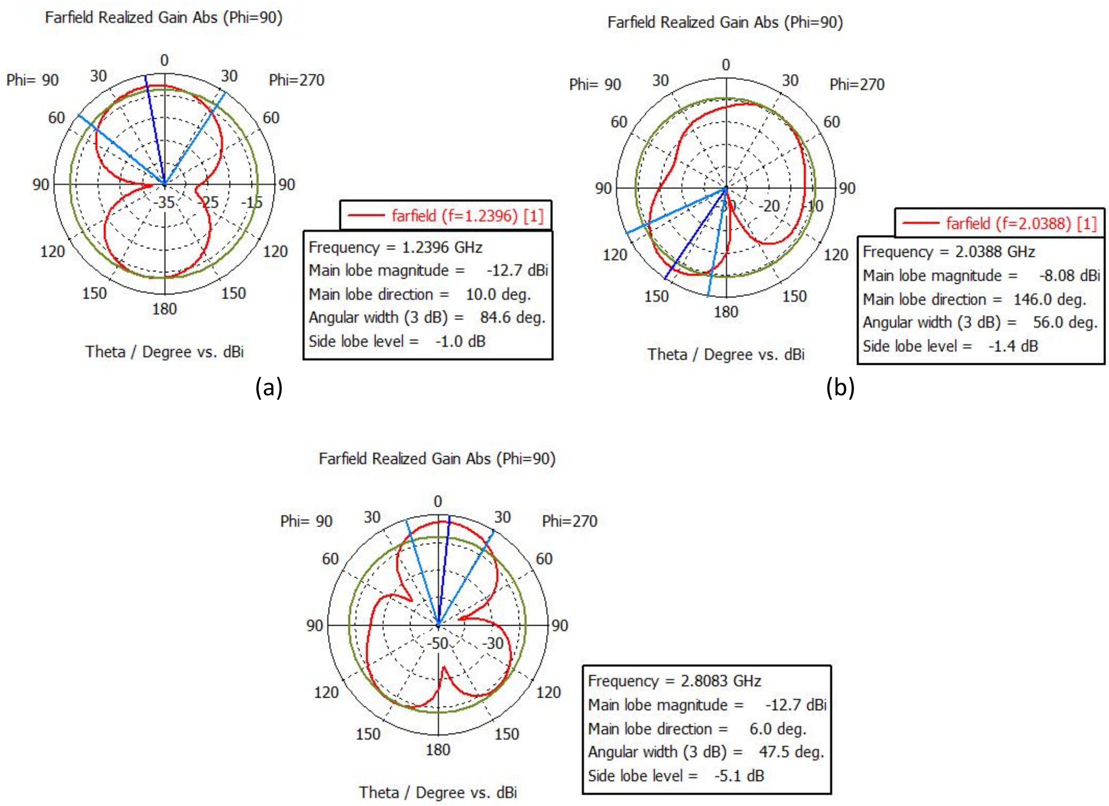



**Fig. 11.** Simulated radiation patterns of the coaxial feed technique at (a) 1.2396 GHz, (b) 2.0388 GHz, (c) 2.8083 GHz

The gain of the antenna shows for the feedline technique and coaxial technique is low and have a negative gain. This is because the size of the antenna is small, so the energy of the electromagnetic wave received by the antenna is low. However, the author in [24] has proposed an amplifier to overcome the problem of low gain. The antenna has a low gain, but its overall performance may be improved with the addition of this amplifier, which can also help compensate for the low gain of the antenna. The antenna is placed inside the power transformer tank in this research. Due to the small range that separates the antenna and the PD source, there is less of a requirement for the antenna to have a high gain.

### *4.4 Fabricated Antenna Results*

Once the design of the Hilbert fractal antenna was finalized with the given feeding techniques, the antenna was fabricated using standard printed circuit board (PCB) procedures to finish the process. The thin strip of copper conductor for the transmission line was etched onto the surface of the patch conductor for the microstrip line feed. The width of the line was adjusted so that it would have an appropriate impedance of 50 ohms. Besides, for the coaxial technique, a hole is drilled on the PCB antenna using the correct size of the drill bit once it has been determined where the connector should attach to the antenna. The coaxial connection is placed into the hole and soldered to the PCB.

After the antenna was fabricated, it was tested and analysed for performance parameters such as return loss to confirm that it satisfied the requirements for each feeding technique. The experimental results were compared to determine the best feeding technique for partial discharge detection. The fabricated antenna for the microstrip line feed technique is depicted in Figure 12(a), while Figure 12(b) illustrates the antenna fabricated using the coaxial feeding technique.

