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Design and Application of Defective Ground Patch Antenna for PD Detection in Underground LV Power Cables

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Abstract*— This article presents a defective ground plane wide band slotted patch antenna designed to detect partial discharges emitted from underground LV power cables. Two slots are incorporated into the patch antenna and band width expansion was investigated by the currents flowing through the patch antenna. The antenna design; simulation was carried out in the Agilent Advanced Design Systems (ADS) environment. The fabricated antenna on FR4 substrate indicates an impedance bandwidth of 40.84% at 284.4 MHz center frequency with return loss of -37 dB. The simulated and measurement results of the antenna designed are discussed.

Index Terms: **Defective ground plane, Patch antenna, Partial discharge detection, LV power cables.**

I. INTRIDUCTION

Partial discharge is an important contributor to insulation deterioration. Failure of a high and medium voltage cable can cause service interruption, costly location repairs, and loss of revenue. These discharges are localized electrical discharges that only partially bridge the insulation between conductors. Utility experience shows that poor termination and jointing is a major source of cable failure Researchers started researching on partial discharge from last 60 years [1, 2]. PD measurement is a well-established criterion for the condition assessment and quality control of high voltage electrical insulation. PD originated from a micro-defect, incepts periodically according to the ac cycle of the operating voltage and gradually degrades and erodes the polymeric material, eventually leading to breakdown [3]. In the detection of PD, depending on the sensing of energy exchange, different detecting methods were approached. In these methods, electromagnetic sensing is one of the best types of partial discharge detection and localization. The occurrence of partial discharges in electrical insulation is always associated with the emission of electromagnetic pulses. A typical PD pulse has a rise timeless than 1 ns and a pulse width of several ns, implying a frequency domain of several GHz [4]. The electromagnetic emission propagates in all directions from the PD source. The attenuation of electromagnetic PD pulse is a function of frequency along the propagation path. The higher frequency components will be attenuated rapidly when they travel along the cable [5, 6]. Therefore, the detectable electromagnetic (EM) wave emitted from the PD includes a broadband signal of VHF/UHF (Very High Frequency: 30 MHz to 300 MHz [7].

In this paper a wide band slotted patch antenna was designed with partial ground plane, which operates in the impedance bandwidth range of 219.5MHz to 385.5 MHz (166 MHz). This accomplishes the purpose of wideband antenna for VHF/UHF range. The discerning feature of this designed antenna was in the ground plane technique which differs from the published literatures that has described.

Section 2 describes the antenna design. Section 3 presents the procedure of measurements that were carried out. Section 4 discusses both the simulated and measured results of the antenna performance and Section 5 concludes with the findings of the simulated and measured results.

II. ANTENNA DESIGN

The antenna designed for wide band slotted patch with partial ground plane is shown in Fig. 1. The topology of the antenna was designed on an FR4 substrate with a 1.6 mm thickness and a dielectric constant εr of 4.3. The antenna size is characterized by length, width and height (L, W, h), fed by a feed line and followed by a partial ground plane. The antenna was designed and optimized to detect partial discharges emitted from underground LV power cables. In order to expand its bandwidth, two parallel slots were incorporated into this patch. The feed line was appropriately positioned at the center point of slotted patch antenna shown in Fig. 1.The slot length, width, and positions were important parameters in controlling the achievable bandwidth.

The patch antenna's basic width and length were denoted by 'W' and 'L' was obtained by equations (1) and (2). Using a permittivity value ε_r of 4.3, the effective dielectric constant ε_{reff} of the antenna is determined from the equation (4) which was obtained from [8, 9].

For W/h > 1

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

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$$L = \frac{\lambda}{2} - \Delta L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \quad (2)$$

where

$$\Delta L = 0.412\,X\,h \times \frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (3)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (4)$$

Table I. Dimensions of antenna geometry

Basic Configuration	Patch antenna						Feed Line		Ground Plane	
Variable	W	L	S1		S2					
			W	L	W	L	W	L	W	L
Dimensions (mm)	214	159.5	22.9	7.6	23.5	7.9	47	5.3	11	174.6

The two slots on the patch antenna were denoted by $S_1$and S_2. The feed line was denoted by F. The structure of the patch antenna and the feed line was printed on one side of the FR4 substrate with the partial ground plane on the other side. The partial ground plane width and length were denoted by G_L and G_W shown in Fig.1.The design parameters such as dimensions (length and width) of patch, slots, the feed line and the partial ground plane are optimized to obtain better return loss and wide impedance bandwidth. The optimized dimensions of the antenna structure are shown in Table I.

