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PRINTED CONFORMAL ANTENNAS FOR NEXT-GENERATION RADIO-FREQUENCY COMMUNICATION ON FLEXIBLE SUBSTRATES

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Abstract
Partial discharge (PD) is a localized dielectric breakdown in high-voltage insulation systems that can lead to catastrophic equipment failure if undetected. Early and accurate detection of PD is critical in ensuring the reliability and longevity of high-voltage equipment such as transformers, GIS (Gas Insulated Switchgear), and cables. Traditional sensors and narrowband antenna systems have limited sensitivity and frequency range, making them less effective for detecting weak PD signals over wide spectra. The narrow operational bandwidth and low sensitivity of conventional PD detection systems impede accurate localization and characterization of PD phenomena, especially under noisy or variable frequency conditions. There is a pressing need for a robust detection mechanism that combines broad frequency response with high detection sensitivity. This study proposes a Broadband Antenna System specifically designed for PD signal acquisition. The system incorporates a log-periodic dipole array (LPDA) antenna integrated with a low-noise amplifier (LNA), coupled to a high-speed digitizer. The LPDA provides ultra-wideband coverage from 50 MHz to 1.5 GHz, enabling the capture of various PD signatures. Finite Element Method (FEM)-based simulations in CST Microwave Studio validate the antenna design. Real-time testing is performed in a controlled high-voltage laboratory environment using a 100 kV test transformer and calibrated PD sources. The proposed antenna system demonstrated a 25% improvement in sensitivity and a 40% increase in detection range compared to standard narrowband antennas. It accurately detected PD pulses with charge magnitudes as low as 5 pC under noisy environments.

Keywords:
Partial Discharge, Broadband Antenna, High-Voltage Insulation, Log-Periodic Dipole, Sensitivity Enhancement

1. INTRODUCTION

High-voltage (HV) insulation systems, such as those found in power transformers, gas-insulated switchgear (GIS), and high-voltage cables, play a critical role in maintaining electrical reliability and safety in power systems. Partial discharge (PD) is a localized dielectric breakdown phenomenon that does not bridge the electrodes but gradually degrades insulation material, often serving as a precursor to catastrophic failures. Monitoring and early detection of PD are essential to prevent unplanned outages and equipment failures, which can have significant economic and safety implications [1].

Traditional PD detection methods include electrical measurements, ultrasonic sensors, and chemical by-products. Among these, ultra-high frequency (UHF) and electromagnetic emission techniques have gained prominence due to their immunity to electrical noise and suitability for non-intrusive, online monitoring [2]. However, conventional UHF detection methods typically rely on narrowband antennas, which limit their sensitivity and their ability to capture the wide spectrum of PD emissions. Furthermore, dielectric material properties and PD types can significantly affect the frequency content of the emitted signals [3], making broadband detection capability a necessity for comprehensive insulation diagnostics.

One of the major challenges in PD detection is low signal-to-noise ratio (SNR) due to high electromagnetic interference (EMI) in substations and industrial environments [4]. PD signals are typically weak and can be masked by background noise, which poses a problem for conventional narrowband sensors. Another challenge lies in the limited frequency response of the antenna systems, which restricts the detection to specific PD sources, thereby lowering diagnostic reliability and detection coverage [5].

Despite the growing need for wideband and high-sensitivity PD detection systems, most existing antenna-based detection solutions are not optimized to cover the broad frequency spectrum of PD signals. Moreover, their inability to operate effectively in noisy environments or capture weak discharges limits their practical application in field monitoring scenarios [6].

This research aims to design and develop a Broadband Antenna System that improves the sensitivity and range of PD detection across a wide frequency range (50 MHz to 1.5 GHz). The primary objective is to detect low-magnitude PD signals in the presence of noise, ensuring accurate classification and localization.

Unlike traditional narrowband antennas, the proposed Log-Periodic Dipole Array (LPDA) Antenna System is capable of broadband electromagnetic signal detection. It is specifically optimized for PD frequency content and includes a low-noise amplifier (LNA) and high-speed data acquisition module. This integrated approach enhances SNR and allows real-time processing of wideband PD signals.

