Design and application of double layer bowtie antenna and single layer bowtie antenna as UHF sensors for partial discharge detection

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Abstract. The reliability of the power system cannot be achieved without good insulation quality of the high voltage apparatus. The Ultra-high frequency (UHF) method has been applied and proven to be accurate in detecting partial discharge (PD) signals emitted from the PD source in the form of electromagnetic waves. This paper discusses the design and application of double layer bowtie antenna and single layer bowtie antenna as UHF sensors for partial discharge detection in air insulation. The PD measurement results obtained by using the designed double layer bowtie antenna were compared with PD measurement results obtained by using the single layer bowtie antenna. The PD characteristics of induced EM waves detected by double layer bowtie antenna and single layer bowtie have been analysed. Based on the simulation results, the double layer bowtie antenna has a minimum return loss values of -31.54 dB and -33.43 dB, with corresponding resonance frequency values of 1.7 GHz and 2.7 GHz, with a total bandwidth of 602 MHz, and corresponding VSWR values of 1.04 and 1.05 while the measurement results by using Vector Network Analyser (VNA) shows that the designed double layer bowtie antenna has a minimum return loss of -20.2 dB, at a resonance frequency of 1.7 GHz, a bandwidth of 576 MHz and corresponding VSWR of 1.2. The single layer bowtie antenna has a bandwidth of 240 MHz, a minimum return loss of -24 dB, at a resonance frequency of 1.28 GHz, and a VSWR of 1.13 based on the simulation results while the single layer bowtie antenna has a bandwidth of 298 MHz, a minimum return loss of -23.32 dB, at a resonance frequency of 1.3 GHz, and a VSWR of 1.14 based on the measurement results by using VNA. The bowtie antennas were designed using the 3D-HFSS software with FR4-epoxy substrate type and later on were printed on the Printed Circuit Board (PCB). The PD measurement data were performed by using the applied voltage level of 7 kV. According to the antennas simulation results, antennas measurement results by VNA and PD measurement results, the double layer bowtie antenna has proven to be more sensitive than the single layer bowtie antenna.

1. Introduction
High voltage transmission has been chosen in an electric power system due to its capability to transfer a large amount of electrical power. Several key types of equipment such as the generator, transformer, GIS, cable and insulator play an important role in determining the reliability of the power system. The high voltage equipment in general contains gas, liquid or solid insulation. The failure of high voltage equipment may significantly contribute to the failure of the power system. Defects and a particular condition such as voids and protrusion in the insulation may lead to an extremely high electric field...
which can further result in the insulation failure. Particularly at interfaces between gas and solid and liquid insulations, the excessive electric field may cause the breakdown of the gas while the liquid and solid insulations are still able to withstand the electric field. This phenomenon is referred to as partial discharge (PD). Partial discharges in high voltage equipment for a long time may degrade the quality of the insulation and at the same time, the appearance of discharges can be used as a diagnostic signal for assessing the condition of the insulation in the high voltage equipment [1]. Diagnosis of PD in the early stage is needed to prevent the breakdown of the high voltage equipment. Partial discharge has been an important subject investigated by many researchers and discussion in many international conferences as well as international journals or transactions. In order to maintain the reliability and availability of the power system, it is needed to design the online measurement system by using the ultra-high frequency (UHF) method. UHF sensors are applied to detect the partial discharge phenomenon which releases energy in the form of electromagnetic (EM) wave during the discharge [1-2].

Ultra-High Frequency antenna is one of the UHF methods used to determine the quality of the insulation system of power apparatus. The main advantage of UHF PD detection system by using antennas is the capability to detect PD signal without prior shutdown of the power apparatus [2-11]. Therefore, it is advisable to perform the PD measurement system based on EM waves induced by PD. To do so, the suitable UHF sensor which is able to detect PD induced electromagnetic (EM) waves in ultra-wideband needs to be designed, manufactured and implemented in order to detect the released energy in the form of electromagnetic waves emitted from the PD source. In addition, the characteristics of PD induced EM wave measured by the sensors need to be investigated [2]. This paper discusses the design and application of double layer bowtie antenna and single layer bowtie antenna as UHF sensors for partial discharge detection. The experiment was conducted in air insulation by using the needle-plate electrode model as a PD source. The bowtie antennas were designed, simulated, fabricated and applied for partial discharge detection in air insulation. The 3D HFSS software with FR4_Epoxy substrate type was used to design the bowtie antennas and later on the bowtie antennas were printed on the Printed Circuit Board (PCB).

