Modification and Optimization of Circular Patch Microstrip Antenna (CPMA) for Partial Discharge Detection Against High Voltage

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Abstract*—The result of the modified reference antenna is based on predefined parameters by optimizing each parameter namely *r1, r2,* and *L* for partial discharge detection of high-voltage, parameter *r1* shows the largest bandwidth when *r1* is changed by 10mm *of* 5.36 GHz. However, the reflection coefficient and VSWR values at 15mm are better if we compare them to 5mm and 10mm. Parameter *r2* shows that the largest bandwidth shown after we changed the size by 6mm of 5.37GHz is better than 3mm and 9mm. However, the reflection coefficient value at 9mm is better than 3mm and 6mm. Simulation results on parameter L based on Fig. *6* show that the largest bandwidth when parameter L is changed to 3mm is better than 2mm and 4mm, but the reflection coefficient value at 4mm is better than 2mm and 3mm, and for VSWR value 2mm is better than 3mm and 4mm. Modification antenna has roughly omnidirectional radiation patterns is 1.96dBi for r1 = 5; r2 = 3; slot = 2; 2.07dBi for r1 = 10; r2 = 6; slot = 3; 2.03dBi for r1 = 15; r2 = 9; slot = 4, the operating frequency band between 1.5 GHz, which is the frequency of interested for PD occurrence. For a voltage of 7 kV, the modified antenna can detect positive and negative cycle partial discharge of 115nPos, while the reference antenna is 80nPos. For a voltage of 8 kV, the modified antenna can detect partial discharge positive and negative cycles of 51nPos, while the reference antenna is 19nPos. For a voltage of 9 kV, the modified antenna can detect partial discharge positive and negative cycles of 27nPos, while the reference antenna is 14nPos.

Keywords*—*Partial Discharge, Antenna, Microstrip, Bandwidth, High Voltage, Sensor

I. INTRODUCTION

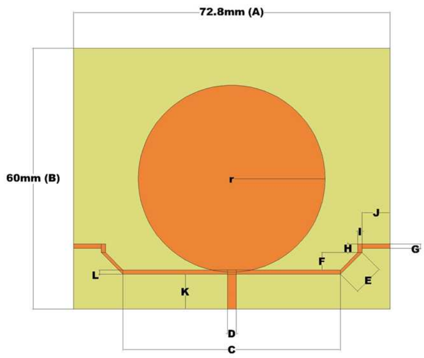
Partial discharge measurements are carried out using electrical methods and non-electrical methods. The electrical method uses the RC Detector sensor. The non-electrical method uses the Loop Antenna sensor[1]. A circular slot geometric shape adjusts the perimeter or length of the patch to enhance the transmission and reception of electromagnetic waves across its entire surface area. Interestingly, circular slot antennas can operate effectively across a wide range of frequencies [17]. The performance of circular patch microstrip antennas can be improved by incorporating slots into the substrate. Notably, reducing the gap between split ring resonators enhances performance compared to designs with larger gaps. This approach leverages the circular slot design in the geometry of the circular patch microstrip antenna to achieve multi-band frequency operation. The presence of the circular slot allows the antenna to function as a wideband or multi-band device, maintaining a compact size, exhibiting frequency independence, and minimizing unwanted radiations from the feed[13].

This study discusses how to enhance the CPMA's performance as a partial discharge detection sensor by modifying the microstrip antenna to achieve a larger bandwidth for detecting partial discharges on high-voltage lines. Section 2 outlines the design parameters for the proposed antenna, while Section 3 details the modifications, optimization, and simulation results obtained using CST Studio software. Section 4 covers the fabrication process using experimental tools, and Section 5 concludes the findings. The final results of this study will provide suggestions for modification antenna with updated parameters, to improve Partial Discharge detection performance in high-voltage equipment.

II. ANTENNA DESIGN

A. Reference Design of Antenna

CST Studio Version 2024 software is used for the simulation and optimization antenna for the process.