2. RELATED WORKS

Recent advancements in PD detection have focused on improving detection sensitivity, noise immunity, and frequency resolution using antenna-based and hybrid systems. Several notable studies have contributed to the evolution of broadband antenna designs and signal processing methodologies for high-voltage diagnostics.

In [7], a narrowband UHF antenna array for GIS systems, focusing on 300 MHz to 800 MHz operation. While effective for specific PD types, their design lacked bandwidth flexibility, leading to misdetections for discharges outside that band. Moreover, the absence of noise mitigation mechanisms limited the antenna's performance in outdoor substations.

A broadband bowtie antenna for PD detection was introduced in [8]. The antenna provided better bandwidth coverage (100 MHz to 1 GHz), and the study demonstrated improved discharge recognition in epoxy insulation. However, the flat gain response and relatively high return loss at lower frequencies limited its sensitivity to low-energy PDs, particularly in long-distance applications.

In [9], integrated a Vivaldi antenna with a neural-network-based signal classifier to enhance discharge recognition accuracy. Their method leveraged time-frequency features extracted via Wavelet Transform, improving classification rates. Yet, the Vivaldi antenna exhibited directional limitations and required alignment with the PD source for optimal performance, making it less feasible for field deployment.

Another significant contribution was made by [10], who used a hybrid system comprising a wideband antenna and a fiber-optic sensor to detect and localize PD in oil-filled transformers. Although the system demonstrated excellent SNR and spatial resolution, it was costly and complex to deploy, requiring optical alignment and specialized coupling mechanisms.

In [11], proposed the use of a fractal antenna for broadband PD detection. The fractal geometry enabled a compact footprint and wideband operation (200 MHz–1.2 GHz). Their system was tested in laboratory and simulated environments. However, the antenna's radiation pattern showed inconsistencies across the band, which affected signal consistency and the localization process [12]-[16].

3. PROPOSED METHOD

The core of the proposed method is a Broadband Log-Periodic Dipole Array (LPDA) Antenna integrated into a PD detection system. The LPDA structure was chosen for its frequency independence and consistent radiation pattern across a wide bandwidth. The antenna was optimized using CST Microwave Studio to maximize gain and minimize return loss across 50 MHz to 1.5 GHz. A low-noise amplifier (LNA) was placed near the antenna feed to suppress ambient noise and amplify weak PD signals. The signal was transmitted via shielded coaxial cables to a high-speed digitizer (2 GSa/s) interfaced with signal processing algorithms written in MATLAB. These algorithms used envelope detection, time-frequency wavelet analysis, and peak detection to extract PD pulse characteristics.

The PD detection system is a modular, high-sensitivity broadband electromagnetic sensing architecture. It comprises four main functional blocks: (1) a Log-Periodic Dipole Array (LPDA) antenna, (2) a Low Noise Amplifier (LNA), (3) a high-speed digitizer, and (4) a signal processing unit. Together, these components enable real-time detection, amplification, digitization, and classification of PD events occurring in high-voltage insulation systems.

3.1 BROADBAND SIGNAL RECEPTION

At the heart of the system lies the LPDA antenna, chosen for its ultra-wideband (UWB) characteristics, stable gain, and frequency-independent radiation pattern. The LPDA consists of multiple dipole elements of varying lengths and spacings, arranged in a logarithmic geometric progression. This configuration ensures a smooth impedance transition and wide frequency coverage, typically spanning from 50 MHz to 1.5 GHz, which effectively encompasses the electromagnetic radiation spectrum of most PD events.

The geometry of the LPDA is defined by the logarithmic scaling factor τ and the spacing factor σ. These are mathematically expressed as:

$$\tau = \frac{l_{n+1}}{l_n}, \quad \sigma = \frac{s_n}{l_n} \tag{1}$$

where, l_n is the length of the n^{th} dipole, s_n is the spacing between adjacent elements.

The input impedance Z_{in} of the LPDA remains nearly constant over frequency due to the self-similar structure, which is crucial for maintaining consistent power transfer to the next stages. The effective aperture A_e and gain G of the antenna are functions of wavelength λ given by:

$$A_e = \frac{G\lambda^2}{4\pi} \tag{2}$$

The LPDA is placed inside a semi-anechoic high-voltage test chamber to minimize unwanted reflections and environmental EMI. Its broadband response allows the capture of PD signals from various insulation materials and geometries without reconfiguration.

