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UHF Detection of Partial Discharge in High-Voltage Air Insulated Switchgear Using Improved Vivaldi Antenna

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Abstract—Partial discharge (PD) is a major concern in high-voltage electrical equipment, and its detection is crucial for ensuring the reliability and safety of power systems. In high voltage (HV) air-insulated switchgear (AIS), which is commonly used in the transmission and distribution of electrical power, PD can occur due to various factors such as insulation defects, voids, or impurities. Detecting PD at an early stage is essential to prevent equipment failure and costly downtime. Ultra-high frequency (UHF) detection methods are widely used for PD detection in HV AIS, as they offer high sensitivity and the capability to detect PD signals over long distances. In this paper, we will discuss using Vivaldi directional antennas for PD detection in HV AIS, focusing on their advantages, challenges, and potential applications. The simulation was carried out using CST Microwave Studio, and the result revealed that the antenna has a wide impedance bandwidth of 100% in the range of 0.5 to 1.5 GHz with $S_{11} < -10$. An average gain of 5 dB and a maximum gain of 8.62 dB are achieved at the operational frequency band.

Keywords-- Partial discharge (PD), UHF, Vivaldi antenna, Air Insulated Switchgear (AIS)

I. INTRODUCTION

Partial discharge (PD) poses a significant risk to high voltage electrical equipment, making its detection vital for maintaining the reliability and safety of power systems

[1-2]. In air-insulated switchgear (AIS), widely utilized in the transmission and distribution of electrical energy, PD can arise from several issues, including insulation flaws, voids, or contaminants [3]. Early detection of PD is critical to avert equipment failures and minimize expensive downtime.

The sources of partial discharge in AIS include [4-8]:

- Insulation breakdown due to high electric field stress
- Presence of impurities or moisture in the insulation material
- Mechanical defects or damages causing PD
- Poor manufacturing or installation quality leading to uneven gaps or sharp edges

The disadvantages of PD in AIS [9-12]:

- Deterioration of insulation material leading to reduced equipment lifespan
- Risk of catastrophic failure due to insulation breakdown, causing short circuits or arcing
- Increased risks of electrical accidents or fires
- Degradation of system performance and reliability
- Higher maintenance and repair costs due to frequent breakdowns and outages

Ultra-high frequency (UHF) detection techniques are extensively employed for identifying PD in AIS due to their exceptional sensitivity and ability to capture PD signals from considerable distances.

In HV GIS substations, where space is limited, using high-

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gain antennas can still be feasible with certain strategies. The planar design of the antenna allows it to occupy minimal physical space while still providing high gain. Strategic placement of the antenna in key locations near critical equipment can optimize detection without occupying excessive space. The directional radiation pattern and wide bandwidth of the antenna ensure that it can detect PD signals over long distances, even in confined environments. Additionally, the antenna's low side lobes and minimal cross-polarization reduce noise and interference in the complex electrical environment of GIS substations, enhancing signal clarity. For further coverage and higher gain, antenna arrays can be employed, consisting of smaller, compact antennas working together to increase the overall gain. Finally, using signal amplifiers can further improve weak PD signal detection, reducing the reliance on a single high-gain antenna and maintaining effective monitoring in the limited space of HV GIS substations.

This paper will explore the application of UHF directional antennas for PD detection in HV AIS, highlighting their benefits, challenges, and possible use cases.

Some solutions are available to detect and eliminate PD [3], [13-15]:

- Online monitoring systems: Install online monitoring systems to continuously monitor the condition of electrical equipment and detect any signs of partial discharge. These systems can provide real-time data and alerts to help identify and address potential issues before they escalate.
- Periodic testing and inspections: Conduct periodic testing and inspections of electrical equipment using techniques such as partial discharge testing, ultrasonic testing, and infrared thermography. This can help identify any potential issues with insulation or electrical components that may lead to partial discharge.
- Use of diagnostic tools: Utilize diagnostic tools such as PD meters, oscilloscopes, and spectrum analyzers to pinpoint the partial discharge source within electrical equipment. This can help determine the severity of the issue and guide appropriate remediation efforts.
- Maintenance and repair: Regular maintenance and timely repair of electrical equipment can help prevent partial discharge by addressing any deteriorating insulation, loose connections, or other issues that may contribute to electrical discharge.
- Upgrading insulation materials: Consider upgrading insulation materials in electrical equipment to enhance its resistance to partial discharge. This can help improve the overall reliability and safety of the equipment.
- Training and education: Provide training and education to personnel responsible for operating and maintaining electrical equipment to raise awareness about the importance of detecting and eliminating partial discharge. This can help ensure that best practices are followed to prevent electrical discharge incidents.

