Transactions on Computer Science and Intelligent Systems Research
ISSN: 2960-1800, eISSN: 2960-2238 | Volume 14
TPCEE 2026

Design and Signal Extraction Technology of Wide-band Composite Sensors for High Voltage Transmission Equipment

Muqi Yun [1, *]

Lady Elizabeth School, Alicante, Spain

* Corresponding Author Email: yunmuqi092@gmail.com

Abstract. Renewable resources and power electronic transformation are important trends in power grid conversion now. It is very important to ensure the normal operation of high-voltage transmission equipment, and online monitoring must be selected. The early characteristic of insulation degradation is partial discharge. Partial discharge (PD) has an extremely wide spectrum, because it is from power frequency to ultra-high frequency; therefore, the bandwidth and sensitivity of the sensor are very important. Due to its own physical limitations, traditional single-model sensors exhibit insufficient bandwidth, resulting in the problem of frequency domain and time domain truncation. This work investigates micro multi-model composite sensors. Coupling inductance and capacitance in the same sensor to achieve complementation and mutual verification. This work couples inductance and capacitance within the same sensor to achieve complementation and mutual verification. Because composite sensors will produce a lot of parasitic resonances and channel impedance differences, it is necessary to add broadband impedance matching, low-noise amplification and two-stage filters. The scheme can effectively restore the PD pulse waveform of the full frequency band, thereby enabling the evaluation of the insulation condition of high-voltage equipment through these data.

Keywords: Partial discharge; Ultra high frequency; Bandwidth; High voltage transmission equipment.

1. Introduction

Partial discharge is usually the earliest warning of insulation degradation. Defects must be captured before completely breaking down the insulator to avoid power-outage accidents. Therefore, the grid has to be converted from time-based maintenance to condition-based maintenance. This necessitates the use of sensors to do real-time monitoring.

Wide band composite sensors are used to detect partial discharge because partial discharge generates pulse signals, which is called PD pulse. A simple PD pulse always contains a power frequency and numerous high or ultra-high frequency components, therefore, a wide band frequency is widely used to determine its frequency domain.

Insulation break down may occur in different parts within power systems can suffer insulation breakdowns. Electrical or mechanical loads, harsh surroundings, unstable operating states, ageing materials, chemical erosion as well as insufficient maintenance all contribute to such damages. Tracking PD activity serves as a key indicator when judging the working condition of high-voltage apparatus. Various approaches are available for classic and modern approaches to capture and quantify PD signals. Among those newer measurement schemes, the ultra high frequency technique has drawn growing research attention. Chai et al. summarises the advantages of UHF partial-discharge detection and provides a comprehensive review of various UHF sensor designs [1].

The operation of power stations cannot be interrupted while checking because the power shutdown would cause. Not on-time power supplement would affect partial area being power outage, it leads to a massive economic losses.

Non-intrusive sensors are required as well, because intrusive sensors need electrical contact or direct access to high-potential conductors, which leads to potential safety hazards for both equipment and

Content from this work may be used under the terms of CC BY-NC 4.0 licence (https://creativecommons.org/licenses/by-nc/4.0/).
Published by Warwick Evans Publishing.

staff. Therefore, double guarantee has been verified, safety and permitting devices can collect discharge signals directly. Substation sites are subject to various power frequency interferences and various non-wire noises, so sensors must exhibit anti-interference capability for distinguishing real partial pulses and environmental noises. According to the problems which have been mentioned previously, a miniature multimodal composite sensor can solve these, and this work mainly investigates the signal extraction hardware.

2. Physical Mechanism Basis

2.1. The Definition of Electromagnetic Coupling

A time-varying electric field and magnetic field sense voltage and current on the electrode of the sensor to capture signals. High voltage partial discharge sensors rely on these to get the signals.