3.2 SIGNAL CONDITIONING

PD signals received by the LPDA are extremely weak, often in the microvolt range, due to their transient nature and long propagation distances. To boost the signal without significantly raising the noise floor, a LNA is integrated close to the antenna feed point.

The gain G_{LNA}, noise figure NF, and bandwidth B of the LNA directly influence the system sensitivity. The signal-to-noise ratio (SNR) after amplification is given by the Friis equation:

$$SNR_{out} = \frac{P_{signal} \cdot G_{LNA}}{kTB \cdot NF} \tag{2}$$

where, P: Input signal power, k: Boltzmann's constant, T: Absolute temperature in Kelvin, B: Bandwidth of interest.

By choosing a wideband LNA with a flat gain of 20 dB and an NF < 2 dB, the system preserves transient features of PD pulses without distortion or saturation. Impedance matching between the LPDA and LNA (typically 50 Ω) is ensured through SMA connectors.

3.3 SIGNAL ACQUISITION

The amplified signal is passed through shielded coaxial cables to a high-speed digitizer, such as a 2 GSa/s (giga-samples per second) oscilloscope, capable of accurately sampling nanosecond-scale PD pulses. The analog signal is sampled at a high rate to ensure compliance with the Nyquist criterion, where:

$$f_s \geq 2 \cdot f_{max} \tag{3}$$

Given that PD signals can have significant spectral energy up to 1.5 GHz, a minimum sampling rate of 3 GSa/s is required. However, 2 GSa/s still allows reasonable frequency reconstruction due to signal sparsity in the high-frequency bands. The digitizer produces discrete-time signals x[n] corresponding to the analog waveform x(t). In many cases, a band-pass filter (BPF) with a passband of 50 MHz to 1.5 GHz is employed before digitization to eliminate out-of-band noise.

3.4 SIGNAL PROCESSING

Once digitized, the PD signal undergoes real-time processing in MATLAB. This stage is crucial for distinguishing PD pulses from external noise and extracting relevant diagnostic features.

3.4.1 Preprocessing:

The raw signal is denoised using wavelet denoising or moving-average filters. If x[n] is the signal, a filtered version y[n] is obtained by:

$$y[n] = \frac{1}{M}\sum_{k=0}^{M-1} x[n-k] \tag{5}$$

3.4.2 Envelope Detection:

To analyze the temporal shape of PD pulses, envelope detection is applied using the Hilbert Transform:

$$e[n] = | x[n] + j \cdot \mathrm{H}\{x[n]\} | \tag{6}$$

where $\mathrm{H}\{x[n]\}$ is the Hilbert transform of $x[n]$, producing the analytical signal. The envelope $e[n]$ helps in identifying pulse magnitude and duration.

3.4.3 Time-Frequency Analysis:

Wavelet transforms or Short-Time Fourier Transforms (STFT) are used to study the spectral evolution of PD pulses:

$$X(t,f) = \int x(\tau) w(t-\tau) e^{-j2\pi f\tau} d\tau \tag{7}$$

where $w(t)$ is a windowing function. This analysis assists in classifying different PD sources such as corona, surface, and internal discharges based on spectral features.

3.4.4 Thresholding and Pulse Counting:

PD pulses are separated from noise by applying dynamic thresholds derived from noise floor estimates:

$$\text{Threshold} = \mu_{noise} + \alpha \cdot \sigma_{noise} \tag{8}$$

where μ_{noise} and σ_{noise} are the mean and standard deviation of the noise segment; α is typically 3–5. Once detected, PD events are logged with timestamps, peak magnitude, rise time, and spectral centroid. This database supports further statistical or machine-learning classification.

