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Antennas Comparison Applied to Detect Partial Discharges Coupled via Dielectric Window and Oil Valve in Power Transformers

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Abstract – **Considering increasing the reliability of electrical systems, continuous equipment maintenance is essential, thus ensuring longevity and avoiding failures that can cause irreparable damage to the equipment. Partial discharges are physical phenomena that cause short circuits in power equipment. There are techniques that use the detection of partial discharges as a condition monitoring techniques for electrical equipment. One of these techniques is the detection of partial discharges in power transformers by means of antennas. Thus, different antennas were analyzed for different coupling to the sensor into the high voltage equipment, either via dielectric window or oil valve. In comparison, the L-probe antenna obtained the best result, at -10 dB, while at -5 dB the log spiral performed better, for insertion via the dielectric window. For coupling via oil valve, the monopole obtained the best result, at -10 dB, considering the bandwidth at -5 dB the conical 70 mm did better.**

I. INTRODUCTION

Power transformers are one of the most important and most expensive equipment for the electrical power system. Therefore, identifying defects, through continuous monitoring techniques, becomes indispensable in order to avoid failures that could damage the equipment in a partial or complete way. Partial discharges (PD) are physical phenomena that generate electrical discharges of low intensity, thus generating short circuits in a partial way, in specific regions of the insulating material that are subjected to intense electric fields[1]. The continuous process of partial discharges can cause degradation and deterioration of the insulating material, which in the medium to long term generates partial or complete rupture of the dielectric, with failure of the equipment. Generally, high voltage equipment has a high market value and plays an essential role in the proper functioning of the electrical system, especially power transformers, whose function is to increase and decrease voltage, load supply, among others. Therefore, transformers directly interfere with the system reliability. Based on the above, several researchers have been studying numerous methods and methodologies that can be applied to the detection of partial discharges, seeking the most efficient and least invasive way. One of these methods is based on the verification of electromagnetic waves that are emitted by current pulses in the event of partial discharge. The frequency range that this phenomenon can be observed is from 300 MHz to 3 GHz [2].

For partial discharges, the frequency spectrum from 300 MHz to 1.5 GHz is the most relevant to be analyzed, as it is in this range that the highest concentrations of energy for pulses of partial discharges in various dielectric materials are reported [3]. Furthermore, as the UHF method is based on a system that works in a high frequency range, the detection system is theoretically immune to common interferences in substations, such as: switching of power electronics equipment and corona discharge, which have components of significant energy signals up to the range of 200 MHz and 300 MHz [4]. To apply the UHF method, it is necessary to use a device to detect partial discharges, in this case, an antenna [5, 6, 7, 8]. A new microstrip antenna was developed in [5], it is designed to detect UHF partial discharge signals for field GIS, it was concluded that the UHF measurement system is suitable for partial discharge detection and diagnosis in GIS field. In [6] microstrip antennas were developed and compared to detect partial discharges. The models developed proved capable of detecting PD. In [7] optimization methods were applied with the aim of increasing the bandwidth of microstrip antennas. It was possible to observe that the antennas developed had a significant increase in bandwidth. In [8] a bio-inspired sensor was developed to apply insertion via dielectric window in power transformers.

That way, this work aims to carry out a comparative study between antennas applied to detect partial discharges in a continuous way in power transformers, distributed in the environment through dielectric windows or coupled via oil valve. Therefore, simulations were carried out in a computational environment in order to validate which antenna has the best result in detecting partial discharges. This paper is composed of four parts including this introduction. Section II present the materials and methods used, section III the results, and the conclusions in section IV.

II. MATERIALS AND METHODS

In order to choose the antennas that would be simulated, the most appropriate antenna shapes for the type of coupling (via dielectric window or oil valve) and the techniques for bandwidth optimization were analyzed, making it possible to select which one is more efficient in comparison to the application. From the researched references, it was possible to reach the result that, in the case of coupling via dielectric window, most of the works use planar antennas with different formats and optimizations. Thus, the U-slot, L-probe and U-slot with L-probe antennas were based on the work of [7] and can be seen in Fig. 1. Dimensions were modified to obtain the optimizations, at that moment aluminum was used as a radiating element and ground plane, obtaining results closer to reality. The log spiral antenna was based on the equations contained in [9, 10] and can be observed in works such as [11]. The same methodology as the previous antenna was used for the design of this, shown in the Fig. 2.

For the case of insertion via oil valve, the simulated antennas were monopolar and conical antennas, considering a DN80 type valve, with size restrictions of 80 mm in diameter. The monopole and conical antennas were based on the equations contained in [9, 10] and can be observed in works such as [12, 13], as show in Fig. 3. For the case of the conical antenna, a length value was fixed in 300 mm (because commercial sensors use this value) and the cone radius varied, to verify the behavior of the bandwidth.