UHF directive antennas are specially designed antennas that can be used to detect PD signals in AIS. These antennas have a narrow beamwidth and high gain, allowing for the selective reception of UHF signals emitted by PD events. By using a directional antenna, it is possible to localize the source

of PD within the switchgear, enabling precise identification and localization of potential insulation defects.

One of the main advantages of using UHF directive antennas for PD detection in HV AIS is their high sensitivity and ability to detect weak PD signals. The high gain of these antennas allows for detecting PD events over long distances, even in noisy electromagnetic environments. Additionally, the narrow beamwidth of the antenna helps reduce interference from external sources, improving the accuracy of PD detection.

Another advantage of UHF directive antennas is their ability to provide real-time and in-service monitoring of PD activity in HV AIS. Compared to the conventional electrical method based on IEC 60270 [16], the most significant advantage of the UHF method is its potential for online detection and localization. Using a network of directional antennas strategically placed around the switchgear makes it possible to continuously monitor the PD activity and detect any abnormal behavior before it escalates into a critical fault. This proactive monitoring approach can help prevent unplanned downtime and optimize maintenance schedules.

The UHF method for PD detection is designed to be robust against high-frequency noise generated during switching operations. Several factors contribute to its effectiveness in this regard:

- Directional Antennas and Localization: UHF directive antennas are strategically placed around the switchgear, which allows the system to isolate the source of the PD signals and differentiate them from other high-frequency electromagnetic interferences generated by switching operations. By focusing on signals from specific directions, the system can filter out unwanted noise from other sources [17]. The advantage of using directional antennas over omnidirectional antennas in the context of PD detection lies in their ability to focus radiation in a specific direction, allowing for greater detection range and improved signal-to-noise ratio. This focus reduces interference from surrounding equipment and external sources, making the detection more accurate and reliable, especially in high-noise environments like substations. Additionally, they are more efficient in terms of power usage, as they concentrate energy in a specific direction, requiring less power to achieve the same detection range. Overall, directional antennas improve the performance of PD detection systems, making them more suitable for high-voltage environments.
- Frequency Range and Signal Processing: UHF PD detection typically operates in the frequency range of 300 MHz to 1 GHz, distinct from the frequency ranges of many high-voltage switching transients. To further enhance this, advanced signal processing techniques, such as digital filtering and Fourier analysis, are used to remove high-frequency interference that does not correspond to PD events [18].
- Use of bandpass Filters: The system employs bandpass filters that allow only signals within the PD frequency range to pass through while attenuating signals outside this range, particularly those generated by switching activities. This helps isolate the PD signals from switching noise and enhances detection accuracy [19].

- Proactive Detection of Abnormal Behavior: One of the significant advantages of the UHF method is its real-time monitoring capability. By continuously analyzing the signals and comparing them with predefined patterns of normal operation, the system can detect deviations that are characteristic of PD activity, even in the presence of high-frequency noise [20].
- Signal Amplification and Noise Suppression: Advanced UHF monitoring systems also employ signal amplification techniques to enhance the strength of the PD signals relative to background noise. This ensures that PD signals remain detectable and distinguishable even in environments with high-frequency disturbances [21].

