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HILBERT CURVE FRACTAL ANTENNA FOR DETECTION AND ON-LINE MONITORING OF PARTIAL DISCHARGES IN POWER TRANSFORMERS

ANTENA FRAKTALNA HILBERTA DO DETEKcji I MONITORINGU WYŁADOWAŃ NIEZUPEŁNYCH W TRANSFORMATORACH ENERGETYCZNYCH

This article describes the design of UHF Hilbert curve fractal antenna (HCFA) specially adapted for the partial discharge monitoring system. The authors present the mathematical apparatus for calculating resonant frequencies of Hilbert fractal antenna and results of a computer simulation of the developed prototype. In the design process, the antenna's working environment (mineral oil) and the mechanical construction of the transformer inspection window were taken into consideration as well. The article also shows the results of laboratory tests carried out in the transformer tank model with different type of partial discharge sources. Both simulations and partial discharge measurements showed that the HCFA, due to such properties as: multi-resonance, small size, low fabrication cost and high sensitivity, is an interesting alternative to other UHF probes installed in transformer inspection window.

Keywords: *fault diagnosis and maintenance of power transformers, partial discharge detection and monitoring, UHF method, Hilbert curve fractal antenna.*

W artykule zaprezentowano projekt anteny fraktalnej Hilberta przeznaczonej do stosowania w systemach monitoringu wyladowań niezupełnych wykorzystujących metodę UHF. Autorzy szczegółowo opisali aparat matematyczny służący do estymacji częstotliwości rezonansowych anteny fraktalnej Hilberta oraz wyniki symulacji komputerowych. Ponadto, w artykule zaprezentowano wyniki pomiarów laboratoryjnych, w trakcie których generowano impulsy wyladowań niezupełnych w modelu kadzi transformatora energetycznego. Zarówno wyniki symulacji komputerowych jak i pomiarów laboratoryjnych wykazały, że prototypowa antena fraktalna Hilberta, dzięki takim własnościom jak: wielorezonansowość, małe wymiary, niski koszt produkcji oraz wysoka czułość, stanowi ciekawą alternatywę dla innych czujników UHF instalowanych w oknie rewizyjnym transformatora energetycznego.

Słowa kluczowe: *diagnostyka uszkodzeń i eksploatacja transformatorów energetycznych, detekcja i monitoring wyladowań niezupełnych, metoda UHF, antena fraktalna Hilberta.*

1. Introduction

Large power transformers are the most critical component in electric power systems, as they are essential in maintaining a reliable supply of electric energy. There are many factors which cause a transformer malfunction, but those, which can potentially lead to catastrophic failure are winding damages (due to short-circuit, lightning, and other over-voltages) and insulation system failure (moisture, thermal aging, partial discharges). The damage from a catastrophic transformer failure may run into tens of millions of dollars [16]. To avoid such a scenario, power utilities are moving towards continuous transformer condition monitoring, based on dissolved gas analysis

and acoustic emission (AE) or electromagnetic (HF/VHF/UHF) partial discharge detection.

According to the newest research results and analyses presented by the experts of the CIGRE Working Group A2.37, in the technical brochure 642: *Transformer Reliability Survey*, the main reason of breakdowns of high voltage power transformers is damage to the windings and the main insulation system [3]. Mechanical defects in the form of winding deformations (axial displacements and radial deformations) and deterioration of insulation properties associated with thermal aging processes [6], can lead to the initiation of the partial discharge (PD) phenomena occurrence.

In recent years, in the electric power industry and research centres, a trend consisting in developing and implementing advanced

on-line PD monitoring systems is observed. These systems are able to detect and warn against defects occurring in a high-voltage insulating system. These monitoring systems most often work on the basis of one of the three relatively well-known and developed diagnostic methods, i.e.: (i) dissolved gas analysis in oil (DGA), (ii) detection of the acoustic emission signals (AE), and (iii) detection of electromagnetic waves in different frequency bands (HF/VHF/UHF) [8, 12, 17, 21, 23, 25, 28, 30].

Electromagnetic PD detection methods are already widely applied in diagnostics of gas insulated lines and substations (GIL/GIS), rotating machines, cables and medium voltage substations [1, 13]. At present, intensive research is being done on the development, implementation, and standardization of electromagnetic methods (particularly the UHF method) in the diagnostics of power transformers [9]. The research is mainly concentrated on development of new designs of sensitive UHF antennas. They are mechanically adapted for their installation in the inspection window (hole) of a transformer tank or the oil drain valve and on implementing on-line monitoring systems with included expert functions based on artificial intelligence algorithms (e.g. the function of automatic fault recognition or the function of generating warnings and alerts on the basis of trend analysis and accumulated knowledge base) [14–15, 20, 24].

2. Design of UHF antenna for partial discharge detection: general requirements

Partial discharge monitoring systems, which functioning is based on recording electromagnetic pulses in the range of ultra-high frequencies (UHF) are gaining their growing popularity due to high resistance to external electromagnetic interference (EMI) and relatively high detection sensitivity of the discharges. Measurement probes (UHF antennas) are installed inside the steel transformer tank, shielding from external interference. For this purpose, inspection windows are used, which unfortunately means the necessity to pump out a large volume of insulating oil, or in available oil drain valves, which does not require switching off the unit. Examples of commercial designs of UHF antennas used for PD monitoring in power transformers are shown in Figure 1.

In order to design a UHF antenna, optimized for monitoring partial discharges generated in the paper/oil insulation system of the power transformer, one should take into consideration both numerous electric parameters which affect detection sensitivity of the PD phenomena, and mechanical ones, which will provide proper tightness and resistance to difficult environment conditions (high pressure and temperature inside the transformer tank, acidity of mineral oil, etc.).