After choosing the antennas, it was possible to move on to the simulation stage. The simulation of the antenna design was performed using the commercial software $Ansys^{TM}$. For the construction of the simulation environment the following steps were followed:

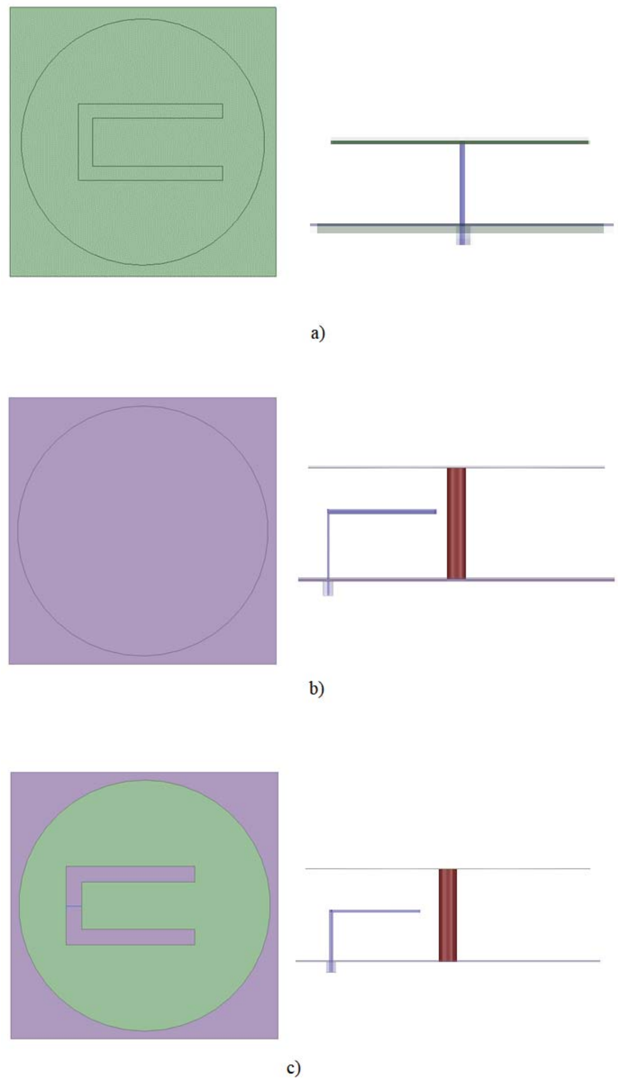

Fig. 1. Computational model of the antenna with a) U-slot, b) L-probe and c) U-slot with L-probe to 0.9 GHz.

1. **Dimensioning of structural parameters of the model:** The physical dimensions of the structure (in this case the antennas) are defined, such as width, thickness, length and positioning of the elements.

2. **Material specification:** The characteristics of each material used in the elements built in the previous step will be assigned. The materials used can come from the software itself, such as copper or epoxy, for example, or they can be created by the user, with the insertion of data such as the dielectric constant, tangent of losses and others. In this paper, copper was considered as the radiating element and ground plane, and as the dielectric substrate, FR4 was used. For the case of the antennas in Fig. 1, air was used as substrate and aluminum as radiating element and ground plane.

Fig. 2. Computer model of planar log spiral antenna to 0.9 GHz.

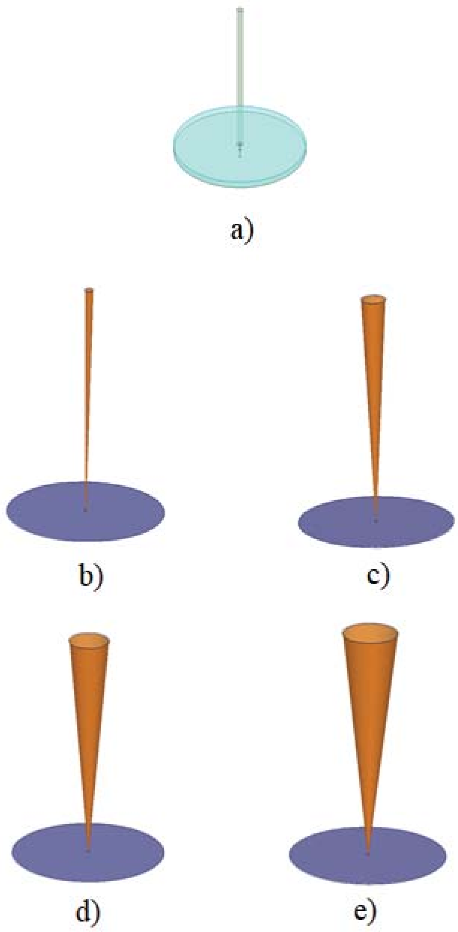

Fig. 3. Computational model of the a) monopole, b) conical (10 mm), c) conical (30 mm), d) conical (50 mm) and e) conical (70 mm) antennas to 0.9 GHz.