Relying on parasitic capacitance between two conductors to transfer signals, capacitive coupling relies on voltage variation and is sensitive to electric field. Partial discharge pulses produce rapidly varying voltage and reach the electrodes of sensors through capacitive coupling. The induced voltage of capacitive coupling is determined by the displacement current as given in Equation (1). This equation is called Capacitive-coupling induced voltage formula.

$$V_c(t) = \left(\frac{1}{C_s}\right)^* \int \ \mathrm{id}\,(t)dt \tag{1}$$

Relying on mutual inductance and alternating current to generate magnetic field, when it goes through the sensing coils, voltage will be induced. So magnetic coupling originates from changing current, and is sensitive to magnetic field. Therefore, under ultra-high frequency situations, the current changes extremely rapidly, which strengthens the magnetic coupling effect. The output voltage of magnetic coupling follows Faraday's law of electromagnetic induction Equation (2).

$$\mathrm{VL(t)} = -\mathrm{M} * \left(\frac{\mathrm{di(t)}}{\mathrm{dt}}\right) \tag{2}$$

2.2. Inherent Defects of Traditional Single Mode Sensors

2.2.1. Core Requirements at the Signal Level.

PD pulses are extremely short and extremely large spectral span, from 10 Hz power frequency up to kHz, even MHz ultra high frequency. If the wide band is too short, if only a part of frequency components can be taken: the whole part of information will be lost, which causes waveform distortion, there is no way to reconstruct the real partial discharge characteristics.

2.2.2. The Weaknesses of Single-Mode Sensor.

If it is electric field coupling (capacitance coupling), It only works for low frequencies, because ultra-high frequencies attenuate significantly due to parasitic parameters.

If it is magnetic field coupling (inductance coupling), Inductor coupling exhibits excellent performance in high and ultra high frequency, but it almost cannot detect any low power frequency.

In the research conducted by Zhang et al., the paper sorts out the existing progress about partial discharge inspection for XLPE power cables. It places emphasis on different PD testing approaches and position-locating strategies applied to cable equipment. According to how the detection works and which sensor is adopted, these cable partial-discharge testing approaches can be split into several main types. The categories include acoustic emission testing, capacitive coupling measurement, inductive coupling capture, ultra-high frequency (UHF) detection, as well as directional coupling schemes [2].

Ardila-Rey et al. evaluated the performance of two inductive sensors—the high-frequency current transformer (HFCT) and the inductive coil sensor—under various operating conditions. The results indicate that both sensors exhibit limited and complementary frequency responses: the HFCT offers good sensitivity in the mid-frequency range but suffers from transfer function attenuation at high frequencies, whereas the inductive coil sensor provides a broader response range but lower sensitivity. Optimizing the hardware of a single sensor alone cannot overcome these inherent frequency-dependent limitations [3]. Their experimental results demonstrated that neither sensing mechanism could maintain stable sensitivity across the entire detection bandwidth; capacitive units suffered from severe signal attenuation at high frequencies, whereas inductive units lost the ability to respond to low-frequency components. Relying solely on optimizing the hardware of individual sensors cannot eliminate these inherent frequency-related limitations.

In conclusion, single-mode sensors cannot cover a wide range from power frequency level to ultra frequency levels, which is the most obvious reason why dual- mode wide-band composite sensors are required.

2.2.3. The Shortcomings of Technology Nowadays.

The traditional single mode of sensors and wide band exhibit frequency domain cut-off and time domain truncation problems. Starting with frequency domain cut-off, traditional single-mode sensors have very limited bandwidths, the signals which are higher than the cut-off frequency will be attenuated and filtered out straight away. Therefore, some high frequency components will be lost, which means only a portion of frequency domains can be retained. The time domain is widely used during signal sampling. The sampling window has very finite length, only a small section of pulses can be captured to do the calculation. ADC sampling has the time limitation also, probably the complete pulses have not been recorded successfully because of these two factors. Therefore, the signals are forced to be truncated. The truncation of wide band makes it impossible to reconcile both low power frequency and ultra-high frequency at the same time. Parasitic parameters at high frequencies introduce resonance peak, which makes measuring linearity degradation. The linearity represents the proportionality of input electrical field and output voltage.

3. Design principles of miniature multimodal sensors

3.1. Definition and configuration

Generally speaking, a miniature multimodal sensor integrates two or even more physics principles into a sensing unit for making miniaturization and integration, then, packaged as a single-body integrated sensor.