UHF PD sensors in HV AIS typically use different types of antennas specifically designed to detect PD signals in high voltage equipment. Examples of such antennas include directional UHF antennas such as:

- Yagi antenna: A directional antenna that consists of multiple parallel elements arranged in a line, typically used in PD detection in HV AIS for its high gain and narrow beam width.
- Patch antenna [22-27]: A type of directional antenna with a flat, rectangular shape commonly used in PD detection in HV AIS due to its compact size and high efficiency.
- Horn antenna: A directional antenna with a conical shape often used in PD detection in HV AIS for its wide bandwidth and high gain [28], [29].
- Log-periodic antenna: A directional antenna with a series of dipole elements of varying lengths, commonly used in PD detection in HV AIS for its wide frequency range and constant impedance.
- Parabolic dish antenna: A directional antenna with a paraboloid-shaped reflector with high-gain and long-range capabilities. Due to their bulky size and weight, parabolic antennas are rarely used as UHF PD sensors in AIS systems.
- Vivaldi antenna: Vivaldi is a type of planar antenna that can be used as a UHF PD sensor in HV AIS. These antennas are designed to operate effectively in the UHF frequency range and can be used to detect and localize PD activity in switchgear equipment. The Vivaldi antenna's wide bandwidth and directional characteristics make it suitable for detecting electromagnetic signals emitted by PD events in the UHF range. By integrating Vivaldi antennas into the sensor system of HV AIS, it is possible to monitor and diagnose potential insulation defects and prevent equipment failure.

The Vivaldi antenna has several advantages over other antennas for PD detection in HV AIS, including:

- Wide bandwidth: The Vivaldi antenna has a wider bandwidth than other antennas, allowing it to detect a larger range of frequencies associated with PD events.
- Directional sensitivity: The Vivaldi antenna has a high directional sensitivity, making it easier to pinpoint the location of partial discharge events within the switchgear.

- Compact size: The Vivaldi antenna is relatively small and compact, making it ideal for use in confined spaces within air-insulated switchgear.
- Low cost: The Vivaldi antenna offers a cost-effective solution compared to similar antenna designs, particularly when considering its performance benefits and manufacturing simplicity. Although the initial costs of development may be higher in some cases, the long-term savings from improved reliability, reduced maintenance, and better detection accuracy make it an economically favorable choice for PD detection systems.

Overall, the Vivaldi antenna offers superior performance, sensitivity, and cost-effectiveness compared to other antennas for PD detection in HV AIS.

While UHF directive antennas offer many advantages for PD detection in HV AIS, there are also some challenges and considerations to be aware of. One of the main challenges is the complexity of the antenna system, which may require careful calibration and positioning to ensure accurate detection of PD signals. Additionally, the cost of implementing a network of directional antennas may be a limiting factor for some utilities or operators.

Another consideration is the potential for false alarms or misinterpretation of PD signals. It is essential to clearly understand the different types of PD signals and their characteristics to differentiate between normal and harmful PD events. Proper training and expertise in interpreting UHF signals are required to avoid unnecessary maintenance or replacements.

Recently, many papers have been presented on detecting PD signals in AIS and gas-insulated switchgear (GIS) by UHF antennas [30-41]. Unlike the conventional electrical method based on IEC 60270, which measures partial discharge through electrical signals (usually requiring physical connection with the equipment), the proposed UHF method provides online detection and localization of PD signals without direct contact. This makes the UHF method more suitable for real-time monitoring, especially in environments with high-voltage and high-current switching operations [42]. In contrast to the standard Vivaldi antenna design, our proposed method utilizes the slotting correction (SC) and triangular director (TD) to improve performance. These modifications significantly enhance the antenna's gain and surface current distribution, ensuring better signal clarity and accuracy in detecting partial discharge events, especially over long distances [43]. While previous studies utilize advanced signal processing techniques to enhance the performance of UHF PD detection, our work focuses on improving the antenna system design itself. By implementing the SC and TD methods, we have shown that the performance enhancement comes not only from signal processing but also from optimizing the antenna structure, which results in improved directionality, gain, and surface current distribution [44].

II. DESIGN OF THE CONVENTIONAL VIVALDI ANTENNA SENSOR

An antenna with an end-fire pattern is generally better for PD detection in the UHF band. End-fire antennas have a directional radiation pattern that focuses the antenna's sensitivity and gain in a specific direction, allowing for more precise detection of signals in that direction. In contrast, boresight antennas have a broader radiation pattern that may

not provide as focused or accurate detection capabilities for partial discharge signals.