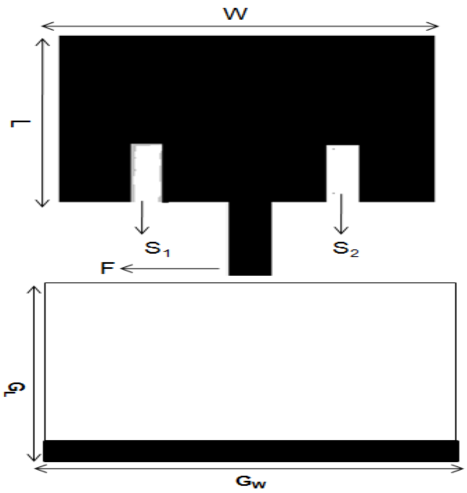

Fig. 1: Basic configuration of wide band slotted patch antenna with feed line and partial ground plane.

The conventional microstrip patch antenna can be modeled as a simple LC resonant circuit shown in Fig. 2(a). Current flows from the feed line to the top and bottom edges of the antenna. The path length of the current flowing through the antenna was the deciding parameter in fixing the values of L and C. The resonant feature of the antenna behaved in a different manner when two slots were incorporated in the conventional patch as shown in Fig. 2(b). The change in the resonant frequency was due to the role played by various factors such as slot dimensions, position, feed line and the partial ground plane. As the feed line was positioned at the center leg of patch, the current flowed around both the slots (S1, S2). This caused the increase in path length of current flowing through the antenna. As a result, inductance ΔL1 and ΔL2 were added in series to the main patch inductance L and modeled shown in Fig. 2(b). The structure of the proposed patch along with the conventional patch coupled together with the feed line formed a wide bandwidth.

The output of the slotted patch antenna was connected to the 50 Ω SMA connector through a microstrip feed line. This connector was used for the coaxial-to-microstrip transition, connecting the antenna to the network analyzer. The effect of ground plane was a vital factor in the present design of antenna for the required application. A finite analysis was carried out on the ground plane, based on the analysis; the partial ground plane with the proposed dimension which was approximately 17 times lesser than the size of the patch antenna was employed using the technique developed in [10].

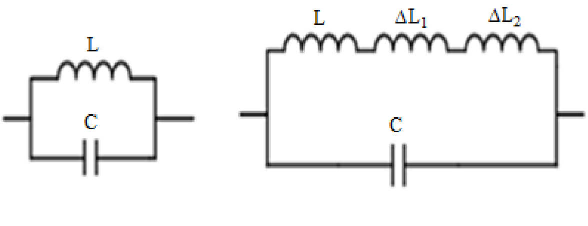

Fig. 2: The wide band mechanism of slotted Patch antenna (a) Equivalent circuit of micro strip patch antenna(b) Equivalent circuit of E-shaped patch antenna.

III. METHODOLOGY

The properties and performance of the proposed antenna were investigated and optimized through electromagnetic simulation software in the ADS environment. The characteristics of the fabricated antenna were measured using the Advantest R3767CG network analyzer. The performance of the antenna was also tested for transient response using the Pico second pulse labs pulse generator (source) by setting the appropriate transient pulse characteristics with pulse repetition frequency of 100 kHz, pulse width (duration) of 5 ns and an amplitude to 20 V for different antenna distances from the source. The screen capture of the source signal is shown in Fig. 3.The chosen parameters of the source was

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made the same with the signal characteristics of PD LV XLPV power cables. The results those were recorded using the Lecroy wave Surfer 454 Digital Oscilloscope.