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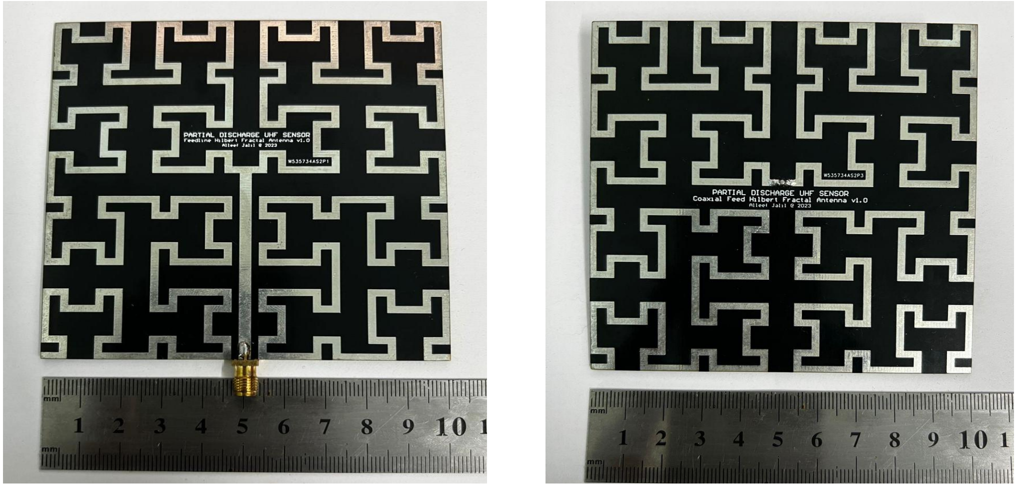


(a) (b)

**Fig. 12.** Fabricated antenna of (a) line feed, (b) coaxial feed

The experimental setup in this study utilizes the Agilent Technologies E5071C Network Analyzer as shown in Figure 13, a highly accurate instrument employed for characterizing RF and microwave components. The measurements were carried out at the Advanced Communication Engineering Centre (ACE), located on Universiti Malaysia Perlis's campus. The main objective of the analysis is to determine the return loss of a Hilbert fractal antenna.

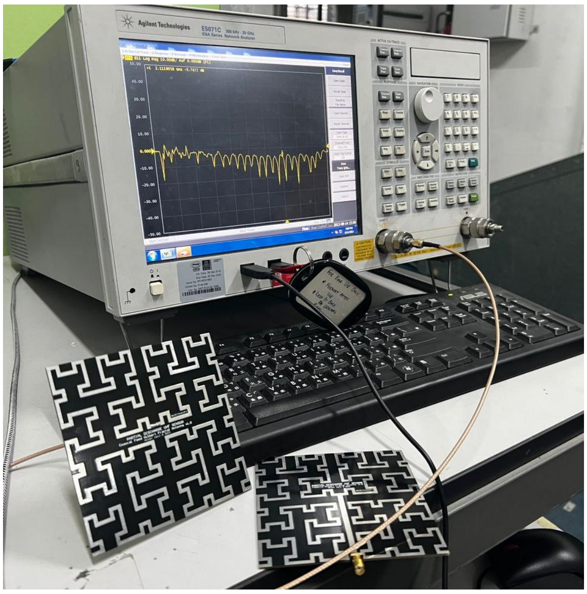


**Fig. 13.** Antenna measurement testing setup

The return loss result shown in Figure 14 for feedline feed has been simulated and fabricated. The results show that the magnitude of return loss for the fabricated antenna is lower than the simulated antenna and the return loss graph patterns are slightly different. The magnitude of the difference between the fabricated and simulated antenna is caused by the process of fabrication such as the slight differences in the dimensions of the antenna.

