



RESEARCH ARTICLE

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ONLINE PARTIAL DISCHARGE DETECTION TECHNIQUE FOR GIS BASED ON UHF SENSORS

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ABSTRACT

Gas-Insulated Switchgear (GIS) have been in operation for more than 45 years and show a high level of reliability. However, experience indicates that some of the in-service failures are related to defects in their insulation system. Many of these defects can be detected by Partial Discharge (PD) diagnostics. PDs generate electromagnetic and acoustic waves, emit light and produce chemical decomposition of insulation materials; these physical and chemical effects can be detected by various diagnostic methods and appropriate sensing elements (sensors). Besides the so-called 'conventional' electrical method described in IEC 60270, it is possible to detect and measure PDs with various 'non-conventional' methods. The Ultra-High Frequency (UHF) measurement method, which was introduced in the late 1980's for PD detection, is used worldwide by GIS manufacturers during routine testing in factory, during commissioning on-site and by utilities for continuous monitoring in service. The UHF method is less sensitive to noise, so it is easier to handle in comparison with the conventional method according to IEC 60270. To avoid technical misinterpretation, there was a special need to give recommendations for this non-conventional method. This paper is based on the experience and describes its practical applications for GIS. A detailed description of the procedure is given and supported by examples. Guidelines will help the users with the effective application of the UHF method for Online PD detection on GIS.



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I. INTRODUCTION

In the ever-growing electrical power network, SF₆ gas-filled GIS (Gas Insulated Substation) have been replacing existing AIS (Air Insulated Substation) systems due to their compact size and less maintenance requirements [1]. The reliability of GIS is very high but there would be outages of several days if there is any internal breakdown inside GIS causing all the consequential losses. In addition, if the GIS is connected to a critical network, it could lead to heavy penalties and financial losses to the utilities [2]. Hence, early detection with all the condition-based monitoring techniques is considered very crucial. Offline PD detection techniques prove very helpful in factory acceptance but such measurements during operation of such panels on site become very difficult due to external uncontrolled conditions [3]. Hence online detection of PD activity would be very crucial information for effective diagnostic assessment of insulation in GIS installed on-site. Recent research by Zhang et al. [4] demonstrates that multi-sensor temporal pulse sequence analysis can significantly improve PD measurement diagnostics, achieving better discrimination between internal PD and external interference. Hence, there is a need for developing an online PD monitoring diagnostics at site for GIS. Online PD testing can be performed while the GIS apparatus is still in service. It is considered non-invasive and is very safe to operate in live conditions [5]. While considering the efficiency of these kinds of tests, one must look at the value of information obtained with less cost and time. This paper further familiarizes the readers with important aspects of online PD detection and its level of practicability at site with UHF sensors, incorporating recent advances in signal processing and artificial intelligence.

II. GIS SPECIFIC ASPECTS

II.1 GENERAL

In gas-insulated switchgear, the defects which can occur and affect the dielectric performance of the equipment fall into several main categories [6]:

- i. Assembly errors.
- ii. Introduction of conductive contaminants, e.g. metallic particles.
- iii. Poor or loose electrical and mechanical contact between conducting parts, e.g. field electrodes and shields, resulting in components at floating potential.
- iv. Fixed defects such as metallic protrusions on the high voltage conductor and particles attached to solid insulator (spacer) surfaces.
- v. Insulator defects including manufacturing defects.
- vi. Surface tracking caused e.g. by flashovers during HV testing.
- vii. Contamination which affects the quality of the SF₆ gas (by-products, moisture content, erroneous gas filling etc).

The short rise times of PD pulse current (<1 ns) excite electromagnetic waves ranging from HF up to the UHF range (3 MHz up to 3 GHz) and exceed several insulation materials [7]. The propagation velocity of the resulting UHF waves is dependent on the resulting relative permittivity (ϵ_r), e.g. in oil estimated to about $2/3 \times C_0$ or 2×10^8 m/s (C_0 denoting the speed of light in a vacuum) [8]. Recent simulation studies by Xu et al. [9] have provided detailed analysis of UHF signal propagation characteristics in GIS, offering improved understanding of signal attenuation and dispersion effects. The measurement frequency range depends on the specific apparatus. Metal parts of GIS enclosures act as waveguides or resonators. Effects such as dispersion, attenuation, cavity resonances, standing waves, reflection and diffraction all influence the propagation of the PD pulse signals and the pulse characteristics respectively [10]. Transmission path characteristics typically depend on:

- i. Material characteristics and dimensions.
- ii. Electromagnetic impedance and dielectric behaviors of the surrounding dielectric medium.
- iii. Distance between source and sensor.

