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PIFA ANTENNA FOR PARTIAL DISCHARGE DETECTION IN POWER TRANSFORMERS

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Abstract

The article presents the process of designing and manufacturing a prototype antenna based on the PIFA (Planar Inverted F Antenna) technology for the detection of UHF signals from partial discharges occurring in the power transformer insulation system. The main objective of the simulation studies was to obtain a frequency band covering the range of radio frequencies emitted by partial discharges in oil-paper insulation (surface discharges) and to adjust the dimensions of the antenna for its installation in the inspection window of the power transformer. The proposed structure consists of a radiating element in the shape of a rectangular meandering line and an additional parasitic element in the form of a specially selected resistor connecting the reflector with the radiator. The design of the prototype antenna was tested during laboratory tests in a high-voltage laboratory using a model of a transformer tank in which partial discharges were generated. The results of the measurements showed that the developed antenna has a higher sensitivity of partial discharge detection than other popular antennas used in transformer diagnostics, i.e. the disk antenna and the Hilbert fractal antenna. Due to high sensitivity, compact and simple structure and low production costs, the proposed PIFA antenna may be an interesting alternative to the currently used commercial antennas (mainly disk antennas) in on-line monitoring systems for partial discharges of power transformers.

Keywords: diagnostics and reliability of power transformers, partial discharge detection, UHF method, PIFA antenna.

1. Introduction

Monitoring the status of a power transformer installed in the electric power network has a major impact on reliability, operation and safety of the power system. The electrical insulation located inside the transformer is susceptible to damage due to excessive electrical loads, therefore its condition should be constantly monitored [1,2]. According to statistical research conducted by CIGRE [3], the most common cause of transformer failure is winding and their insulation defects. Damage to the coil windings of a transformer may result from a lightning, switching or short circuit currents in the power grid. The dynamic forces associated with short-circuit currents can

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shift or deform the coil and reduce the oil gap between them, which directly results in a decrease in the electrical strength of the system, especially in an area with a strong field [4]. The presence of a strong electric field inside the device may determine the formation of *partial discharges* (PDs). Increased PD intensity leads to accelerated and permanent damage to the electrical insulation of the transformer. Permanent damage to the insulation, in turn, can lead to a reduction in the efficiency of the device, and later to the damage of the device itself. Detection of PDs at low intensity of their occurrence can protect against progressive degradation of the electrical insulation used in the transformer. In order to detect partial discharges, monitoring systems using methods of *acoustic emission* (AE), analysis of the gases dissolved in transformer oil (DGA), and a methods using a electromagnetic sensor of *high frequency* (HF) and *ultra-high frequency* (UHF) are adapted [5–10]. The UHF method shows high resistance to external electromagnetic interference, while maintaining a good ratio of useful signal level to noise level [11]. Measuring sensors play a key role in capturing signals from PD sources. In earlier publications, the author presented constructions that could be used as such measurement sensors. [12] discusses the design of the Hilbert fractal antenna designed for use in incomplete discharge monitoring systems using the UHF method, while the publication [4] presents a prototype *planar inverted F antenna* (PIFA) which is the first construction of this type created by the author. This paper presents the process of designing a UHF sensor for recording of electromagnetic signals coming from PD based on the modified PIFA design. The following chapters present the basic structure, which was modified in the later stages of the work. Then, the influence of changing the antenna parameters on the bandwidth and resonant frequency of the antenna was examined. In the final stage of the work, the results of laboratory tests showing the effectiveness of the developed PIFA antenna were presented.

2. Designing a conventional PIFA antenna

The UHF antenna should be adapted to the installation site. In the case of a power transformer, the UHF antenna will be placed in a dielectric window, which is round and has a diameter of 0.15 m. The frequency characteristics of the UHF antenna should be adapted to the registration of surface discharges which are the most degrading phenomenon for the paper-oil insulation in the transformer [6]. The antenna should register signals mainly from surface discharges. The appropriate directional characteristics of the antenna should allow for its registration of signals arriving along the shortest path from the source to the antenna, but also for the registration of signals reflected from the walls of the power transformer.

The basic antenna structure is the monopole antenna comprising a vertical rod located above the grounded limited plane. The resonant frequency of the monopole antenna depends on the antenna length, according to the formula:

$$L = \frac{\lambda}{4}, \tag{1}$$

where: L – monopole antenna length, λ – electromagnetic wave length.

The IFA (inverted F antenna) is a special case of a monopoly in which the upper section has been folded so that it is parallel to the grounded plane. IFA consists of two elements parallel to each other: a rod radiator and a grounded surface (Fig. 1) [13, 14]. The antenna elements are short-circuited by a perpendicular surface or a shorting pin. The antenna output is connected to the radiator via a hole in a grounded surface. Bending of the monopoly reduces the height of the antenna while maintaining its resonant length.

