

A Miniaturised LS Peano Fractal Antenna for Partial Discharge Detection in Gas Insulated Switchgear

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Abstract: An LS Peano fractal antenna, which integrates the self-similarity and spatial filling features of fractal technology, was designed for detecting the ultra-high frequency signals generated by gas insulated switchgear (GIS) partial discharge (PD). Firstly, we analyse the design principle of a miniaturised antenna based on the LS Peano fractal curve, using ANSYS HFSS to simulate and design the LS Peano fractal antenna. Then we made the antenna object according to the optimised simulation results, and the standing wave ratio of this antenna was tested by vector network analyser. Finally, the GIS PD test platform was built in a laboratory, and PD trials involving a metal protrusion defect are conducted therewith. The test results show that: the LS Peano fractal antenna has ellipsoidal directivity; the antenna is small, the actual size is only 27.6 mm × 27.6 mm × 2 mm; the measured results indicate that the voltage standing wave ratio (VSWR) of this antenna is less than 4.5 in the range from 300 MHz to 3 GHz, which has better partial discharge monitoring ability; the VSWR of this antenna is less than 2 in the range from 1.1 GHz MHz to 3 GHz, which has a higher density of monitoring partial discharge; the laboratory test results show that the LS Peano fractal antenna offers good performance, and can therefore be applied to on-line PD monitoring applications.

Keywords: Gas insulated substation, LS Peano fractal antenna, Miniaturization, Partial discharge, Ultra-high frequency.

1. Introduction

GAS insulated switchgear (GIS) has been widely used because of its small size, its small occupied area, ease of installation, reliable operation, and long maintenance cycle. The statistical data reported by CIGRE [1] show that the insulation fault caused by partial discharge (PD) in GIS equipment is the main cause of GIS failure, and is an early symptom of insulation failure. The current pulse generated by PD rises steeply and lasts for a short time, which can stimulate the electromagnetic signals in the ultra-high frequency range (UHF, 300 MHz to 3 GHz). Therefore, a UHF test method could be used for the on-line detection of GIS PD [2].

The UHF sensor is key to sensing electromagnetic wave signals and to UHF detection technology. UHF sensors are classified as either internal or external sensors according to installation method. An internal sensor [3, 4] is placed inside the GIS cavity, which has strong anti-interference ability and high detection sensitivity, but it is difficult to install on GIS devices in service. At present, internal sensors [5] are mainly circular, or conical, sensors combined with the principle of capacitive coupling and antenna theoretical analysis. An external sensor can be installed on GIS basin insulators which have been put into operation on site, and the purpose of detecting the GIS insulation condition can be achieved by detecting leaking UHF electromagnetic wave signals. The

advantage is that the installation is convenient and does not affect the internal electrical field of the device. The disadvantage is that the antenna is large and its anti-interference ability is poor. Research on external sensors includes analyses of: planar spiral antenna sensors [6], dipole antenna sensors [7], microstrip patch antenna sensors [8], quasi-TEM horn antenna sensors [9], fractal antenna sensors [10], etc.; however, considering the low central frequency of external UHF antenna used for GIS PD, researchers have to increase the size of the antenna to reduce the resonant frequency, but their greater size is not suitable for in site installation and detection. Thus, higher requirements are imposed on miniaturization.

A fractal antenna allows high compressive filling of space, self-similarity of structure, and has a combination of different radiating edges of fractals [11], which has attracted much attention among those interested in the miniaturisation, wideband use, and multi-frequency signalling of antenna. They have been widely used in the development of GIS UHF antenna. Current research on fractal antenna includes work on Koch fractal antenna [12], Sierpinski carpet fractal antenna [13], and Hilbert fractal antenna [14]. A Koch fractal pattern can reduce the size of an antenna, but it reduces the quality factor thereof and increases the complexity of the antenna design; A Sierpinski carpet fractal antenna has multiple resonant frequency bands, but its space-filling ability is not high, so it has no advantage in the miniaturisation process; A Hilbert fractal antenna has unique advantages in size compression, but suffers an inherent weakness in radiation. These antenna give rise to problems related to a large standing wave, narrow detection frequency band, and their large size.