II.2 ADVANTAGES OF UHF MEASUREMENT METHOD

Compared to the conventional PD measurement techniques as described by IEC 60270, the main advantages of UHF PD measurement methods include:

- Greater immunity to disturbances and noise, which implies that sensitive measurement of PD can be made with AC supplies that are noisy themselves or when the test object is connected to the HV source. This can greatly reduce the costs of performing PD tests and increase the probability of achieving reliable results.
- Since the associated frequencies are preserved with wideband UHF detectors, it is sometimes possible to determine the nature of the PD source with the UHF method [11].
- Higher signal-to-noise ratio when measuring PD in the UHF range as most of the energy from electromagnetic noise in the power system tends to occur at frequencies below several hundred MHz [12].

Recent work by Ahmed et al. [13] has extended UHF detection to alternative insulation gases such as HFO(E), demonstrating the method's adaptability to environmentally friendly SF₆ substitutes.

II.3 UHF MEASURING SYSTEM

For detecting and measuring the electromagnetic waves emitted by partial discharges, different aspects of the method are shown in Figure 1.

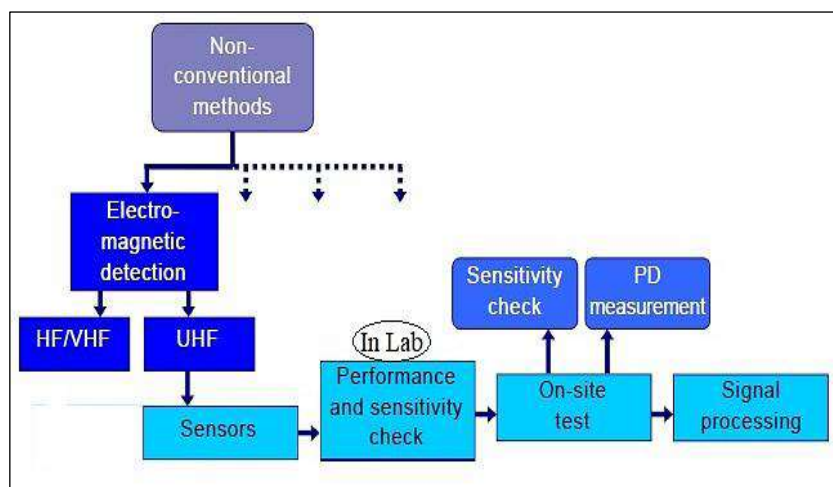


Figure 1: Overview of UHF PD Detection.

Source: Authors, (2026).

Some examples of sensors mainly used in the UHF range include [14]:

- Disc and cone-shaped sensors.
- External window couplers.
- Hatch couplers.
- Barrier sensors.
- Field grading electrodes.
- Waveguide sensors.
- UHF antennas.
- Directional electromagnetic couplers.

Chen et al. [8] recently proposed a novel composite sensor for simultaneous UHF PD and gas state measurement, addressing the need for multi-parameter monitoring in modern GIS condition assessment.



Figure 2: External UHF sensor for GIS application.
Source: Authors, (2026).

The output of UHF sensors is typically a voltage signal. These values measured by the instruments are in linear correlation to the measured electromagnetic field and the sensor transfer characteristic. Derived quantities, however, should be in correlation to the PD parameters. This can be linear when using the direct output voltage of the UHF sensor, or quadratic by processing the power quantity (W) of the sensor signal, or the signal energy (J) as related to the defined resistance of the PD measurement system. The UHF sensor is described with its characteristic in terms of its effective height (m), effective aperture (mm^2) and antenna gain (dBi). It should be emphasized that when employing the electromagnetic detection (radio frequency) method, the PD magnitude as apparent charge cannot be evaluated directly as a calibrated value. However, a verification of the detection sensitivity can be performed and has proven to be useful in practice. Mier et al. [15] proposed advanced calibration techniques for magnetic and electric antennas to enable PD charge estimation in gas-insulated substations. Achievable detection sensitivity is demonstrated in a worst-case configuration by direct comparison in a simultaneous IEC 60270 measurement of apparent charge (pC) from an actual, significant and meaningful PD source taken in laboratory setup as shown in figure 3.