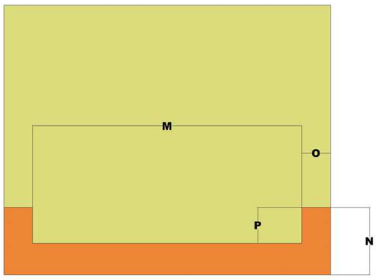


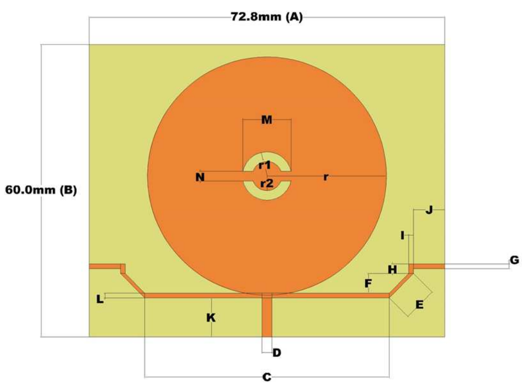
Fig. 1. Reference design of antenna [10]

TABLE I. Dimension of Reference Antenna [10]

Parameter Specification		Values
Substrate length	A	72.8 mm
Substrate width	B	60 mm
Arm length	C	50 mm
Feedline length	D	2 mm
Position of right arm length	E	7 mm
Position of right arm length	F	4 mm
Resistive loading width	G	1 mm
Arm after transition width	H	2 mm
Arm after transition length	I	3 mm
Arm of right after transition length	J	6.4 mm
Feedline width	K	8 mm
Arm width	L	1 mm
Ground-plane length	M	60 mm
Outer width	N	15 mm
Inner ground plane length	O	6.4 mm
Inner ground plane width	P	8 mm
Patch radius	r	21.5 mm
Substrate thickness		1.6 mm
Copper thickness		0.035 mm
(M. Hadi, U. Khayam and Rachmawati, 2023)		

B. *Antenna Parameter Modification and Optimization Results*

The circular slot geometric shape adjusts the perimeter or length of the patch to improve the transmission and reception of electromagnetic waves over its entire surface area. Notably, circular slot antennas can operate efficiently across a broad range of frequencies. The performance of circular patch microstrip antennas can be enhanced by adding slots to the substrate. This method utilizes the circular slot design within the circular patch microstrip antenna's geometry to enable multi-band frequency operation. The inclusion of the circular slot allows the antenna to function as a wideband or multi-band device, while also keeping a compact size, demonstrating frequency independence, and reducing unwanted radiation from the feed.



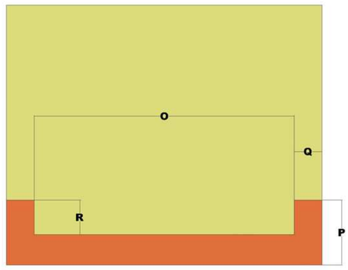


Fig. 2. Modification design result

TABLE II. Dimensions of Modified Antenna

Parameter Specification		Values
Substrate length	A	72.8 mm
Substrate width	B	60 mm
Arm length	C	50 mm
Feedline length	D	2 mm
Position of right arm length	E	7 mm
Position of right arm length	F	4 mm
Resistive loading width	G	1 mm
Arm after transition width	H	2 mm
Arm after transition length	I	3 mm
Arm of right after transition length	J	6.4 mm
Feedline width	K	8 mm
Arm width	L	1 mm
Slot length	M	9.8 mm
Slot width	N	2 mm
Ground-plane length	O	60 mm
Outer width	P	15 mm
Inner ground plane length	Q	6.4 mm
Inner ground plane width	R	8 mm
Diameter inner patch big radius	r1	5 mm
Diameter inner patch small radius	r2	3 mm
Patch radius	r	24.5 mm
Resistive loading value		82 Ohms
Substrate thickness		1.6 mm
Copper thickness		0.035 mm
FR-4 dielectric substrate		

