Design of a Circularly-Polarized UHF Antenna for Partial Discharge Detection

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ABSTRACT
In this work, a circularly-polarized ultra-high frequency (UHF) partial discharge (PD) antenna is proposed to detect the PD in 0.6 GHz – 1.7 GHz. The proposed PD antenna consists of an Archimedean spiral antenna, a balun, and a cavity. The Archimedean spiral antenna is embedded by FR-4 as substrate and superstrate for miniaturization. The microstrip-to-paired strips balun is designed to yield good performance in the return loss, insertion loss, and amplitude and phase imbalances which are of great necessity for low axial ratio. The cavity is employed to obtain unidirectional radiation patterns and prevent external signal interference. However, it is found that the originally-designed cavity-backed antenna does not work properly near 1.35 GHz due to resonance phenomena in the cavity. In this work, the cavity is modified to tackle this problem. The proposed UHF PD antenna is fabricated and measured and the results show that it provides good impedance matching, realized gain, radiation pattern, and circular polarization.

INDEX TERMS
Broadband antennas, partial discharges, UHF antennas.

I. INTRODUCTION
When the localized electric field strength in high-voltage equipment is larger than the breakdown electric field strength of a dielectric, the partial discharge (PD) may happen. Repeated PDs may result in destroying high-voltage power equipment. Therefore, diagnosing PDs is of great importance to maintain high-voltage power equipment. PD events are accompanied with physical phenomena such as electromagnetic (EM) wave radiation, acoustic pressure, chemical reaction, etc. Until now, various PD detection methods have been developed by measuring physical phenomena. The ultra-high frequency (UHF) method based on the utilization of EM waves is one of the most promising methods since it can provide PD localization and online monitoring. The PD antenna for the UHF method can be primarily classified as an external sensor and an internal sensor and it is employed in transformers, gas-insulated switchgears, wind power devices, power cables, etc. The external sensor and the internal sensor are determined by the installing location of the PD antenna. In contrast with the external sensor, the internal sensor has several main advantage such as high signal-to-noise ratio, high sensitivity, and anti-interference [1]–[4].

The favorable performances of the UHF PD antenna include broadband characteristic and unidirectional radiation pattern. In addition, circular polarization is highly desirable since it is robust in multipath environment such as high-voltage power equipment [5]–[7]. A cavity-backed spiral antenna is widely utilized for PD detection sensors because a spiral antenna can have broadband and circular polarization characteristics and a cavity can provide unidirectional radiation patterns and simultaneously prevent external signal interference. Recently, some researchers studied spiral-type antennas for PD detection [8]–[14]. Various cavity-backed spiral antennas were studied by using inductors [8], resistors [9], a ring-shaped absorber [10], or bow-tie loading [11]. In addition, a spiral antenna was proposed to reduce its size by employing sine-wave meandered arms [12] and an equiangular spiral antenna with a horizontal balun was proposed for easy package [13]. A single-arm spiral antenna directly fed by a coaxial cable was also proposed in [14]. Although circular polarization performance is significantly important, the axial ratio of the PD antennas was not presented to clarify the circular polarization performance [8]–[13] or the PD antenna does not satisfy the axial ratio less than 3 dB in the frequency of interest [14]. A stand-alone spiral antenna is usually circularly polarized but a cavity-backed spiral PD antenna may not provide circular polarization characteristic.
In this work, we propose a circularly-polarized UHF PD antenna in the frequency range from 0.6 GHz to 1.7 GHz. The designed UHF PD antenna consists of an Archimedean spiral antenna, a balun, and a cavity. The Archimedean spiral antenna is employed since it can provide broadband and circular polarization characteristics. The balun is made of microstrip line for the single-ended SMA connector and paired strips for the differential input of the Archimedean spiral antenna. The cavity is utilized to provide unidirectional radiation pattern and prevent external signal interference. However, we found that the originally-designed UHF PD antenna performs worse than expected because its performance is determined by not only the spiral antenna but also both cavity and balun. For example, it is found that the axial ratio for the UHF PD antenna in [14] is larger than 3 dB in 2 GHz – 2.2 GHz although a spiral antenna was employed. Therefore, it is of great necessity to design a circularly-polarized UHF PD antenna by considering the performance of the spiral antenna with a cavity and a balun.
antenna does not operate as a radiator near 1.35 GHz. To tackle this problem, the cavity is modified and the resulting UHF PD antenna yields good performance in the frequency range of interest. The remainder of this paper is organized as follows. We first present the design of the two-arm Archimedean spiral antenna and the balun. Next, we investigate performance of the original cavity-backed UHF PD and then propose the modified cavity-backed UHF PD antenna to eliminate the cavity resonance problem. Experimental results of the fabricated circularly-polarized UHF PD antenna are presented. Finally, concluding remarks are provided.