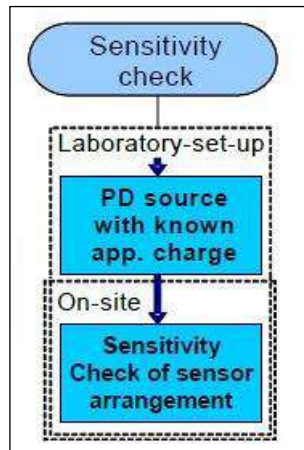


Figure 3: Sensitivity check for GIS apparatus.
Source: Authors, (2026).

On-site, the UHF Sensors can be installed inside the high voltage component or externally mounted at dielectric apertures such as GIS joints or inspection windows or valves. Recent research by Birla et al. [16] on 230 kV GIS substations using combined UHF and ultrasonic sensors demonstrated effective failure prediction capabilities. The sensors should be installed as close as possible to the particular PD detection area and inside the metallic enclosure or on the spacer joints of the GIS. In larger high voltage GIS systems, it is beneficial to install multiple sensors to improve measurement sensitivity and to help in PD source detection as shown in figure 4. Liang et al. [17] presented optimization methods for UHF sensor placement to achieve accurate localization of PD sources. Multiple sensors can also be used for the sensitivity check of the arrangement. The sensors should not have any negative impact on the dielectric design and functionality of the high voltage equipment. The output signals of these sensors can be processed in the time or frequency domain. Narrowband frequency domain signal processing may allow better noise suppression capability where noise and external disturbances may be present and consequently features improved sensitivity in noisy environments.

The PD measurement system processes the output of a swept frequency or a so-called ‘real-time spectrum analyzer’ processes a power spectrum versus a defined frequency band. This can also be displayed as a spectrum of measured signals (PD and other signals). Recent advances in deep learning have enabled more sophisticated signal processing approaches. Wang et al. [18] proposed a domain adaptive graph convolutional network for GIS insulation defect diagnosis, while Yadam et al. [19] conducted comprehensive numerical and experimental investigations on the influence of internal defect parameters on PD-induced UHF signals.

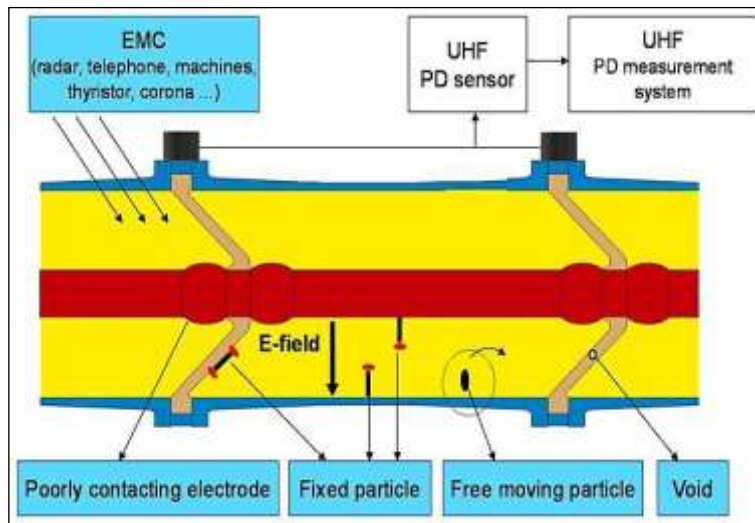


Figure 4: UHF measuring system for GIS PD defects.
Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS

III.1 LABORATORY VERIFICATION

As described in the above section, UHF sensor output was compared with a simultaneous IEC 60270 measurement of apparent charge 100 pC from an actual, significant and meaningful PD source from a 10 KVA 11 kV/ 433 V transformer having internal PD for verification of detection sensitivity in the lab having faraday cage. Base trace is of 1 pC as shown in figure 5 which was first taken to verify presence of EM emissions from another object in the lab. Then the transformer was given high voltage till it gave a 100 pC apparent charge reading in an IEC 60270 measurement. The output signals for both the traces from UHF sensor were processed in frequency domain and displayed as a spectrum of actual PD amplitude in terms of power quantity (dBm) versus the frequency band of 50 to 500 MHz.