The basic parameter of an antenna is its frequency response, which should be fitted to the

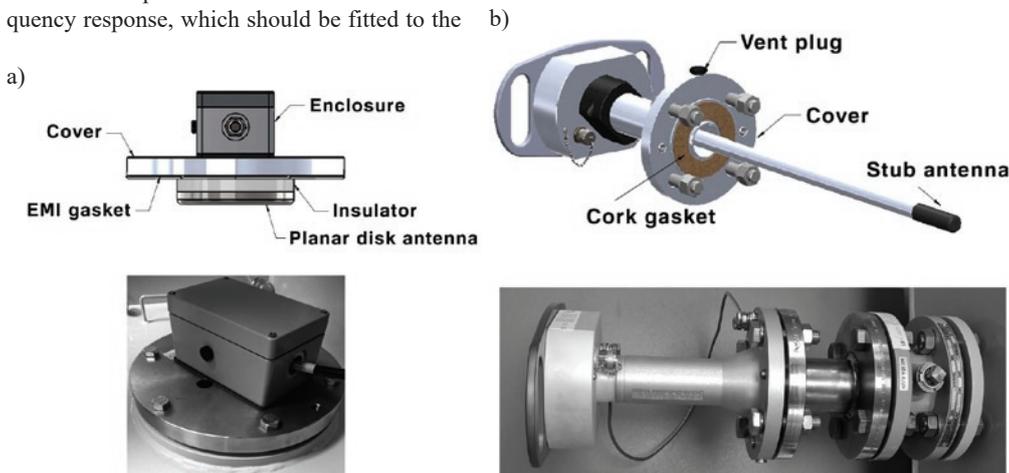


Fig. 1. Schematic diagram and assembly example for UHF antenna installed in the inspection window (a), and in the oil drain valve (b)

frequency of partial discharges. The laboratory and field investigations conducted so far, reveal that partial discharges generate UHF signals in a wide frequency band from about 200 MHz to 2 GHz [18]. Unfortunately, such a wide band covers different sources of radio signals (e.g. radio broadcasting stations or digital television transmitters). This involves the necessity to design more complicated antennas, which have a multi-band (multi-resonance) frequency response, which allows high sensitivity of PD detection and at the same time, resistance to narrow-band interference signals. The issue of proper matching the antenna's working band is more widely discussed in Section 3.

Another parameter of the antenna is input impedance. Due to connections made with coaxial cables, applied connectors, input impedance of the amplifiers, and the measurement equipment used for checking the parameters, the antenna's input impedance should be equal or close to 50 Ω . It is a standard generally accepted in radio communication. The level of impedance matching is described by means of the Voltage Standing Wave Ratio (VSWR) or Return Loss (RL).

It is assumed for the broadcast-receiving antennas in semi-professional system that the value of VSWR = 2 (RL = 9.5 dB), which means that 11.1% of the power will be reflected from the antenna input (the signal will decrease by 0.5 dB). In reality, for antennas in mobile phones, the commonly assumed threshold is VSWR = 2.5 or RL = 7.4 dB (reflection of 18.4% of the power from the antenna input or increase of signal attenuation by 0.9 dB). For receiving antennas which, for example, monitor the electromagnetic spectrum, the acceptable value is still VSWR = 3 or RL = 6 dB (reflection of 25% of power or signal attenuation equal to 1.25 dB). Signal attenuation of 3 dB is acceptable for discharge detection, especially when an amplifier which rises the power level of the received signals is applied. It should be noted that input impedance of the antenna is strongly affected by the working environment (space around the antenna), particularly objects made of conducting materials.

The antenna also has its own radiation pattern and a parameter linked with it, called antenna's power gain. For antennas placed inside the transformer tank, it is favourable to use antenna with an omnidirectional radiation pattern. Thus we will obtain an increase of the antenna's power gain and sensitivity increase of PD detection (the increase of the antenna's power gain means voltage signal increase on the antenna's output at the same electric field intensity of the received wave).

The value of the antenna's power gain is directly linked with the antenna factor, which can be useful for investigations of absolute values of electric field intensity in the transformer.

The antenna applied in a power transformer should also meet other requirements. One includes here resistance to high temperature in the range of 80–90°C, resistance to harmful influence of the oil (the condition for antennas immersed in the oil), or resistance to mechanical vibrations. The antenna placed in the dielectric window should be shielded from the external electromagnetic interferences, if possible. Shielding should reduce the level of interfering signals (radio, television, GSM etc.). The limits of mechanical dimensions are imposed by the dimensions of the inspection

window (the diameter of about 150 mm) and the oil drain valve (the diameter of about 20 mm).

3. External radio frequency interferences

Wireless signal and data transmission very soon caused load of bandwidth in the UHF range. Developing telecommunications technologies, almost within all this range, make use of very strong transmitters and receivers. Their presence in close neighbourhood of the power substation can even disturb effective discharge detection because the transformer tank does not make a uniform Faraday cage. Unfortunately, the radio interferences can penetrate into transformer tank through bushings connected to HV transmission lines (Fig. 2). The main sources of radio interferences are:

- FM radio stations (87.5–108 MHz),
- aerial navigation systems (108–117.9 MHz),
- civilian and military aviation (117.9–143.9 MHz),
- transmitters of civil services (146–173.9 MHz),
- transmitters of DVB-T digital television (474–797 MHz),
- transmitters of GSM operators (890–960 MHz),
- LTE wireless internet (791–862 MHz).

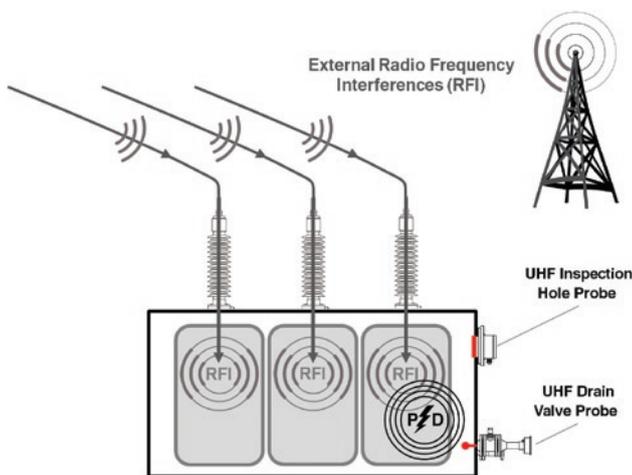


Fig. 2. The radio frequency interferences entering the inside of the transformer tank

The presented above sources of VHF/UHF signals can act with different intensities in a given area. Their occurrence mainly depends on the location of the power substation, e.g. its distance from radio transmitters or the topography of the area where it is located. Analysing the issue of interfering signals, we may not ignore the interference coming from the electric power station itself, which source can be corona discharges from transmission lines or any connecting operations, such as connecting or disconnecting the line, transformer, generator, shunt reactor, capacitor battery or switching devices on the systems of busbar system in the substation.