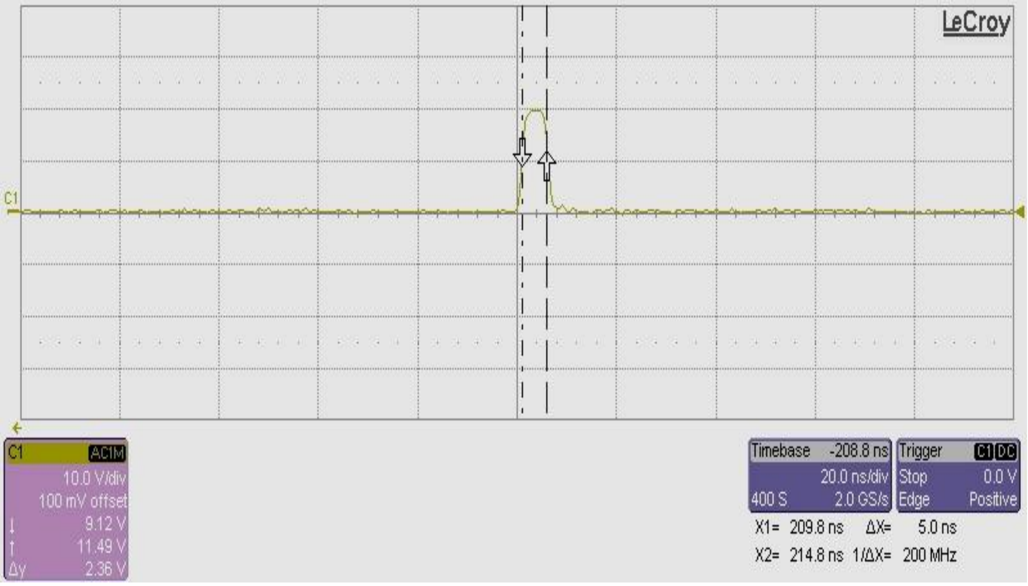

Fig. 3: Screen capture of source signal

The far field radiation measurement was performed using the fabricated antenna as receiver and the pulse generator source as transmitter, keeping them apart at the fixed distance of 50 cm. The fabricated antenna was connected through a SMA connector to the oscilloscope. This antenna was made to rotate from 0 to 180 degrees and the results obtained on the oscilloscope were recorded for every 20.degree.The reason for the angle (0-180 degree) being used in the measurement is based on the application requirement that needs incident or forward radiation.

IV. RESULTS AND DISCUSSION

The picture of fabricated wideband slotted patch the antenna on a FR4 substrate is shown in Figure 4. The simulated and measured results of the return loss obtained for the antenna are shown in Figure 5. In the simulation, and test a return loss of -30.76 dB and -37 dB at resonant frequency 289.2 MHz and 284.4 MHz respectively were achieved. The analysis showed that the results of the return loss for measurement were better than simulation but the resonant frequency was slightly shifted to the lower side (289. 4MHz to 284.4 MHz). However the results for both simulation and test are quite similar and close to each other. The real and imaginary part of the impedance obtained at resonance frequency 289.2 MHz were 49.1ohm (real), 2.75 ohm (imaginary) respectively. The analysis shows that the real part of the impedance is close to 50 Ω and a smaller amount of external reactive component is to be introduced to nullify the reactive component in the desired range of frequency band. This indicates good impedance match from the load to the source.

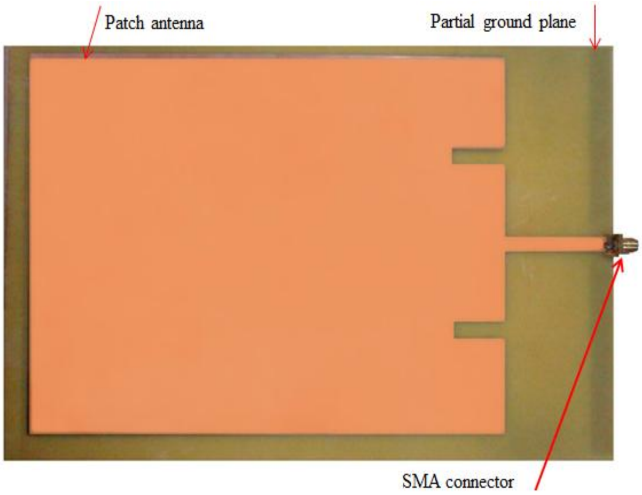

Fig. 4: Picture of fabricated wide band slotted patch antenna

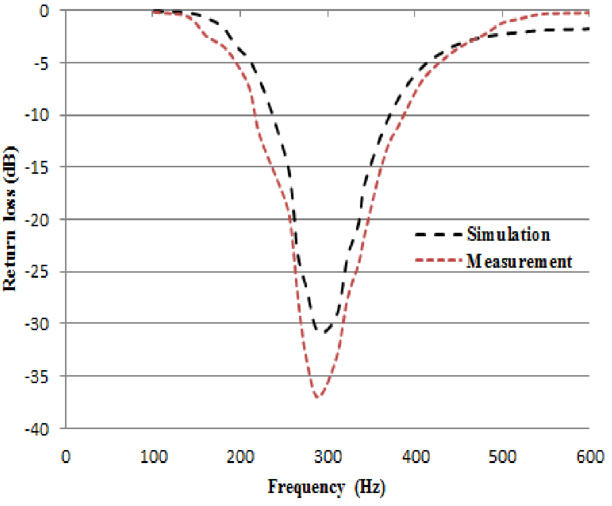

Fig. 5: Simulated and Measured results of return loss (dB) against frequency (MHz)

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Table II. Results of simulation and Test for return loss and impedance bandwidth.