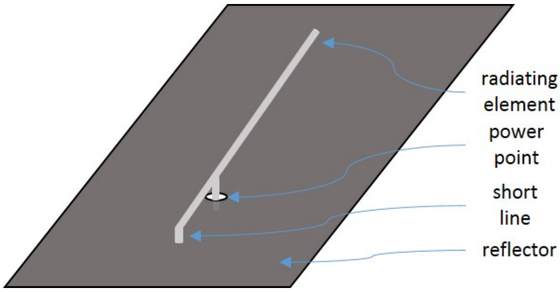

Fig. 1. Inverted F antenna.

The ground plane (reflector) plays a significant role in the antenna's operation, because the value of the current induced in the radiator and reflector depends on the surface absorbing the electromagnetic field. In the event that the reflector's plane is infinitely long or much larger than the length of the radiator, the reflector is an ideal reflector of the energy received by the antenna, that is, all the energy falling on the antenna will be directed to the radiator. Another advantage resulting from proper selection of reflector size is the change of the antenna directional characteristics to omnidirectional, *i.e.* the electromagnetic signal falling at different angles on the antenna is directed at the radiator. Due to this property, it is assumed that the ground plane must be $1/4$ of the received working wave length. The introduction of a dielectric between the reflector and the antenna radiator results in an additional capacity added to the antenna impedance which is compensated by a shorting pin. The optimum output impedance of the antenna is 50 Ω, and this value can be achieved by positioning the signal output from the antenna in the vicinity of the short-circuiting pin. Adjusting the antenna to this value eliminates the reflection losses in the cable connecting the receiver with the antenna [15, 16].

The inverted F planar antenna (Fig. 2) is a type of IFA planar antenna where the bar heat sink has been replaced by a plate. The PIFA design allows it to be used wherever monopole antennas such as bat, rod or spiral cannot be used.

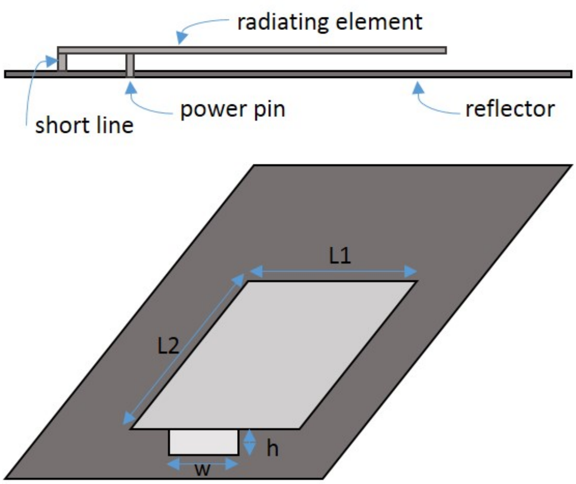

Fig. 2. Planar inverted F antenna.

PIFA has a high performance in signal reception because the value of the electromagnetic field received by the antenna is the sum of the vertical and horizontal polarization vectors. This property is used when the antenna position is not specified. One of the disadvantages of the PIFA antenna is the very narrow frequency band which may limit the possibilities of its use. This property is the result of a short circuiting the reflector surface of the radiator, which reduces the dimensions of the antenna. The bandwidth of the antenna is also dependent on the size of the plane of the reflector. In order to expand the antenna band, resistors are used in the pin path connecting the reflector with the radiator [16, 17]. The use of parasitic capacities in the space between the reflector and the radiator in the form of additional planes reduces the resonance frequency from $\lambda/4$ to $\lambda/8$, unfortunately also reducing bandwidth and impedance matching [17]. Forming the surface of the radiator in the shape of a spiral or meander results in introduction of parasitic inductance which allows to reduce the resonant frequency of the antenna, and at the same time reduce its surface [18–21].

The PIFA resonance frequency is approximately:

$$f = \frac{c}{\sqrt{\varepsilon_r}(L1 + L2 + h - W)}, \tag{2}$$

where: c – electromagnetic wave speed, ε_r – relative electric permittivity of the dielectric located between the radiator and the reflector, $L1$, $L2$ – length and width of the radiating element, h – distance between the emitter and reflector, W – width of the shorting pin.

The short-circuit pin width is important in regulating the PIFA antenna resonance frequency which decreases respectively as the pin surface decreases. Antenna impedance matching can be achieved by positioning the antenna output relative to the short-circuit pin. According to the assumption of the PIFA design, matching the antenna impedance to the transmission line does not require additional passive elements.