Therefore, already at the early stage of the antenna designing process, the influence of external interferences has a fundamental significance and should be taken into account. A properly designed and produced antenna should have the properties of a multiband filter, i.e. provide high sensitivity in those frequency ranges, where the energy of partial discharges is transmitted (800–2000 MHz) and low sensitivity in the frequency ranges that are typical for interfering signals (< 800 MHz).

4. Designing and computer simulations of Hilbert curve fractal antenna for partial discharges detection

4.1. Introduction

One of the most popular designs providing the required feature of multiband characteristic is fractal antenna. The application of the fractal theory allows considerable reduction of the size of the antenna without deteriorating its parameters, and this means that there is a relationship between the features of fractal geometry and electromagnetic properties of the antennas. The most important benefits referring to the application of fractal geometry in designing antennas are:

- more effective filling the space occupied by the antenna, which provides better energy transmission from the antenna feed line to the wave propagating in free space (this means better matching of input impedance),
- possibility to make (due to the property of self-similarity of fractals) multi-band antennas, i.e. antennas with a few resonance frequencies,
- lowering resonance frequencies in comparison to antennas of a traditional shape and similar dimensions,
- simple production process and easy for automation,
- possibility to obtain demanded properties without the necessity (as in the case of traditional antennas) to add concentrated reactive elements [29].

In the antenna technology we use dipoles, monopoles, loop or planar antennas of the geometry of the most popular fractals: Koch [2], Minkowski [5], Sierpinski [3], and also Hilbert fractal [26], which was applied by the authors. Hilbert fractal curve consists of the same, mutually perpendicular sections, which fill the surface of the square. An example of the first four iterations of Hilbert fractal is presented in Figure 3.

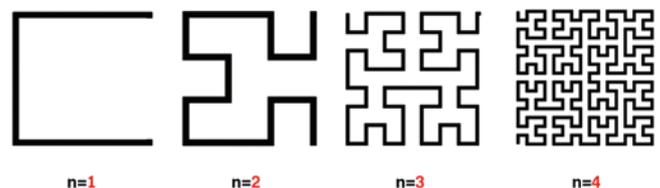


Fig. 3. The first four geometrical iterations of Hilbert's fractal

Filling the surface of a square antenna with the fractal curve is the reason of a relatively low resonance frequency. With an increasing number of iterations, the sum of fractal lines increases exponentially. This fact is useful at the moment of designing a small UHF antenna.

The concept to use the fractal curve for designing antennas is based on the effect observed in case of the meander line dipole antenna (Fig. 4a). In this approach, the inductance of the meander line, which consists of a line (creating a chain) of the letter-C shape is calculated [7, 10]. Next, the inductance of the straight line connecting all contours is added, in order to obtain the total inductance of the antenna. Finally, the obtained result is compared with the inductance of the half-wave dipole antenna.

The resonance feature of a dipole antenna occurs, when capacitive and inductive input reactances cancel each other. Assuming that input capacitive reactance of an antenna is constant, decreasing the apparent antenna length through bending of the antenna wire, the resonant condition is derived [27].

In the case of HCFA (Fig. 4b) of the external dimension l and subsequent iterations n (order of fractal), the length of each segment d is expressed by [27]:

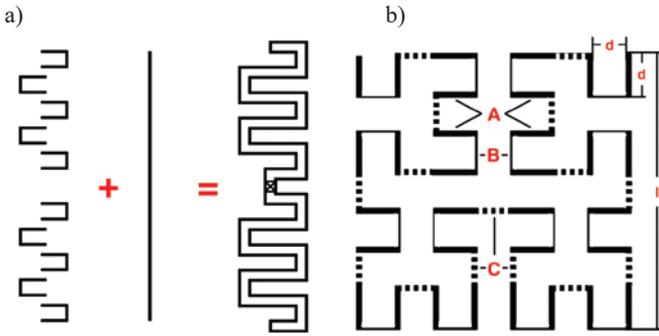


Fig. 4. Schematic diagram of: a) meander dipole antenna, b) Hilbert fractal antenna made of parallel sections A of the length of d and diameter b (bold line), segments connecting ends of parallel sections B (thin line), and segments connecting C (dashed line, length d)

$$d = \frac{l}{2^n - 1} \quad (1)$$

The geometry obtained after the fourth iteration ($n=4$) is shown in Figure 3. Moreover, in the HCFA geometry of order 4, there is $m=4^{n-1}$ of the parallel compact sections, which consist of segments, each of the length of d . As it was shown in Figure 4a, for the segments which do not make parallel sections, their total length s is equal to:

$$s = (2^{2n-1} - 1)d \quad (2)$$

The impedance of the parallel sections A which consists of wires of the diameter b and distance d is:

$$Z_0 = \frac{\eta}{\pi} \log \frac{2d}{b} \quad (3)$$

where η is intrinsic impedance of the free space. Equation (3) can be used for calculating input impedance at the line ends, which has purely inductive character:

$$L_{in} = \frac{Z_0}{\omega} \tan \beta d \quad (4)$$

where β stands for reduction factor [10]:

$$\beta = \frac{l}{d(4^n - 1)} \quad (5)$$

The antenna has m sections, where self-induction of a single straight line of the length of s determined in Equation (2) is equal to:

$$L_s = \frac{\mu_0}{\pi} s \left(\log \frac{8s}{b} - 1 \right) \quad (6)$$

Substituting Equation (3) into Equation (4) and adding to (6), we can determine the antenna's total inductance L_T :

$$L_T = \frac{\mu_0}{\pi} s \left(\log \frac{8s}{b} - 1 \right) + m \frac{\eta}{\pi \omega} \log \frac{2d}{b} \tan \beta \quad (7)$$

