Design and fabrication of double layer bowtie antenna with modification of wing edge as UHF sensor for partial discharge detection in air insulation

J P Uwiringiyimana* and U Khayam
School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Bandung, Indonesia

*upeter1@yahoo.fr

Abstract. Partial discharge (PD) has been used as a reliable diagnostic technique for High voltage equipment. UHF methods have been widely applied for the detection of electromagnetic waves emitted from PD source in High Voltage equipment. EM wave propagation produced by PD can be detected by using UHF sensors. This paper discusses the new design of double layer bowtie antenna with modification of the wing edge of the antenna as a UHF sensor for PD detection in air insulation. The double layer bowtie antenna was designed by using FR4-epoxy substrate type and later on printed on PCB. The 3D-HFSS software was used to design the bowtie antenna. Based on simulation results of double layer bowtie antenna, the optimum design for PD measurement was obtained with a minimum return loss (RL) of -34.7 dB, the bandwidth of 560 MHz, and Voltage Standing Wave Ratio (VSWR) of 1.03. Based on the measurement results for the designed bowtie antenna by using the Vector Network Analyser (VNA), the bowtie antenna has a return loss of -14 dB, the bandwidth of 555 MHz, and VSWR of 1.05. The designed UHF double layer bowtie antenna is capable of detecting PD in UHF range since PD signal have a frequency range of 300 MHz - 3 GHz.

1. Introduction
High voltage insulation system plays a vital role in high voltage equipment used in an electric power system. Electrical insulation has the main role to withstand the high electric field between phase conductors or between phase and neutral conductors [1]. In excessive high electric field due to the appearance of field enhancement sites like void or protrusion, Partial Discharge (PD) may occur. The presence of PD in the electrical insulations may indicate the insulation aging and in the long term, this may further reduce the integrity of the insulation leading to the failure of the equipment. Diagnosis of PD in the early stage is needed to prevent the breakdown of the high voltage equipment. The failure of high voltage equipment may significantly contribute to the failure of the power system. Several key high voltage types of equipment such as the generator, power transformer, GIS, power cables and insulators play an important role in determining the reliability of the power system. The high voltage equipment in general contains gas, liquid or solid insulation [1-2]. Defects and a particular condition may lead to an extremely high electric field. 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 as Partial Discharge (PD). Partial discharges in high voltage equipment for 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 inside the high voltage equipment. Partial discharge has been an important subject investigated by many researchers and discussed in many international conferences as well as international journals or transactions. Diagnosis of PD is considered to highly represent the actual condition of the equipment [1-10]. PD detection is the first step in the power apparatus diagnosis. In order to maintain the reliability and availability of the power system, it is needed to design the online PD measurement system. PD occurring in power apparatus releases energy in various forms such as light emission, acoustic wave, heat, and the electromagnetic wave which can be detected by the suitable sensors [2]. The UHF method is one of the methods used to detect the PD signal. The UHF antennas are used to detect the PD signal in high voltage equipment [2-11]. They can be used as external sensors to detect PD signal online by placing the antennas near the high voltage equipment [2]. Different types of antennas have been developed in previous many kinds of research to detect PD in high voltage equipment [2-9]. PD signal has a frequency range of 300 MHz - 3 GHz [5-11]. Bowtie antenna is one example of the antennas types that have been developed to detect PD in air insulation [5-10]. In this paper, the UHF double layer bowtie antenna with modified wing edge has been designed and fabricated to detect partial discharge in air insulation. The designed double layer bowtie antenna has a minimum return loss value of -34.7 dB and a bandwidth of 560 MHz based on the simulation results. Based on the measurement results by using a vector network analyser, the designed double layer bowtie antenna has a return loss value of -14.7 dB and a bandwidth of 555 MHz.