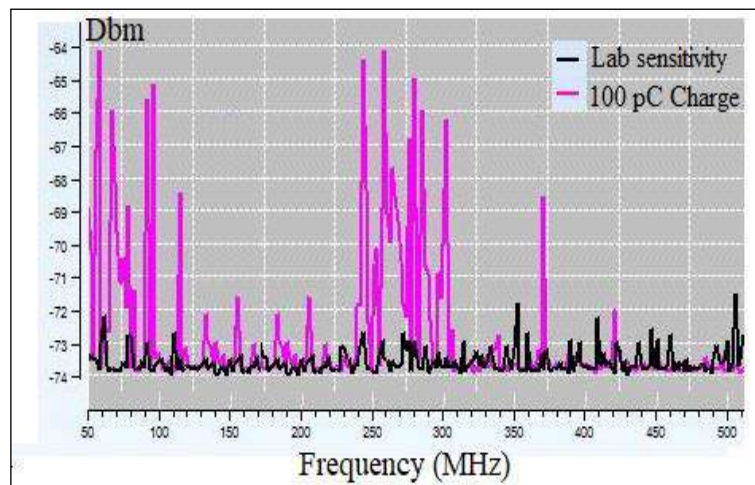


Figure 5: Detection sensitivity checks in Lab.
Source: Authors, (2026).

III.2 FIELD APPLICATION WITH EXTERNAL SENSORS

The lack of field applications of UHF sensors is due to difficulties faced in mounting the UHF sensor inside the GIS and its safe operation during shutdowns. To overcome this issue an external integrated UHF sensor was placed on dielectric aperture spacer joints on the physical real GIS as UHF waves cannot travel through the thick metal apertures. Recent research has addressed sensor degradation issues. Roslizan et al. [20] presented a comprehensive review of PD detection using UHF sensors, while Shu et al. [21] proposed a field calibration method based on forward transport coefficient for UHF PD detection sensors in GIS.

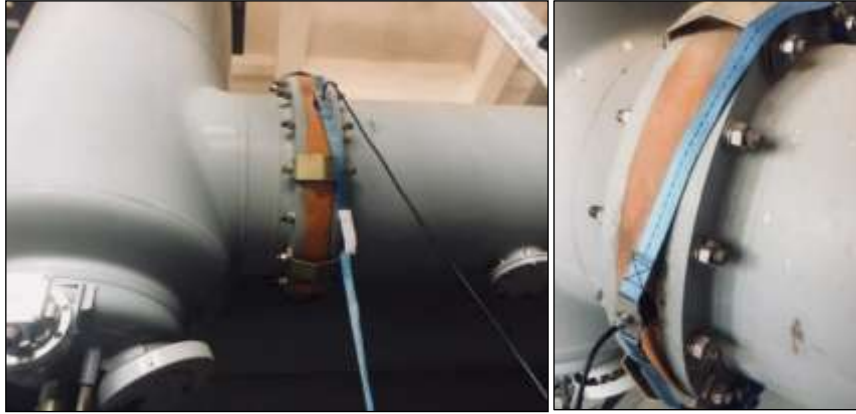


Figure 6: UHF Sensor arrangement on physical real GIS spacer joint.
Source: Authors, (2026).

III.3 ONLINE PD MEASUREMENT ANALYSIS

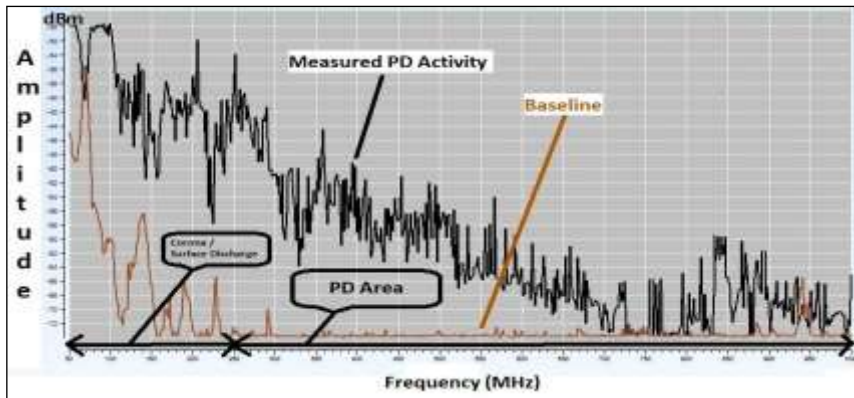


Figure 7: Online PD Measurement of GIS panel with UHF sensor.
Source: Authors, (2026).