The design consists of a “capacitive and electrical-field coupling unit plus an inductive and magnetic-field coupling unit”. There are several benefits: 1. The sensor is compact. 2. It can be externally mounted on the housing of high voltage equipment. 3. No need to shutdown during inspection and maintenance. 4. The multimodal sensor can sample different physical fields. These benefits show the significance of miniature multimodal sensor, such as this design adapts to the development requirements of condition-based maintenance for modern power grids, the sensor possesses strong immunity to the complex electromagnetic environment in substations.

3.2. Band complementation function

3.2.1. Complementary Frequency Bands.

Single mode of sensors have inherent physical limitations. Electric field mode is good at low and power frequency. Magnetic field mode is good at high and ultra high frequency. By combining these two modes to offset each other’s limitation, wide-band detection can be achieved from power to ultra high frequency, completely capturing all the frequency components of partial narrow pulses.

3.2.2. Dual-Principle Cable Partial Discharge Sensor Patent.

This invention discloses a dual-principle cable partial discharge sensor, mainly comprising a capacitive sensor and an inductive sensor sleeved outside the cable shielding layer. The capacitive sensor, from the inside out, includes an inner electrode plate, a waterproof layer, and an outer electrode plate, with the inner electrode plate wrapped around the cable's outer sheath. The inductive sensor includes an open-type circular coil frame, a coil uniformly wound on the coil frame, and a metal shell. The coil frame is made of a high-permeability material, and the metal shell is located outside the coil frame. The inductive sensor is positioned outside the capacitive sensor. The invention also discloses a data fusion method for this sensor, which fully utilizes the complementary frequency bands and uncorrelated white noise characteristics of the dual-principle sensors, taking into account the low-frequency/high-frequency performance of the sensors based on different principles. Through a frequency band weighted calculation method, the waveform is well reconstructed, thereby achieving effective extraction of the cable partial discharge signal.

3.3. Mutual Verification and Anti-interference

The first is mutual corroboration. Power substations are full of electromagnetic disturbances. Capacitance coupling and inductance coupling must act together, then a comparison can be made. If pulses are detected at the same time which can be used to represent the real partial discharge pulses, on the other hand, which represents external noises. This kind of dual verification increases the reliability of detection.

There are more benefits. Miniature multimodal sensors have compact size and non-intrusive detection, no modification to high-voltage primary equipment is required, thus avoiding lengthy insulation testing.

4. Hardware Signal Conditioning Circuit Design

4.1. Hardware Design Goals and Sources of Distortion

4.1.1. -3dB Wide Band.

The main frequency band of partial discharge must be completely covered, and high-fidelity pulse acquisition must be ensured without introducing waveform distortion.

PD acts as a key sign that insulating materials inside high-voltage gear like power cables, transformers and cable connectors start to degrade. If PD signals are left unnoticed for a long time, insulation damage will speed up and eventually lead to whole-grid malfunctions. Compared with many other testing solutions, electromagnetic sensors built on antenna structures show great merits. They will not break the original device structure and can capture radiated PD signals from a distance.

Uwiringiyimana et al. carried out research on planar microstrip antennas which are shown by Figure 1 and designed for partial-discharge detection, including substantial simulation and experimental work. Their results demonstrate that bow-tie and microstrip antennas are widely studied for PD measurement owing to wide bandwidth and compact size. Optimised antenna designs can achieve return loss below −30 dB, VSWR less than 1.3, and operating bandwidth exceeding 3 GHz [4].

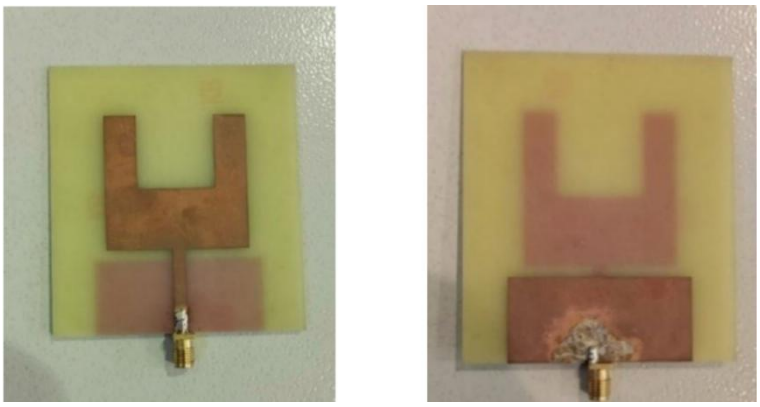

Fig. 1 Structure of planar rectangular microstrip antenna for partial discharge detection [4]