2. Design and simulation of bowtie antenna

2.1. Previously designed double layer bowtie antennas

The new design of double layer bowtie antenna is based on the previous researches on bowtie antennas [8-9]. However, the previous design of bowtie antenna has a smaller bandwidth and greater return loss. The first design was double layer bowtie antenna whose bandwidth is 345 MHz and a return loss of -13.17 dB while the second design of bowtie antenna in the previous research was double layer bowtie antenna with edge modification whose bandwidth is 370 MHz and a return loss of -24.7 dB [8-9]. The new design of double layer bowtie antenna with modification of wing edge was designed to have the lower minimum return loss and a wider bandwidth compared to two designs that were previously designed. The designed antenna is the double layer bowtie antenna with a flare angle of 60° and a wing radius of 36 mm. This double layer bowtie antenna has been designed based on the modification of the edge of the antenna. Figure 1 represents the design of the bowtie antenna in the previous research. The design of the bowtie antenna was simulated in a 3D-HFSS software and fabricated on a double-layer PCB with FR4-epoxy substrate material whose relative permittivity 4.4 and the substrate thickness of 1.6 mm.

![Figure 1. The initial design of double layer bowtie antenna in previous research [8].](image1)

![Figure 2. Design of bowtie antenna with edge modification in previous research [9].](image2)

The initial design of double layer bowtie antenna in the previous research has the following specification parameters: Wing radius = 40 mm, gap distance = 2.0 mm, flare angle = 60°, substrate dielectric = 4.4, stub = 23 mm.
2.2. Newly designed double layer bowtie antenna with modification of wing edge

The design of double layer bowtie antenna with modified wing edges has been designed based on the initial shape of the bow-tie antenna design in the previous research. The new design of double layer bowtie antenna was simulated with FR4-epoxy substrate material whose thickness is 1.6 mm. The optimal designed double layer bowtie antenna has a flare angle of 60° with wing radius of 36 mm, a rectangular plane substrate of 70 mm by 40 mm and with a stub length of 20 mm. In this study, the modifications were made on the edge of the double layer bowtie antenna by cutting the part of the antenna wing with low current destiny in order to increase current distribution on the surface of the antenna. During the modification of the wing of the bowtie antenna, the edge of the antenna was curved to the extent that the patches of bowtie antenna have a concave form based on the radius of curvature created in the wing of the antenna. The optimal design by modification of the wing edge of the bowtie was achieved by varying the radius of the curvature of the antenna wing. Figure 3 shows the modification of the wing edge of the double layer bowtie antenna based on the initial design of the bowtie antenna in the previous research.

![Figure 3. Modification of wing edges of the double layer bowtie antenna.](image)

2.2.1. Optimization of wing radius for double layer bowtie antenna. The designed double layer bow-tie antenna with wing edge modification was designed by optimizing the wing radius where the optimal design has a wing radius of 36 mm instead of 40 mm of the initial design in the previous research [8]. The variation of wing radius has influenced return loss and bandwidth of the bowtie antenna. Figure 4 represents the optimization of wing radius based on the variations from 32 mm, 34 mm, 36 mm and 40 mm against return loss value, bandwidth and resonance frequency for each wing radius value used in the simulation. The effect of changes in wing radius is seen in the width of the bandwidth produced as well as in return loss of the antenna. The optimal design of double layer bowtie antenna with a modified wing edge is achieved by using a wing radius of 36 mm long. This wing radius of 36 mm gives a return loss (RL) value of -34.7 dB, the bandwidth of 560 MHz at a resonance frequency of 2.4 GHz. Table 1 shows the RL, bandwidth and resonance frequency of four samples of wing radius used in the simulation.

![Figure 4. Wing radius against return loss (RL) value.](image)
Table 1. Simulation results based on variation of wing radius.

| Wing radius (mm) | Bandwidth (MHz) | Return Loss (dB) | Resonance Frequency (GHz) |
|------------------|-----------------|------------------|---------------------------|
| 32               | 459             | -28.2            | 2.4                       |
| 36               | 560             | -34.7            | 2.4                       |
| 40               | 378             | -17.9            | 2.3                       |
| 44               | 270             | -12.7            | 2.14                      |

