Development of Loop Antennas for Partial Discharge Detection

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Abstract: This paper discusses the development of loop antenna to detect partial discharge (PD). The loop antenna is designed to measure PD induced EM wave in the frequency up to 100 MHz. The form, the circumference, the number of rounds of loop antenna affect the frequency response of the antenna. In the design, the circumference of a loop antenna is set to be a tenth of a wavelength of PD induced EM wave. The conductor wire length of loop antenna is set to be 30 cm to achieve 100 MHz bandwidth. Various forms of the loop antenna: circle, square, and triangle have been designed and implemented. The designed loop antennas were applied to measure PD in high voltage laboratory. The needle-plate electrodes in air is used as a PD source. The test results showed that the new designed loop antennas were able to detect and measure PD. PD induced EM wave waveform and pattern were measured. The effect of distance between PD source and the antennas was observed. The sensitivity of the circle loop antenna is the best among the new designed loop antennas.

Keywords: circle, square, triangle, loop antenna; partial discharge

1. Introduction

Insulation failure is one of causes of damage in power apparatus. The failure caused by insulation fault reaches 95% in the switchgear, 89% in power cable, 47% in generators and 84% in transformers [1,2]. Partial discharge (PD) is known as the initial cause of insulation failure. PD may lead breakdown of insulation. The insulation diagnosis is needed to detect PD in early stage.

PD causes a physical phenomenon in several forms: light, electromagnetic (EM) wave, and acoustic. One of the physical phenomena is EM wave. EM wave propagates in radial directions. It can be detected using an antenna. Various types of sensor such as bowtie antenna, spiral antenna, and loop antenna has been developed to detect and to measure PD induced EM wave [3-6]. The loop antenna is designed and tested in this research because it is simple and cheap.

At first loop antenna is used for radio communication, as a transmitter and receiver [3]. The advantage is a simple, cheap manufacturing costs (wire conductors) and can be directly connected to the transmission line [4]. The application of loop antenna on power apparatus to detect PD has been investigated recently [5, 6, 7]. The planar loop sensors designed for signal frequency of 25-75 MHz are used to detect PD in power cable [5]. The circle loop antennas with three different diameters (d=5cm, d=8cm, d=13cm) have been developed to measure PD in gas insulated switchgear (GIS) [7]. However, the sensors has the narrow bandwidth around 40-50 MHz.

In this research, the loop antenna is designed to be able to detect PD induced EM wave in the certain frequency range with wider bandwith. The frequency of PD induced EM wave depends on the electrode structure and the insulation between the electrode. In the first step, the loop antenna was designed to detect PD induced EM wave in air in frequency up to 100 MHz. Testing was conducted to determine the loop antenna characteristics. The antenna was tested using a Network Analyzer. The designed loop antennas were applied to measure PD in high voltage laboratory. The needle-plate electrodes in air is used as a PD source. The design, the implementation and the testing of loop antena to measure PD is reported in this paper.

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2. Loop Antenna Design and Impementation

An antenna in a radio application is needed for two main objectives: to transmit and to receive signal. A small loop coil could be functioned as both transmitting and receiving antenna utilizing near field magnetic induction coupling. In the application of loop antenna on power apparatus application, the small loop sensor is needed only for receiving UHF signal.
When time-varying magnetic field is passing through a coil, it induces voltage across a coil terminal. A loop sensor must be designed to maximize this induced voltage for the certain frequency resonance type. For PD sensor requiring flat frequency response, resonance frequency band should be avoided by adequate design process.

Based on Faraday's law, a time-varying magnetic field through a surface bounded by a closed path induces a voltage around the loop as expressed by equations (1) and (2). A time-varying magnetic field over a surface bounded by a closed loop induces a voltage around the loop (Faraday's law) as shown in equation:

$$V_{ind} = -N\frac{d\Psi}{dt} \tag{1}$$

$$\Psi = \int B.dS \tag{2}$$

where :
N = number of turns
Ψ = magnetic flux
B = magnetic field
S = surface area.

In designing loop antenna, the dimension of loop antenna must be calculated. Equation (3) shows the relationship between frequency (f), wavelength (λ), and the speed of light (C).

$$f = \frac{C}{\lambda} \tag{3}$$

The circumference of a loop antenna should be a tenth of a wavelength for the valid uniform-current approximation [9]. Since the loop antenna is designed to detect PD induced EM wave in air in frequency up to 100 MHz, the conductor wire length (l_{100}) of loop antenna is 30 cm. The loop antenna is designed in three forms: circle, triangle, and square. For a turn the circumference of loop antenna is 30 cm. The diameter of circle shaped loop antenna is designed to be 9.55 cm. The lateral of square shaped loop antenna is designed to be 7.5 cm. The lateral of triangle shaped loop antenna is designed to be 10 cm. Figure 1 shows a sketch of the loop antennas. The loop antenna is then implemented using copper wire. Figure 2 shows the implemented loop antenna. Table 1 shows the specification of the designed loop antenna.