PD predominantly occurs within the frequency range of 0.5 to 1.5 GHz [45-48]. Therefore, it is essential for UHF antennas to have a bandwidth that encompasses this 1 GHz range (0.5-1.5 GHz) to diagnose PD effectively. The Vivaldi antenna designed for the 0.5 GHz to 1.5 GHz frequency range offers several advantages for PD detection. In the lower frequency range (below 0.5 GHz), ambient noise from power line communication (PLC) systems and electromagnetic interference (EMI) [49] can degrade signal quality, making it harder to distinguish PD signals from background noise. The Vivaldi antenna avoids this issue by operating in a more defined frequency range, minimizing the noise presence at lower frequencies. On the other hand, at higher frequencies (above 1.5 GHz), signal attenuation increases due to dielectric losses and absorption by atmospheric moisture, limiting the antenna's detection range. Additionally, radio-frequency interference (RFI) becomes more pronounced, introducing additional noise that can interfere with PD detection. Operating in the 0.5 GHz to 1.5 GHz range allows the Vivaldi antenna to effectively capture PD signals while minimizing the impact of both lower-frequency noise and higher-frequency attenuation. This range balances long-range detection and high resolution, ensuring optimal performance in high-voltage AIS and GIS substations. The compact and directional design of the antenna ensures that it focuses on the most relevant PD signals, reducing interference and noise from irrelevant frequencies, making it an excellent choice for space-constrained environments like substations or aerial monitoring systems. Overall, the 0.5 GHz to 1.5 GHz frequency range optimizes PD detection, providing high gain, low side lobes, and precise localization, which enhances detection accuracy and reliability.

In summary, environmental noise and electromagnetic interference pose significant challenges in PD detection. However, these can be mitigated through strategies like frequency selection, directional antenna design, signal processing, and multiple sensor networks. The Vivaldi antenna, operating in the 0.5–1.5 GHz range with directional gain and advanced processing, effectively reduces noise, ensuring accurate PD detection and localization.

In HV AIS, the antenna gain required for PD in the UHF band is provided at a safe distance from the equipment, which will depend on various factors such as the receiver's sensitivity, the background noise level, and the signal strength of the PD. A high-gain antenna may be required to improve the signal-to-noise ratio and increase the receiver sensitivity. However, the exact gain required may vary depending on the specific conditions and requirements of the application.

An example of a directional antenna for use in a commercial PD sensor with a directivity of 13.6 dBi at a frequency of 800 MHz is presented in [50].

The conventional Vivaldi antenna (CVA) is a traveling-wave antenna characterized by its end-fire radiation properties, as illustrated in Fig. 1. Energy is coupled to the metal patch through a microstrip slot, facilitating further radiation. As a tapered slot antenna, the Vivaldi antenna is renowned for its high gain, directive radiation pattern, planar design, and relatively wide bandwidth [51], with the potential for theoretically infinite bandwidth. Additionally, the Vivaldi antenna exhibits linear polarization, with its electric field vector aligned parallel to the dielectric surface. The Vivaldi

antenna maintains a high degree of linear polarization in the primary radiation planes, featuring low cross-polarization levels and minimal side lobes. Equation (1) defines the taper profile, which employs a mirror exponential function optimized to achieve the desired bandwidth.

$$f(y) = 2.3e^{0.0335y} - 3.3 \quad (30 \text{ mm} < y < 145 \text{ mm}) \quad (1)$$

Equation (1) was derived based on our own optimization process and analysis of similar structures. Through these simulations and the analysis of the results, we extracted the best mathematical model to describe the system's behavior. This formula specifically represents the relationship between design parameters in similar systems, and it was derived by combining experimental data and numerical simulations.

This design proposes a conventional Vivaldi antenna (CVA) with a compact size and high gain. The FR-4 ($\epsilon_r = 4.3$) high-frequency plate is used as the antenna dielectric substrate with a thickness of 2 mm. According to the configuration shown in Fig. 1, the element model is built in CST Microwave Studio software with a size of 244×195 mm². The proposed antenna is formed by a feed microstrip line terminated by a fan-shaped microstrip line on the top layer and a conical slot terminated by a circular slot notch on the bottom layer.

After optimization by CST, the optimized parameters of the CVA are listed in Table I.

