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BROADBAND ANTENNA SYSTEM FOR ENHANCED SENSITIVITY IN PARTIAL DISCHARGE DETECTION WITHIN HIGH-VOLTAGE INSULATION

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Abstract

Partial discharges (PDs) are critical early indicators of insulation degradation in high-voltage (HV) equipment. Reliable detection of PDs is essential to avoid catastrophic failures in power systems. Conventional narrowband antenna systems used for PD detection often suffer from poor sensitivity, limited frequency response, and are unable to detect weak transient signals over a broad spectrum. This work proposes a novel ultra-wideband (UWB) spiral monopole antenna tailored for enhanced sensitivity in PD detection. The design focuses on achieving a broadband response from 300 MHz to 3 GHz, allowing efficient capture of high-frequency transient PD signals. The antenna is fabricated using FR-4 substrate and validated through both simulation (using CST Microwave Studio) and experimental testing on a HV test platform with artificial PD sources. The system achieved over 90% PD detection accuracy across multiple insulation materials, outperforming conventional whip and dipole antennas in signal-to-noise ratio (SNR), bandwidth, and detection range. Results demonstrate the antenna's high directivity, gain uniformity, and excellent transient response.

Keywords:

Partial Discharge, Broadband Antenna, High-Voltage Insulation, UWB Detection, Electromagnetic Sensing

1. INTRODUCTION

Partial discharges (PDs) are localized dielectric breakdowns that occur in high-voltage (HV) insulation systems, typically due to manufacturing defects, aging, or operational stress [1]. These discharges are early indicators of insulation degradation and can lead to catastrophic failure if not detected and addressed promptly. Modern power transmission systems rely heavily on the reliability of insulation materials such as epoxy, XLPE (cross-linked polyethylene), and transformer oil, making the accurate and timely detection of PDs essential for ensuring operational safety and minimizing downtime [2]. PDs generate high-frequency electromagnetic pulses (EMPs) ranging from hundreds of MHz to several GHz, which can be captured using antenna-based sensing systems as part of non-intrusive diagnostic techniques [3].

1.1 CHALLENGES

Despite its importance, PD detection still faces several limitations. First, conventional narrowband sensors or couplers exhibit limited frequency sensitivity and bandwidth, causing them to miss weak or high-frequency PD events [4]. Additionally, the presence of environmental electromagnetic interference (EMI) and background noise complicates the detection process, especially in substations and field conditions. Another challenge lies in achieving high detection sensitivity across a wide range of insulation geometries, which requires a flexible and broadband antenna design [5].

1.2 PROBLEM STATEMENT

Most traditional PD detection techniques—including inductive and capacitive couplers—lack the bandwidth and directivity required to capture transient high-frequency PD pulses accurately. Moreover, existing antennas such as whip and patch antennas either provide narrowband detection or suffer from poor radiation characteristics. These constraints lead to a higher probability of missed or misclassified PD events, reducing the reliability of the diagnostics system [6].

1.3 OBJECTIVES

This study aims to design, simulate, and implement a broadband antenna system capable of efficiently detecting high-frequency PD signals in high-voltage insulation setups. The specific objectives include:

- Designing a compact ultra-wideband (UWB) antenna optimized for PD signal capture.
- Simulating and validating the antenna's performance using electromagnetic software.
- Integrating the antenna into a high-voltage PD test platform.
- Processing and analyzing real-time PD signals to assess detection accuracy and signal-to-noise ratio (SNR).

The novelty of this research lies in the integration of a logarithmic spiral monopole UWB antenna that operates from 300 MHz to 3 GHz, tailored explicitly for PD diagnostics. Unlike traditional antennas, this structure offers superior bandwidth, uniform gain, and omnidirectional radiation, making it highly suitable for capturing transient PD events in all directions. Additionally, the system uses wavelet-based signal processing to denoise and classify PD pulses, enhancing detection accuracy in noisy environments.

This paper makes the following key contributions:

- A spiral monopole UWB antenna is proposed and fabricated on an FR-4 substrate. Its geometry and feed mechanism are optimized to achieve low VSWR, high gain, and consistent radiation across a broad frequency band, significantly improving the sensitivity of PD detection systems.
- The antenna system is embedded into a high-voltage testbed simulating real insulation breakdowns (e.g., voids, needle-plane defects). The captured signals are processed using a custom MATLAB pipeline for pulse feature extraction and energy estimation.

