Preliminary Studies on Circular and Square Loop Antenna Design for Partial Discharge Detection

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Abstract. The objective of this study was to design and compare the performance of geometrical shape circular loop antenna and square loop antenna towards partial discharge (PD) detection. PD is an early stage of fault occurs before major breakdown may due to electrical insulation failure, natural disaster and mis-operation. The electromagnetic (EM) signal radiated from PD event was measured and analyse over a range of frequency 300 MHz – 3 GHz. A circular and square loop antennas were modeled using CST Microwave Studio software based on the PD’s characteristics. The loop antenna parameters such as circumference, radius and end to end gap were varied accordingly to assess the effect of return loss and radiation pattern. The results revealed that the circular loop antenna had the greatest influence towards PD detection than a square antenna.

1. Introduction

PD detection is an important technique that can be used to predict the life of power equipment before major breakdown happens. PD causes many forms of physical phenomenon such as EM waves, light, and acoustic wave. EM wave propagates in radial directions and capable of being detected by ultra-high frequency (UHF) antennas beginning at 300MHz to 3GHz [1]. In operating systems, the occurrence of PD depends on the breakdown voltage of gas which is at 3kV/cm and higher. The insulation failure in gas insulated switchgear (GIS) will cause a serious problem to electrical power distribution system. One of the basic roles of switchgear is protection, which is interruption of short-circuit and overload fault currents while maintaining service to unaffected circuits. To avoid the insulation failure, PD must be detected as early as possible. The main problem in detecting the PD is to pinpoint the exact location of the PD occurred. This is because the PD location is unpredictable because of the noise from other sources such as discrete spectral interference and also white Gaussian noise [11]. Although there are many PD sensors have been developed nowadays, there is certain part of the GIS cannot be penetrated by the sensors [4]. This limit the overall PD measurement in GIS. Therefore, numerous types of sensors such as bowtie antenna, dipoles antenna, end fires antenna, slot antenna, spiral antenna and triangular loop antenna [10] have been developed to detect and measure EM wave induced by PD [2-4].

Nowadays, there are several antennas that been used for PD detection has poor efficiency. As an example, small loop antenna has poor efficiency performance in high frequency application [3]. Different shape of antenna can lead to different value of data collected [5]. This can affect the precision of data that have been collected for any application of the antenna. There are some criteria that must be focused in designing the antenna such as the characteristic, the design and the application of the antenna. Therefore, it is sensible to modify the antenna’s criteria to improve the antenna performance in order to realise the full potential of the antenna designed.
In this work, loop antenna has been choosing because it has good characteristic, simple, small and cheap [6]. Two geometrical shapes were designed using CST Microwave Studio software that is circular and square loop antennas. The goal was to model both shapes of antennas based on the range of radiation frequency between 300 MHz to 3 GHz that have good detection for potential use in PD measurement. Then, the simulation methods used to model the loop antennas, the factors investigated and the characterisation methods are described.

2. Antenna Design and Configuration
The loop antenna has various types of design, shape and form. In this study, the main focused is on circular and square shape loop antenna. The performances of both antennas are compared to determine the most suitable and reliable antenna to be used as PD detection sensor. Both circular and square loop antenna are being designed and analysed by using CST Microwave Studio Suite software.

The initial design represents selection of parameters. Circular and square loop antennas design are being focused on radius of loop, \( r_i \), thickness, the gap between end to end of the antenna, \( g \), and the number of loops, \( N \). The number of turns and the electric field strength are both inversely proportional to the square of signal wavelength and the distance between the antenna and PD source while the magnetic field strength and electric field stress are directly proportional to loop area [9]. Once the parameters have been finalised, the antennas are drawn in the CST software. The parameters of antenna are being match into 3D Cartesian plane which \( x \), \( y \) and \( z \) axis represent the length, width and thickness of the antenna.

The parameters are being set as variable that to be varied to determine the most suitable and optimal design of loop antenna for PD detection. Every parameter is analysed and calculated with references from other researches. Based on studies, the range of frequency for EM wave to induced PD in GIS is from 300 MHz to 3 GHz [1]. On the other hand, the antenna also need to radiates in between range of 700MHz-2000MHz because the corona types of PD which is being focused in this project has the emission within those range of frequency [6].

| Table 1 Parameters for circular and square (constant for Loop A) |
|---------------------------------------------------------------|
| Circumference, \( C_o \) (mm)       | Antenna’s radius, \( r_i \) (mm) | End to end gap, \( g \) (mm) |
|------------------------------------|----------------------------------|-----------------------------|
| 238.76                             | 38                               | 24                          |

| Table 2 Parameters for circular and square (constant for Loop B) |
|---------------------------------------------------------------|
| Circumference, \( C_o \) (mm)       | Antenna’s radius, \( R_i \) (mm) |
|------------------------------------|----------------------------------|
| 320.44                             | 51                               |

Figure 1 and Figure 2 show the model of circular and square loop antenna that being designed. Boths have been designed with inner loop antenna which named as Loop A and outer loop antenna which named as Loop B. Table 1 and Table 2 show the parameters for circular and square antenna in 2 different conditions.
3. Results and Discussion

Two distinct cases were investigated notably. Firstly, by varying the thickness of inner loop antenna for single loop and secondly, by varying the thickness of outer loop antenna for double loop.