In order to find HCFA resonance frequency, all its total inductance is compared with the inductance of the half-wave dipole antenna (of

the approximate antenna length $l=2/\lambda$) of the same resonance frequency. This leads to the condition determining the first HCFA resonance frequency, i.e.:

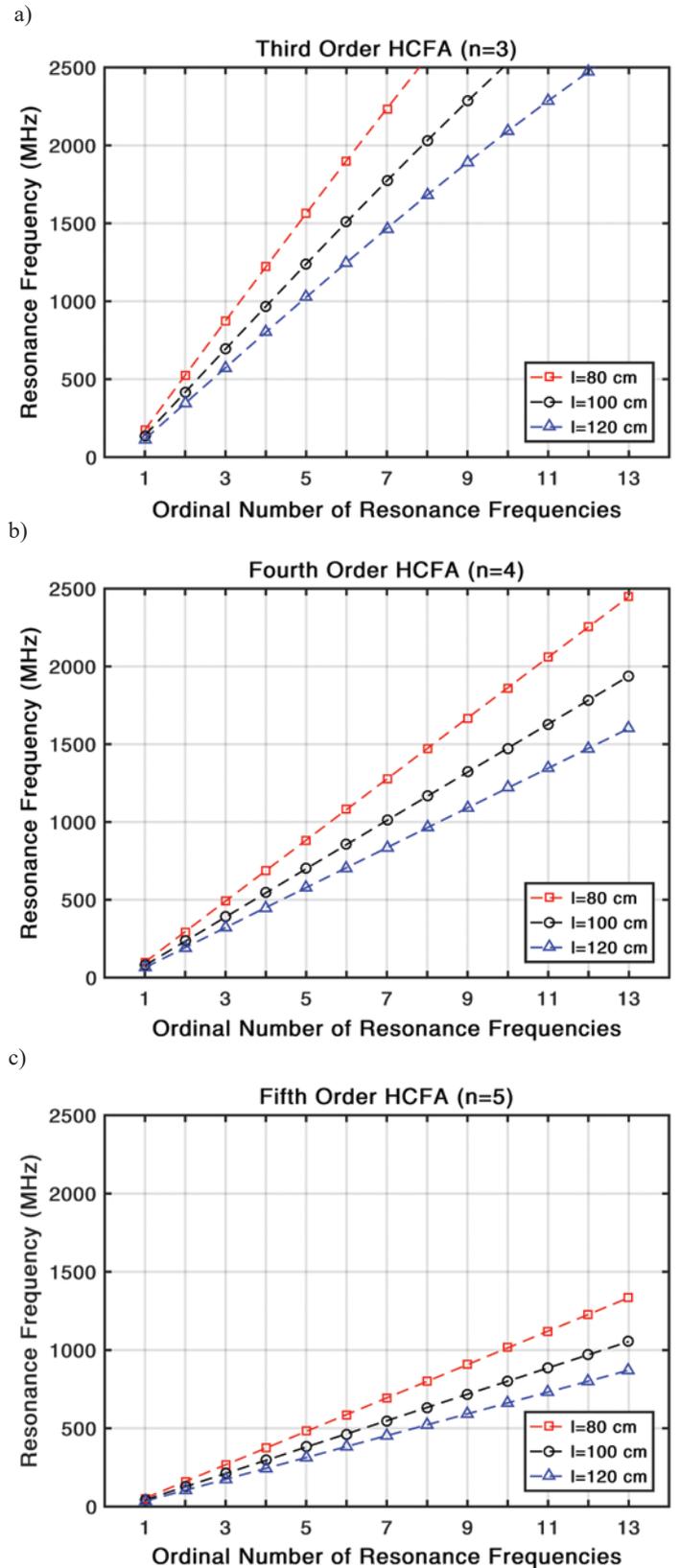


Fig. 5. Calculated values of the first few resonant frequencies for HCFA with different external dimension ($l = 80, 100$ and 120 mm), wire diameter $b = 2$ mm, and different fractal order: $n = 3$ (a), $n = 4$ (b), $n = 5$ (c)

$$m \frac{\eta}{\pi \omega} \log \frac{2d}{b} \tan \beta d + \frac{\mu_0}{\pi} s \left(\log \frac{8s}{b} - 1 \right) = \frac{\mu_0}{\pi} \frac{\lambda}{4} \left(\log \frac{2\lambda}{b} - 1 \right) \quad (8)$$

It should be noted that dipole antennas resonate when the arm length is a multiple of the quarter wavelength. By this means, changing values linked with the wave length on the right side of equation (8), one can obtain all resonance frequencies of a multiband HCFA. Therefore, a few of the first resonance frequencies of HCFA can be determined on the basis of the following equation:

$$m \frac{\eta}{\pi \omega} \log \frac{2d}{b} \tan \beta d + \frac{\mu_0}{\pi} s \left(\log \frac{8s}{b} - 1 \right) = \frac{\mu_0}{\pi} \frac{k\lambda}{4} \left(\log \frac{8k\lambda}{b} - 1 \right) \quad (9)$$

where k is an odd integer [24].

The way in which the antenna geometry (fractal order, external dimension) affects its resonant frequencies is shown in the Figure 5. The calculations were performed based on formula given in Equation (9).

Hilbert fractal antenna, due to its unique geometrical design, which consists of perpendicularly arranged segments, can be easily modelled in available software for numerical analysis and modelling of antenna design [4].