C. *Comparison Chart of Reference Antenna and Modified Antenna*

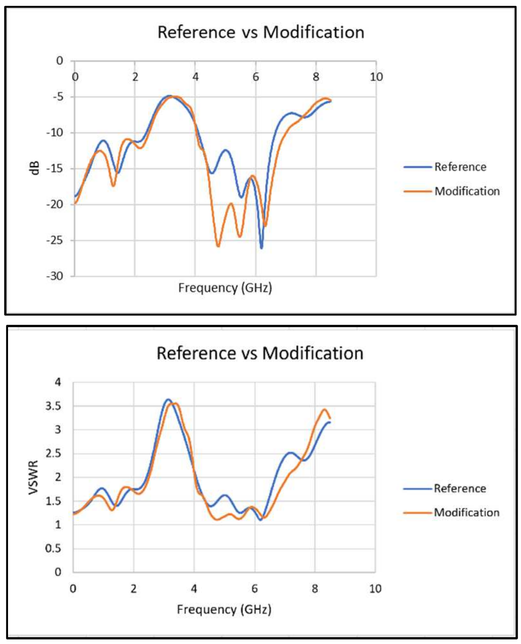


Fig. 3 . Comparison of bandwidth, reflection coefficient, and VSWR between reference antenna and modified antenna

The above graph shows the comparative values of having a very large bandwidth in the frequency range of 5.36GHz, then reflection coefficient and VSWR averaging 24.85 dB and 1.12, respectively. Compared with the reference antenna, with a bandwidth of 4.8GHz, a reflection coefficient of -25.01, and a VSWR of 1.13.

III. OPTIMIZATION SIMULATION

A. *Results of Parameter Optimization (r1)*

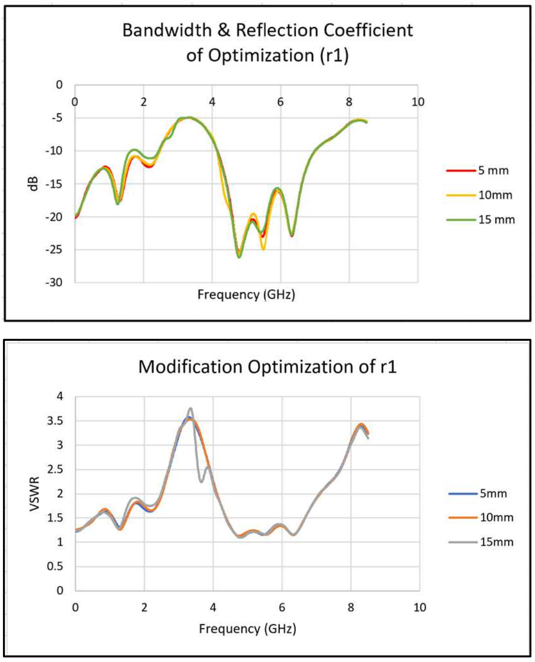


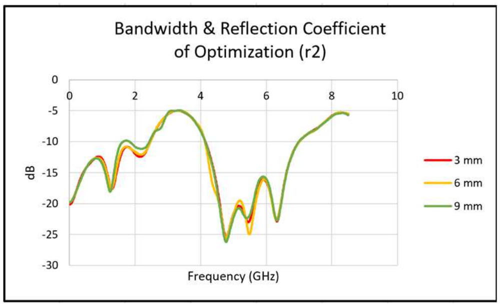
Fig. 4. Bandwidth, reflection coefficient, VSWR graph of r1 parameter optimization

TABLE III. Parameter Simulation Results of r1

No.	Parameter r1 (Radius/Diameter)	Bandwidth	Reflection coefficient	VSWR
1.	5 mm	5.33 GHz	-25.40 dB	1.11
2.	10 mm	5.36 GHz	-24.09 dB	1.13
3.	15 mm	5.31 GHz	-27.06 dB	1.09

Simulation results on parameter r1 based on Fig. 4 show the largest bandwidth when *r1* is changed by 10mm of 5.36 GHz. However, the reflection coefficient and VSWR values at 15mm are better if we compare them to 5mm and 10mm. Then, the bandwidth size for parameter *r1* was selected at a diameter size of 10mm of 5.36GHz.