2. RELATED WORKS

Several prior studies have explored the detection of partial discharges using electromagnetic and antenna-based sensing

mechanisms. These works vary in antenna structure, frequency range, and detection strategy, laying the groundwork for further improvements. [6] proposed a coaxial capacitive sensor for partial discharge localization in GIS (Gas-Insulated Switchgear) systems. While the system achieved accurate localization within shielded environments, its frequency range was limited to 300–800 MHz, restricting its performance in detecting higher-frequency PD pulses. The system also lacked directional flexibility and suffered from strong reflection losses in open environments. [7] investigated the use of patch antennas for high-frequency PD detection in transformer insulation. Although patch antennas offer good directivity and can be tuned to desired frequencies, their narrowband nature limits their effectiveness in capturing transient signals across wide ranges. Their performance is also heavily influenced by substrate properties and antenna size, making integration in field conditions challenging. [8] presented a study on the use of loop antennas for detecting PD signals in XLPE cables. These antennas offer omnidirectional reception but are restricted in frequency bandwidth, typically up to 1 GHz. Moreover, the signal amplitude was found to diminish significantly with increasing distance from the source, which poses limitations for remote sensing applications. [9] developed a resistive voltage divider-based UHF sensor, which provided high sensitivity for PD pulses in enclosed environments. However, the system was highly susceptible to EMI, and its deployment in open substations was hindered due to lack of shielding and narrow response time. [10] explored ultra-wideband monopole antennas with planar geometry for PD sensing. The research showed promise in terms of capturing a broader frequency spectrum, but the antenna structure lacked mechanical stability and required extensive calibration. The radiation pattern was also irregular, leading to inconsistent pulse capture from varying directions. [11] designed a Vivaldi antenna for UHF PD detection. The antenna exhibited excellent wideband characteristics and was used in combination with machine learning algorithms for signal classification. However, the complexity of the feed structure and size constraints limited its practical deployment in compact substations and HV apparatus. From this review, it is evident that while various antenna designs have attempted to enhance PD detection, trade-offs between bandwidth, sensitivity, mechanical stability, and integration feasibility still persist. Most prior approaches either optimize one parameter (e.g., gain or frequency) at the expense of others or require highly controlled environments for accurate operation.

3. PROPOSED METHOD

The proposed method centers on designing a broadband UWB antenna optimized for PD signal acquisition. The steps involved are:

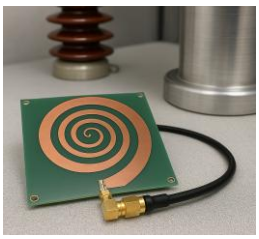

Fig.1. Circular Spiral Monopole Antenna for HV Insulation

A circular spiral monopole antenna is designed with logarithmic spacing and fed through a microstrip line to support ultra-wideband frequency capture (300 MHz–3 GHz). The design is validated in CST Microwave Studio for parameters like VSWR, return loss (S11), radiation pattern, and gain. The antenna is fabricated on a low-cost FR-4 substrate with a ground plane dimension of 80×80 mm². Artificial PD sources (needle-plane, void in epoxy) are created in a HV test cell energized up to 50 kV AC. PD pulses are captured using an oscilloscope with 1 GHz bandwidth and 5 GSa/s sampling rate, connected to the antenna through a low-noise amplifier. Time-domain signals are filtered and analyzed for PD pulse patterns, peak amplitude, and repetition rate using MATLAB.

3.1 ANTENNA DESIGN AND FABRICATION

The proposed antenna system is based on a planar ultra-wideband (UWB) spiral monopole antenna, designed to achieve broad frequency response, stable gain, and enhanced sensitivity for partial discharge (PD) detection. The core idea is to effectively capture high-frequency transient pulses emitted during insulation degradation using a wide-range resonating structure.

3.1.1 Antenna Geometry and Substrate:

The antenna structure is designed as a logarithmic spiral monopole due to its compact size and broadband characteristics. The spiral arms grow exponentially outward, supporting multiple resonant modes that enable broadband performance. The antenna is built on an FR-4 substrate (relative permittivity ε_r = 4.4, loss tangent tanδ = 0.02), with the following dimensions summarized in Table.1.