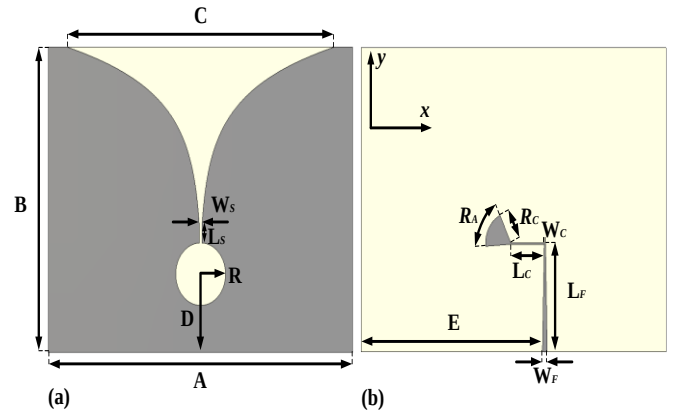


Fig. 1. Design of the Conventional Vivaldi Antenna (CVA).

TABLE I
Parameters of the Conventional Vivaldi Antenna.

Parameter	Value (mm)	Parameter	Value (mm)
A	244	Wf	3.82
B	195	Lf	70
C	107	Wc	1
D	50	Lc	27.2
R	20	Rc	19.5
Ws	2	RA	24.4
Ls	10	E	145.14

III. IMPROVED VIVALDI ANTENNA SENSOR (IVA)

To achieve optimal detection accuracy of the PD signals, the Vivaldi antenna must possess characteristics such as ultra-wideband capability, a narrow beam, and high gain. Consequently, it was essential to minimize the beam width of the antenna system.

In the proposed design for the improved Vivaldi antenna (IVA), key strategies for reducing the beam width and increasing gain include the slotting correction (SC) in the metal patch (designated as IVA-1) and the addition of a triangular director (TD) (designated as IVA-2). It is important to note that both approaches will impact the standing wave ratio of the antenna.

Finally, structures IVA-1 and IVA-2 are designed based on the main structure CVA, which consists of SC and SC+TD, shown in Fig. 2.

After optimization by CST, the optimized parameters of the IVA are listed in Table II.

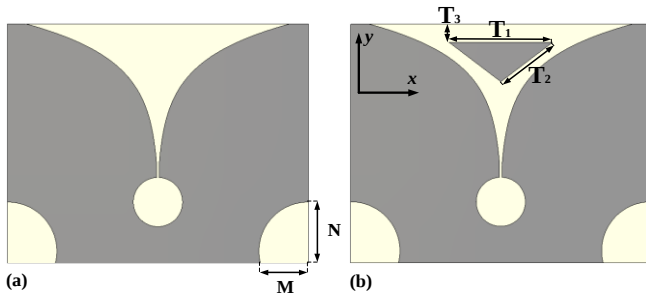


Fig. 2. Design of the Improved Vivaldi Antenna (IVA-1 and IVA-2).

TABLE II

Parameters of the Improved Vivaldi Antenna (IVA-1 and IVA-2).

Parameter	Value (mm)	Parameter	Value (mm)
M	38.7	T2	48.4
N	50	T3	0
T1	76		

IV. SIMULATED RESULTS

According to the simulation results shown in Fig.3, the return losses for the proposed antennas are below -10 dB in the entire frequency range of 0.5-1.5 GHz. Also, a better performance in terms of impedance matching is observed in the frequency range of 0.71-1.36 GHz.

The gain versus frequency plots of CVA, IVA-1, and IVA-2 are shown in Fig. 4. It is clear that by presenting IVA-1, the antenna gain is improved compared to CVA, especially at the frequencies of 0.65 and 1.4 GHz. It is illustrated that by presenting IVA-2, the antenna's gain has been significantly improved in the entire frequency range compared to both previous antenna models. According to Fig. 4, the average gain during the frequency range is equal to 5.51 dB, and the maximum gain reaches 8.56 dB at 1.5 GHz. The results indicate an increase of 0.64 dB in the average value of gain and 1.13 dB in the maximum gain value.

The E-plane radiation patterns of CVA, IVA-1, and IVA-2 at 0.5 GHz, 1.0 GHz, and 1.5 GHz are presented in Fig. 5.

The beams in both E-planes become narrower, and the gain increases with frequency. The half-power beamwidths (HPBW) of E-plane patterns are presented in Table III.