B. *Results of Parameter Optimization (r2)*



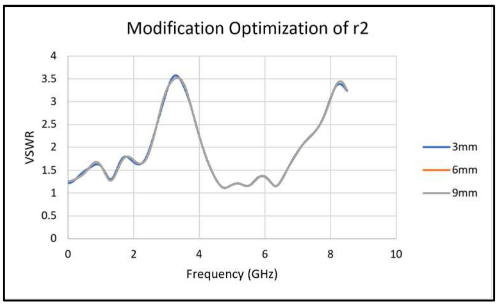


Fig. 5. Bandwidth, reflection coefficient, VSWR graph of r2 parameter optimization

TABLE IV. Parameter Simulation Results of R2

No.	Parameter R2 (Radius)	Bandwidth	Reflection coefficient	VSWR
1.	3 mm	5.32 GHz	-25.20 dB	1.13
2.	6 mm	5.37 Ghz	-25.24 dB	1.11
3.	9 mm	5.36 Ghz	-25.26 dB	1.12

Simulation results on parameter *r2* based on Fig. 5 show that the largest bandwidth shown after we changed the size by 6mm of 5.37GHz is better than 3mm and 9mm. However, the reflection coefficient value at 9mm is better than 3mm and 6mm, as shown in Table IV. Therefore, optimization based on the size of the bandwidth for the *r2* parameter is chosen to be 10mm.

C. *Slot Parameter Optimization Results (L)*

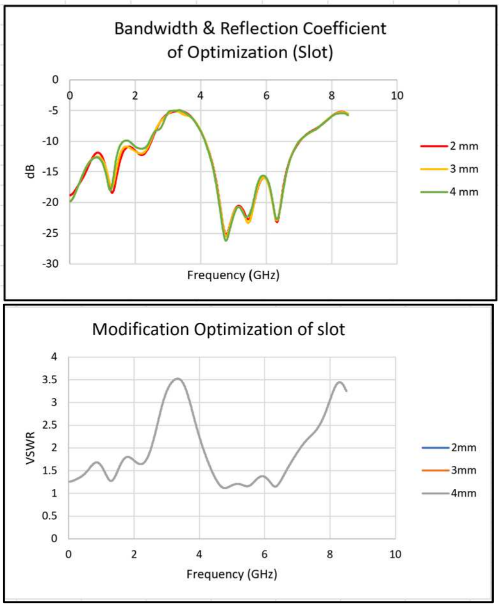


Fig. 6. Bandwidth, reflection coefficient, & VSWR graph of slot parameter optimization

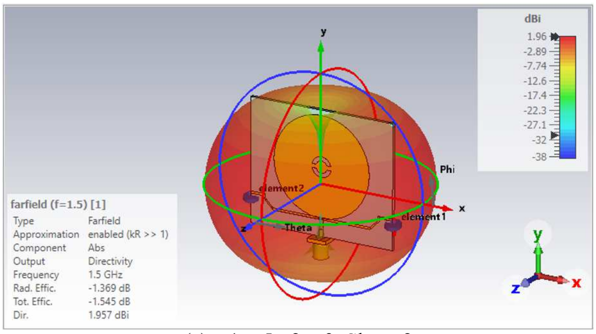
TABLE V. Parameter Simulation Results of Slot

No.	Parameter Slot	Bandwidth	Reflection coefficient	VSWR
1.	2 mm	5.36 GHz	-25.22 dB	1.11
2.	3 mm	5.37 Ghz	-25.24 dB	1.14
3.	4 mm	5.35 Ghz	-25.89 dB	1.15

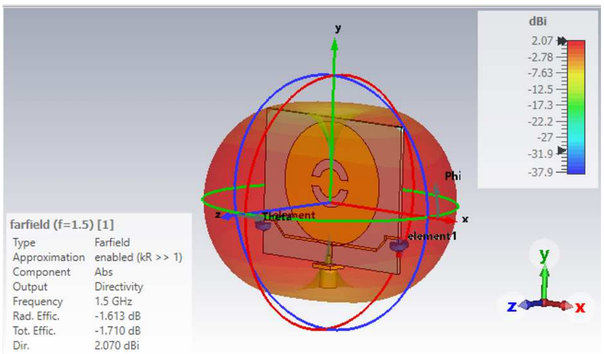
Simulation results on parameter *L* based on Fig. 6 show that the largest bandwidth when parameter *L* is changed to 3mm is better than 2mm and 4mm, but the reflection coefficient value at 4mm diameter is better than 2mm and 3mm, and for VSWR value 2mm is better than 3mm and 4mm. As shown in Table V. Therefore, optimization based on the size of the bandwidth for the *L* parameter is selected as 3mm.