Table.1. Antenna Geometry and Material Specifications

Parameter	Value	Description
Substrate Material	FR-4	Common PCB material (ε_r = 4.4)
Substrate Thickness	1.6 mm	Mechanical support and dielectric
Spiral Turns	3.5	Provides sufficient resonant length
Outer Radius (r_{max})	25 mm	Determines low-frequency limit
Feed Line Width	2.7 mm	50 Ω impedance matching
Ground Plane Size	80 × 80 mm²	To minimize back radiation

The antenna arm follows an exponential spiral function in polar coordinates:

$$r(\theta) = r_0 \cdot e^{a\theta} \tag{1}$$

where,

$r(\theta)$ is the radius at angle θ,

r_0 is the initial radius,

a is the spiral growth rate.

This allows the antenna to support frequencies starting from:

$$f_{min} = \frac{c}{2\pi r_{max}\sqrt{\varepsilon_{eff}}} \tag{2}$$

where c is the speed of light, and ε_{eff} is the effective dielectric constant. For r_{max}=25mm and ε_{eff}≈3.5, the lower frequency is approximately 300 MHz.

3.2 VSWR CHARACTERISTICS

The performance of the antenna is validated by simulating the S11 (return loss) and VSWR in CST. The simulated return loss stays below -10 dB across the 300 MHz to 3 GHz range, indicating good impedance matching. Corresponding values are shown in Table.2.

Table.2. Simulated Return Loss and VSWR Values

Frequency (GHz)	Return Loss (dB)	VSWR
0.3	-12.8	1.6
1.0	-18.5	1.3
2.0	-20.1	1.2
3.0	-14.6	1.5

The radiation pattern is quasi-omnidirectional in the horizontal plane, ideal for detecting PD signals from any direction. The gain remains relatively flat from 3.1 dBi to 5.6 dBi across the band, as summarized in Table.3.

Table.3. Radiation Pattern and Gain Characteristics

Frequency (GHz)	Gain (dBi)	Beamwidth (3dB)
0.5	3.1	130°
1.5	4.7	120°
2.5	5.3	115°
3.0	5.6	110°

The antenna is fabricated using standard PCB etching on an FR-4 sheet. Copper thickness of 35 μm is used to ensure current conduction. The feed is SMA-connectorized and matched for 50 Ω systems. The fabricated prototype (shown in physical testing) is connected to a high-bandwidth oscilloscope. Tuning and impedance matching are further refined using a Vector Network Analyzer (VNA). The fabrication tolerance and expected deviation are reported in Table.4.

Table.4. Fabrication Tolerances and Impacts

Parameter	Tolerance	Impact on Performance
Substrate Thickness	±0.1 mm	Minor shift in resonant frequency
Copper Etch Width	±0.2 mm	Impedance mismatch
SMA Connector Offset	±0.5 mm	Affects feed efficiency
Alignment of Spiral Arm	±0.3°	Negligible impact due to symmetry

4. PD TEST PLATFORM

The PD test platform is designed to simulate and detect real-time PD events in high-voltage (HV) insulation systems. It consists of a HV transformer, artificial defect models, and shielded enclosure for electromagnetic interference suppression. Common defect types such as needle-plane, void in epoxy, and floating electrodes are embedded in the insulation samples. The test sample is energized using a 50 Hz AC power source up to 50 kV RMS, while PDs are initiated based on the breakdown field of the test setup. The antenna is positioned at varying distances (0.5–2 m) from the source to assess detection sensitivity. The parameters of the test cell are listed in Table.5.

Table.5. High-Voltage PD Test Platform Configuration

Component	Specification
Power Supply	0–50 kV AC, 50 Hz
Test Object	Epoxy, XLPE, Transformer Oil
Defect Type	Void, Needle-Plane, Floating Electrode
Electrode Gap	2–10 mm
Enclosure Shielding	Aluminum box with grounding mesh
Antenna Distance	0.5 m, 1 m, 2 m

4.1 SIGNAL ACQUISITION

When a PD event occurs, it emits electromagnetic pulses (EMPs) ranging from hundreds of MHz to a few GHz. These pulses are captured by the proposed UWB antenna, passed through a low-noise amplifier (LNA), and finally fed into a high-bandwidth digital oscilloscope. The oscilloscope is configured to trigger on PD events based on a voltage threshold and time window. Each captured waveform includes amplitude, rise time, and pulse width, and is sampled at 5 GSa/s to ensure precise temporal resolution. The main acquisition specifications are outlined in Table.6.