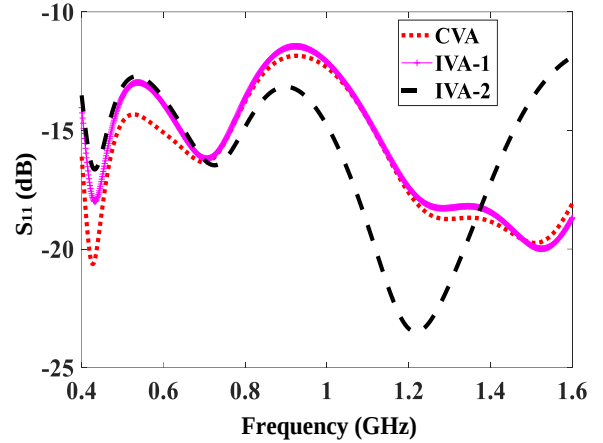


Fig. 3. Simulated S-parameters of CVA, IVA-1, and IVA-2.

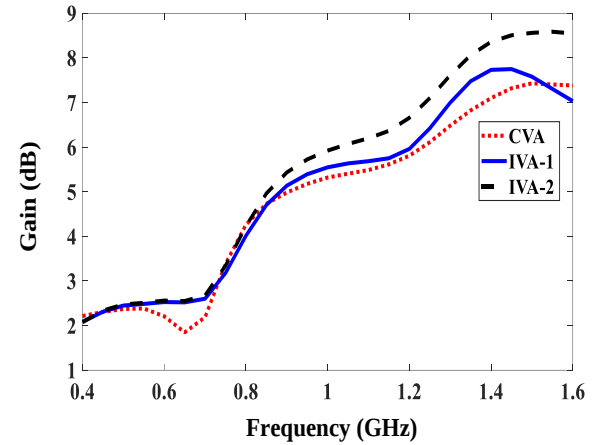


Fig. 4. Simulated gain result of CVA, IVA-1, and IVA-2.

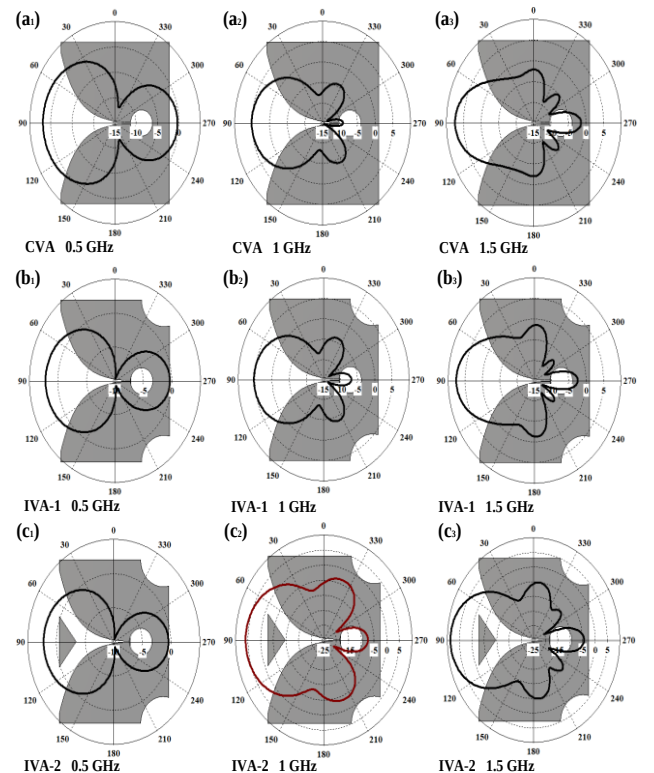


Fig. 5. Simulated E-plane radiation patterns of CVA, IVA-1, and IVA-2 at 0.5 GHz, 1.0 GHz, and 1.5 GHz