The construction of the meandered PIFA antenna is characterized by a meander-shaped radiator (Fig. 3) and has a compact design and a wider impedance band than the corresponding dimensions of a conventional PIFA antenna. The increase in the antenna bandwidth is an effect of a passive element (resistor) in the short-circuit pin circuit usage. The structure shown in Fig. 3

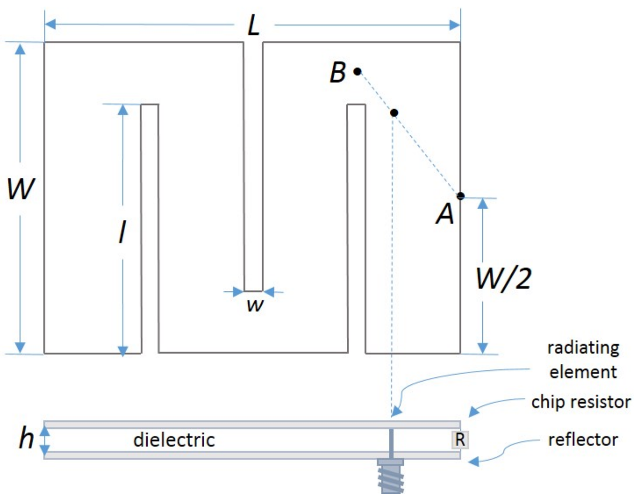

Fig. 3. Geometry of the meandered PIFA.

*Metrol. Meas. Syst.,*Vol. 28 (2021), No. 2, pp. 343–355
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has the dimensions $L \times W$ and the shorting pin replaced by a resistor at point A. The distance between the radiator and earth is h and this space is filled with a dielectric. The radiating element has indentations of length l and width w ($l \gg w$) which are evenly spaced along the edge L. The antenna can be powered by a source with an impedance of 50 Ω, with the power point located on section AB, and point B located in $(W - l)/2$. According to the literature, the best place to power the antenna can be determined experimentally and depends on the value of the resistance of the shorting point [18].

3. Designing a PIFA antenna with a meandered radiator shape

In order to adapt the PIFA structure for receiving the frequency signals generated by PDs, publications [4, 22, 23] showing the results of defects in paper-oil insulation were analysed. [22] presents the recording of PD pulses using narrowband antennas. In [4] studies are presented during which registration of UHF signals coming from the partial discharge sources was carried out. In this case UHF signals were recorded by HK116, HL223, HF907 broadband antennas by Rohde & Schwarz. The use of three antennas allowed recording UHF signals in a wide frequency band ranging from 20 MHz to 18 GHz. This study considered five defects in the transformer insulation system that generated discharges: (i) sliding, (ii) surface, (iii) in the oil wedge, (iv) in gas bubbles and (v) from the blade in the oil. These studies show that the frequency range from 160 MHz to 490 MHz includes all signals from modelled partial discharges.

It was decided to create a PIFA antenna structure with a meander-shaped radiator (Fig. 4), which allows recording low-frequency UHF signals with small geometrical dimensions. The size and shape of the antenna was adapted to the dimensions of the dielectric window used in power transformers [4, 24, 25]. The surface of the antenna reflector is a circle in order to increase the antenna's bandwidth and take full advantage of the size of the transformer's dielectric window. The antenna shown has a length L which was chosen according to the $\lambda/8$ relationship for 300 MHz. However, the distance between the heat sink and the radiator was chosen so that it was not greater than 0.01λ. The final dimensions of the antenna were: $L = 100$ mm, $W = 62.5$ mm, $l = 50$ mm, $w = 2$ mm and $h = 5$ mm.

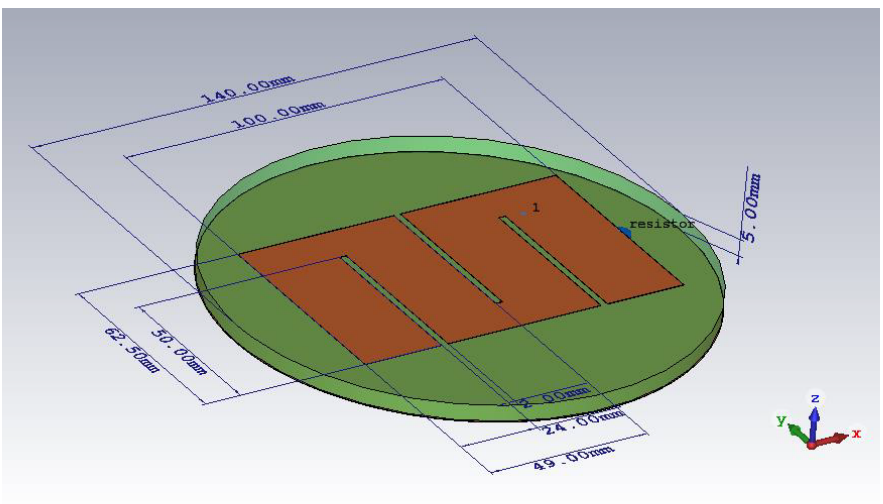

Fig. 4. View of the PIFA antenna designed and dimensioned in the simulation program with a meandering radiator.