2.2.2. Optimization of stub length for double layer bowtie antenna. After optimization of the wing radius, the next step was to find the optimal design by variations of stub lengths. Figure 5 shows the variations of stub length from 20 mm, 23 mm, 25 mm, and 27 mm. The stub length of 20 mm gives optimal result compared to other stub lengths used in the simulation. As it can be seen from the simulation results based on the variation of stub length of the antenna in Figure 5, the optimal design of double layer bowtie antenna with modification of antenna tip was obtained by using the stub length of 20 mm due to its minimum return loss (RL) of -34.7 dB with a corresponding bandwidth of 560 MHz. Table 2 shows the RL, bandwidth and resonance frequency of four samples of stub length used in the simulation.

Table 2. Simulation results based on variation of stub length.

| Stub length (mm) | Bandwidth (MHz) | Return Loss (dB) | Resonance Frequency (GHz) |
|------------------|-----------------|------------------|---------------------------|
| 20               | 560             | -34.7            | 2.4                       |
| 23               | 410             | -35.9            | 2.23                      |
| 25               | 360             | -28.6            | 2.04                      |
| 27               | 350             | -34.2            | 2.0                       |

2.2.3. Variation of the radius of curvature for double layer bowtie antenna. The modification of double layer bowtie antenna was conducted based on the variation of radius of curvature of the patch of the antenna. The radius of curvature used in the simulation of double layer bowtie antenna is of four samples namely, 16 mm, 16.5 mm, 17 mm, and 17.5 mm. The simulation results for double layer bowtie antenna based on the modification of the wing edges are shown in Figure 6. The radius of curvature of 17.5 mm has demonstrated a significant optimal design where the associated minimum RL is -34.7 dB, the bandwidth of 560 MHz and resonance frequency of 2.4 GHz. Table 3 shows the RL, bandwidth and resonance frequency of four samples of the radius of curvature used in the simulation.
Figure 6. Radius of curvature against return loss (RL).

Table 3. Simulation results based on variation of radius of curvature.

| Radius of curvature | Bandwidth (MHz) | Return Loss (dB) | Resonance Frequency (GHz) |
|---------------------|-----------------|------------------|---------------------------|
| 16mm                | 450             | -22.5            | 2.36                      |
| 16.5mm              | 420             | -23.7            | 2.36                      |
| 17mm                | 490             | -31              | 2.35                      |
| 17.5mm              | 560             | -34.7            | 2.4                       |

2.2.4. Current distribution for double layer bowtie antenna. The modification of the bowtie antenna was performed based on the analysis of the current distribution on the antenna surface. The edge of the bowtie antenna had the lowest current density. The bowtie antenna has been modified by cutting the edge of antenna wing which was having a low current distribution. This was done in such a way that the antenna patch has a concave form in order to have a uniform current density distribution on the surface of the antenna. To make a concave form in the antenna wing, a radius of curvature was created in the wing of the antenna and four variations of the radius of curvature have been used in simulation as it is indicated in Figure 7. The radius of curvature of 17.5 mm produces high current distribution compared to radius of curvatures of 17 mm, 16.5 mm, and 16mm.

Figure 7. Current distribution for the bowtie antenna with a variation of radius of curvatures.
Based on the simulation results for the double layer bowtie antenna with modification of the wing edge of the antenna with optimization of wing radius, stub length and radius of curvature, the following specifications parameters for the double layer bowtie antenna were confirmed for the optimal design as follows: Wing radius = 36 mm, gap distance = 2 mm, flare angle = 60°, dielectric substrate = 4.4, stub length = 20 mm, radius of curvature = 17.5 mm, substrate material: FR4 epoxy, substrate thickness = 1.6 mm, substrate form = Rectangular, Substrate dimensions = 70 mm x 40 mm.

3. Fabrication of double layer bowtie antenna with wing edge modification

After design and simulation of the double layer bowtie antenna with wing edge modification, the next stage was to fabricate the bowtie antenna. The double layer bowtie antenna was fabricated on the double layer printed circuit board (PCB) with FR4-epoxy substrate. Figure 8 shows the fabricated UHF double layer bowtie antenna for PD detection.