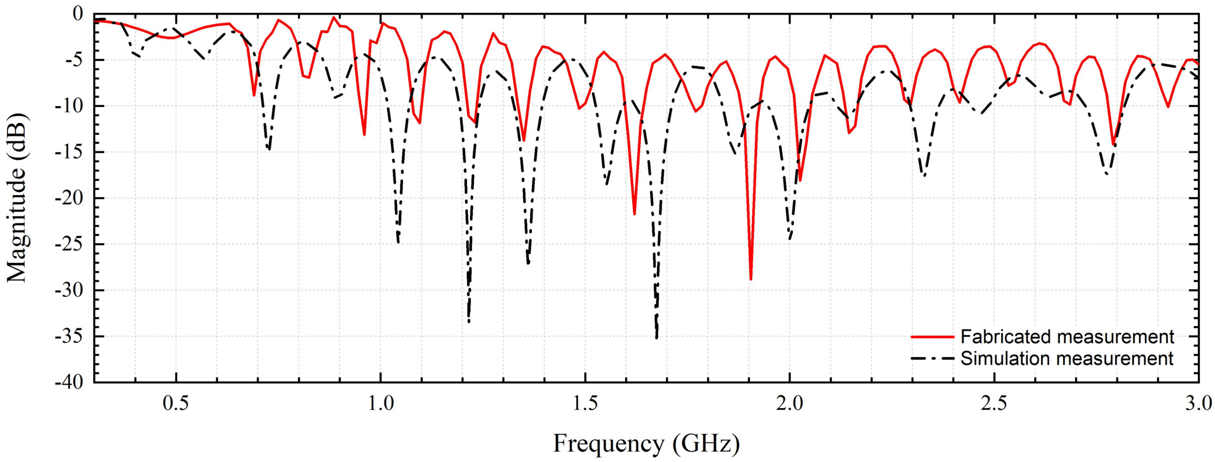


**Fig. 14.** Simulated and measured return loss of feed line technique

The return loss result for coaxial feed shows in Figure 15 compared the fabricated and simulation measurement of Hilbert fractal antenna. The graph shows the return loss for both the simulated and fabricated antennas show very similar patterns with small shifts which indicates that the fabrication process was successful.

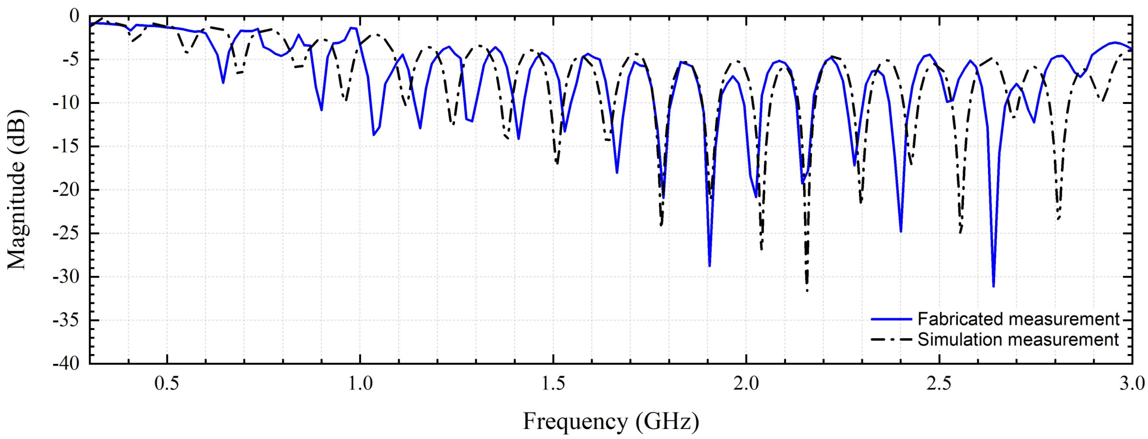


**Fig. 15.** Simulated and measured return loss of coaxial feed technique

Figure 16 shows the comparison for the fabricated antenna between coaxial feed and line feed technique. The resonant frequencies for the coaxial feed range from 1.035 GHz to 2.745 GHz, with the highest magnitude return loss of -31.10 dB at 2.640 GHz. While the resonant frequencies for the line feed technique range from 0.96 GHz to 2.790 GHz, with the highest magnitude return loss of -28.79 dB observed at 1.905 GHz. In addition, it is shows that the results of the coaxial feed for the antenna are satisfied with the simulation. While the results for the line feed do not fully match the simulated results. However, the results of the line feed still show resonant frequencies that are suitable for UHF partial discharge detection in power transformers.