Results	At -10dB f_l and f_h Frequency (MHz)	Impedance Bandwidth (MHz)	Return loss (dB)
Simulation	236.2 and 380.8	134.6(46.54% @289.2)	-30.6(289.2 MHz)
Measurement	219.5 and 385.5	166(58.37% @284.4)	37(284.4 MHz)

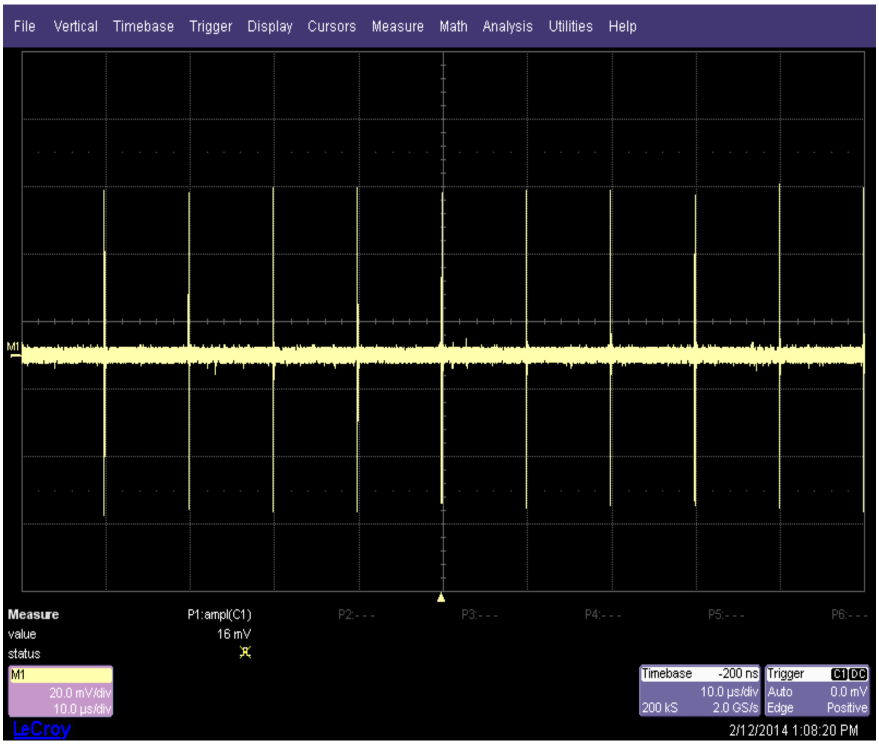

Fig. 6: Results of transient response at 70 cm distance

The summarized results of the return loss and impedance bandwidth for both simulation and measurement are shown in Table II. The analysis shows that the impedance bandwidth in measurement was better by 11.83 %. Also the s measured return los closely agrees with the simulated results of return loss. This clearly shows that the antenna was well suited for PD detection for the application of underground LV XLPE power cables.

One of the measured transient response (70 cm distance) obtained was shown in Fig. 6. The results obtained for test transient response (10 cm – 90 cm distance) were shown in Fig. 7. The analysis showed that the amplitude of the signal was decaying exponentially with an amplitude decay factor of 0.02/cm in air. One of the measured angular radiation distrubution (120 degree) obtained was shown in Fig. 8. The results of the measured angular radiation distrubution was shown in Fig. 9. The analysis showed hat the distrubution is failry constant from 0 to 180 degree.Hence this anenna behaved quite omnidirecional for the specified angles. This characteristics was suitabe for partial discharge detection in the field.