Figure 8. Fabricated double layer bowtie antenna.

4. Testing the designed bowtie antenna by using Vector Network Analyser

After fabrication of double layer bowtie antenna with modified wing edges, the next stage was to test the designed bowtie antenna by using the vector network analyser (VNA). The purpose of this testing was to measure some of the antenna parameters such as return loss (RL), bandwidth, vector standing wave ratio (VSWR) and resonance frequency. Figure 9 shows the measurement setup with the VNA. Table 4 shows the comparison between simulation results by using HFSS and the measurement results obtained by using the VNA. Figure 10 shows the comparison between simulation and measurement results of return loss for the designed bowtie antenna while Figure 11 shows the comparison between simulation and measurement results of VSWR for the designed bowtie antenna.

Figure 9. Measurement setup for the antenna with VNA.
Table 4. Comparison between simulation results and measurement results for the designed bowtie antenna.

| Results       | Bandwidth (MHz) | Return Loss (dB) | VSWR | Resonance Frequency (GHz) |
|---------------|-----------------|------------------|------|--------------------------|
| Simulation    | 560             | -34.7            | 1.03 | 2.4                      |
| Measurement   | 555             | -14              | 1.5  | 2.5                      |

Figure 10. Comparison of simulation and measurement of RL for a designed bowtie antenna.

Figure 11. Comparison of simulation and measurement of VSWR for a designed bowtie antenna.

5. Partial discharge detection in air insulation by using the designed double layer bowtie antenna

After testing the designed double layer bowtie antenna by using the VNA, the antenna was implemented in detecting the PD in air insulation. The needle-plate electrode model was used as PD source to generate the electromagnetic waves captured by the designed double layer bowtie antenna placed near the PD source. The experiment for PD measurement in air insulation was performed at three different applied voltage levels namely, 5 kV, 6 kV and 7 kV. Figure 12 shows the PD measurement circuit used to conduct the experiment.

5.1. Background noise
Background noise is the amount of noise present in the laboratory before changing gradually the applied voltage. The measurement of background noise is conducted in order to obtain accurate data during the PD measurement experimental. There are two kinds of background noise, namely background noise OFF (BGN OFF) which is observed on the oscilloscope when the power source is still in OFF mode and
background ON that is found on the oscilloscope when the power source is switched ON. The background noise is the number of noise signals that can originate from external systems or from the internal system itself of the measurement circuit. The background noise observed on the oscilloscope comes from the environment around the experimental circuit, for example, from the car engines or due to electromagnetic interference of some equipment in the laboratory. The background noise measurement is conducted before the PD experiment to distinguish the noise signal from PD signal [3]. Figure 13 and 14 shows the background noise ON for the designed antenna and for the RC detector (comparison sensor). The peak-to-peak voltage (Vpp) magnitude for BGN ON detected designed double layer bowtie antenna and RC detector are 24 mV and 12 mV respectively.

5.2. Partial discharge inception voltage

The partial discharge inception voltage (PDIV) is the possible minimum voltage needed to make the first PD signal to appear. Figure 15 and 16 show the negative PDIV (first PD which occurs in a negative half cycle) while the Figure 17 and 18 show the positive PDIV (first PD signal which occurs in a positive half cycle) for both antenna and RC. The Vpp magnitude for negative PDIV detected by double layer bowtie antenna and RC detector are 15.2 mV and 33.3 mV respectively while the Vpp magnitude for positive PDIV detected by double layer bowtie antenna and RC detector are 36.35 mV and 188.3 mV respectively. Alternatively, the needed applied voltage for negative PDIV detected by double layer bowtie antenna and RC detector are 3.36 mV and 2.84 mV respectively and the applied voltage for positive PDIV are 4.4 mV and 4.0 mV respectively.