So, to meet the requirements of GIS UHF detection using antenna miniaturisation and a wide frequency band, we designed a miniature LS Peano fractal antenna. Firstly, we analyse the design principle of a miniaturised antenna based on the LS Peano fractal curve, using ANSYS HFSS to simulate and design the LS Peano fractal antenna. And then we made the antenna object according to the optimised simulation results, and the standing wave ratio of this antenna was tested by vector network analyser. Finally, we built the GIS PD test platform in a laboratory, and PD trials involving a metal protrusion defect were conducted therewith. It has been verified, by laboratory testing, that the antenna can detect the UHF signal of PD in GIS.

2. Design Principle of Miniaturised LS Peano Fractal Antenna

The LS Peano fractal curve is printed on the dielectric substrate in the form of a microstrip and fed by coaxial line. The fractal antenna makes use of the spatial filling of the fractal geometry to increase the electrical length of the antenna, so that the antenna can realise a larger current path in a limited space, improve

the radiation efficiency, and allow miniaturisation of the antenna structure. The filling performance of a fractal is determined by fractal dimension and the structure with a larger fractal dimension has better miniaturisation effect. Fractal dimension is defined as follows:

If a fractal object A (whole) can be divided into $N(A,r)$ subsets of the same size, and each subset is similar to the original similarity ratio r , the fractal dimension of fractal set A is defined as:

$$D_f = \frac{\log N(A,r)}{\log(1/r)} \quad (1)$$

The LS Peano fractal curve is a curve form derived from the Peano fractal curve using the L-Systems algorithm [15] (LS algorithm). The LS algorithm is a unique iterative process, and its core concept is rewriting. The drawing rules of two-dimensional LS algorithm are: F represents a step forward in the current direction drawing lines; f represents a step forward in the current direction without drawing a line; $+$ represents counterclockwise rotation δ ; $-$ represents a clockwise rotation of δ ; $[$ represents pushing current information onto the stack; $]$ represents putting information “ $]$ ” out of the stack. Here, we set the alphabet to L , the initial rule to ω , for a Peano curve as:

$$\begin{aligned} \delta &= 45^\circ; \\ \omega: L &\rightarrow F - - F - - L - - F; \\ P_1: L &\rightarrow + R - F - R +; \\ P_2: R &\rightarrow - L + F + L -. \end{aligned}$$

Fig. 1 shows the shape of the Peano fractal curve after different numbers of iterations.

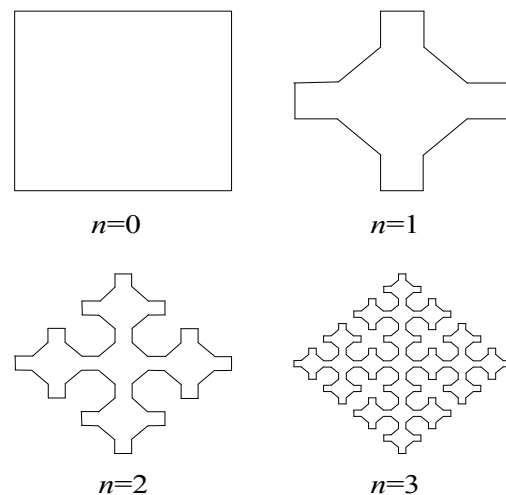


Fig. 1. 0 to 3 order LS Peano fractal curve.

Fig. 1 shows that the LS Peano fractal curve is strictly self-similar, and can be regarded as consisting of four similar parts with a similarity ratio of 0.5, so its fractal dimension is:

$$D_f = \frac{\log 4}{\log 2} = 2 \quad (2)$$

Compared with the Koch fractal curve ($D_f = 1.26$), the Sierpinski triangle fractal curve ($D_f = 1.58$) and the Hilbert fractal curve ($D_f < 2$, with increasing fractal order, D_f tends to 2), the LS Peano fractal curve has the largest fractal dimension and is more suitable for the design of small antenna.

For calculating the resonant frequency conveniently [16], the three line segments of the third-order LS Peano fractal curve are split (Fig. 2): the two sides of the paired LS Peano fractal curve are parallel wires, as shown by the thin solid lines in Fig. 2; the sides connecting the parallel wires are short-circuit terminals, as shown by the thick solid line in Fig. 2; the side connecting the fractal unit as a complete curve is an additional wire segment, as shown by the dashed line in Fig. 2.