There are two waveforms shown in one spectrum where firstly the ambient background waveform pattern was taken to verify presence of EM emissions from other objects in the vicinity. Baseline trace was taken 20 to 30 meters away from the GIS bay under test. The second waveform was taken when UHF sensor was mounted on the dielectric aperture of the GIS bay which is the closest possible distance for PD detection providing the highest sensitivity. Frequency response from 50 MHz to 250 MHz gives corona or surface discharge depending upon environmental factors and condition of GIS [22]. Internal PD extends up to 1000 MHz where signal strength of any PD activity is determined by high amplitudes and continuous wide signal response when compared to baseline. The reference level is the maximum magnitude of the decibel scale on the Y axis of the above plot. Every level of power at a given frequency has a value less than 1 (0 dBm) relative to 1mW of radiated power. When the signal received by UHF sensor is converted from watts to dBm, all the values below 0 dBm become negative. The Y axis shows the signal strength in terms of power. Power quantity (mW) of the sensor signal is in correlation with the PD parameters with the help of formula [23] below in equation 1:

Power quantity (mW) of the sensor signal

$$[\text{dBm}] \text{ at a particular frequency} = 10 \cdot \log_{10} \left(\frac{P_{\text{Output at that frequency}}}{0.001 \text{ Watt}} \right) \quad (1)$$

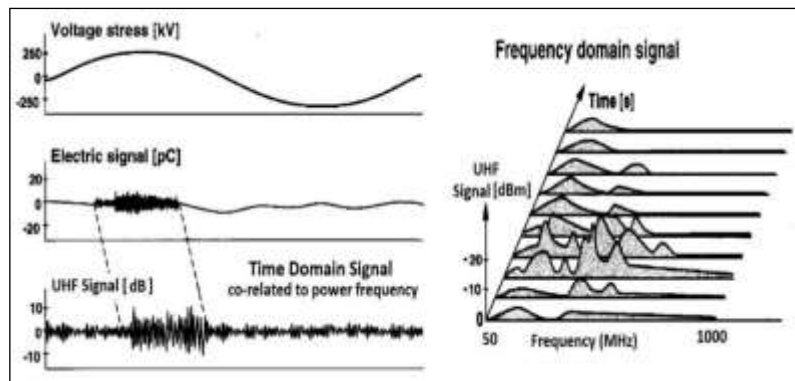


Figure 8: Co-relation of derived quantities with PD Parameters.
Source: Authors, (2026).

The time resolved UHF signal from high frequency electrical PD signal graphically displays signal amplitude in dB with respect to time as shown in figure 8. The time window is 20 ms (50 Hz) and pulse train with different width appears within that time window. As discussed in the earlier section, output of the UHF sensor is dependent in terms of its effective height (m), effective aperture (mm^2) and antenna gain (dBi). We can clearly see in figure 7 that P_{output} values at a particular frequency are more when the sensor is kept on the dielectric aperture of GIS (PD detection area) when compared to P_{output} values taken in the baseline trace at the same frequency where sensor is kept around about 20 meters away from the HV equipment.

III.4 RECENT ADVANCES IN SIGNAL PROCESSING AND AI INTEGRATION

Recent research has significantly advanced UHF PD detection through artificial intelligence and sophisticated signal processing techniques:

III.4.1 Deep Learning Approaches

Ma et al. [24] proposed a self-supervised asynchronous federated learning framework for diagnosing PD in GIS, addressing data privacy concerns while maintaining high diagnostic accuracy. Their approach uses Phase-Resolved PD (PRPD) patterns with MobileNetV2 architecture, achieving superior classification performance compared to traditional methods. Fan et al. [25] developed a hybrid Acoustic-VMD and CNN-LSTM model for PD signal recognition, combining variational mode decomposition with deep spatiotemporal feature learning. This approach captures both transient discharge morphologies and their evolutionary patterns, overcoming limitations of conventional single-path models.

III.4.2 multi-Sensor Fusion

Recent studies emphasize the importance of multi-sensor fusion for improved PD detection reliability. Khan et al. [26] provided a comprehensive review of PD detection and diagnosis in GIS, highlighting the state-of-the-art in multi-sensor approaches. The combination of UHF, ultrasonic, and optical sensors provides complementary information that enhances defect classification accuracy [27]. Zhang et al. [28] proposed multi-sensor temporal pulse sequence analysis for PD diagnostics, demonstrating improved discrimination capabilities between different PD sources and external interference.