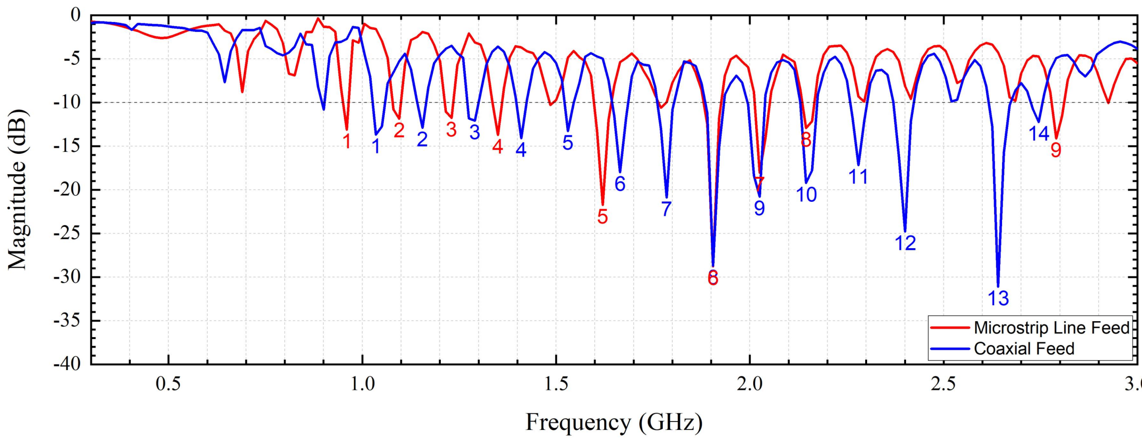


**Fig. 16.** Comparison of fabricated Hilbert antenna for linefeed and coaxial feed technique

In conclusion, both the coaxial feed and line feed antennas are suitable for UHF partial discharge detection in power transformers. However, the coaxial feed antenna is more preferable as it demonstrated consistency with the simulation and had a higher number of resonant frequencies which are 14 resonant frequencies compared to the line feed technique. Therefore, the use of a coaxial feed antenna for UHF partial discharge detection is recommended for better accuracy and reliability in power transformer monitoring.

## 5. Conclusion

This paper discusses a comparative analysis of two feeding techniques for a 4th order Hilbert fractal antenna, specifically focusing on microstrip line feed and coaxial feed. The primary objective of this study is to analyse and determine the most suitable antenna design for partial discharge detection in power transformer. By conducting a comparative analysis of two feeding techniques, the best performance of the feeding technique is determined for PD detection in power transformer.

Based on the results, both feeding techniques for the Hilbert fractal antenna showed suitable resonant frequencies and potential use for the detection of UHF PD signals in power transformers. However, the simulation and the fabrication of the coaxial feed antenna produced the same results indicating that the technique is more efficient for fabrication compared to the line feed technique. In addition, the coaxial feed antenna shows a greater number of resonant frequencies which indicates the capability of the antenna to capture more PD signals.

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## References
[1] Bohari, Zul Hasrizal, Muzamir Isa, Faizah Abu Bakar, Ahmad Zaidi Abdullah, Ayob Nazmy Nanyan, Mohamad Na'im Mohd Nasir, Mohamad Fani Sulaima, and Emy Zairah Ahmad. "A Contemporary Review of High Voltage Partial Discharge Detection and Recognition Techniques." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 107, no. 1 (2023): 58-79. https://doi.org/10.37934/arfmts.107.1.5879

[2] Rohani, M. N. K. H., A. A. H. Zaidi, A. Sakanovic, C. L. Wooi, A. S. Rosmi, M. Isa, and B. Ismail. "Classification of partial discharge detection technique in high voltage power component: A review." *International Journal of Integrated Engineering* 11, no. 4 (2019).

[3] Suganya, G., S. Jayalalitha, K. Kannan, and S. Venkatesh. "Survey of de-noising techniques for partial discharge interferences." *ARPN J. Eng. Appl. Sci* 12, no. 2 (2017): 414-427.

[4] Hekmati, Arsalan, and Rasoul Hekmati. "Optimum acoustic sensor placement for partial discharge allocation in transformers." *IET Science, Measurement & Technology* 11, no. 5 (2017): 581-589. https://doi.org/10.1049/iet-smt.2016.0417

[5] Jangjoo, Mohammad Amin, Mehdi Allahbakhshi, and Hassan Reza Mirzaei. "UHF sensors positioning on the power transformer tank to enhance the partial discharge localization accuracy." *Electric Power Systems Research* 218 (2023): 109174. https://doi.org/10.1016/j.epsr.2023.109174

[6] Azizie, Nurin Ainanie, Nuriziani Hussin, Hana Abdull Halim, and Muhamad Irwanto. "Experimental Investigation on Thermal Conductivity of Palm Oil and Zinc Oxide PFAE-based Nanofluids." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 108, no. 1 (2023): 93-102. https://doi.org/10.37934/arfmts.108.1.93102

[7] Bansal, Aakash, and Richa Gupta. "A review on microstrip patch antenna and feeding techniques." *International Journal of Information Technology* 12, no. 1 (2020): 149-154. https://doi.org/10.1007/s41870-018-0121-4