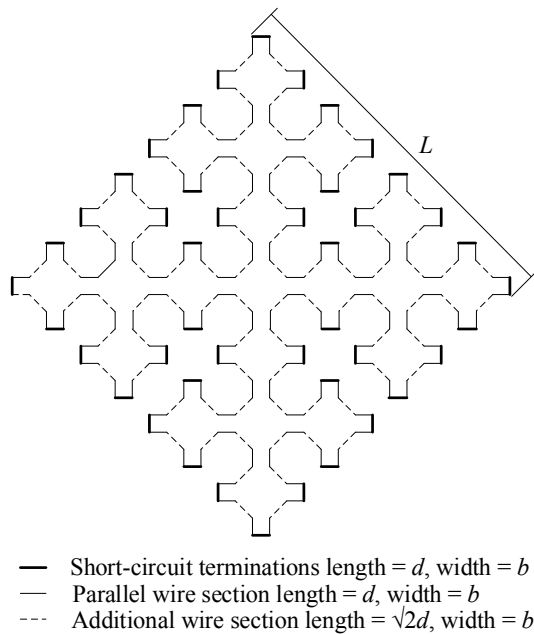


Fig. 2. Schematic diagram of wire classification in a third-order LS Peano fractal curve.

3. Structural Design and Simulation Analysis of Third-order LS Peano Fractal Antenna

Determining the order of the LS Peano fractal antenna makes it important for us to reduce the difficulty of making the antenna while meeting the requirements of the partial discharge UHF detection method. In the process of simulation design, it is found that the first-order and second-order LS Peano fractal antenna give rise to problems such as a paucity of resonant frequency points and a standing wave ratio much greater than 5; it can be seen from Fig. 4 that the third-order LS Peano fractal antenna increases the

resonant frequency points and widens the detection frequency band, which can meet the requirements of UHF detection of PD. The fourth-order LS Peano fractal antenna can also meet the requirements of the partial discharge UHF detection method, but the LS Peano fractal curves of the fourth order (and above) become complicated and antenna fabrication becomes more difficult. Therefore, the third-order LS Peano fractal antenna is taken as the research object in the present study.

3.1. Antenna Design Method

The third-order LS Peano fractal antenna designed here works from 300 MHz to 3 GHz. When designing the LS Peano fractal antenna of the third order, the number of parallel wires, short-circuit terminals, and additional wires should be determined first, then, assuming that the lengths of the parallel wires and short-circuit terminal wires are equal and the length of additional wires is the square root of 2 times the length of the parallel wire, the resonance frequency f of the LS Peano fractal antenna can be determined as follows [16]:

$$f = \frac{kc_0 \left(\log \left(\frac{60kd}{b} \right) - 1 \right)}{2 \left[md \log \left(\frac{2d}{b} \right) \left(1 + \frac{1}{3} \left(\frac{\beta d}{2} \right)^2 \right) + s \left(\log \left(\frac{4s}{b} \right) - 1 \right) \right]} \quad (3)$$

where c_0 is the speed of light in vacuo (3×10^8 m/s); β is the phase constant, $\beta = 2\pi/\lambda$; λ is the wavelength of the received electromagnetic wave; b is the width of the wire (1mm); m , n , and t are the number of parallel double wires, short-circuit terminals, and additional wires, respectively; s is the total length of all wire segments, $s = md + nd + \sqrt{2}td$; k is an odd number, $k \in \{0, R+\}$; and d is the length of the parallel wire.

For different d values, the resonant frequency f of the antenna is calculated separately, and then the optimum value of the length of the parallel wire is determined according to the available range of resonant frequencies f . Finally, the antenna is fabricated according to the optimum value of the length of the parallel wire.

3.2. Antenna Structure Design and Simulation Analysis

Based on the on the above design method, we used antenna simulation software ANSYS HFSS15.0 [17] to establish a third order LS Peano fractal antenna model (Fig. 3). Taking the length d of the parallel wire and the short-circuit terminating wire, the thickness D of the dielectric substrate, and the width L of the substrate side as variables, the standing wave ratio VSWR, gain coefficient, and directivity of the antenna

are simultaneously set as the objective function, and the antenna parameters are further optimised and simulated over the frequency range from 300 MHz to 3 GHz. When the length of the parallel conductor and short-circuit terminal conductor is $d = 1.3$ mm, the thickness of dielectric substrate is $D = 2$ mm, the width of substrate side is $L = 27.6$ mm, and the dielectric substrate is an FR4_epoxy, the space occupied by the antenna radiation substrate is optimal, and the VSWR, gain coefficient, and directivity coefficient are optimal. Salient antenna parameters are listed in Table 1.