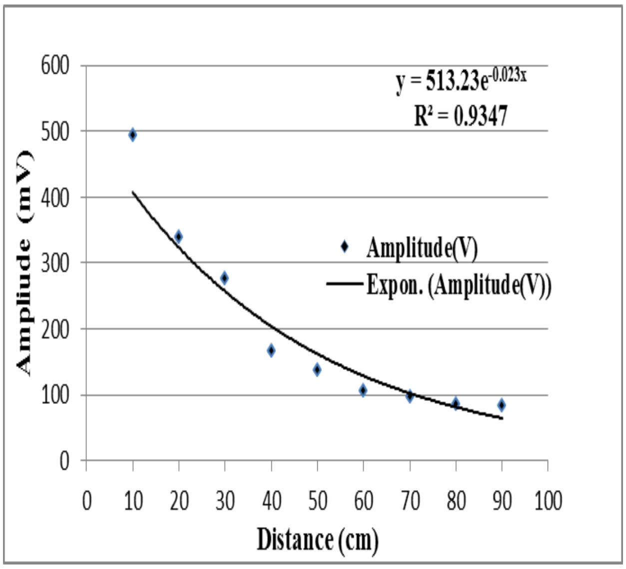

Fig. 7: Results of transient response: Amplitude verses Distance

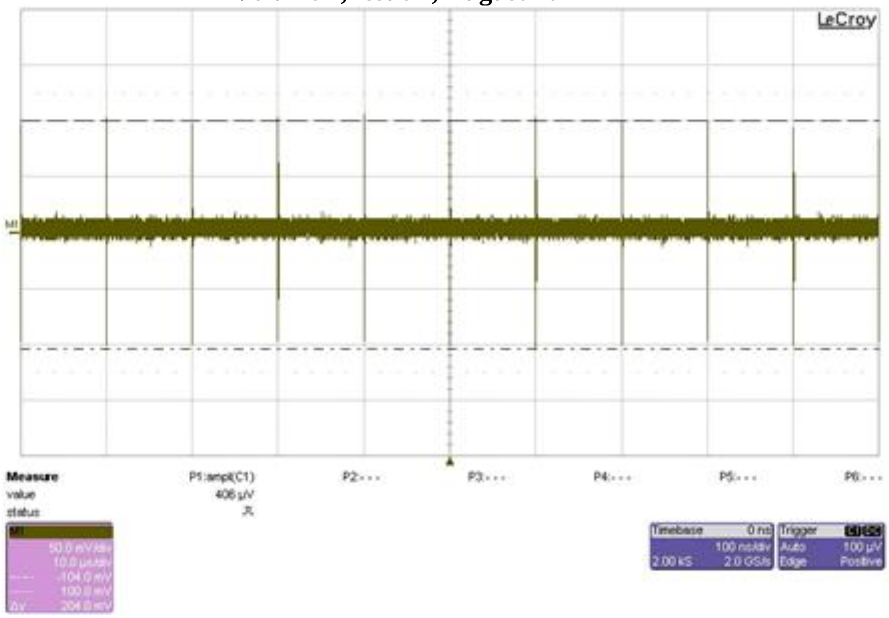

Fig. 8: Results of angular radiation distribution (120 degree)

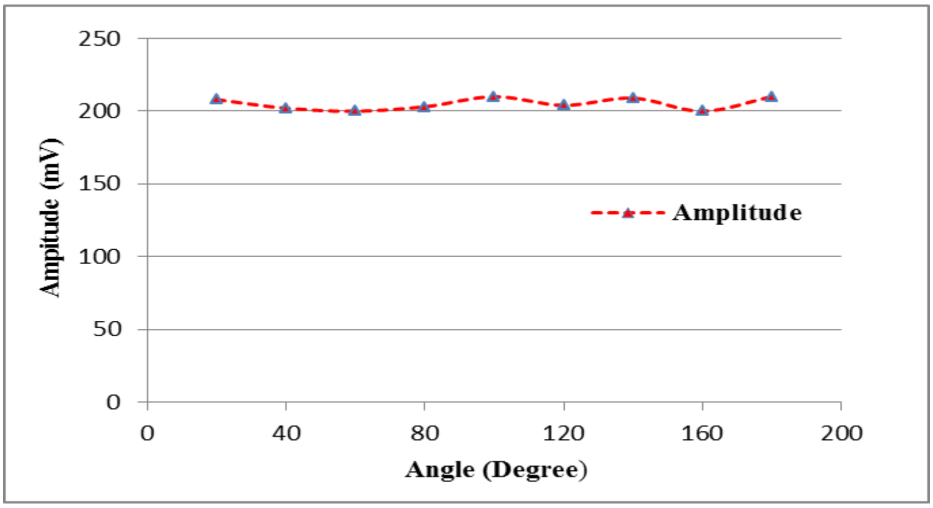

Fig. 9: Results of Radiation pattern: Amplitude verses angle (Degree)

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