TABLE III

The HPBW of the CVA, IVA-1, and IVA-2 at 0.5 GHz, 1.0 GHz, and 1.5 GHz

	HPBW		
	0.5 GHz	1 GHz	1.5 GHz
CVA	121.1°	75.1°	51°
IVA-1	111.6°	70.1°	50°
IVA-2	111°	68.5°	48°

To gain insights into how the slotting correction (SC) and triangular director (TD) structures enhance the antenna's radiation performance, we examine the surface electric field distribution across the CVA, IVA-1, and IVA-2 configurations at varying frequencies, as illustrated in Fig. 6. At a frequency of 0.65 GHz, the surface electric field of both CVA and IVA-1 is primarily focused along the taper slot line, with the field strength in IVA-1 exceeding that of CVA. This pattern remains consistent at frequencies of 1 GHz and 1.5 GHz. For IVA-2, which incorporates both SC and TD elements, the electric field distribution at frequencies of 0.5, 1, and 1.5 GHz shows a concentration not only along the taper slot but also significantly within the TD itself. This indicates that the TD structure is crucial for effectively directing the electric field along the radiation exponential slot line.

The proposed Vivaldi antenna enhances PD detection by offering several key advantages. Its high gain and directive radiation pattern improve the detection range and accuracy, especially for long-distance PD detection in high-voltage air-insulated switchgear. The wide bandwidth (0.5 GHz to 1.5 GHz) enables the antenna to capture a broader spectrum of PD signals, thus enhancing its ability to detect partial discharge across varying frequencies and equipment conditions. Additionally, the antenna's linear polarization, low side lobes, and minimal cross-polarization help reduce interference from external noise, resulting in more reliable and precise PD detection. These characteristics make the proposed antenna system more effective in pinpointing PD sources, improving the signal-to-noise ratio, and reducing false positives compared to traditional methods.

The proposed Vivaldi antenna can also be used in distribution network substations, aerial environments, and similar applications. Its high gain, wide bandwidth, and directional radiation pattern make distribution network substations suitable for detecting (PD) and monitoring electrical equipment over long distances. Careful placement is necessary to minimize interference from nearby equipment. The antenna's compact design, lightweight nature, and broadband capability are advantageous in aerial environments, such as monitoring equipment on poles and transmission towers. Its directional radiation pattern helps focus detection on specific areas, reducing external interference. However, considerations such as mounting stability, weather protection, and electromagnetic interference should be addressed to ensure optimal performance in these environments.

By combining theoretical models, simulation software, and practical field testing, the simulation results and antenna performance can be verified and optimized for both ideal conditions and real-world applications. This comprehensive validation process ensures that the antenna meets its design goals, effectively detects partial discharges, and remains reliable under practical application conditions.

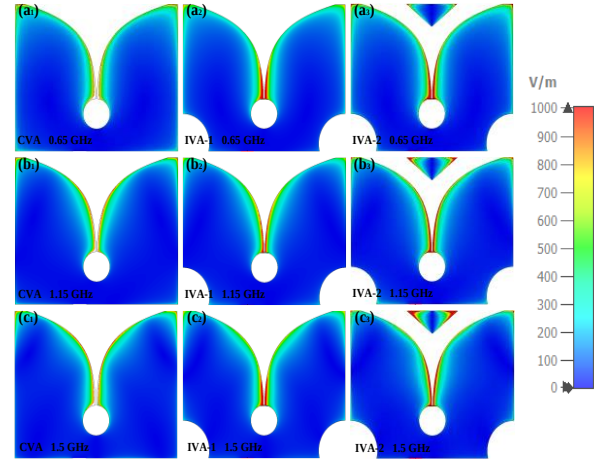


Fig. 6. Electric field distribution across the CVA, IVA-1, and IVA-2 at different frequencies

V. CONCLUSION

In this paper, an improved Vivaldi antenna system with a size of 244×195 mm² for long-distance UHF PD in high voltage (HV) air-insulated switchgear (AIS) detection has been proposed, and it covers the frequency range of less than 0.5 to more than 1.5 GHz to ensure the proper performance of the PD sensor. The antenna was an ultra-wide bandwidth with an average gain of 5 dB and a maximum gain of 8.62 dB. Two methods, slotting correction (SC) and triangular director (TD), were proposed to improve the performance of the Vivaldi antenna, and how they are effective according to the changes in the surface current distribution of the antenna was explained. In summary, antenna optimization for practical applications involves carefully balancing physical space limitations, material properties, and noise interference while achieving the key goals of detection sensitivity, noise rejection, and operational reliability in real-world conditions.

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