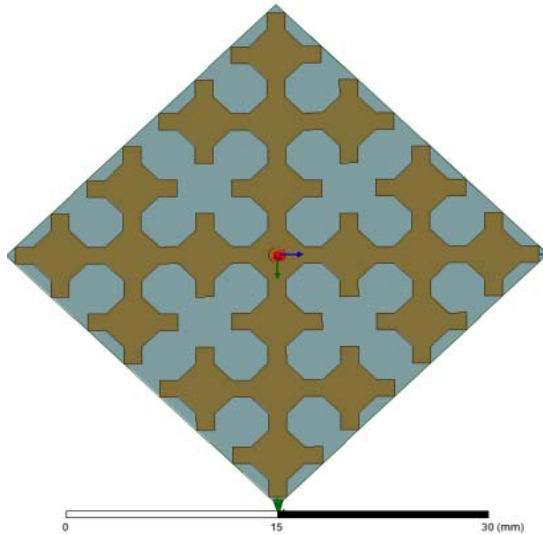


Fig. 3. HFSS model of third-order LS Peano fractal antenna.

Table 1. Antenna Parameters.

Parameter symbol	Optimal Result
d	1.3 mm
D	2 mm
L	27.6 mm
m	128
n	44
t	94
s	396.4 mm

The simulated standing wave ratio curve is shown in Fig. 4. From Fig. 4, it can be seen that the VSWR of the antenna is less than 4.5 in the frequency band from 300 MHz to 3 GHz, which can meet design and application requirements. Fig. 5 shows the three-dimensional (3-D) radiation pattern of the LS Peano fractal antenna at 300 MHz. From Fig. 5, it can be seen that the antenna may have good axial radiation characteristics in the z-direction and can receive electromagnetic wave signals from all directions. When the frequency changes, the gain and 3-D radiation pattern of the antenna change. Table 2 records the gain results of the antenna at 7 different frequencies, it can be seen from Table 2 that as the

frequency of the radiated electromagnetic wave increases, the gain generally increases, from -21.5 dB at 300 MHz to 3.6 dB at 3 GHz. Higher gain is beneficial for detecting ultra-high frequency weak signals of partial discharge.

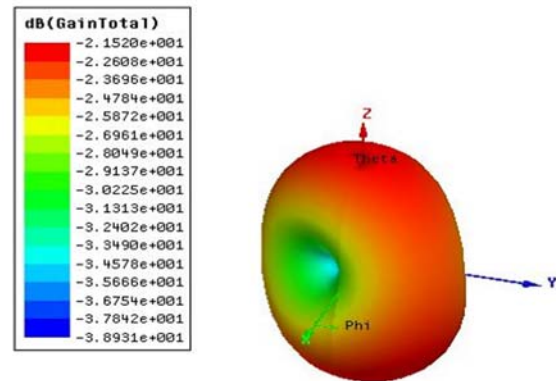


Fig. 5. Three-dimensional gain pattern.

Table 2. Testing record of gain.

Frequen cy/GHz	0.3	0.5	1.0	1.5	2.0	2.5	3.0
Gain/dB	-21.5	-11.2	-1.3	2.2	2.9	3.1	3.6

4. Fabrication and Test of Third-order LS Peano Fractal Antenna

4.1. Fabrication and Standing Wave Ratio Test

According to the optimised parameters (Section 2.2), the physical map of the antenna after PCB printing is as shown in Fig. 6.

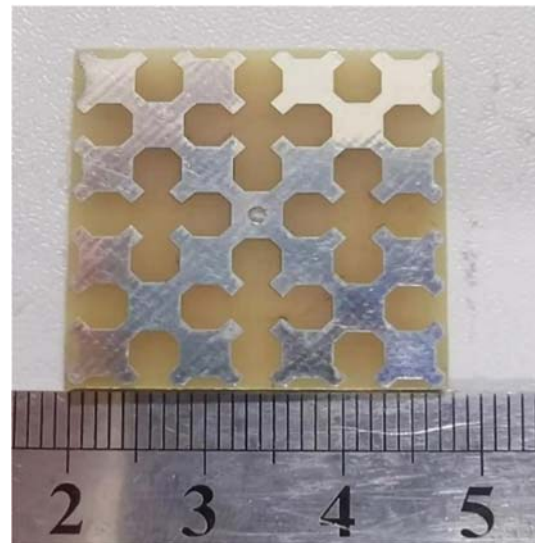


Fig. 6. Physical map of the antenna.