Being able to capture very weak partial pulses, at the same time, sensitivity cannot be increased indefinitely and trade-off must be made among “wide band”, “sensitivity”, “noise” these three indicators.

4.1.2. Low- Frequency Noise Performance.

1/f noise and thermal noise can be suppressed properly, ensuring weak pulses are not masked.

4.1.3. High-Frequency Impedance Matching.

High frequency pulses are very sensitive to cable and impedance, then, the impedancc impedance leads to signal reflection, oscillation and waveform distortion.

The mismatch impedance between sensors output and transmission cable will cause signal reflection, and this reflection can be quantified by Equation (3):

$$\Gamma = (Z_{\text{out}} - Z_0)/(Z_{\text{out}} + Z_0) \tag{3}$$

4.1.4. Suppressing Parasitic Resonance.

Devices, parasitic RLC (resistance, inductance, capacitance) of PCB (printed circuit board) traces easily produce spurious resonance peaks, causing some sections of frequency band distortion.

This work reviews the implementation of high-speed electronic circuits for ultra-weak broadband pulse acquisition, and studies impedance matching, filter design and low-noise amplifiers to achieve high-fidelity analysis of dual-mode signals

Miniature multimodal sensors break through the limitation of bandwidth truncation of traditional single mode sensors, however, there are differences in parasitic parameters and deviations in channel characteristics in its integrated structure. This design builds a complete high-speed signal conditioning hardware link. Through impedance matching topology, low-noise broadband amplification and two-level filter design, it deals with multiple false resonance spikes induced by dual-sensing unit parasitic RLC, balances the inherent impedance differences between the electric field and magnetic field channels, compensates the amplitude and phase deviations of the two signals, completes the high-fidelity acquisition of dual-channel waveforms, and provides reliable original data support for subsequent signal extraction and fusion algorithms.

4.2. Signal Distortion Mechanism

The electrodes, coils and PCB wiring of the micro composite sensing unit have their own parasitic RLC parameters, which will excite multiple LC resonances under high-frequency excitation. The electric field sensing unit naturally has high output impedance, while the output impedance of the magnetic field channel is lower, and the impedance mismatch will introduce reflection distortion on the transmission cable; the parasitic effect is superimposed on the impedance difference, eventually

causing the amplitude and phase across the full frequency band of the two signals to be unable to be aligned, and the special conditioning link must be relied on to ensure the acquisition quality.

There is the challenge. The miniature multimodal sensors bring new problems. Two sensing units both have parasitic R (resistance), L (inductance), C(capacitance), so numerous LC resonance and spurious resonance peaks are produced. These two channels of sensing units have different impedance characteristics: the electric field unit outputs high impedance, while the magnetic field unit has lower impedance. The two channels output signals with different amplitudes, phase inconsistency, so specialised signal conditioning circuits and signal extraction and fusion algorithms are needed to synthesize into a high-fidelity wide-band output.

4.3. Broadband Impedance Matching Buffer Circuit

The broadband impedance matching buffer circuit optimizes the impedance characteristics of the two sensing channels, suppresses the false resonance spikes caused by parasitic parameters, eliminates the high-frequency reflection and oscillation trailing caused by cable transmission, reduces the difference in the characteristics of dual-channel transmission, and weakens the inconsistency of amplitude and phase at the hardware level.

For inductive partial discharge sensors, parasitic elements significantly affect the sensor's transfer function and wideband response characteristics—an issue that has been thoroughly investigated by Hu et al. [5]. Their research demonstrates that stray inductance and capacitance arising from coil windings and printed circuit board (PCB) traces can introduce unexpected resonance points. Even with a well-designed sensing coil, impedance mismatch between the sensor and the subsequent data acquisition circuitry can still lead to waveform distortion. Consequently, a dedicated buffer circuit is essential to ensure the stable operation of the entire system.