3.1 Varying the thickness of inner loop antenna, a. (single loop)

In this section, the thickness, $a$, of single loop antenna (Loop A), as shown in Figure 3 was varied in increment of 2 mm. Based on observation in Table 3 and the figures in Appendix A, varying the thickness of Loop A shows in figure A1, A2 and A3, that the larger the thickness of Loop A, the lower $S_{11}$ values which lead to higher radiation power generated by the antenna. This is because, when the size of antenna increase, the higher the current flow through the antenna $[8]$. This is applied to both circle and square antenna. The result also shows that the square antenna has lower return loss compare to circular antenna. The return loss, $S_{11}$ is still not below than -10 dB and the resonant frequency for both antennas is between 800 MHz to 1.5 GHz which means still far than the result needed for PD detection. Thus, the modification had been done by adding outer loop to both antennas.

3.2 Varying the thickness of outer loop antenna, b, (double loop antenna)

| Thickness of Loop A, $a$ (mm) | Circle loop Return loss, $S_{11}$ (dB) | Square loop Return loss, $S_{11}$ (dB) |
|-----------------------------|----------------------------------------|-----------------------------------------|
| 2                           | -7.1214                                | -7.3173                                 |
| 6                           | -7.4565                                | -7.8423                                 |
| 10                          | -7.9848                                | -8.248                                  |

Figure 1. (a) Circular antenna (inner loop) (b) Circular antenna (outer loop)

Figure 2. (a) square antenna (inner loop) (b) square antenna (outer loop)

Figure 3 (a) Circular (b) square for single loop antenna
Meanwhile, the thickness of Loop B, \( b \) on double loop antenna as shown in Figure 4 was varied in increment of 2 mm to get the return loss of the antenna while fixing inner loop antenna or Loop A to 2 mm, 4 mm and 6 mm of thickness to demonstrate the effect of varying the outer loop.

![Figure 4](a) Circular (b) square for double loop antenna

### Table 4 Return loss (dB) (thickness of Loop B 2 mm)

| Thickness of Loop B (mm) | Circle loop Return loss, \( S_{11} \) (dB) | Square loop Return loss, \( S_{11} \) (dB) |
|--------------------------|---------------------------------------------|------------------------------------------|
| 2                        | -5.798                                      | -6.2309                                  |
| 6                        | -8.0145                                     | -10.6708                                 |
| 10                       | -12.1899                                    | -20.8974                                 |

Based on Table 4 and the figures from appendices B as in B1, B2 and B3, the result shows that the operation of both antennas are affected by added the outer loop where both the return loss of antenna lower than -10dB. The performance of antenna is slightly increased. This proved that the number of loops will affect the performance of antenna. In term of return loss, the performance of square antenna is better than circular loop antenna. On the other hand, the increasing of Loop B’s thickness, the return loss will be decreased. This will lead to increasing of the radiation power for both patterns. But, from the simulation result in term of resonant frequency, the square is far from required resonant frequency for detecting PD which is 900 MHz compare to circular loop antenna. The circular antenna is maintaining its resonant frequency constantly in between 1 GHz to 1.200 GHz. Furthermore, there are so many losses from both antennas that can be seen in simulation results.

### Table 5 Return loss (dB) (thickness of Loop B 4 mm)

| Thickness of Loop B (mm) | Circle loop Return loss, \( S_{11} \) (dB) | Square loop Return loss, \( S_{11} \) (dB) |
|--------------------------|---------------------------------------------|------------------------------------------|
| 2                        | -6.8187                                      | -13.2387                                  |
| 6                        | -10.2889                                     | -13.521                                  |
| 10                       | -14.5916                                     | -20.6329                                 |

Based on the Table 5 and figures in Appendices C1, C2 and C3, result shows that the return loss decreasing as the thickness of Loop B is varied while loop A is fixed to 4mm. The return loss for square antenna was increasing when the loop B changes from 2 to 4 but decreasing after that. From Table 4.3, it can be seen, that return loss of square loop is greater compare to circular loop. But in term of resonant frequency, the circular antenna is nearer to 900 MHz and more stable compare to square loop antenna. The resonant frequency for circular loop antenna is maintained in range of 900 MHz to 1 GHz. While square loop antenna’s resonant frequency is around 700 MHz to 800MHz at first when Loop B is at 2 mm to 8 mm, but the resonant frequency shift towards 1600MHz to 1.7 GHz when Loop B is at 10 mm. beside from the simulation result also shows the losses for both antennas is high and the requirement of return loss is not achieved. Besides, both antennas still have more losses based on simulation result. So, the Loop B is being varied as the Loop A of antenna is fixed at 6mm.
Table 6 Return loss (dB) by varying the thickness of Loop B while fixing the Loop A to 6 mm

| thickness of Loop B (mm) | circle loop Return loss, $S_{11}$ (dB) | square loop Return loss, $S_{11}$ (dB) |
|-------------------------|---------------------------------------|---------------------------------------|
| 2                       | -20.5514                              | -12.1528                              |
| 4                       | -25.4437                              | -15.9185                              |
| 6                       | -36.3724                              | -18.9359                              |