4.2. Computer simulation results

The authors initially assumed that the prepared design should be of overall small dimensions and allow easy installation in the transformer inspection window with a built-in dielectric window (see Fig. 1a). On the basis of the catalogue data of the dielectric window designs available on the market, the authors decided to reduce the antenna dimensions down to a square of the side length equal to 110 mm (Fig. 6). For the needs of the simulation, it was assumed that the antenna will be made using the microstrip technology on the glass-reinforced epoxy laminate (FR-4), 1.5 mm thick. Additionally, the antenna model included a uniform copper reflector of the dimensions 110×110 mm and N-type connector.

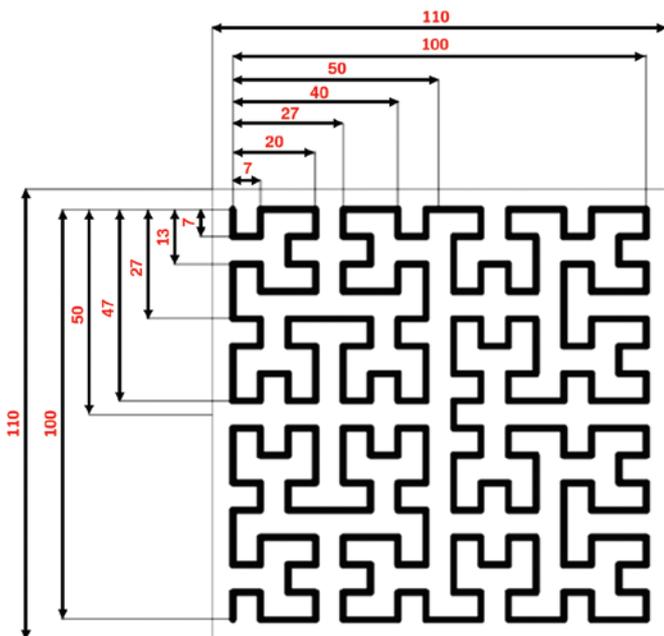


Fig. 6. The schematic diagram and dimensions of investigated Hilbert curve fractal antenna of the 4th order

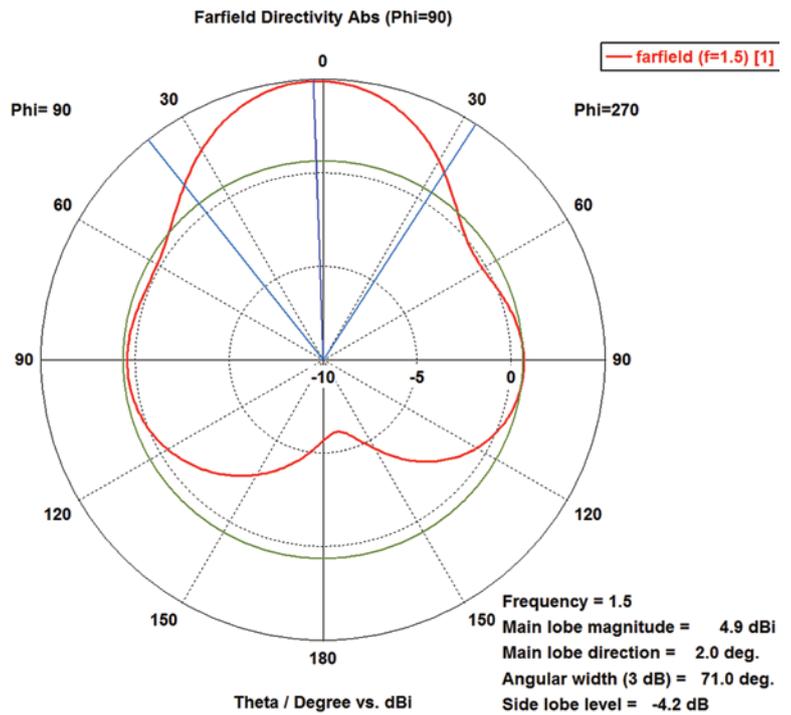


Fig. 7. Simulated two-dimensional (a) and three-dimensional (b) radiation pattern for the proposed Hilbert curve fractal antenna of the 4th order at 1.5 GHz

In order to determine the voltage standing wave ratio (VSWR) and the radiation pattern, the CST Studio Suite® package was used. The VSWR parameter describes the impedance matching of the antenna to the transmission line. When the antenna is not matched to the receiver, power is reflected. This causes a “reflected voltage wave”, which creates standing waves along the transmission line. The minimum VSWR is 1.0. In this case, no power is reflected from the antenna, which is ideal situation. As mentioned before in Section 2, the antenna has good sensitivity if the VSWR value in the working bandwidth is less than 3.0.

The obtained simulation results show that investigated HCF antenna has, at 1.5 GHz, broad radiation pattern with main lobe magnitude of 4.8 dBi and –3 dB angular bandwidth of 71° (Fig. 7), while the acceptable low values of VSWR parameter occur in the range of higher frequencies (over 800 MHz) and the investigated design of Hilbert fractal antenna has the ability to filtrate radio signals from most of the transmitting stations mentioned in Section 3. The lowest values of VSWR occur in the frequency band above 1500 MHz, which is free of the most of external radio interferences (Fig. 8).

4.3. Result of laboratory measurements

Figure 9 presents a picture of the fractal antenna’s prototype prepared by the authors. In order to verify the results obtained by means of computer simulations, the authors did a measurement of real values of factor VSWR using a Rhode&Schwarz ZVL Vector Network Analyzer.