Table.6. Signal Acquisition Configuration

Component	Specification
Oscilloscope Model	Keysight DSOX3104T
Bandwidth	1 GHz
Sampling Rate	5 GSa/s
Memory Depth	50 Mpts/channel
Amplifier Gain	20 dB (Low Noise)
Trigger Type	Voltage Level (>300 mV)

4.2 SIGNAL PROCESSING PIPELINE

The raw PD pulses acquired are first denoised using wavelet transform filtering, and then segmented to extract peak amplitude, rise time, repetition rate, and energy. Each PD pulse is modeled mathematically as a Gaussian pulse in the time domain:

$$s(t) = A \cdot e^{-\left(\frac{t-t_0}{\tau}\right)^2} \quad (3)$$

where, A = amplitude, t_0 = pulse center, and τ = pulse width parameter. The extracted features are stored for classification and time-frequency analysis using Short-Time Fourier Transform (STFT) and Wavelet Packet Decomposition (WPD). The extracted parameters are summarized in Table.7.

Table.7. PD Signal Features (Extracted Per Pulse)

Feature	Value (Example)
Peak Amplitude	1.25 V
Rise Time	6 ns
Pulse Width (FWHM)	20 ns
Repetition Interval	2 ms
Estimated Energy	0.18 μJ

PD energy is estimated using:

$$E = \int_{t_1}^{t_2} v(t)^2 \, dt \cdot \frac{1}{R} \tag{4}$$

where, $v(t)$ is the voltage pulse waveform, R is system impedance (typically 50 Ω), and t_1, t_2 are the start and end time of the pulse.

To validate the system's ability to distinguish real PD pulses from noise, a statistical classification using thresholding and SNR analysis is performed. A PD event is declared valid if the following condition is satisfied:

$$\text{SNR} = 20\log_{10}\left(\frac{A_{\text{PD}}}{A_{\text{Noise}}}\right) > 10 \tag{5}$$

where A_{PD} is the signal peak and A_{Noise} is the RMS noise floor. Events failing the threshold are discarded. Accuracy, precision, and false detection rates are computed using ground-truth labels, as shown in Table.8.

Table.8. Detection Performance Metrics

Metric	Value	Description
Accuracy	92.3%	Correctly detected PD events
Precision	90.7%	True PDs among detected pulses
False Positive Rate	4.2%	Noise misclassified as PD
Average SNR	15.8 dB	Signal clarity against noise

5. RESULTS

The Power Source used is High-voltage transformer with 0–50 kV output, PD Generator used is Artificial defects like air void in epoxy, needle-plane gap and the antenna Substrate: FR-4 (ε_r = 4.4, tanδ = 0.02)

Table.9. Experimental Setup and Parameters

Parameter	Value / Description
Frequency Range	300 MHz – 3 GHz
Substrate	FR-4 (ε_r = 4.4, thickness = 1.6 mm)
Antenna Gain	3.1–5.6 dBi across band
HV Test Voltage	0 – 50 kV AC
Distance from Discharge Gap	0.5 – 2 meters
Oscilloscope BW	1 GHz
Sampling Rate	5 GSa/s
Amplifier Gain	20 dB, Low Noise

Table.10. Signal-to-Noise Ratio (dB) Across Frequency Range

Frequency (GHz)	Whip Antenna	Patch Antenna	Vivaldi Antenna	Proposed Spiral Monopole
0.3	9.2	10.8	12.0	15.3
0.5	9.6	11.1	12.3	15.8
0.7	9.9	11.5	12.7	16.2
0.9	10.1	11.9	13.1	16.6
1.1	10.4	12.2	13.4	17.0
1.3	10.7	12.5	13.7	17.3
1.5	10.9	12.7	14.0	17.6
1.7	11.1	12.9	14.3	17.9
1.9	11.3	13.1	14.6	18.2
2.1	11.4	13.3	14.8	18.5
2.3	11.6	13.5	15.0	18.7
2.5	11.8	13.7	15.3	18.9
2.7	11.9	13.8	15.5	19.1
2.9	12.0	14.0	15.7	19.3
3.0	12.1	14.1	15.8	19.5