3. **Boundary Conditions:** The radiation box is defined, which corresponds to the limits of the simulated space for which the incident radiation on the antenna is absorbed and does not generate return reflections. Thus, the dimensions of the radiation box should be $\frac{\lambda}{4}$ of the central frequency of the antenna and filled with air.

4. **Structure excitation:** The waveport was chosen as excitation source. In order for the result obtained to be accurate, it is necessary to properly define both impedance values and dimensional values. Therefore, the impedance value of $50\,\Omega$ was considered for the project, which is the dimension equivalent to the external diameter of the simulated coaxial cable (5 mm).

5. **Analysis settings:** The frequency for solving the problem was determined, as well as the number of steps performed to solve the matrices implemented by the finite element method. For the work, 20 execution steps will be considered and the value 900 MHz as the central frequency.

After the simulations, the results were compared considering some aspects, namely, the bandwidth, physical dimensions, radiation pattern and gain. For the calculation of the bandwidth of the antennas, values below -10 dB and -5 dB were considered for the S_{11}.

III. SIMULATION RESULTS

In this section, the results obtained in this work are presented and discussed. The first section refers to the results related to the antenna coupled via dielectric window, presenting analyzes regarding the simulations and comparisons. For the second section, there are the results related to the antenna coupled via the oil valve.

A. Antennas with dielectric window coupling

After the simulations with the results obtained, it was possible to build Table 1 and Fig. 4, in which the antennas intended for dielectric window coupling in power transformers will be compared.

Table 1. Comparative table between the simulated antennas intended for dielectric window coupling.

Antennas	BW (%)		Size (mm)	Gain (dBi)
	-5 dB	-10 dB		
U-slot	30.77	22.22	87	9.33
L-probe	43.81	28.89	75	9.61
U-slot with L-probe	48.69	5.56	80	9.51
Planar log spiral	95.75	–	100	6.09

The analysis of Table 1 and Fig. 4 allows us to observe some interesting aspects. The antenna that has the highest bandwidth in the comparison is the L-probe, with a result of 28.89%, important in applications for detecting partial discharges. The antenna that has the highest bandwidth,

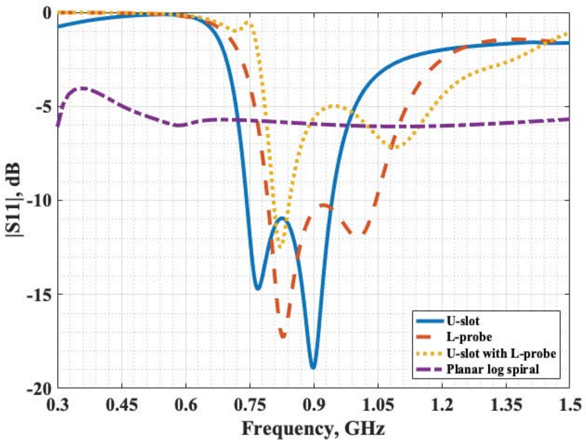

Fig. 4. Comparison between the magnitude of reflection coefficient of antennas inserted into the dielectric window.

gain and smaller size in the comparison is the L-probe, with 9.61 dBi and 75 mm radius. Thus, for the application of via dielectric window, the most suitable antenna would be the antenna with L-probe, because in the comparison it was the one that obtained the best results, in terms of bandwidth, gain and physical dimensions. It is also worth considering that a limit of −5 dB in the magnitude of reflection coefficient for the definition of the antenna bandwidth is possible for PD detection, as it allows the transmission of approximately 70% of the power signal. As can be seen in studies [14, 15], in which the results were satisfactory for the values of the order of −3.5 dB. There are also studies that prove that with a gain of 2 dB it is possible to detect PD [16]. Considering the bandwidth at −5 dB, the spiral log antenna obtains better results compared to the others for bandwidth.