Figure 13. BGN ON for bowtie antenna.  
Figure 14. BGN ON for RC detector.  
Figure 15. Negative PDIV for bowtie antenna.  
Figure 16. Negative PDIV for RC detector.
5.3. Partial discharge waveform
The PD waveform is another PD parameter that was measured during the experiment. Figure 19 and 20 show the shape of negative PD waveform while Figure 21 and 22 show the positive PD waveform detected by the designed antenna and RC detector. The PD measurement data was performed at 5 kV. As it can be seen in figures below, the Vpp magnitude for negative PD waveform detected by the designed double layer bowtie antenna and RC detector are 10 mV and 27.4 mV respectively while the Vpp magnitude for positive PD waveform detected by the designed double layer bowtie antenna and RC detector are 32 mV and 437.2 mV respectively.

5.4. Partial discharge patterns
The PD patterns is another PD characteristic which indicates the PD charge magnitude, PD phase and PD number. In other words, it is a graph $\phi - q - n$ that shows the appearance of the phase location
where PD occurs and the charge magnitude of the PD occurrence. Figure 23 and 24 show the PD patterns detected by the designed bowtie antenna and RC detector at 5 kV.

![Figure 23. PD patterns by bowtie antenna.](image1)
![Figure 24. PD patterns by RC detector.](image2)

6. Discussion and analysis
The designed double layer bowtie antenna with modified wing edges was designed based on the initial design in the previous research [8-9]. The optimal design for double layer bowtie antenna has a wider bandwidth of 560 MHz, a minimum return loss of -34.7 dB and a resonance frequency of 2.4 GHz based on the simulation results while in the previous research, the double layer bowtie antenna that was designed had only a bandwidth of 345 MHz and a return loss of -13.17 dB, and a resonance frequency of 1.8 GHz. It is clearly seen that the new design of double layer bowtie antenna has been improved to have better sensitivity for PD detection in air insulation in the ultra-high frequency range, 300 MHz - 3 GHz [11]. After design and simulation for the new design of the bowtie antenna, the antenna was fabricated on double layer PCB with FR4-epoxy substrate. After fabrication of the double layer bowtie antenna with modification of wing edges, the antenna was tested by using the vector network analyser (VNA) to measure some antenna parameters such as, return loss (RL), bandwidth, VSWR and resonance frequency of the antenna. The antenna measurement by using VNA as shown that the designed antenna has a bandwidth of 555 MHz, return loss of -14 dB and a resonance frequency of 2.5 GHz. There has been a little bit difference between simulation results by using HFSS and measurement results by using VNA due to some errors that might have happened during the fabrication of the antenna. The fabricated antenna was applied in detecting PD in air insulation by using RC detector as a comparison sensor. The designed double layer bowtie antenna was used to measure BGN, PDIV, PD waveform and PD phase patterns. According to the PD phase patterns, the designed double layer bowtie antenna detect PD signals in the same patterns as the RC detector. According to the PDIV measurement, it can be said that the RC detector detects the first PD signal earlier than the designed double layer bowtie antenna because RC detector needs lower applied voltage for both negative PDIV and positive PDIV compared to the double layer bowtie antenna which needs a little bit higher voltage to detect negative PDIV. This indicates that the RC detector is more sensitive than the double layer bowtie antenna because RC detector is directly connected to the PD measurement circuit and it uses the electrical method while the bowtie antenna is not connected to the circuit, it is only placed near the PD source to detect the induced EM waves for PD source. So, the two sensors use a different method in detecting PD. Bowtie antenna uses a UHF method (non-electric) while the RC use an electric method. This is one of the reasons that makes RC detector more sensitive than an antenna.

7. Conclusion
The designed double layer bowtie antenna with modification of wing edges has proven to detect PD in air insulation. The radius of curvature created in the wing of the bowtie antenna has influenced the antenna characteristics, namely return loss (RL), bandwidth and vector standing wave ratio (VSWR). During the PD measurement, the designed double layer bowtie antenna has proven to detect PD in air
insulation in the same PD patterns as the RC detector except for a little bit different in the sensitivity. The RC detector has higher sensitivity compared to the designed double layer bowtie antenna since RC detector uses an electrical method in detecting PD while Antenna uses UHF method.

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