The measurement results showed that the prototype Hilbert fractal antenna, in comparison to the results obtained by means of computer simulation, are characteristic of considerably better impedance matching to the transmission line in the frequency band from 800 to 2000 MHz. In this range, the VSWR values at resonant frequencies are in the range from 1.08 to 1.91 (Fig. 10). Some differences in VSWR values obtained in the simulations can result from assuming some simplifications that accelerate the calculations, such as: decreasing dimensions of the transformer tank, omission of the active part (or

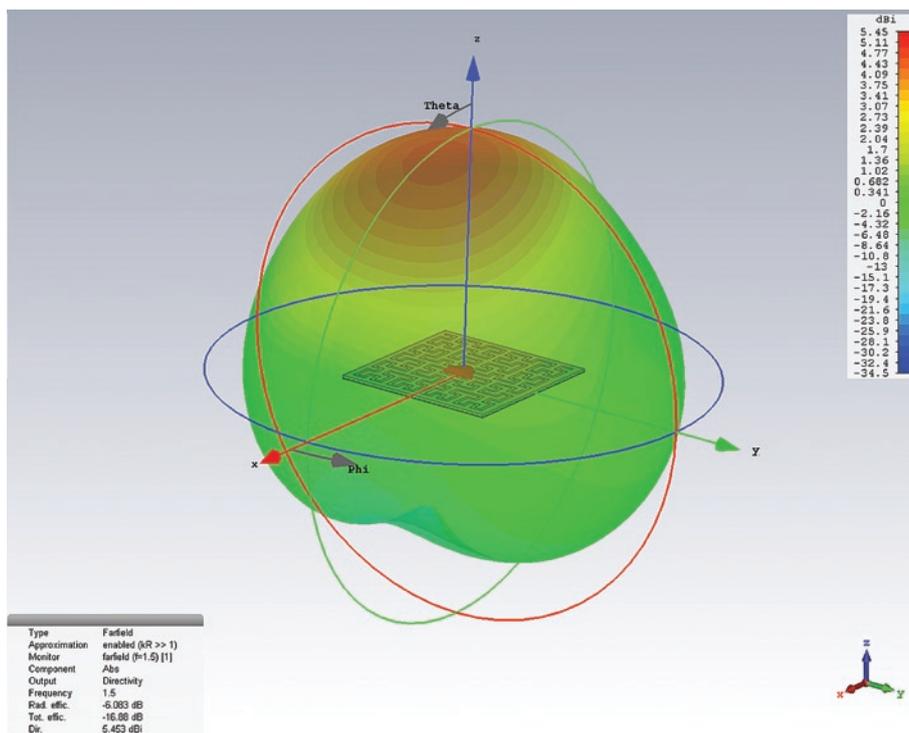


Fig. 8. Computer simulated VSWR for the proposed Hilbert curve fractal antenna of the 4th order

the insulating system with the discharge source) and the mechanical elements of the tank, dielectric window and the antenna housing.

In the next stage of the research, a laboratory experiment was performed to evaluate the effectiveness of partial discharge detection by

a prototype antenna. For this purpose a model of oil-filled transformer tank was used (1200×800×900 mm), where a prototype Hilbert curve fractal antenna, and a standard microstrip disk antenna with a diameter of 100 mm, were installed. The disk antenna was used as a refer-

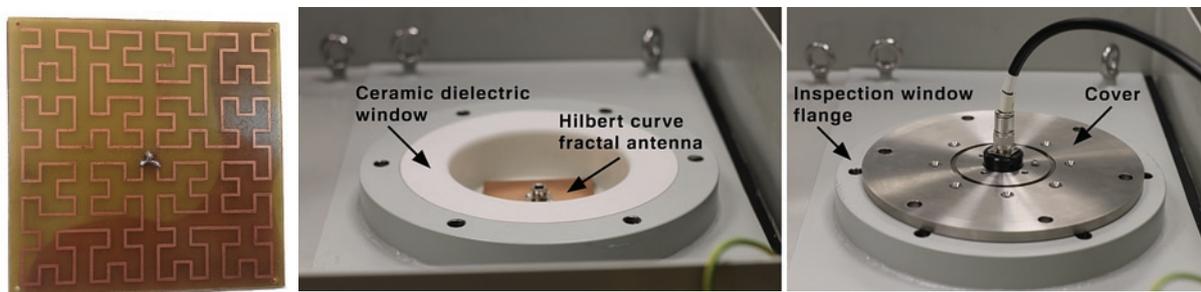


Fig. 9. Prototype Hilbert curve fractal antenna (a) and a photograph presenting the way of its installation in the inspection window of a laboratory model of a power transformer tank (b)