B. Antennas with coupling via oil valve

The first simulated antenna model was the monopole antenna. Then, the conical antenna model was built that would fit the physical limitations imposed by the oil valve, varying the cone diameter to observe the bandwidth behavior. After the simulations with the results obtained, it was possible to construct Table 2, Table 3 and Fig. 5, in which the antennas intended for insertion via oil valve in power transformers will be compared. In Table 2, the bandwidth results in −10 dB are presented, considering different operating bands, the size and gain of the antennas. In Table 3, the bandwidth results are presented in −5 dB considering different operating bands and the total bandwidth value in megahertz.

The monopole antenna has a bandwidth of about 12.22%, being characterized as a broadband antenna, its dimensions would be ideal for the application, due to its diameter being less than 80 mm. Analyzing the graph

Table 2. Comparative table between the simulated antennas intended for oil valve insertion, with bandwidth (operating band) at −10 dB.

Antennas	BW (%)		Size (mm)	Gain (dBi)
	1°	2°		
Monopole	12.22	–	38 x 98	2.19
Con. (10 mm)	5.00	3.42	10 x 300	2.59
Con. (30 mm)	3.35	1.74	30 x 300	2.22
Con. (50 mm)	–	–	50 x 300	3.47
Con. (70 mm)	–	–	70 x 300	2.53

Table 3. Bandwidth comparison table (operating band and total) of simulated antennas inserted via oil valve at −5 dB.

Antennas	BW (%)				BW (MHz)
	1°	2°	3°	4°	
Monopole	54.13	–	–	–	419.00
Con. (10 mm)	16.46	10.26	–	–	235.20
Con. (30 mm)	6.67	20.91	12.17	–	304.30
Con. (50 mm)	13.33	26.47	15.04	2.13	422.00
Con. (70 mm)	20.00	32.84	17.86	4.67	550.00

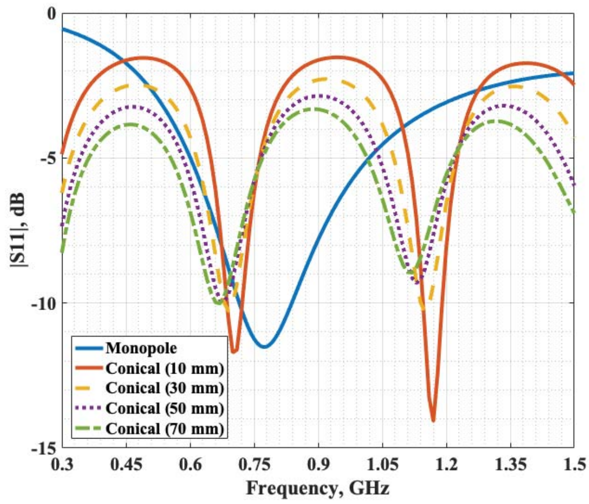

Fig. 5. Comparison between the magnitude of reflection coefficient of antennas inserted into the oil valve.

and the tables, it is possible to observe that when the radius of the conical antenna is increased, the bandwidth decreases. However, if the same analysis is performed for -5 dB, the path is the opposite, that is, there is a significant improvement.

Comparing the conical antennas, the one with the best gain result was the antenna with 50 mm diameter, however the bandwidth at -10 dB for it is narrow. Observing the bandwidth, the antenna with a diameter of 10 mm obtained the best result. For -5 dB, the result is different, in this case the conical antenna with 70 mm of diameter is the one that obtained the best bandwidth.

When looking at the physical dimensions of the antennas, it is important to highlight some aspects, the first of which is that as the antennas are intended for different forms of insertion (via dielectric window or oil valve) the diameter x height ratio will vary greatly. For example, for antennas for oil valves, it is possible to verify that the height is in most cases much greater than the radius. On the other hand, for antennas coupled via the dielectric window, the relationship is opposite. The radiation patterns will depend on the constructive model applied to the antenna, it is possible to see that for the case of planars, there are generally unidirectional patterns. In the case of monopolar antennas, the characteristic is omnidirectional.

IV. CONCLUSION

In this paper, a comparative analysis was performed between antennas for continuous measurements applied to detect partial discharges coupled via dielectric window or oil valve in power transformers. It was found that for the coupling via the dielectric window, the L-probe antenna obtained the best results, since it was the most compact, had a bandwidth of 28.89% (at -10 dB) and a gain of 9.61 dBi. For -5 dB the spiral log antenna obtained the best result with bandwidth of 95.75% and gain of 6.09 dBi. In the case of coupling via oil valve, the most suitable antenna, considering -10 dB, would be the monopole, with bandwidth of 12.22% and a gain of 2.19 dBi, at -5 dB the conical 70 mm achieved the best results with 550 MHz of bandwidth and gain of 2.53 dBi. As a next step, tests will be carried out at high voltage to verify if the antennas can detect partial discharges in practice.

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