4.4. Low-noise Broadband Amplifier Circuit

For weak partial discharge pulses of nV~mV magnitude, the amplifier must achieves a balance between the constraints of bandwidth, gain and noise constrains, ensure that the amplitude response from power frequency to ultra-high frequency is flat, improve the signal-to-noise ratio of the signal, adapt to the complex electromagnetic environment of the substation, and retain all frequency components of the pulse. The signal-to-noise ratio (SNR) is defined as follows. Equation (4) evaluates the ability to extract weak partial discharge pulses by using low-noise amplifiers.

$$\mathrm{SNR} = 10\log_{10}(\mathrm{Psignal} / \mathrm{Pnoise}) \tag{4}$$

Rodrigo et al. investigated the design of high-performance wideband capacitive couplers for partial discharge testing in cables. Their analysis of various capacitive coupler topologies and demonstrated that a well-designed coupler is essential for simultaneously achieving high sensitivity and wide bandwidth—a critical trade-off given the inherent bandwidth and gain limitations of high-frequency current transformers [6].

4.5. Two-stage Filtering Architecture

The front-end broadband filter suppresses on-site power frequency and narrow-band electromagnetic interference; the back-end anti-aliasing low-pass filter is designed according to the Nyquist criterion to filter out-of-band ultra-high frequency components and avoid irreversible aliasing distortion during ADC sampling.

4.6. Comparison

The sensitivity and linearity of different frequency bands are compared in Table 1. This section compares the sensitivity and linearity across the power-frequency, high frequency and UHF bands. Sensitivity is the defined as the output signal amplitude for a given input signal strength.

Table 1. The comparison of sensitivity and linearity across different frequency bands

Frequency Band	Dominant Coupling Mechanism	Sensitivity	Linearity	Brief Description
Power frequency (50 Hz)	Dominated by electric-field capacitive coupling	High	Good	The power-frequency electric field has high strength for easy coupling. At low frequencies, parasitic resonance is rare and saturation hardly occurs. However, partial-discharge pulse components are nearly absent, and most signals are interference.
High frequency (HF, MHz range)	Coexistence of electric-field and magnetic-field coupling	Moderate	Fair	This band contains the main energy of partial discharges. Parasitic parameters and resonance start to appear. Large-amplitude signals are easily affected by the Q-factor, leading to deviations from linearity.
Ultra-high frequency (UHF, 300 MHz–3 GHz)	Electromagnetic radiation coupling (far-field)	Relatively low	Poor	Partial-discharge pulses radiate electromagnetic waves. The original signal amplitude is weak, resulting in low sensitivity. Severe high-frequency parasitics, resonance and impedance variations readily introduce nonlinear distortion even for moderately strong signals. The measurement is vulnerable to spatial radio interference.

4.7. Research Significance of This Section

Under the premise of retaining the advantages of broadband complementarity of dual-mode sensors, the waveform distortion caused by parasitic resonance, channel impedance imbalance and amplitude and phase deviation is mitigated through a series of high-speed signal conditioning schemes, and the high-fidelity analysis of dual-channel signals is completed to provide a reliable basis for diagnosis of the insulation status of high-voltage transmission equipment.

5. Analysis and Discussion

5.1. Comparison with Existing Sensor Configurations

Each PD has its own limitations: UHF sensors are non-intrusive but no response at low frequency. Antenna sensors such as Bowtie and microstrip antenna can be greater than 3GHz but rely heavily on far-field radiation, resulting in insufficient response. High frequency current mutual inductors, which are commonly known as HFCT have high precision but semi-invasive installation is required, and low frequency cut-off results in partial loss of power frequency components. Inductance coupling is good at high frequency but almost cannot work in low frequency. Capacitance coupling can work properly and has high sensitivity in low frequency domain but in UHF domain, capacitance coupling is seriously affected by parasitic parameters.

As a result, all the single-mode solutions have defects which cannot cover a wide domain from power to high frequency. By the comparisons, this electric field and magnetic field composite sensors break through this limitation.