II. DESIGN

A. ARCHIMEDEAN SPIRAL ANTENNA

In the Archimedean spiral antenna, the width $W$ is equal to the spacing $S$ due to the self-complementary structure [15]. The input impedance of the Archimedean spiral antenna is ideally $188 \ \Omega$ [16]. However, the input impedance of the practical Archimedean spiral antenna is lower than $188 \ \Omega$ because of its finite size. The designed Archimedean spiral antenna is shown in Fig. 1. In theory, when the curve drawn by the antenna arm is one-wavelength circumference, the Archimedean spiral antenna can radiate at the corresponding frequency. Note that the lower the operating frequency, the larger antenna size. For the purpose of decreasing the size
and input impedance of the antenna, the antenna is embedded between substrate and superstrate, which are FR-4 (thickness $= 1.6$ mm, $\varepsilon_r = 4.4$, tan\(\delta = 0.02$) [17]. Note that high input impedance of the Archimedean spiral antenna makes it difficult to fabricate a balun since the width of paired strips in the balun should be extremely narrow.

In the Archimedean spiral antenna design, to determine its overall size, the antenna size is gradually increased until the input impedance of the antenna embedded by superstrate and substrate is almost constant in the frequency of interest. The maximum radius $R_2$ of the antenna is 93 mm, which leads to the input impedance of almost constant 90 $\Omega$ as shown in Fig. 2. The width of the antenna should be properly determined since it affects the axial ratio and the realized gain of the antenna, especially for lower operating frequencies. The axial ratio and the realized gain are depicted in Figs. 3 and 4. From Fig. 3, it is observed that $W$ should be less than 2 mm to marginally have an axial ratio less than 3 dB. Note that it turns out that $W = 2$ mm leads to the axial ratio of 4 dB at 0.6 GHz when the spiral antenna is connected with a balun and a cavity. According to Fig. 4, the realized gain is low at lower operating frequencies for $W = 1$ mm. Therefore, in this work, $W$ is chosen as 1.5 mm. The number of turns $N$ by an antenna arm is determined in [14]. In this work, the turns $N$ is 15.3 and the minimum radius $R_1$ is 0.8 mm.

FIGURE 11. Simulated realized gain results of the designed PD antenna. (a) Axial ratio. (b) Realized gain.

B. BALUN

The input port of the Archimedean spiral antenna is fed by a differential feed line whereas an SMA connector is inherently single-ended. To match the input port of the Archimedean spiral antenna with the SMA connector, the balun should be employed. The balun is made of microstrip line (for matching the single-ended 50 $\Omega$ SMA connector) and paired strips (for the differential 90 $\Omega$ input of the antenna). The width $W_1$ of a microstrip line for a given 50 $\Omega$ characteristic impedance ($Z_{C,M}$) and the width $W_2$ of paired strips for a given 90 $\Omega$ characteristic impedance ($Z_{C,P}$) in Fig. 5 can be obtained well-known formulation [18]. In this work, a FR-4 dielectric substrate with the thickness of 1.6 mm is used in the microstrip-to-paired strips balun. It is found that the width $W_1$ of 3 mm and the width $W_2$ of 1.2 mm lead to the desired characteristic impedances. Note that the width of the...
FR-4 substrate is chosen as 50 mm in order for the balun to be robustly attached to the antenna. Note that the taper function of the balun is linear and the geometrical parameters of the transition region in the balun is optimized to have good performance. Figure 6 shows the top and the bottom views of the designed balun.

The performance evaluation of the balun is performed by the methodology employed in [19]. The return loss is larger than 10 dB and the insertion loss is less than 3 dB as shown in Figure 7. The amplitude and phase imbalances can be obtained by a three-port network as in [19]. Figure 8 (a) and (b) show the results of the amplitude and phase differences between $S_{21}$ and $S_{31}$. Note that port 1 indicates the differential input of the balun and port 2 and port 3 indicate the other two output ports. It is observed that the amplitude and phase imbalances are low in the frequency range of interest. Figure 9 shows the simulated axial ratio for the Archimedean spiral antenna connected with the designed balun. As shown in the figure, it is observed that the axial ratio of is less than 3 dB in the frequency of interest.