D. Pattern Radiation, Directivity, Sensitivity

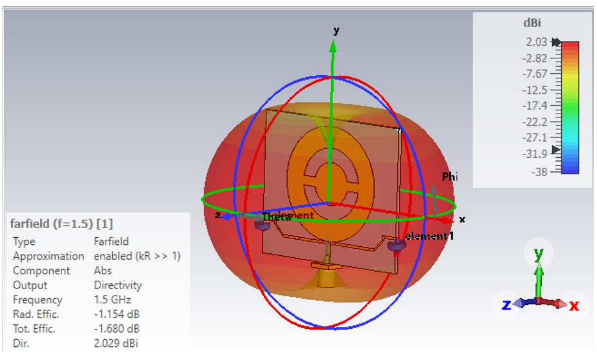
The radiation pattern is a crucial factor to consider when designing an antenna. It provides insight into the directions from which the antenna emits or receives electromagnetic waves. Three-dimensional (3-D) radiation patterns at various frequencies, it is seen that the proposed modification antenna has roughly omnidirectional radiation patterns is 1.96dBi for r1 = 5; r2 = 3; slot = 2; 1.99dBi for r1 = 10; r2 = 6; slot = 3; 2.06dBi for r1 = 15; r2 = 9; slot = 4, the operating frequency band between 1.5 GHz, which is the frequency of interested for PD occurrence. The antenna with omnidirectional radiation patterns allows it to receive PD signal energy from all directions.



(a) r1 = 5, r2 = 3, Slot = 2



(b) r1 = 10, r2 = 6, Slot = 3



(c) r1 = 15, r2 = 9, Slot = 4

Fig.7. 3-D radiation patterns of the designed antenna

IV. Antenna Fabrication and Measurement

A. Antenna Modification Fabrication

Antenna modifications have been optimized using CST Studio software.

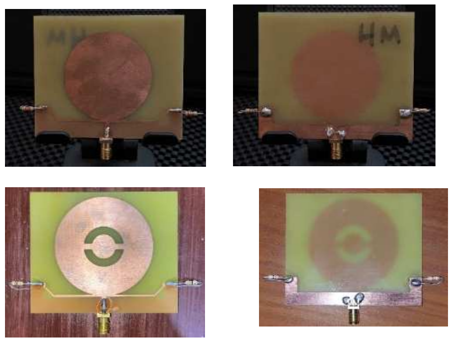


Fig. 8. Reference antenna and Modification antenna fabrication results

B. Components of The Experimental Setup

TABLE VI. Experimental Tools

RC Detector	**Capacitor Voltage Divider**
	
Coupling Capacitor (100pF)	**Needle-Plate in Air Insulation**
	
HV Testing Transformer	**Resistor (6100 Ω)**
	
Voltage Regulator	**Oscilloscope**
	
Connecting Cup	**Floor Pedestal**
	

C. Partial Discharge Testing

The schematic of the complete partial discharge testing system can be seen.