The antenna measures $27.6 \text{ mm} \times 27.6 \text{ mm} \times 2 \text{ mm}$, the dielectric substrate material is FR4 and its dielectric constant is 4.4. The feeding mode is coaxial feeding. The position of the coaxial feeding point is in its geometric centre, and the characteristic impedance of the feeding point is 50Ω . The VSWR of the antenna is tested by using the AV36580 vector network analyser produced by the 41st Research Institute of China Electronics Technology Group Corporation. The frequency scanning range is 300 MHz to 3 GHz and the measured VSWR curve is shown in Fig. 7. The test results show that the variation trend and amplitude of the simulated VSWR curve and the measured VSWR curve are basically the same, which verifies the accuracy of the simulation model.

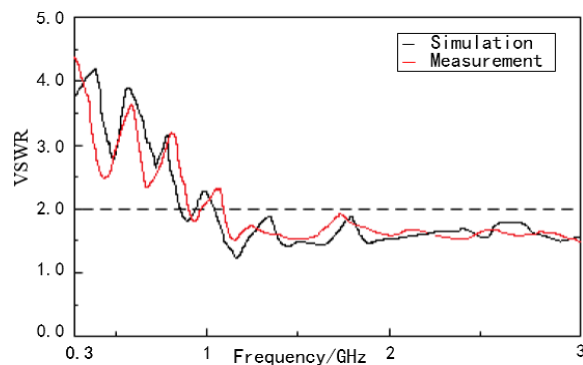


Fig. 7. Measured VSWR curve of the antenna.

4.2. Laboratory Test Verification

During the discharge breakout stage, as shown in Fig. 4(d), the discharge form is mainly arc discharge, the discharge duration is about 5 min. The arc discharge makes the discharge phenomenon more

intense, the discharge current is significantly enhanced, and the discharge spark is brighter. The carbonized conductive circuit gradually formed and the surface of the material showed localized damage which was close to breakdown. The arc discharge is far away from the sample surface and the discharge current runs through the upper and lower electrodes. As shown in Fig. 5(d), since the discharge at this stage eventually developed to the entire surface, the discharge phase of partial discharge signals of the sample spread over the whole interval and was relatively uniform, and the two-dimensional phase distribution was in the shape of a "sharp mountain". The insulation will be destroyed in a short time after the occurrence of this stage.

To verify the performance of the miniature LS Peano fractal antenna when detecting the UHF PD signals, we built a 252 kV GIS partial discharge experimental platform [18], [19] on which to test the new antenna. The test system includes: a 252 kV GIS model, 250 kV no partial discharge power supply, broadband oscilloscope, and a UHF antenna sensor. In this experiment, a metallic spinal protrusion is brought into contact with the high-voltage bushing to simulate PD in the needle-plate model. SF₆ gas at 0.4 MPa is used to fill the GIS PD simulation platform, and the LS Peano fractal antenna is mounted on a sensor hole specially provided in the GIS cavity. The diameter of the sensor hole is 100 mm. A Tektronix high-speed digital oscilloscope is used for collecting the PD signal time-domain waveform (Tektronix DPO7254 four-channel digital storage oscilloscope with 2.5 GHz bandwidth and 10 GS/s real-time sampling rate on all channels, one channel up to 40 GS/s). The wiring diagram for this experiment is shown in Fig. 8. Figs. 9 and 10 show the physical map of the 252 kV GIS PD experimental platform and the antenna installation position.