In the simulation process in the CST Microwave program the influence of parameter changes on the receiving capabilities of the antenna was examined. The analysed parameters were: (i) the short-circuit pin resistance, (ii) the distance between the radiator and the reflector, (iii) the change in permittivity of the dielectric located between the radiator and the reflector. The factors that constituted the criterion for assessing the antenna structure were: *Voltage Standing Wave Ratio* (VSWR) and *Return Loss* (RL). VSWR is the coefficient determining the impedance matching of the antenna to the transmission line, where the ideal match is 1 ($RL <= -30$ dB), while the acceptable value for correct signal reception is 2. On the other hand, the Return Loss factor determines the signal loss in the transmission path expressed in decibels, however for antennas the permissible attenuation value is –10 dB ($VSWR = 2$) [26, 27].

The influence of the short-circuit pin resistance value on the PIFA antenna bandwidth was presented in the form of graphs of VSWR and Return Loss coefficients as a function of frequency in Fig. 5. From the analysis of the results obtained, it can be concluded that the appropriate selection of resistance allows the antenna to be perfectly matched to the transmission line for two values: 5.4 Ω and 5.6 Ω. For the value of 5.4 Ω the signal attenuation is lower ($RL = -45.83$ dB) than for the resistance equal to 5.6 Ω ($RL = -36.34$ dB). An additional advantage of increasing the short-circuit pin resistance is the extension of the bandwidth for the permissible value VSWR = 2, which amounted to 35 MHz for 5.4 Ω and 40 MHz for 5.6 Ω, respectively. Increasing the PIFA bandwidth by adding resistance in the short-circuit pin circuit also results in a higher signal loss which follows from the RL diagram (Fig. 5).

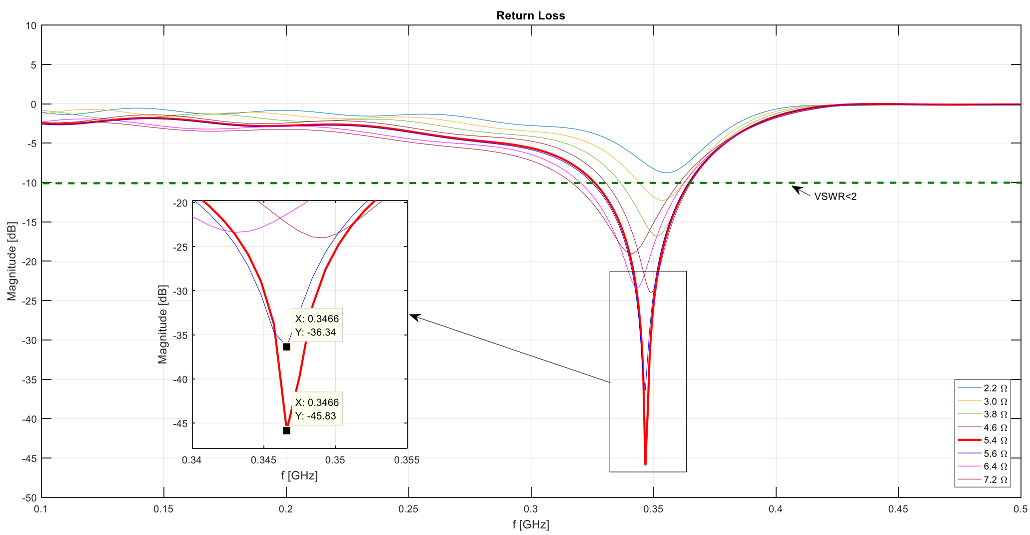

Fig. 5. The impact of changes in the resistance of the short-circuiting pin on the resonant frequency of the PIFA antenna.

The graphs shown in Fig. 6 illustrate the effect of distance between the radiator and reflector on the resonant frequency of the PIFA antenna. This distance was changed every 0.5 mm in the range of 3.0 – 6.0 mm. The value of the impedance matching parameter was $VSWR = 1$, when the distance between the radiator and the antenna reflector was equal to $h = 5$ mm. Signal attenuation for this distance was –36.34 dB.