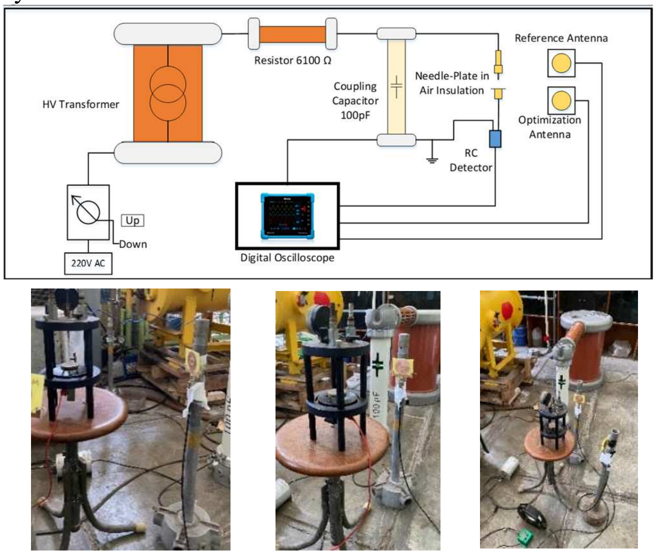


Fig. 9. Circuit of air insulation partial discharge data

- 7 kV Reference Antenna

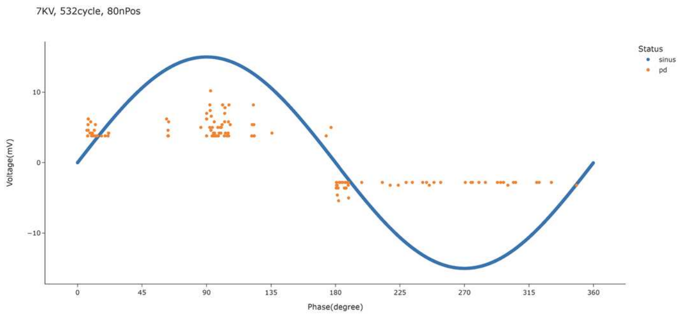


Fig. 10. *Partial discharge* pattern of reference antenna 7 kV

- 7 kV Modification Antenna

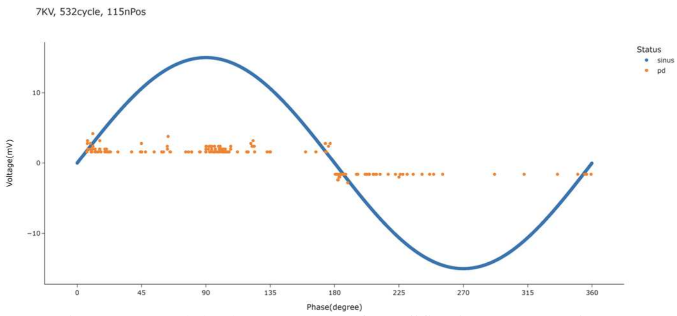


Fig. 11. *Partial discharge* pattern of modification antenna 7 kV

- 8 kV Reference Antenna

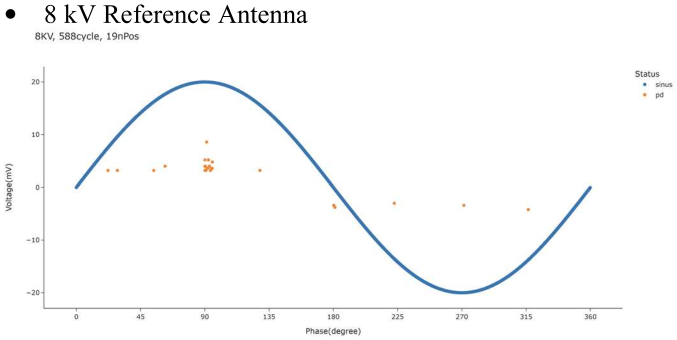


Fig. 12. *Partial discharge* pattern of reference antenna 8 kV

- 8 kV Modification Antenna

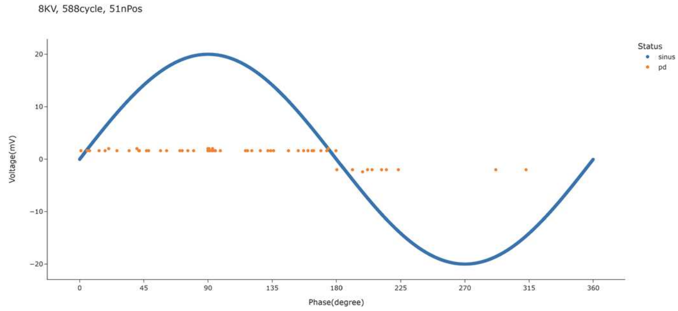


Fig. 13. *Partial discharge* pattern of modification antenna 8 kV

- 9 kV Reference Antenna

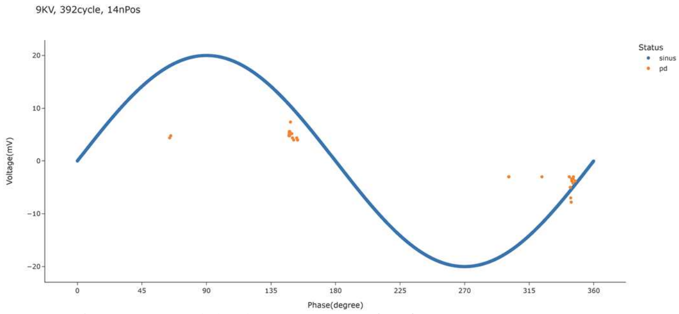


Fig. 14. *Partial discharge* pattern of reference antenna 9 Kv

- 9 kV Modification Antenna

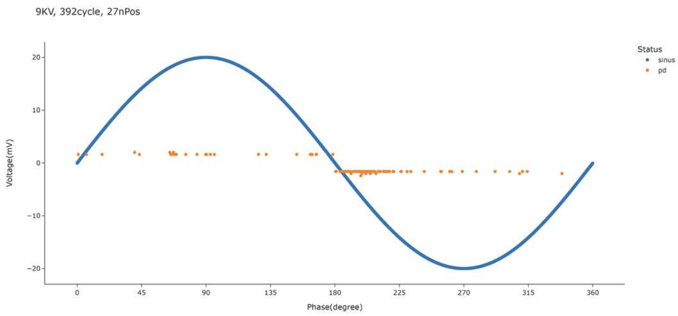


Fig. 15. *Partial discharge* pattern of modification Antenna 9 kV

Fig. 10 to Fig. 15 show the detection of partial discharge by the RC Detector, reference antenna, and modified antenna in insulating air. For a voltage of 7 kV, the modified antenna can detect positive and negative cycle partial discharge of 115nPos, while the reference antenna is 80nPos. For a voltage of 8 kV, the modified antenna can detect partial discharge positive and negative cycles of 51nPos, while the reference antenna is 19nPos. For a voltage of 9 kV, the modified antenna can detect partial discharge positive and negative cycles of 27nPos, while the reference antenna is 14nPos. The RC sensor is used as a reference in the appearance of partial discharge. With Partial Discharge testing carried out on insulating air with needle-plate electrodes, the distance between the two electrodes is 20 mm, and the distance between the reference antenna and the modified antenna is 30 mm from the needle-plate electrode, with the same distance of the modified antenna and reference antenna showing the sensitivity of each antenna in capturing partial discharge in the same wave cycle.

V. Conclusion

The modification antenna shows a very large bandwidth in the frequency range of 5.36GHz, then reflection coefficient and VSWR averaging 24.85 dB and 1.12, respectively. Compared with the reference antenna shows a bandwidth of 4.8GHz, a reflection coefficient of -25.01, and a VSWR of 1.13.