Various types of bowtie antennas have been developed in the previous researches for PD induced EM wave measurement [4-9]. The bowtie antenna has been chosen for PD detection in this research because it has broadband, good characteristic parameters, small shape, simple design, high radiation efficiency and it is cheap [5-6]. The basic characteristics of PD induced EM waves such as PDIV and PD waveform, PD patterns are reported in this paper. The PD measurement data were performed by using the applied voltage level of 7kV. The double layer bowtie antenna has shown a better performance antenna characteristic parameters and higher sensitivity in detecting partial discharge compared to the single layer bowtie antenna.

2. Design and simulation of double layer bowtie antenna

2.1. The geometry of double layer bowtie antenna

The double layer bowtie antenna was designed by using 3-D HFSS software and later on was printed on double layer PCB with FR4-epoxy substrate of the relative permittivity of 4.4 and substrate thickness of 1.6. The designed double layer bowtie antenna has a wing radius of 36mm and a flare angle of 120°. It was designed of a rectangular substrate whose dimension is 110 mm x 92 mm x 1.6 mm. The stub length (antenna prolongation) used is 46 mm. The double layer bowtie antenna was designed by modifying the edge of the antenna in order to improve the current density distribution on the antenna surface. The modification of the edge of the antenna was performed by creating a radius of curvature in the wing of the antenna and later on by cutting out the part whose low current density at the tip of the antenna. Figure 1 shows the initial design of a bowtie antenna with wing radius R1, the radius of curvature R2 and stub length h. The figure 2 shows the current distribution for the new design of double layer bowtie antenna with edge modification. Figure 3 shows the variation of radius of curvature against return loss of the designed double layer bowtie antenna. By changing the radius of curvature with sizes 21.5 mm, 22 mm, 22.5 mm and 23 mm, the optimum design was achieved by using the radius of curvature of 22.5 mm.
Based on the simulation results, the optimal design of double layer bowtie antenna has a minimum return loss values of -31.54 dB and -33.43 dB, with corresponding resonance frequency values of 1.7 GHz and 2.7 GHz, with a total bandwidth of 602 MHz, and corresponding VSWR values of 1.04 and 1.05.

**Figure 1.** The initial design of double layer bowtie antenna in the previous research.

**Figure 2.** The new design of double layer bowtie antenna with edge modification.

**Figure 3.** The radius of curvature against return loss.

2.2. **Fabrication of double layer bowtie antenna**

Figure 4 shows the fabricated double layer bowtie antenna. The double layer bowtie antenna was fabricated on double layer PCB with FR4-epoxy substrate.

**Figure 4.** Fabricated double layer bowtie antenna.

2.3. **Testing double layer bowtie antenna by using Vector Network Analyzer (VNA)**

After design and fabrication of double layer bowtie antenna, the antenna was tested by using the vector network analyzer (VNA) in order to measure some basic antenna parameters such as Return Loss (RL), Vector Standing Wave Ratio (VSWR), bandwidth, and the resonance frequency. Figure 5 shows the measurement setup of the designed double layer bowtie antenna by using the VNA. Figure 6 and Table 1 show the comparison between the simulation results of the designed double layer bowtie antenna and measurement results by using the VNA.
Figure 5. Measurement setup of double layer bowtie antenna by using VNA.

Figure 6. Comparison between simulation and measurement results for double layer bowtie antenna.

Table 1. Comparison between simulation results and measurement results for double layer bowtie antenna.

|        | RL1 (dB) | RL2 (dB) | BW1 (MHz) | BW2 (MHz) | FR1 (GHz) | FR2 (GHz) | VSWR1 | VSWR2 |
|--------|----------|----------|-----------|-----------|-----------|-----------|-------|-------|
| Simulation | -31.54   | -33.43   | 222       | 380       | 1.7       | 2.7       | 1.054 | 1.043 |
| Measurement | -20.2   | 576      |           |           | 1.7       |           | 1.21  |       |

3. Design and simulation of single layer bowtie antenna

3.1. The geometry of single layer bowtie antenna

The single layer bowtie antenna is designed on only one side of the substrate while the double layer bowtie antenna is designed on both sides of the substrate. In this research, the single layer bowtie antenna has been designed as a comparison sensor to the double layer bowtie antenna in order to see which bowtie antenna is more sensitive than the other in detecting partial discharge. The single layer bowtie antenna was also designed and simulated in a 3-D HFSS software with FR4-epoxy substrate whose relative permittivity is 4.4 and whose thickness is 1.6 mm. Later on the single layer bowtie antenna was fabricated on the single layer circuit board (PCB). The single layer bowtie antenna was designed by optimizing the antenna parameters such as wing radius, flare angle, and gap distance between the two patches of the antenna. The optimal designed was obtained by using a wing radius of 36 mm, a flare angle of 60°, a gap distance of 2 mm with a circular substrate whose diameter 84 mm. Figure 7 shows the geometry of the designed single layer bowtie antenna. Figure 8 shows the variation of wing radius
while figure 9 shows the variation of flare angle in the design optimization for the single layer bowtie antenna.