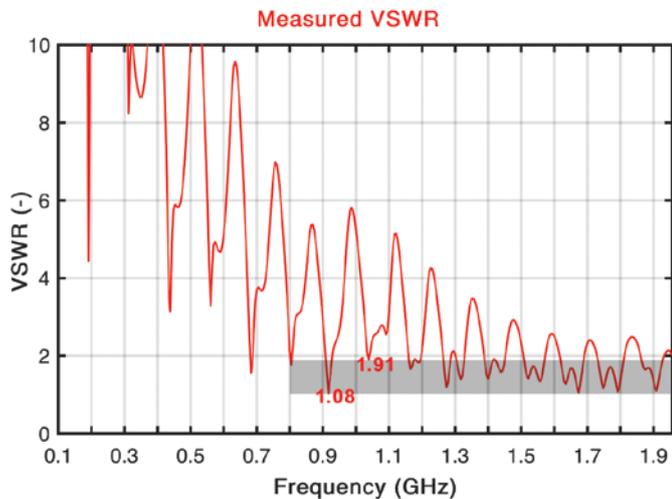


Fig. 10. Measured VSWR values of the prototype Hilbert curve fractal antenna

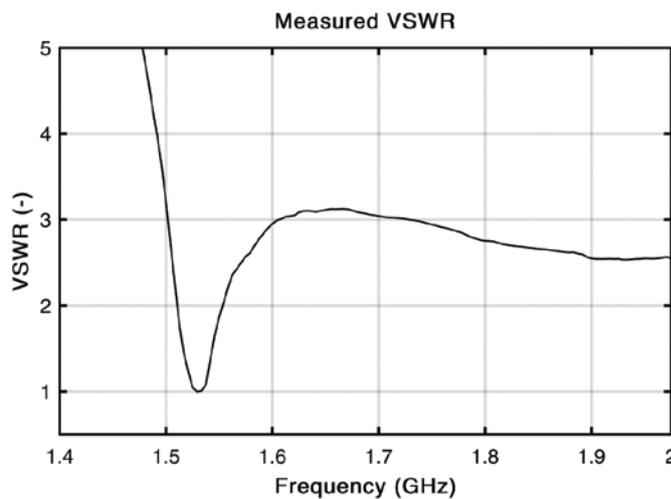


Fig. 11. Measured VSWR of the reference disk antenna

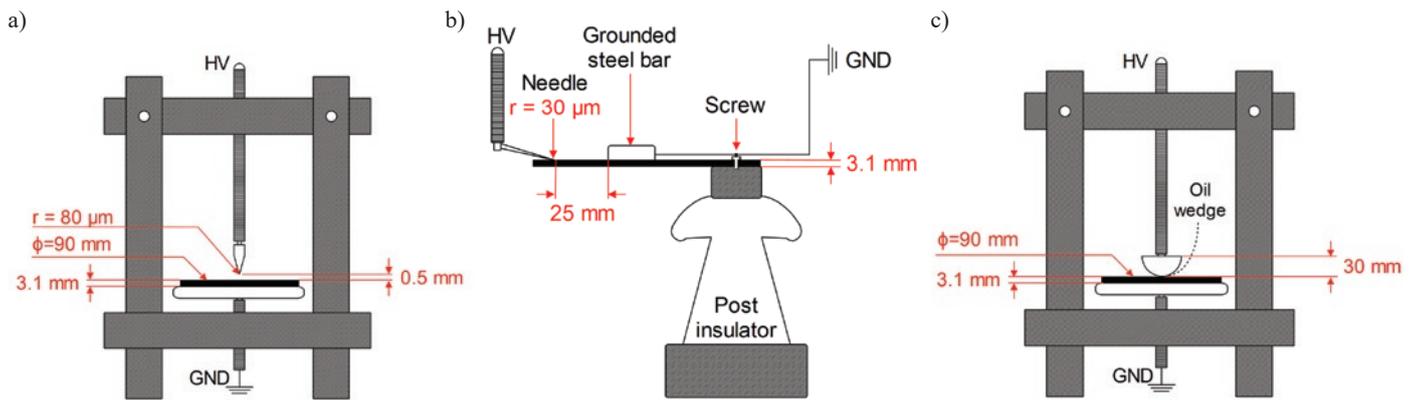


Fig. 12. Applied electrode systems for generation of: (a) surface discharges on pressboard sample in oil with large normal component of field strength vector – defect #1; (b) surface discharges on pressboard sample in oil where the normal component of field strength vector is insignificant – defect #2; (c) partial discharges in oil wedge/gap (so called “triple junction”) – defect #3

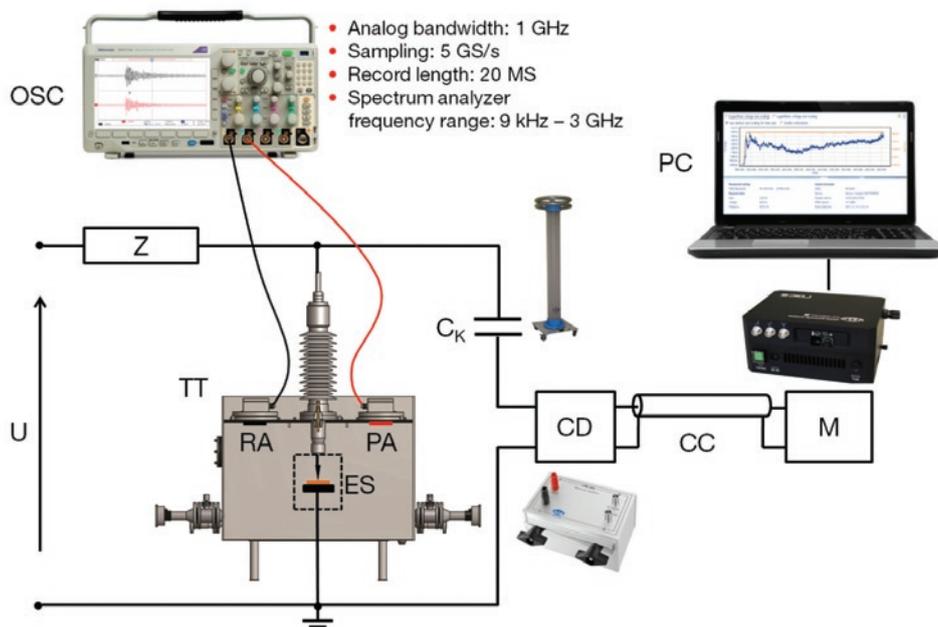


Fig. 13. Schematic diagram of the measurement set-up: U – high-voltage supply; Z – short-circuit current limiting resistor; OSC – oscilloscope; TT – transformer tank model filled with mineral oil; RA – reference disk antenna; PA – prototype Hilbert curve fractal antenna; ES – electrode system for partial discharges generation; C_K – coupling capacitor; CD – coupling device (measuring impedance); CC – connecting cable; M – conventional PD measuring instrument (in accordance with standard IEC 60270)

ence, because it is the most commonly used for power transformer and GIS/GIL diagnostics [11, 19]. The measured VSWR plot is shown in Figure 11.

Using the electrode systems shown in Figure 12, three main types of PD pulses occurring in oil-paper insulation were generated: (a) surface/creeping discharges on pressboard sample in oil with large normal component of field strength vector (*defect #1*), (b) surface discharges on pressboard sample in oil, where the normal component of field strength vector is insignificant (*defect #2*); (c) partial discharge in oil wedge/gap (so called “triple junction”) – *defect #3*.

The distance between the antennas and the source of impulses was about 45 cm. Partial discharge pulses were detected simultaneously with both antennas and recorded using Textronix MDO3100 oscilloscope (sampling rate 5 GS/s). In addition, a conventional electrical method (IEC 60270) was used to make sure that the recorded pulses were related to partial discharges and not to external radio disturbances. All elements of the measuring set-up were placed

in a shielded high-voltage laboratory. The schematic diagram of the measurement set-up is shown in Figure 13.