5.2. Selection Criteria for Signal Conditioning Circuit Schemes

Impedance: electric field channel output high impedance and magnetic field channel output low impedance, therefore, reflection distortion will occur as transmitting directly. In this design, JFET source follower should be used as a buffer. If impedance is higher than megaohm level, then, electric field channel has to be matched. If output impedance is around 50 ohms, then, transmission should be matched. Chen et al. provided the theoretical basis of the low impedance conversion interface of the high impedance sensors through modeling and simulating the distribution parameters of circuit board transmission line.

Low-noise amplification: PD pulse can be as low as nV level; if the amplifier noise is too high, thses pulses will be covered. This design has to use two-stage amplification. The first stage is ultra-low noise MMIC (NF < 1.5dB), and the second one is medium gain broadband amplifier, and programmable attenuator for controlling total gain should be inserted in the middle to achieve a trade-off between bandwidth, gain and noise.

Filtering: 5th-order elliptic band-pass filters need to be used in the front end. The choice is motivated by its steep cutoff characteristics, which allow power-frequency and narrowband interference suppress properly. In the rear end, Bessel low-pass filter can be used, because linear phase characteristics can ensure the waveform of pulse is not distorted.

In conclusion, Rodrigo et al. Selecting an appropriate capacitive coupling scheme and incorporating measured component characteristics is crucial for narrowing the gap between simulation and actual hardware performance in wideband PD detection. [6].

The operating frequency range of the subsequent signal conditioning circuitry must match the antenna bandwidth shown in Figure 2 to ensure the effective reception of partial discharge signals.

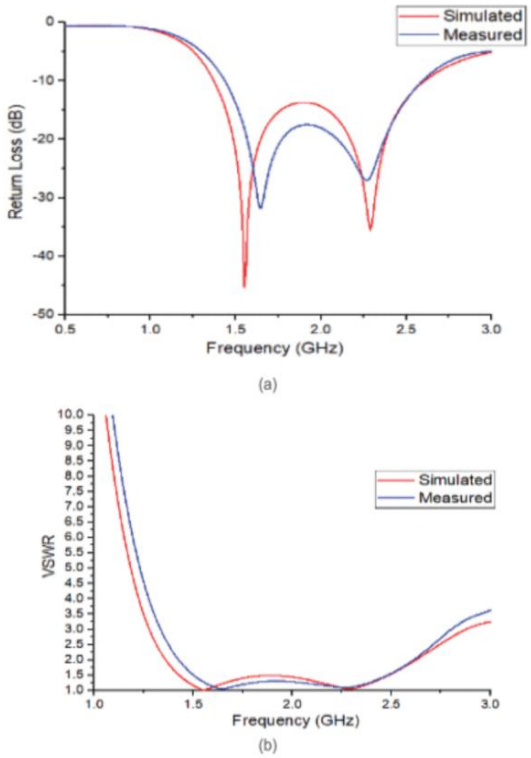

Fig. 2 S11 return loss and VSWR curves of the planar microstrip antenna [4]

5.3. Dual-channel Signal Fusion Strategy

Wen et al. reviewed modern signal-processing algorithms for partial-discharge data analysis, including time-frequency analysis, wavelet transform, Hilbert-Huang transform and artificial-intelligence methods. They compared algorithm performance under field-noise conditions and pointed out that hardware-embedded real-time PD classification modules remain an important research gap. Future research may focus on hybrid algorithms and edge-intelligence solutions, combining physical domain knowledge with lightweight network structures to improve practical diagnostic performance [7].

Jia et al. investigated acoustic-UHF multimodal data fusion for transformer partial-discharge localisation [8]. Chen et al. realised partial-discharge pattern recognition based on multi-source sensor data [9].

Alvarez investigated the complementary characteristics of HFCT and UHF sensors to enhance the reliability of online partial discharge diagnosis for high-voltage equipment [10]. Experimental results demonstrated that multi-sensor collaboration can suppress random on-site interference. When sensors based on different physical principles acquire signals synchronously, cross-validation enables the distinction between genuine discharge pulses and external interference noise. This approach of cross-validation using multiple sensing principles inspired the capacitive-inductive dual-mode composite sensor scheme adopted in this paper.