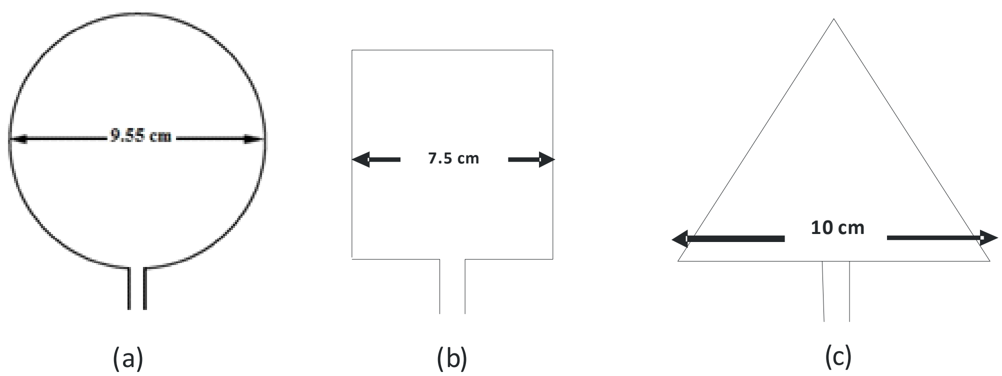
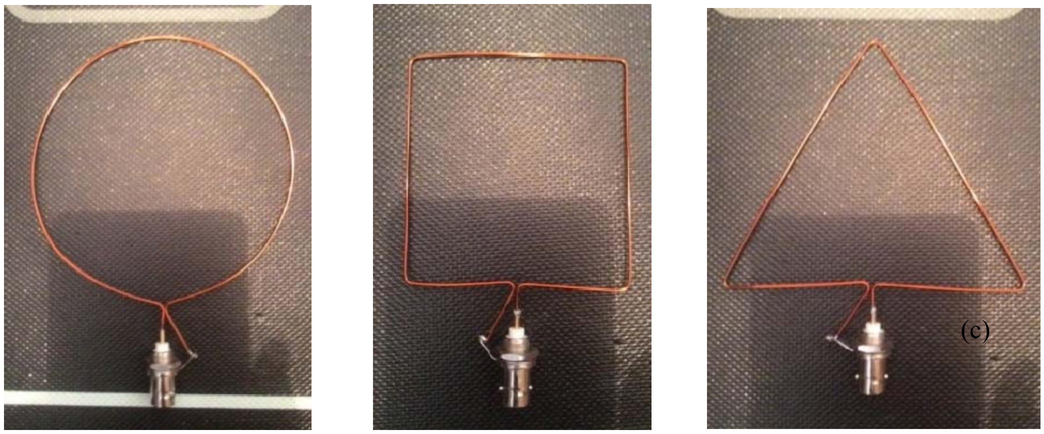


Figure 1. Sketch of the loop antenna
(a). Circle Loop Antenna (b). Square Loop Antenna (c). Triangle Loop Antenna



(a) (b) (c)

Figure 2. Loop Antenna
(a). Circle Loop Antenna (b). Square Loop Antenna (c). Triangle Loop Antenna

Table 1. Specification of Loop Antennas

ShapeAntenna	Number of turns	Diameter or lateral (cm)	Frequency (MHz)
Circle	1	9.55	0-100
Square	1	7.5	0-100
Triangle	1	10	0-100

3. Loop Antenna Testing as Partial Discharge Sensor

A. Partial Discharge Source

The designed loop antenas were examined to measure partial discharge in air (electrical corona). The PD source is the needle-plate electrode system as shown in Figure 3. The needle diameter is 1 mm with the tip radius 3 um and the curvature angle 30^{O}. The gap distance is 10 mm. The insulation is air.

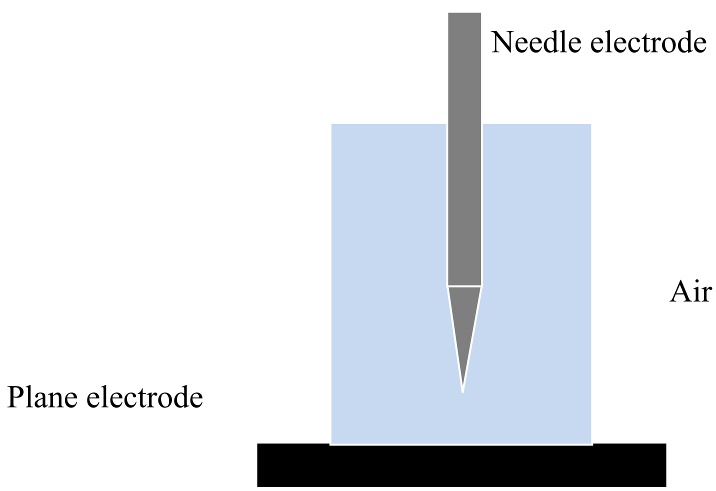


Figure 3. System Needle-Plate Electrode

B. Experimental Setup

The experimental set up is shown in Figure 4. The single phase AC voltage was supplied from a single phase 220 V / 100 kV, 5 kVA corona free transformer through limiting resistor. PD source is needle-plate electrode system. The coupling capacitor enables high frequency PD current flowing in the circuit. PD was measured by 50 ohm detecting impedance. PD induces EM wave. The EM wave was measured by the designed loop antenna: circle, square, and triangle. The loop antenna was placed in the distance of 5 cm away from PD source. The loop antenna was connected to the oscillocope. The measured PD signal was displayed in the form of phase resolved PD pattern or $(\varphi - q - n)$ pattern.