[8] Abd Razak, Jeefferie, Nor Aisah Khalid, Hazman Hasib, Mazlin Aida Mahamood, Mohd Muzafar Ismail, Noraiham Mohamad, Poppy Puspitasari, and Moayad Husein Flaifel. "Electrical conductivity and antenna properties of polyaniline filled GNPs nanocomposites." *Malaysian Journal on Composites Science and Manufacturing* 4, no. 1 (2021). https://doi.org/10.37934/mjcsm.4.1.1127

[9] Parasuraman, S., S. Yogeeswaran, and G. P. Ramesh. "Design of Microstrip Patch Antenna with improved characteristics and its performance at 5.1 GHz for Wireless Applications." In *IOP Conference Series: Materials Science and Engineering*, vol. 925, no. 1, p. 012005. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/925/1/012005

[10] 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

[11] Abd Jalil, M. A., A. S. Rosmi, M. N. K. H. Rohani, M. Isa, N. D. Roslizan, W. Z. Leow, and M. A. Jamlos. "UHF Sensors for On-line Partial Discharge Detection on Power Transformer: Hilbert fractal, Moore Fractal and Peano fractal." In *2020 IEEE 8th Conference on Systems, Process and Control (ICSPC)*, pp. 202-207. IEEE, 2020. https://doi.org/10.1109/ICSPC50992.2020.9305777

[12] Peng, Wang, Kuang Fen, Liu Mingjun, and Zhou Qiukuan. "UHF enclosed Hilbert antenna for partial discharge on-site testing." In *2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, pp. 1-4. IEEE, 2016. https://doi.org/10.1109/ICHVE.2016.7800680

[13] 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

[14] Mokal, Ms Varsharani, Prof SR Gagare, and Dr RP Labade. "Analysis of Micro strip patch Antenna Using Coaxial feed and Micro strip line feed for Wireless Application." *IOSR Journal of Electronics and Communication Engineering* 12, no. 03 (2017): 36-41. https://doi.org/10.9790/2834-1203033641

[15] Chakravarthy, S. Sibi, N. Sarveshwaran, S. Sriharini, and M. Shanmugapriya. "Comparative study on different feeding techniques of rectangular patch antenna." In *2016 Thirteenth International Conference on Wireless and Optical Communications Networks (WOCN)*, pp. 1-6. IEEE, 2016. https://doi.org/10.1109/WOCN.2016.7759032

[16] Szymczak, Cyprian. "PIFA antenna for partial discharge detection in power transformers." *Metrology and Measurement Systems* (2021): 343-355. https://doi.org/10.24425/mms.2021.136611

[17] 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

[18] 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

[19] Bara, Pourush, and Dinesh Yadav. "A comparative investigation of microstrip patch antenna using FR-4/RT-Duroid/RO3003 materials for bluetooth and WLAN applications." In *Optical and Wireless Technologies: Proceedings of OWT 2017*, pp. 685-696. Springer Singapore, 2018. https://doi.org/10.1007/978-981-10-7395-3_76

[20] Uwiringiyimana, Jean Pierre, and Umar Khayam. "Application of a Novel Type of UHF Antenna for Partial Discharge Detection in Power Transformers Oil Insulation." In *2022 9th International Conference on Condition Monitoring and Diagnosis (CMD)*, pp. 442-447. IEEE, 2022. https://doi.org/10.23919/CMD54214.2022.9991524

[21] Xu, Zheng, and Guoyu Hei. "Rectangular spiral antenna with a Hilbert unit for detecting corona discharge in overhead lines." *IEEE Sensors Journal* 21, no. 2 (2020): 930-936. https://doi.org/10.1109/JSEN.2020.2979238

[22] Mukhtaruddin, Azharudin, Muzamir Isa, Mohd Fadzil Ain, Mazlee Mohd Noor, Mohd Rafi Adzman, and Mohamad Nur Khairul Hafizi Rohani. "Application of ultra-high frequency antenna for partial discharge detection in oil-filled power transformer: a review." *Zulfaqar Journal of Defence Science, Engineering & Technology* 3, no. 2 (2020). https://doi.org/10.58247/jdset-2020-0302-06

[23] Salah, Walid S., Ahmed H. Gad, Mahmoud A. Attia, Soliman M. Eldebeikey, and Abdelhady R. Salama. "Design of a compact ultra-high frequency antenna for partial discharge detection in oil immersed power transformers." *Ain Shams Engineering Journal* 13, no. 2 (2022): 101568. https://doi.org/10.1016/j.asej.2021.08.011

[24] 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