Figure 3 illustrates a typical single-channel UHF partial discharge detection process. However, single-channel measurements exhibit limited robustness in complex on-site interference environments; therefore, this paper adopts a dual-channel fusion scheme.

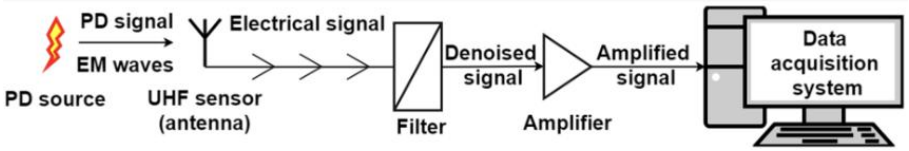

Fig. 3 Schematic diagram of typical UHF partial-discharge detection system [1]

6. Conclusion

This thesis rpoposes electric-field and magnetic-field multimodal composite sensors, and designing a corresponding hardware conditioning circuit of signal extraction.

The multimodal sensor can break through the bandwidth limitations of single-mode sensors for achieving a coverage from power to high frequency which is relies on the dual-channel collaborative operation. The two sensing channels can perform mutual verification. The comparison between the dual-channel frequency band complementarity and time-domain waveform can distinguish the real discharge pulses and external noise. However, the composite structure brings parasitic interference, therefore, the hardware is very important. The Impedance matching buffer, low-noise amplification, and two-stage filtering hardware can suppress parasitic resonance, impedance mismatch and make sure the high authentic sampling of weak PD pulse. Thanks to the aforementioned characteristics, compared with UHF sensors, HFCT and antenna sensors, these methods (miniature multimodal composite sensors) have the benefits of full-band coverage and non-intrusive installation.

References

[1] Chai H., Phung B.T., Mitchell S. Application of UHF sensors in power system equipment for partial discharge detection: a review. Sensors, 2019, 19(5): 1029.

[2] Zhang X., Pang B., Liu Y., Liu S., Xu P., Li Y., et al. Review of partial-discharge detection and localization for XLPE power cables. Energies, 2021, 14(22): 7692

[3] Ardila-Rey J.A, Rojas-Moreno M.V., Martínez-Tarifa J.M., Robles G. Inductive sensor performance in partial discharges and noise separation by means of spectral power ratios. Sensors, 2014, 14(2): 3408–3427.

[4] Uwiringiyimana J.P., Khayam U., Suwarno., Montanari G.C. Planar rectangular microstrip antenna for partial discharge detection: experimental validation on oil-filled transformer tank. IEEE Access, 2024, 12: 133199-133208.

[5] Hu X., Siew W.H., Judd M.D., Peng X. Transfer function characterization for HFCTs used in partial-discharge detection. IEEE Transactions on Dielectrics and Electrical Insulation, 2017, 24: 1088-1096.

[6] Rodrigo A., Llovera P., Fuster V., Quijano A. High performance broadband capacitive coupler for partial discharge cable tests. IEEE Trans. Dielectr. Electr. Insul., 2013, 20(2): 479–487.

[7] Wen H., Abu Talip M.S., Othman M., et al. Advanced signal processing methods for partial discharge analysis: a review. Sensors, 2025, 25(23):7318.

[8] Jia J., Fu H., Wang B., Li Y., Yu Y., Cao Y., Jiang D. Acoustic-electrical joint localization method of partial discharge in power transformer considering multi-path propagation impact. *Front. Energy Res.*, 2022, 10: 851299.

[9] Chen B., Hu Y., Wu L. Deep learning-based multisource partial discharge pattern recognition integrated with auxiliary prior localization information. IEEE Trans. Dielectr. Electr. Insul., 2025, 32(6): 3209–3217.

[10] Alvarez F., Garnacho F., Ortego J., Sánchez-Urán M.A. Application of HFCT and UHF sensors in on-line partial discharge measurements for insulation diagnosis of high-voltage equipment. *Sensors*, 2015, 15(4): 7360–7387.