The effect of the change in dielectric permittivity between the radiator and the PIFA reflector on the resonance frequency is shown in Fig. 7. The electrical permittivity was changed in the range 1.0–6.0, in steps of 0.5. The dielectric change significantly affected the antenna resonance

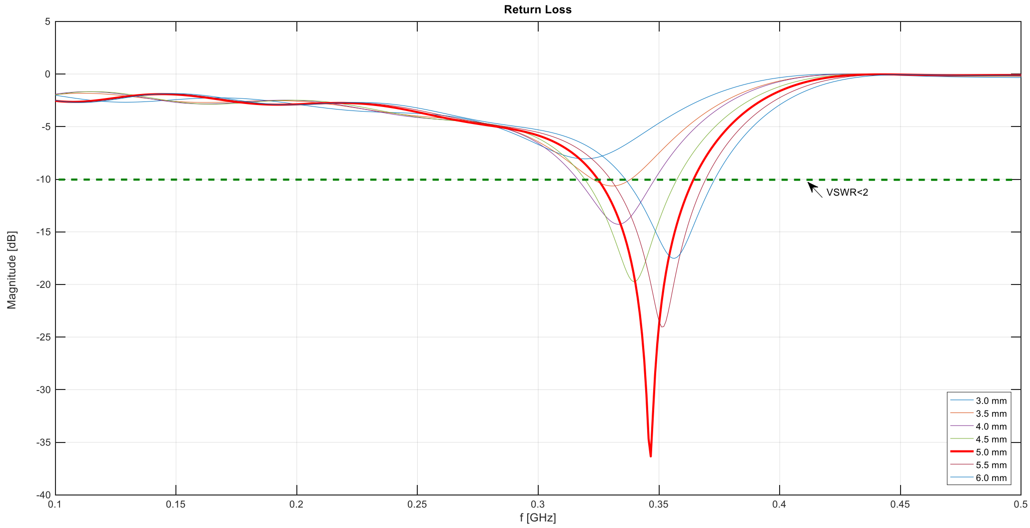

Fig. 6. The impact of changes in the distance between the emitter and reflector on the resonant frequency of a PIFA antenna.

frequency. As can be seen in Fig. 7, as the permittivity of the dielectric used increases, the resonance frequency decreases and the signal attenuation increases.

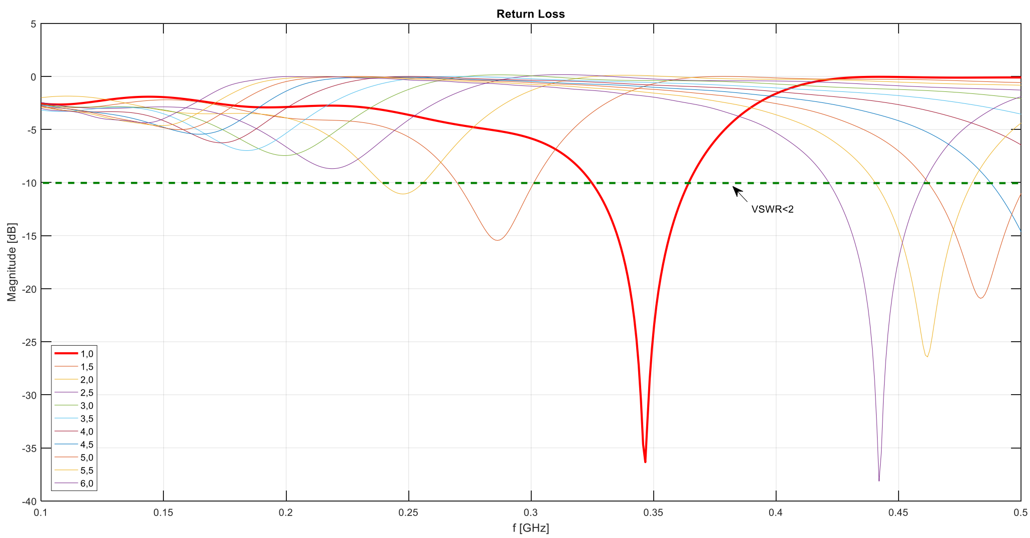

Fig. 7. The impact of changes in the permittivity of the dielectric between the radiator and the radiator on the resonant frequency of the PIFA antenna.

The simulation process allowed for accurate selection of PIFA geometrical parameters. It shows that a 5.6 Ω resistor should be placed at the spot where the reflector meets the radiator. The short-circuit resistance of this value is to ensure a 40 MHz bandwidth at VSWR = 2. The selected distance between the radiator and reflector is $h = 5$ mm, while the dielectric used should be a material with a permittivity close to $\varepsilon_r = 1$, *i.e.* air ($\varepsilon_r = 1.00054$). During the simulation tests, PIFA directional characteristics were also created, which illustrates the antenna's ability to radiate energy in a given direction (Fig. 8). The direction of the leaf of the main radiation pattern is parallel to the plane of the antenna radiator. According to the simulations, the main flap width is 109.1°, while the back flap is 105.3°. The characteristics of the antenna are lateral radiation. In connection with this characteristic it can be assumed that the presented antenna placed in the window of the dielectric transformer is capable of registering UHF signals, which arrive from all directions. Note that in a given situation signals reaching perpendicular to the antenna radiator will be attenuated by –6 dB.