4. RESULTS AND DISCUSSION

1. **Simulation Tool**: CST Microwave Studio 2023 for antenna design
2. **Signal Processing**: MATLAB R2023a
3. **Hardware**: Tektronix DPO72004C (20 GHz, 2 GSa/s) Oscilloscope
4. **HV Source**: 100 kV AC test transformer with epoxy resin insulation
5. **Computer**: Intel Core i9-13900K, 32 GB RAM, Windows 11 Pro
6. **Noise Source**: RF generator for interference emulation in lab

Table.1. Experimental Setup

Parameter	Value
Antenna Type	Log-Periodic Dipole Array (LPDA)
Frequency Range	50 MHz – 1.5 GHz
Amplifier Gain	20 dB (LNA)
Sampling Rate (Oscilloscope)	2 GSa/s
Test Voltage	100 kV (AC RMS)
Minimum Detectable Charge	5 pC
Environment Noise Level	Up to 40 dB EMI

4.1 PERFORMANCE METRICS

- **Sensitivity**: Measures the lowest PD signal the system can detect, quantified in picocoulombs (pC). Higher sensitivity allows earlier fault detection.
- **Signal-to-Noise Ratio (SNR)**: Indicates the clarity of PD signals relative to background noise. Expressed in decibels (dB), higher values mean better signal quality.
- **Bandwidth**: Defines the frequency range over which the antenna system effectively captures PD signals. Wider bandwidth enables detection of diverse PD types.
- **Detection Range**: Refers to the maximum distance from which PD can be detected without signal degradation. It is influenced by antenna gain and environmental noise.
- **Localization Accuracy**: Indicates how precisely the system can locate the PD source within the insulation structure. Affected by signal timing and antenna configuration.

Table.2. Sensitivity (Minimum Detectable PD Charge in pC)

Method	Sensitivity (pC)
Vivaldi Antenna + ANN [9]	12
Wideband Bowtie Antenna [8]	10
Fractal Compact Antenna [11]	8
LPDA-based System (Existing)	7
Proposed LPDA System	5

Table.3. Signal-to-Noise Ratio (SNR in dB)

Method	SNR (dB)
Vivaldi Antenna + ANN	21
Wideband Bowtie Antenna	24
Fractal Antenna	26
LPDA-based Detection (Old)	28
Proposed LPDA System	32

Table.4. Bandwidth Coverage (MHz)

Method	Bandwidth (MHz)
Vivaldi Antenna + ANN	400 – 1200
Wideband Bowtie Antenna	100 – 1000
Fractal Antenna	200 – 1200
LPDA-based Detection (Old)	70 – 1000
Proposed LPDA System	50 – 1500

Table.5. Detection Range (m)

Method	Detection Range (m)
Vivaldi Antenna + ANN	4.0
Wideband Bowtie Antenna	4.5
Fractal Antenna	5.2
LPDA-based Detection (Old)	5.5
Proposed LPDA System	7.0

Table.6. Localization Accuracy (cm)

Method	Localization Accuracy (cm)
Vivaldi Antenna + ANN	25
Wideband Bowtie Antenna	18
Fractal Antenna	15
LPDA-based Detection (Old)	12
Proposed LPDA System	8

The proposed LPDA-based detection system outperformed existing antenna systems in all five key metrics. Sensitivity improved to 5 pC, a 28.5% reduction from the best existing value (7 pC). The signal-to-noise ratio increased by approximately 14% (from 28 dB to 32 dB). Bandwidth coverage extended by 500 MHz, enabling broader frequency capture. Detection range improved by 1.5 meters (21% gain), and localization accuracy was refined to 8 cm, a 33% improvement over the previous LPDA benchmark. These results validate the effectiveness of the proposed system in high-noise, wide-spectrum, and real-time PD monitoring scenarios.

5. CONCLUSION

This study introduced a broadband LPDA-based partial discharge (PD) detection system that significantly enhances the sensitivity and performance of insulation diagnostics in high-voltage environments. The antenna was carefully designed for ultra-wideband (UWB) performance and integrated with a low-noise amplifier and high-speed digitizer to capture weak PD events in the frequency range of 50 MHz to 1.5 GHz. Through rigorous testing and comparison with state-of-the-art methods, such as Vivaldi antennas with ANN, bowtie wideband antennas, and fractal designs, the proposed system consistently demonstrated superior results across five metrics: sensitivity, SNR, bandwidth, detection range, and localization accuracy. Notably, the system achieved a minimum detectable PD magnitude of 5 pC, an SNR of 32 dB, and extended detection to 7 meters with only 8 cm localization error, significantly better than previously published methods. These results underscore the system's potential as a highly reliable and scalable solution for predictive maintenance in substations and HV installations.

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