### C. UHF PD ANTENNA

As alluded previously, the cavity should be employed in PD detection to prevent external noise interference. The cavity material is aluminum and the diameter of the inner cavity is 190 mm, which is equal to the superstrate and substrate of the Archimedean spiral antenna. The height of the cavity is 153 mm. The schematic of the originally-designed PD antenna is depicted in Fig. 10 (a). Figure 11 presents the simulated results of the axial ratio and the realized gain for the original PD antenna. The results imply that the original PD antenna does not work as a radiator at 1.35 GHz. In other words, the original PD antenna may operate as a resonator at 1.35 GHz. To investigate how the original PD antenna operates at 1.35 GHz, we examine electric field distribution at...
TABLE 1. Comparison of spiral-type PD antennas.

| Ref. | -10 dB S_{11} Bandwidth (GHz) | Antenna Diameter (mm) | Antenna Substrate | Measured Realized Gain (dBi) | Radiation Pattern | 3dB Axial Ratio Bandwidth (GHz) |
|------|-------------------------------|-----------------------|------------------|-----------------------------|------------------|-------------------------------|
| This work | 0.6 – 1.7 | 200 | FR-4 | 0.3 @ f_{min} / 4.6 @ f_{max} | Unidirectional | 0.6 – 1.7 |
| [8] | 1.15 – 2.4 | 212.1 \* | FR-4 | -1 @ f_{min} / 8 @ f_{max} | Unidirectional | Not presented |
| [9] | 0.925 – 1.6 | 95 | FR-4 | 6 @ f_{c} | Unidirectional | Not presented |
| [10] | 0.5 – 1.5 | 192 | TLY-5A | 3 @ f_{min} / 7.5 @ f_{max} | Unidirectional | Not presented |
| [11] | 1 – 3 | 132 | Not presented | 2.5 @ f_{min} / 11.7 @ f_{max} | Unidirectional | Not presented |
| [12] | 0.92 - 3 | 95.2 | FR-4 | 1.4 @ f_{min} / 5.1 @ f_{max} | Bidirectional | Not presented |
| [13] | 0.7 – 3 | 218 | Not presented | Not presented | Bidirectional | Not presented |
| [14] | 1.2 – 2.4 | 95.6 | FR-4 | Not presented | Not presented | 0.6 – 2.0 |

\*Diagonal length of the antenna.

The designed circularly-polarized PD antenna is fabricated and measured in Fig. 13. The simulated and measured results of the reflection coefficient and the axial ratio for the proposed PD antenna are shown in Fig. 14. The measurement results are generally in agreement with the simulation results. Discrepancies between the measurement results and simulation results may be caused by the fabrication errors (of the spiral antenna, the balun, and the cavity) and measurement errors. The measured reflection coefficient of the fabricated PD antenna is below -10 dB from 0.6 GHz to 1.7 GHz depicted in Fig. 14 (a) and the good axial ratio is observed in Fig. 14 (b). The measured realized gain is larger than 0 dBic in the frequency range of interest as shown in Fig. 15 (a). The radiation patterns at various frequencies are also shown in Fig. 15 (b) and (c). Unidirectional radiation patterns can be observed. It is also observed that radiation pattern tends to be tilted at the high frequency. The proposed PD antenna consists of not only the Archimedean spiral...
antenna but also the balun and the cavity. Therefore, the current distribution of the proposed PD antenna is different from that of the Archimedean spiral antenna. We plot the current distribution for the stand-alone Archimedean spiral antenna and the proposed PD antenna in Fig. 16 (a) and Fig. 16 (b) respectively. As shown in the figure, the current distribution of the proposed PD antenna is different from the stand-alone Archimedean spiral. That is why the radiation pattern is little bit tilted. Finally, Table 1 shows the comparison between the proposed PD antenna and the previous spiral-type PD antennas. Some PD antennas yield bidirectional radiation patterns since a cavity was not employed and thus they are vulnerable to external signal interference. As shown in the table, the proposed PD antenna can present unidirectional radiation patterns and circular polarization simultaneously in the frequency range of interest.

IV. CONCLUSION

In this paper, a circularly-polarized PD antenna is proposed to detect UHF PD signals in a high-voltage power equipment. The PD antenna is designed on the basis of a two-arm Archimedean spiral antenna, which is embedded between FR-4 substrate and superstrate. The microstrip-to-paired strips balun is employed to match the single-ended SMA connector to the differential input of the two-arm Archimedean spiral antenna. The antenna is covered with a cavity to have unidirectional radiation pattern and to protect external noise interference. However, when the spiral antenna covered by the original cavity, the antenna does not operate properly at 1.35 GHz because of resonance phenomena in the cavity. To avoid the cavity resonance, the modified cavity is proposed. The proposed PD antenna is fabricated and measured. Experimental results demonstrate that the proposed PD antenna has good performance in impedance matching, realized gain, radiation pattern, and circular polarization and thus it is suitable for PD detection systems.

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