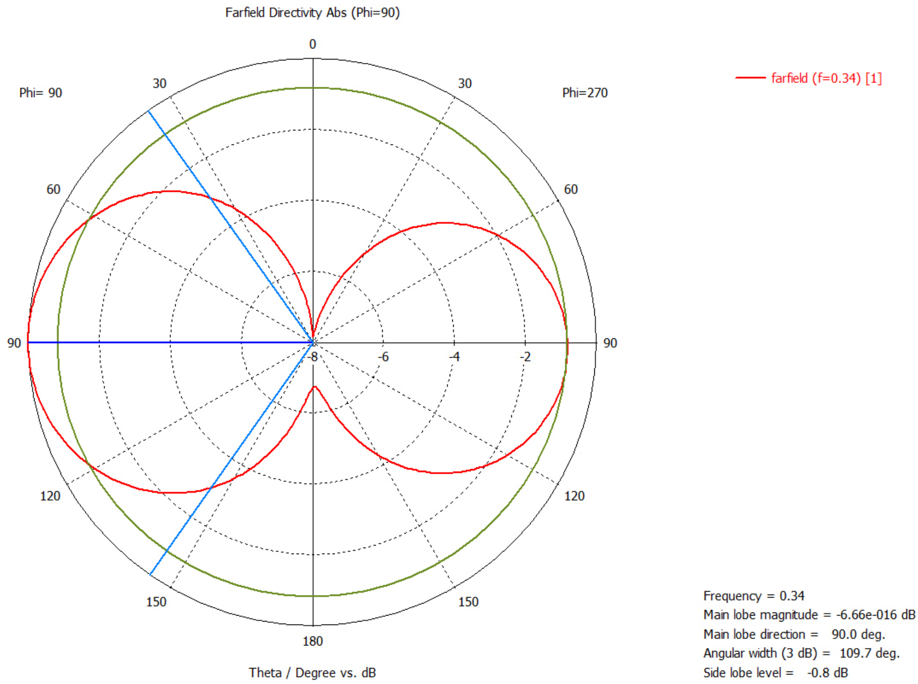

Fig. 8. Directional characteristics of the PIFA antenna.

4. Comparison of the operation of different antenna designs

Modelling the antenna work in the simulation program allowed the creation of a physical PIFA model according to the dimensions presented in chapter 3. The antenna elements were made of 0.4 mm thick PCB boards with a 18 μm thick copper layer. The antenna is equipped with a 50 Ω N-type connector, which allowed the signal to be received from the antenna (Fig. 9).

The characteristics in Fig. 10 illustrate the Return Loss and VSWR antenna coefficients. The characteristics show a comparison of results of computer simulation and PIFA measurement. Real antenna coefficients were measured using a portable antenna analyser KC901S with a measuring band from 150 kHz to 3 GHz. The created antenna has a lower resonant frequency ($f = 328.9$ MHz) than it results from the simulation ($f = 346.6$ MHz). Impedance matching to the VSWR transmission line in both simulations and measurements is close to 1, which means almost perfect matching. As the graph shows, in the case of the measured RL parameter of the real

Metrol. Meas. Syst.,Vol. 28 (2021), No. 2, pp. 343–355
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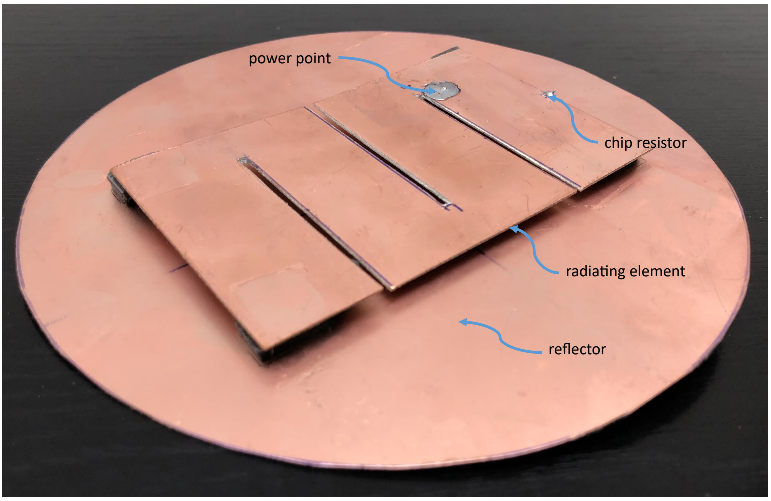

Fig. 9. PIFA antenna design adapted for installation in the dielectric window of the transformer.

antenna, a greater signal loss (–24 dB) can be seen compared to the simulation results (–36 dB). The antenna bandwidth for VSWR equal to 2 is identical, both for the simulation results and the real measurement.