Table 6 shows the results that obtained from simulation when Loop A been fixed to 6 mm. the simulation on the $S_{11}$ can be refer in appendix D until D3. The return loss decreases as the thickness of loop B increases. The final design is being able to be achieving when the circle antenna able to achieve the return loss lower than -35 dB and its resonant frequency is at 921MHz at Loop B 6 mm, which is suitable to be used for PD detection. The circular antenna also has no significant losses. As for square loop antenna, at the same parameters, the square loop antenna only able to achieve return loss at around -19 dB and its resonant frequency is at 761 MHz. Although square antenna also can be used as PD detection as it already achieves return loss lower than -10 dB. From the result also, the square antenna still has a significant loss compare to circular antenna.

From the simulation done in previous studies, finally, parametric simulation experiments were carried out for determining the best criteria to be used as PD detection antenna compare to others. The thickness of Loop A is at 6 mm while the thickness of Loop B is also at 6 mm. The result comparison has been done in Figure 5. The variation of antenna loop thickness on either inner loop or outer loop and addition of outer loop plays a huge role in obtaining the final design of loop antenna for this project. It is proved that, the thicker the antenna, the lower the return loss of antenna. Then, the higher the radiation power of the antenna [8].

Figure 5. Final design comparison of circular and square loop antenna

3.3 3-D radiation pattern for gain

The 3-D radiation pattern shows the power of EM wave radiated by an antenna. Based on the result shown in Figure 6, the gain is being measured on the most dominant frequency for PD occur which is at 900 MHz. The gain from circular and square loop antenna can be seen higher towards z-axis direction compared to x-axis and y-axis as the center of loop antenna is facing z-axis. This shows the strongest radiation from loop antenna comes from its center. Gain are related with efficiency of antenna. The higher the gain, the higher the efficiency of the antenna.

The value of gain in circular loop antenna is 3.694dB while the value of gain in square loop antenna is 3.514 dB at 900 MHz. The gain in circular loop antenna is higher compared to the gain...
square loop antenna. This means the circular loop antenna radiates more power at 900 MHz. This shows that the circular loop antenna is more efficient compared to square loop antenna.

![Figure 6](a) circle loop (b) square loop antenna 3-D radiation pattern for gain.

4. Conclusion
In conclusion, the suitable parameters for loop antenna for PD detection manage to be identified. Based on the simulations, the circular loop antenna is more suitable to use PD detection because the return loss is lower compared to square loop antenna. Besides, circular loop antenna’s resonant frequency is closer to 900 MHz which is the dominant frequency for PD to occur compared to square loop antenna [7]. Square loop antenna still can be used as other type PD detection as the range for PD to occur is from 300 MHz to 3 GHz which is the resonant frequency of square loop antenna is still in range, but it will less precise than circular loop antenna. The result got from this project is acceptable. Besides, in term of return loss, the antenna designed from this project has lower return loss, $S_{11}$ than the research compared to. This show, the antenna designed from this project is better PD detector. The circular loop design in this project has a very low losses and high in efficiency. Implementing this to be hardware, the detection of PD will be more convenient. Furthermore, for future work also is recommended to compare to other shape of loop antenna such as hexagon, triangle and pentagon. This can increase the information and to improve the performances of circular loop antenna to work under any condition to detect the PD.
5. Appendices

Appendix A

**Figure A1.** (a) circle loop (b) square loop antenna simulation with thickness of Loop A 2mm.

**Figure A2.** (a) circle loop (b) square loop antenna simulation with thickness of Loop A 6mm

**Figure A3.** (a) circle loop (b) square loop antenna simulation with thickness of Loop A 10mm
Appendix B

**Figure B1.** (a) circle loop (b) square loop antenna simulation with thickness of Loop B 2mm

**Figure B2.** (a) circle loop (b) square loop antenna simulation with thickness of Loop B 6mm

**Figure B3.** (a) circle loop (b) square loop antenna simulation with thickness of Loop B 10mm
Appendix C

Figure C1. (a) circle loop (b) square loop antenna simulation with thickness of Loop B 2mm

Figure C2. (a) circle loop (b) square loop antenna simulation with thickness of Loop B 6mm

Figure C3. (a) circle loop (b) square loop antenna simulation with thickness of Loop B 10mm
Appendix D

**Figure D1.** (a) circle loop (b) square loop antenna simulation with thickness of Loop B 2mm

**Figure D2.** (a) circle loop (b) square loop antenna simulation with thickness of Loop B 4mm

**Figure D3.** (a) circle loop (b) square loop antenna simulation with thickness of Loop B 6mm
6. References

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