![Figure 7. Single layer bowtie antenna.](image)

**Figure 7.** Single layer bowtie antenna.

**Figure 8.** Variation of wing radius against return loss.

**Figure 9.** Variation of flare angle against return loss.

### 3.2. Fabrication of single layer bowtie antenna

After the simulation of the designed single layer bowtie antenna, the next step was to fabricate the bowtie antenna on single-layer PCB with FR4-epoxy substrate. Figure 10 shows the fabricated single layer bowtie antenna.

![Figure 10. Fabricated single layer bowtie antenna.](image)

**Figure 10.** Fabricated single layer bowtie antenna.

### 3.3. Testing single layer bowtie antenna by using the Vector Network Analyzer (VNA)

After design and fabrication of single layer bowtie antenna, the antenna was test by using the Vector Network Analyser (VNA) in order to measure some basic antenna parameters such as Return Loss (RL), Vector Standing Wave Ratio (VSWR), bandwidth, and the resonance frequency. Figure 11 shows the measurement setup of the designed single layer bowtie antenna by using the VNA.
Figure 11. Measurement setup of single layer bowtie antenna by using VNA.

Figure 12 and Table 2 show the comparison between the simulation results of the designed single layer bowtie antenna and measurement results by using the VNA. As can be seen, there is a little difference between the simulation and the measurement results.

Figure 12. Comparison between simulation and measurement results.

Table 2. Comparison between Simulation results and measurement results for single layer bowtie antenna.

| Results     | Return Loss (dB) | Bandwidth (MHz) | Resonance Frequency (GHz) | VSWR |
|-------------|------------------|-----------------|---------------------------|------|
| Simulation  | -25.15           | 240             | 1.28                      | 1.13 |
| Measurement | -23.32           | 298             | 1.30                      | 1.4  |

4. Application of designed double layer bowtie antenna and single layer bowtie antenna as UHF sensors for partial discharge detection in air insulation

After testing the designed double layer bowtie antennas by using the VNA, the bowtie antennas were implemented in detecting the PD in air insulation. The needle-plate electrode model was used as a PD source to generate the electromagnetic waves induced from the PD source. After that, the designed double layer bowtie and single layer bowtie antenna were placed near the PD source to capture the induced EM waves. The experiment for PD measurement in air insulation was conducted at the applied voltage level of 7 kV. Figure 13 shows the PD measurement circuit used to experiment.
4.1. Background noise
The measurement of background noise is conducted in order to obtain accurate data during the PD measurement experiment by distinguishing the noise signal from the PD signal [3]. Figure 14 shows the background noise ON detected by the designed double layer bowtie antenna, while Figure 15 shows the background noise detected by the single layer bowtie antenna. The peak-to-peak voltage (Vpp) for BGN ON detected by double layer bowtie antenna is 20mV while the Vpp magnitude for BGN ON detected by the single layer bowtie antenna is 16.8 mV.

4.2. Partial discharge inception voltage
The partial discharge inception voltage (PDIV) is another parameter for PD that is defined as the voltage at which the first PD will appear. The Figure 16 and 17 show the negative PDIV in a negative half cycle while the Figure 18 and 19 show the positive PDIV in a positive half cycle for both double layer bowtie antenna and single layer bowtie antenna. The applied voltage for negative PDIV detected by both double layer bowtie antenna and single layer bowtie antenna are 3.21 kV and 3.42 kV respectively while the applied voltage for the positive PDIV detected by both double layer bowtie antenna and single layer bowtie antenna are 4.24 kV and 4.47 kV respectively. The Vpp magnitude for negative PDIV detected by double layer bowtie antenna and single layer bowtie antenna are 26.13 mV and 14.02 mV respectively while the Vpp magnitude for positive PDIV detected by double layer bowtie antenna and single layer bowtie antenna are 44.9 mV and 19.33 mV respectively.
4.3. Partial discharge waveform

The PD waveform is another PD parameter that was measured during the experiment. Figure 20 and 21 show the shape of negative PD waveform while the Figure 22 and 23 show the positive PD waveform detected by the designed double layer bowtie antenna and single layer bowtie antenna. The PD measurement data was performed at 7 kV. As it can be seen on Figure 20 and 21, the Vpp magnitude for the negative PD waveform detected by double layer bowtie antenna and single layer bowtie antenna are 20.57 mV and 8.75 mV respectively while the Vpp magnitude for the positive PD waveform detected by double layer bowtie antenna and single layer bowtie antenna are 76.8 mV and 42 mV respectively as seen in Figure 22 and 23.
4.4. Partial discharge patterns

Figure 24 and 25 show the PD patterns detected by designed double layer bowtie antenna and single layer bowtie antenna at 7kV. The PD patterns is another PD characteristic commonly known as graph $\phi - q$ - n that shows the appearance of the phase angle where the PD occurs and the charge magnitude of the PD occurrence as well as the PD number.