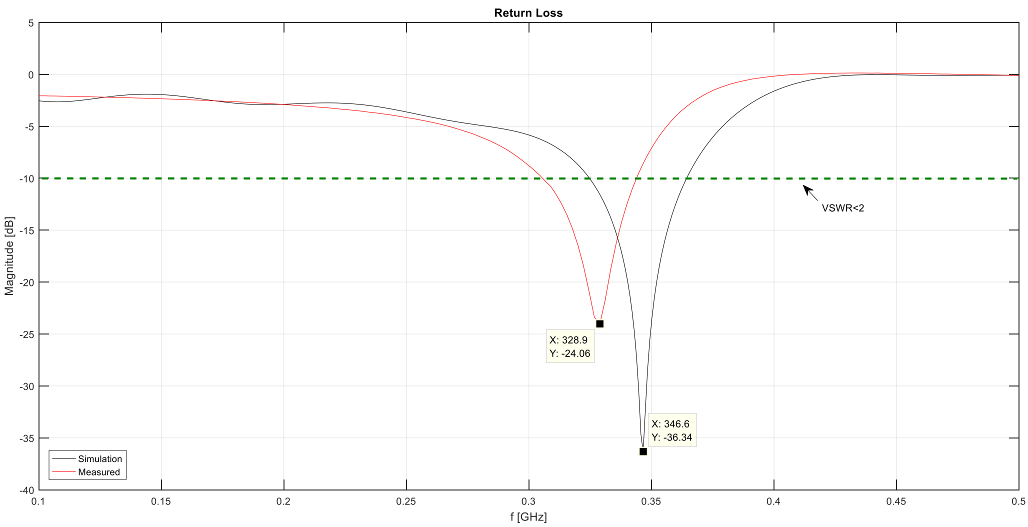

Fig. 10. Comparison of VSWR and Return Loss characteristics for the simulation model and the actual PIFA design.

PIFA was tested in a high voltage laboratory. A comparative study was carried out to determine the differences in performance between PIFA and a 100 × 100 mm Hilbert fractal antenna and a 150 mm diameter disk antenna that is used in commercial sensors. The tests were carried out on a laboratory model of a power transformer tank with dimensions of 800 × 1200 × 750 mm. (Fig. 11). The antennas were placed in dielectric windows at the same distance (80 cm) from the source of partial discharges on a pressboard sample. Partial discharge pulses were recorded simultaneously on four channels of a Textronix MDO3100 oscilloscope which sampled the signals at the frequency of 5 GS/s. Three channels recorded UHF signals from antennas, the fourth channel of the oscilloscope recorded a signal from the current transformer – Rogowski coil. In addition, a conventional partial discharge measurement method, in accordance with IEC60270, was used to ensure that recorded pulses are associated with partial discharges rather than external radio interference.

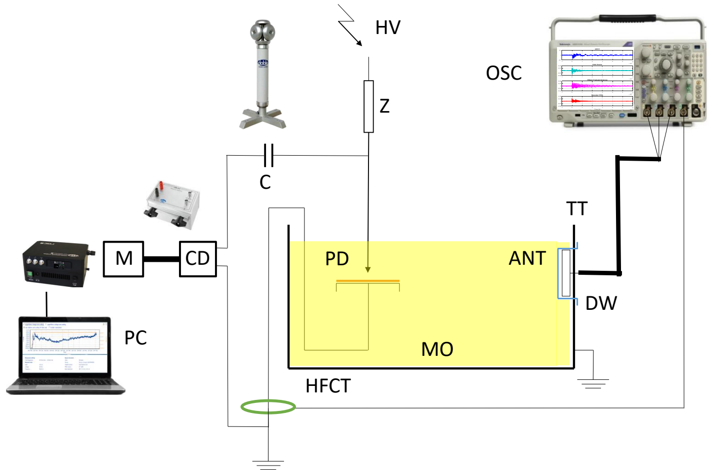

Fig. 11. Schematic diagram of the measuring system: M – conventional method of measuring partial discharges (in accordance with IEC 60270); CD – measuring impedance; C – coupling capacitor; Z – resistor, short-circuit current limiter; HV – high voltage source; PD – electrode system for generating surface discharges; TT – a transformer tank model filled with mineral oil (MO); DW – dielectric window; HFCT – Rogowski coil; ANT – UHF antennas: disk, Hilbert fractal antenna, PIFA; OSC – oscilloscope.