Optimize each parameter namely *r1, r2,* and *L* for partial discharge detection of high-voltage, parameter *r1* shows the largest bandwidth when *r1* is changed by 10mm of 5.36 GHz. However, the reflection coefficient and VSWR values at 15mm are better if we compare them to 5mm and 10mm. Parameter *r2* shows that the largest bandwidth shown after we changed the size by 6mm of 5.37GHz is better than 3mm and 9mm. However, the reflection coefficient value at 9mm is better than 3mm and 6mm. Simulation results on parameter L based on Fig. 6 show that the largest bandwidth when parameter L is changed to 3mm is better than 2mm and 4mm, but the reflection coefficient value at 4mm is better than 2mm and 3mm, and for VSWR value 2mm is better than 3mm and 4mm. Then, the result of the largest bandwidth after optimization modification antenna is r1 = 10, r2 = 6, slot = 3.

Modification antenna has roughly omnidirectional radiation patterns is 1.96dBi for r1 = 5; r2 = 3; slot = 2; 2.07dBi for r1 = 10; r2 = 6; slot = 3; 2.03dBi for r1 = 15; r2 = 9; slot = 4, the operating frequency band between 1.5 GHz, which is the frequency of interested for PD occurrence. Then, the r1 = 10; r2 = 6; slot = 3 have a big range of radiation pattern by 2.07dBi.

For a voltage of 7 kV, the modified antenna can detect positive and negative cycle partial discharge of 115nPos, while the reference antenna is 80nPos. For a voltage of 8 kV, the modified antenna can detect partial discharge positive and negative cycles of 51nPos, while the reference antenna is 19nPos. For a voltage of 9 kV, the modified antenna can detect partial discharge positive and negative cycles of 27nPos, while the reference antenna is 14nPos. Then, the modification antenna shows a dominant detect the partial discharge in positive and negative cycles than the reference antenna.

Optimizing the antenna with updated parameters shows that can improve the quality of antenna performance in detecting partial discharge.

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