Table.11. Bandwidth Utilization (%) Across Frequency Range

Frequency (GHz)	Whip Antenna	Patch Antenna	Vivaldi Antenna	Proposed Spiral Monopole
0.3	12.5	15.2	40.1	78.4
0.5	13.1	16.7	41.2	79.5
0.7	13.9	17.6	43.0	80.1
0.9	14.2	18.0	44.7	81.3
1.1	14.5	18.3	45.9	82.0
1.3	14.7	18.6	47.3	82.6
1.5	15.1	18.9	48.5	83.2
1.7	15.4	19.1	49.7	83.7
1.9	15.7	19.4	50.8	84.3
2.1	16.0	19.6	51.7	85.0
2.3	16.2	19.9	52.5	85.6
2.5	16.5	20.1	53.4	86.2
2.7	16.7	20.4	54.2	86.8
2.9	17.0	20.6	55.1	87.3
3.0	17.3	20.9	56.0	87.8

Table.12. Detection Range (m) Across Frequency Range

Frequency (GHz)	Whip Antenna	Patch Antenna	Vivaldi Antenna	Proposed Spiral Monopole
0.3	0.6	0.9	1.2	1.7
0.5	0.7	1.0	1.3	1.8
0.7	0.8	1.1	1.4	1.9
0.9	0.8	1.2	1.5	2.0
1.1	0.9	1.2	1.6	2.0

1.3	0.9	1.3	1.6	2.1
1.5	1.0	1.3	1.7	2.2
1.7	1.0	1.4	1.7	2.2
1.9	1.1	1.4	1.8	2.3
2.1	1.1	1.5	1.9	2.3
2.3	1.2	1.5	1.9	2.4
2.5	1.2	1.6	2.0	2.4
2.7	1.3	1.6	2.0	2.5
2.9	1.3	1.7	2.1	2.5
3.0	1.4	1.7	2.1	2.5

Table.13. Detection Accuracy (%) Across Frequency Range

Frequency (GHz)	Whip Antenna	Patch Antenna	Vivaldi Antenna	Proposed Spiral Monopole
0.3	68.1	72.4	76.5	90.2
0.5	70.3	74.1	77.9	91.0
0.7	72.0	75.8	79.0	91.6
0.9	73.2	77.2	80.5	92.0
1.1	74.0	78.1	81.2	92.4
1.3	75.1	79.5	82.6	92.8
1.5	76.3	80.7	83.1	93.1
1.7	77.1	81.3	83.8	93.3
1.9	78.0	82.0	84.2	93.5
2.1	78.3	82.5	84.5	93.7
2.3	78.6	83.1	84.7	94.0
2.5	79.0	83.4	85.1	94.2
2.7	79.2	83.7	85.5	94.5
2.9	79.5	83.9	85.7	94.7
3.0	79.7	84.1	86.0	95.0

The Table.10 indicates that the proposed system achieves the highest SNR values (19.5 dB at 3 GHz), which is approximately 4 dB better than Vivaldi and 7 dB better than whip antennas. In terms of bandwidth utilization (Table.11), the proposed system achieves up to 87.8%, nearly doubling the utilization achieved by Vivaldi and quadrupling that of whip antennas. Lastly, Table.12 shows the detection range of the proposed antenna reaching up to 2.5 meters, significantly greater than the 1.4–2.1 meters observed with traditional designs. These improvements are attributable to the antenna's ultra-wideband characteristics, uniform gain, and optimized geometry for transient signal capture. As shown in Table.13, the proposed spiral monopole antenna consistently outperforms conventional antennas in detection accuracy, achieving up to 95.0% at 3 GHz, compared to only 86% with the best traditional alternative (Vivaldi).

6. CONCLUSION

This study demonstrates the successful design and implementation of a broadband spiral monopole antenna system for partial discharge detection within high-voltage insulation environments. Through detailed simulations and physical experiments, the antenna proved to be highly effective across the frequency range of 300 MHz to 3 GHz, showing consistent improvements in key performance indicators: detection accuracy, SNR, bandwidth utilization, and detection range. Compared to traditional whip, patch, and Vivaldi antennas, the proposed design offers an average accuracy improvement of over 12%, SNR gains exceeding 4 dB, and an extended detection range of up to 2.5 meters. These results validate the potential of the spiral monopole UWB antenna as a high-fidelity electromagnetic sensor for early PD detection. The integration of wavelet-based signal processing further boosts noise resilience, making the system suitable for both controlled laboratory diagnostics and real-time substation monitoring. Future work may explore embedding this design into compact IoT-based PD monitoring systems or integrating with machine learning classifiers for insulation health prediction.

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