The Rogowski coil installed on the grounding wire of the discharge system registered impulses that triggered the recording of signals from the installed antennas in the oscilloscope. Examples of voltage waveforms recorded with an oscilloscope are shown in Fig. 12. Measurement data obtained using the conventional method are presented in Table 1 together with the parameters of signals recorded with individual antennas. The average amplitude of the signal recorded by PIFA is two times higher compared to other tested antenna constructions. Higher effectiveness of PIFA compared to other tested antenna constructions means that defects in transformer oil-paper insulation will be detected at lower intensity, therefore signals from deeply hidden defects (*e.g.* inside the winding) that are very damped can be recorded with a PIFA antenna.

Table 1. Parameters of partial discharge pulses.

	Initial voltage surface discharge	**Surface discharge charge**	**Average peak-to-peak signal value**		
			Disk antenna	**Hilbert fractal antenna**	**PIFA**
number of measurements	147	147	147	147	147
average value	23 kV	2,8 nC	24 mV	23 mV	48 mV
standard deviation	0	0.38 nC	11 mV	10 mV	13 mV

Metrol. Meas. Syst., Vol. 28 (2021), No. 2, pp. 343–355
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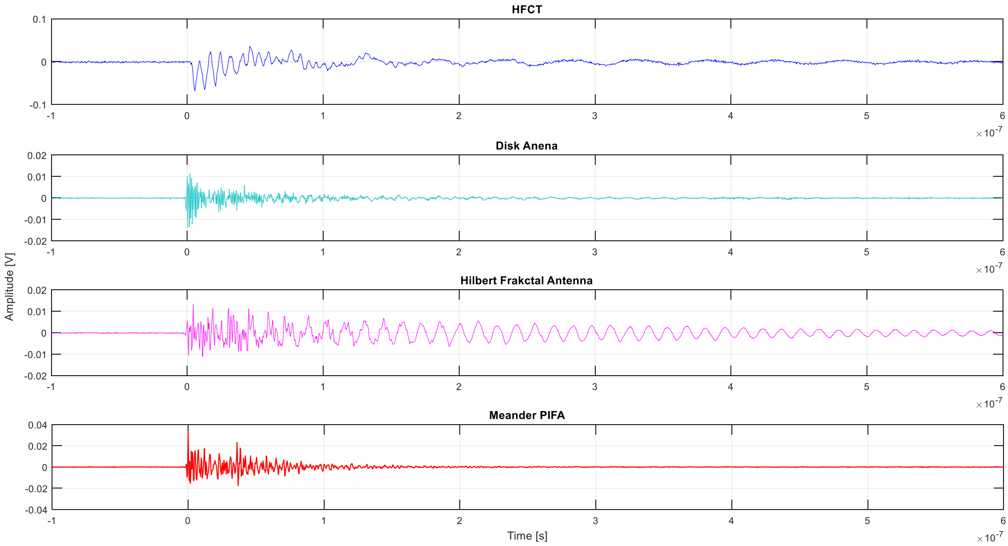

Fig. 12. Recorded time series of partial discharges pulses.

5. Conclusions

The PIFA antenna with the meandered plane of radiator presented in this article, in light of the research conducted, can be an effective measurement sensor used for recording electromagnetic pulses from defects in oil-paper insulation. The simulation process allowed the appropriate selection of the geometrical parameters of this antenna so as to ensure its appropriate efficiency and sensitivity. The frequency characteristics of the constructed antenna are close to the characteristics created in the simulations, which confirms the properly carried out antenna design and construction process.

Laboratory tests have allowed the comparison of the new PIFA design with the commercially used disk antenna and the Hilbert fractal antenna. The created antenna structure has: (i) compact and simple construction enabling its installation in the dielectric window of an energy transformer, (ii) low production cost, (iii) the ability to correct the bandwidth by changing the short-circuit pin resistance, (iv) the ability to change the resonant frequency of the antenna by proper selection of dielectric between the radiator and the reflector, (v) directional characteristics of the side radiation.

Although the antenna does not have omnidirectional radiation characteristics, it is not an obstacle to recording UHF signals from partial discharges generated inside the transformer. Effective detection of defects in the transformer insulation system will be possible by using several measuring sensors installed in different locations of the transformer tank.

Application work is currently underway on the construction of a transformer monitoring system using UHF antennas including PIFA described in this article. Parallel to laboratory researches on this antenna, field research is carried out with the use of an electric power transformer operating in the power system [28].

Acknowledgements

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