The results of the measurements showed that for all three insulation defects, the prototype HCFA, compared to the reference disk antenna, has a higher sensitivity of partial discharge detection at UHF. In the case of the defect #1, the average peak-to-peak amplitude for prototype Hilbert fractal antenna was 43% higher, while for *defect #2* and *defect #3* it was 18% and 16% higher, respectively. The measurement data obtained using the conventional electrical method and both UHF antennas are presented in Table 1, while the comparative analysis of registered PD pulses is shown in Figure 14.

5. Summary

Both simulation and measurement results confirmed that the designed Hilbert curve fractal antenna can be effectively used for partial discharges detection and easily adapted to installation in the inspection window of power transformer tank or GIS/GIL.

The performance of prepared HCFA compared to the widely used disk antenna is, from 16% to 43% higher, depending on the type of insulation defect. Although the gain is slightly lower than expected, the proposed antenna also has other important advantages, such as: (i) wideband and multi-resonant, (ii) low fabrication cost (can be printed directly on the PCB), (iii) small dimensions (miniaturization), (iv) consistent performance over huge frequency range (frequency independent), (v) added inductance and capacitance without components, (vi) better matching of input impedance.

The relatively small gain is not a serious disadvantage, because in practice, it can be easily increased by using a RF amplifier.

Due to the fact, that the HCF antenna does not have fully omnidirectional radiation pattern, effective detection of partial discharge pulses using single HCF antenna – especially in a power transformer with a complicated internal structure – may be difficult to perform. This problem can be solved by installing several antennas, both on the side walls and on the top cover of transformer tank.

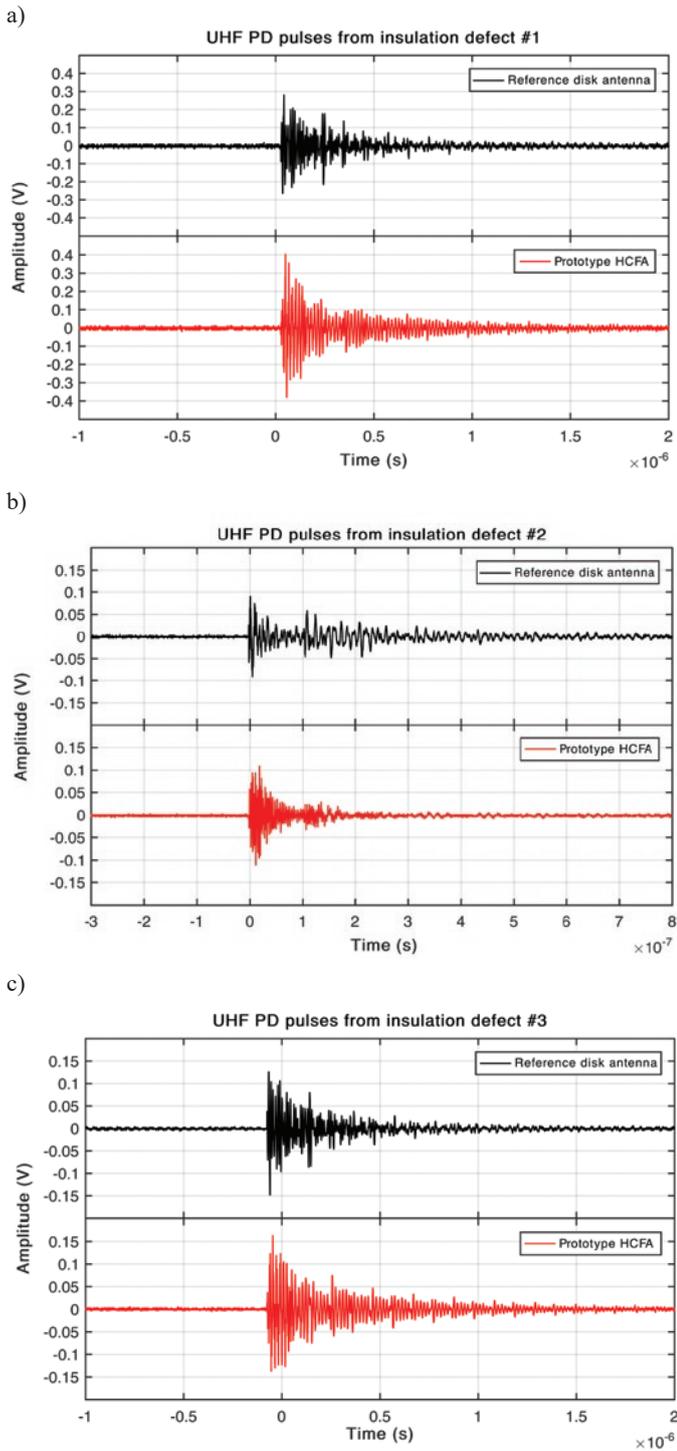


Fig. 14. Comparison of UHF PD pulses recorded using the reference disk antenna and the prototype Hilbert fractal antenna from: insulation defect #1 (a), insulation defect #2 (b) and insulation defect #3 (c)

Table 1. Partial discharge measurement data

Partial discharge type	Surface discharges Pressboard barrier within needle-plane electrode system (defect #1)	Surface discharges Needle placed nearly horizontal to the pressboard barrier (defect #2)	Partial discharges in oil wedge ‘Triple junction’ electrodes (defect #3)
Partial discharge inception voltage	18.5 kV	23.0 kV	15.5 kV
Average apparent charge	2.87 nC	418 pC	3.48 nC
Pulse length	~500 ns	~400 ns	~600 ns
Average peak-to-peak amplitude for reference disk antenna	239 mV	171 mV	280 mV
Average peak-to-peak amplitude for prototype Hilbert fractal antenna	342 mV	203 mV	326 mV

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