III.4.3 Pattern Recognition Advances

Yuan et al. [29] developed a PD pattern recognition method based on time-frequency energy grayscale maps and improved variational Bayesian autoencoder, achieving high classification accuracy with uncertainty quantification. This addresses the critical need for interpretability in AI-based diagnostic systems. Hu et al. [30] proposed an improved deep learning method for PD fault identification in GIS equipment using CNN-BiLSTM networks with attention mechanisms, achieving accuracy, recall, and F1 values of 0.876, 0.812, and 0.843 respectively.

IV. PROPOSED RESEARCH CONTRIBUTIONS

Based on the literature review and identify gaps, the following research contributions are proposed to enhance this work:

IV.1 ADVANCED SIGNAL PROCESSING FRAMEWORK

Proposed Enhancement: Implement a Denoiser-based Approximate Message Passing (D-AMP) algorithm for UHF signal denoising, as suggested by recent research [31]. This compressed sensing approach can reconstruct PD signals from sub-Nyquist samples while maintaining robust performance across multiple noise types (periodic narrowband interference, white noise, and colored noise).
Implementation:

- i. Apply D-AMP with optimized sampling rate $\delta = 0.5$ and threshold coefficient $\alpha = 1.4$
- ii. Use Hilbert-Huang Transform (HHT) to extract time-instantaneous frequency energy maps
- iii. Convert to 2D time-frequency energy grayscale images for pattern recognition

IV.2 DEEP LEARNING-BASED PATTERN RECOGNITION

Proposed Enhancement: Integrate a lightweight Multi-source Convolutional Neural Network (MCNN) for real-time PD pattern classification [32]. **Architecture:**

- Input: PRPD images from UHF, optical, and ultrasonic sensors (multi-source fusion)
- Preprocessing: PRPD-Grab cut segmentation for noise reduction
- Feature Extraction: Inverted Residual Bottleneck (IRB) modules with depth wise separable convolutions

Expected Outcome: Recognition accuracy exceeding 99% with significantly reduced computational burden compared to traditional CNNs, enabling real-time diagnostics on resource-constrained devices.

IV.3 MULTI-SENSOR FUSION STRATEGY

Proposed Enhancement: Develop an adaptive multi-sensor fusion framework combining:

- UHF sensors (300 MHz – 3 GHz) for electromagnetic detection
- Optical sensors (PMT) for photon detection

- Acoustic emission sensors (20-200 kHz) for ultrasonic detection

Fusion Method: Dempster-Shafer (D-S) evidence theory for decision-level fusion, combining statistical features and deep learning outputs [33]. Advantages:

- 300% improvement in detection accuracy over single-sensor approaches
- False alarm reduction to below 0.5%
- Enhanced PD source localization through spatiotemporal correlation analysis

V. CONCLUSIONS

This paper provides helpful information to improve online PD detection and proposes a new on-field PD detection method for GIS. In near future, with improvisation in GIS designs, authors suggest that extensive online diagnostic monitoring should be supplemented with it. This will have mainly two advantages; first the utilities would adapt to online condition-based maintenance and secondly it would reduce the unplanned outages of the GIS switchgear which in turn will reduce the revenue expenditure. The method presented in the paper is not calibration. However, the aim is to find the best possible match for a real PD defect to verify the sensitivity of the UHF measurement in GIS. A comparison with the spectra of different output power pulses was done by visual comparison. However, our field trials for GIS show that there are still problems in UHF PD detection method due to its difficulties in sensor arrangement on metal enclosures and complex environments on-site. Author has also suggested that future work should focus on implementation of the proposed D-AMP and MCNN framework, field validation of the multi-sensor fusion approach in 220 kV and 400 kV GIS installations, development of a digital twin model for GIS insulation health prediction and integration with asset management systems for predictive maintenance scheduling.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Sagar Bhutada.

Methodology: Sagar Bhutada.

Investigation: Sagar Bhutada.

Discussion of results: Sagar Bhutada.

Writing – Original Draft: Sagar Bhutada.

Writing – Review and Editing: Sagar Bhutada.

Approval of the final text: Sagar Bhutada.

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