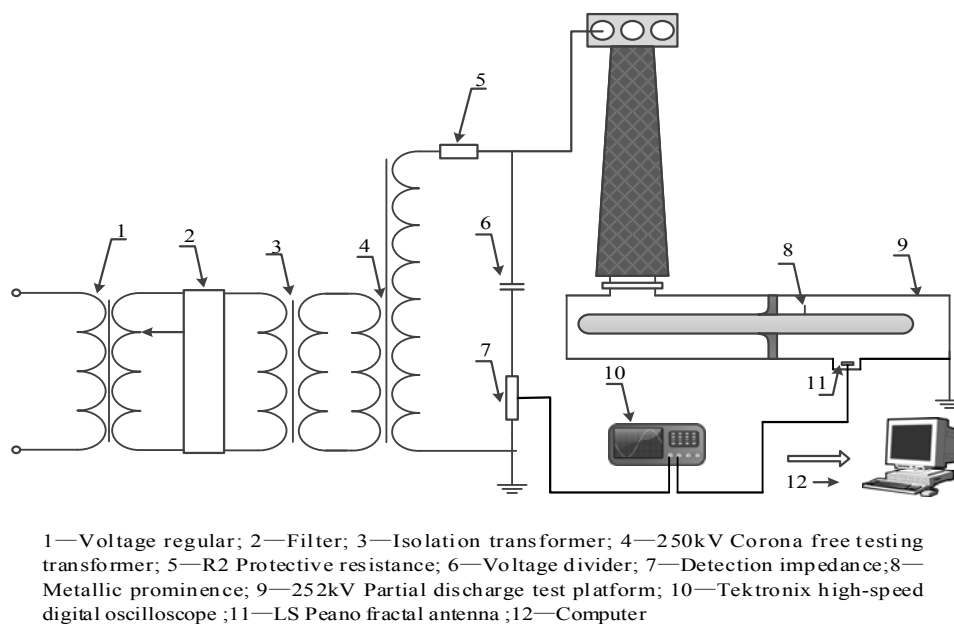


Fig. 8. Experimental circuit wiring diagram.



Fig. 9. The 252 kV GIS PD experimental platform.

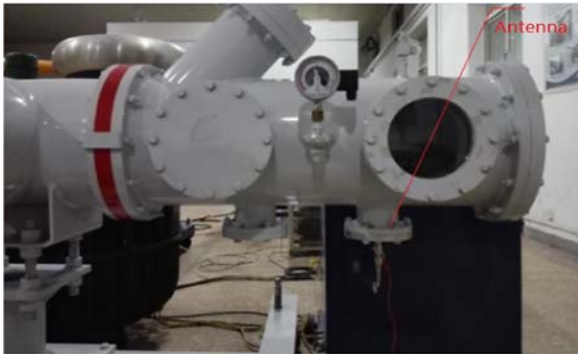


Fig. 10. Antenna installation position.

When the voltage increased to 59.2 kV, the single partial discharge waveform detected by LS Peano fractal antenna sensor is as shown in Fig. 11. From the experimental results, it can be seen that the amplitude of the PD time-domain signal measured by LS Peano fractal antenna is 53.3 mV, evincing its ability to detect PD signals at high signal-to-noise ratio, implying an ability to distinguish a PD signal from noise and interference signals. Compared with published data [20], the sizes of the Hilbert fractal antenna and the Moore fractal antenna are both 60 mm × 60 mm × 2 mm, and the amplitude of the detected PD signal is about 20 mV, as shown in Fig. 11. The proposed LS Peano fractal antenna designed here detects a larger signal amplitude, steeper initial edge, higher detection sensitivity and smaller volume, which facilitates UHF detection of PD in GIS.

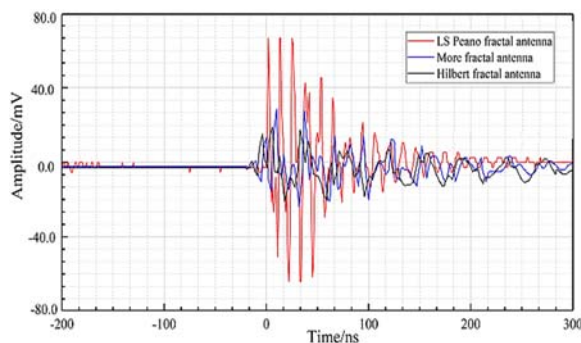


Fig. 11. PD detection results.

5. Conclusions

Through the structural design and HFSS simulation of an LS Peano fractal antenna, the simulated VSWR and measured VSWR of an LS Peano fractal antenna are compared and analysed. The radiation characteristics of the antenna are tested and analysed. A test platform is built in the laboratory on which to evaluate this new antenna. The following conclusions can be drawn:

(1) A third-order LS Peano fractal antenna based on fractal technology is designed to ensure miniaturisation of the antenna while broadening the antenna bandwidth. The antenna is small, simple in structure, and has an output impedance of 50 Ω, which facilitates impedance matching with the signal transmission line. It can be used as a portable external sensor, or as a built-in sensor installed in the GIS hand-hole.

(2) The VSWR of this antenna is less than 4.5 in the range from 300 MHz to 3 GHz, and VSWR of this antenna is less than 2 in the range from 1.1 GHz to 3 GHz, allowing it to record most PD information. It has ellipsoidal directivity and can accept electromagnetic wave signals from any direction in space. Its directivity and gain are good, and it has high sensitivity to weak signals.

(3) The PD signal that can be measured by the antenna when the amplification is not connected is about 53.3 mV, implying a high signal-to-noise ratio and an ability to detect a PD signal.

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