5. Discussion and analysis

This research was about the design and application of the double layer bowtie antenna and single layer bowtie antenna as UHF sensor for partial discharge detection. The designed double layer bowtie antenna has been fabricated to operate in the UHF range of 300 MHz-3 GHz, with a minimum return loss, $RL \leq -10$ dB and a VSWR $\leq 2$ in order to be able to detect the PD signal which is the UHF signal [11]. The optimal design for the double layer bowtie antenna has a total bandwidth of 602 MHz according to the simulation results and a bandwidth of 576 MHz based on the measurement results by using the vector network analyser while the optimal design for the single layer bowtie antenna has a bandwidth of 240 MHz according to the simulation results and a bandwidth of 298 MHz based on the measurement results. As can be seen, there has been a little difference between the simulation and the measurement results. This difference may be caused by several factors which make the actual shape of the antenna to be not uniform between the design and fabrication results. The use of connectors can also be a factor that makes the results to be different. The next factor was the effect of environmental noise when testing was carried out. On the simulation side, the limitations of computer calculations can also be another factor that causes a difference between simulation results and measurement to the results obtained by using the VNA.

The experiment was conducted in air insulation by using the PD measurement circuit which include the voltage regulator, HV test transformer, limiting resistor, coupling capacitor, voltage capacitor
divider, needle-plate electrode model (PD source), digital oscilloscope and the UHF sensor (bowtie antenna) which is placed near the PD source 10cm away to capture the induced EM waves emitted from the PD source. The bowtie antenna is then connected to the oscilloscope in order to measure the PD signal. Before beginning the PD measurement experiment, the background noise was measured in advance in order to know the amount of noise that is present in the laboratory and in order to distinguish noise signal from the PD signal [3]. Another PD characteristic that was measured is PDIV. During the PDIV measurement, it has been seen that the designed double layer bowtie antenna needs lower applied voltage to detect the first PD in both negative and positive half cycles compared to the single layer bowtie antenna. For example, from the PD measurement, the applied voltage for negative PDIV by double layer bowtie antenna is 3.21 mV while the needed voltage for negative PDIV by single layer bowtie antenna is 3.42 mV. This means that the double layer bowtie antenna will detect the first PD earlier than the single layer bowtie antenna. Alternatively, the peak-to-peak voltage (Vpp) magnitude for negative PDIV detected by double layer bowtie antenna is 26.13 mV while the Vpp magnitude for negative PDIV detected by single layer bowtie antenna is 14.02 mV. This indicates that the double layer bowtie antenna is more sensitive than single layer bowtie antenna in detecting PD. According to the PD waveform measured by the designed bowtie antennas at 7 kV, the Vpp magnitude for PD waveform detected by double layer bowtie antenna is higher than the Vpp magnitude for PD waveform detected by the single layer bowtie antenna. For example, the Vpp magnitude for positive PD waveform detected by double layer bowtie antenna is 76.8 mV while the Vpp magnitude for positive PD waveform detected by single layer bowtie antenna is 42 mV. This confirms again that the double layer bowtie antenna has higher sensitivity in detecting PD than the single layer bowtie antenna.

6. Conclusion
This paper has discussed the design and implementation of double layer bowtie antenna and single layer bowtie antenna as UHF sensor for PD detection in air insulation. The following conclusion has been made.

- The designed double layer bowtie antenna has a better performance than the single layer bowtie antenna based on the antenna characteristic parameters, namely return loss (RL), bandwidth and vector standing wave ratio (VSWR).
- The double layer bowtie antenna and single layer bowtie antenna were designed by using 3-D software and later on fabricated on the PCB with FR4-epoxy substrate whose relative permittivity is 4.4. After fabrication, the designed bowtie antennas were tested by using the Vector Network Analyzer (VNA) to measure some basic antenna characteristic parameters.
- According to the simulation results, the designed double layer bowtie antenna has a total bandwidth of 602 MHz while the single layer bowtie antenna has a bandwidth of 240 MHz.
- The designed double layer bowtie antenna and single layer bowtie antenna have been implemented to detect partial discharge (PD) signals in air insulation by measuring the PD characteristics such as background noise, PDIV, PD waveform and PD phase patterns.
- The designed double layer bowtie antenna is more sensitive than the single layer bowtie antenna in detecting PD in air insulation.

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