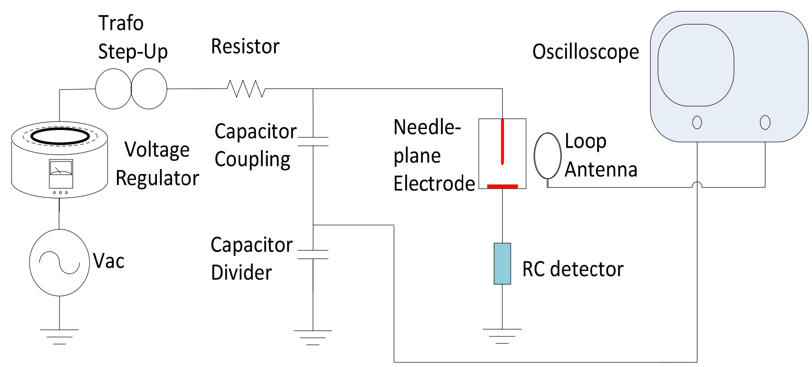


Figure 4. Experimental Setup for PD Measurement

C. PD Measurement Results

C.1. Negative PD Waveform

PD measurements were taken at three-voltage level 4 kV, 4.8 kV and 5.6 kV. The PD measurement results are displayed in the PD- waveform and PD pattern $(\varphi - q - n)$. We will observe peak to peak voltage (Vpp) of PD waveform as shown in figure 5.

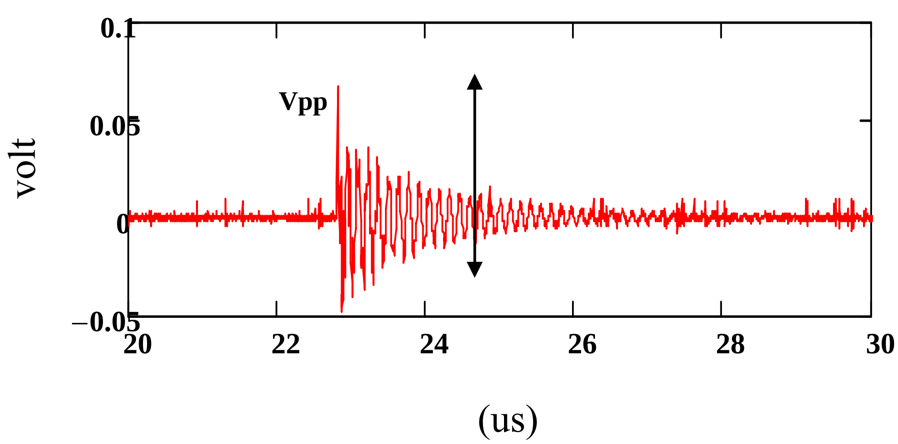
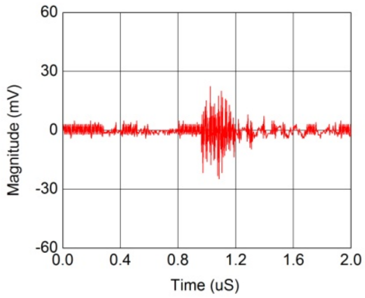
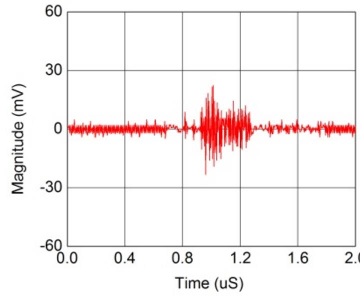


Figure 5. Vpp Loop Antenna

PD- waveform in air (corona) measured by each antenna at 4 kV applied voltage is shown in Figure 6. Detection of circle loop antenna is 47.2mV, while Vpp of the triangle and square loop antennas is 26.4 mV and 45.6mV, respectively.



(a)



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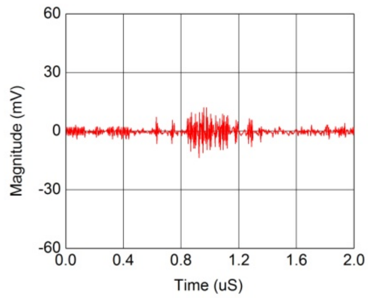
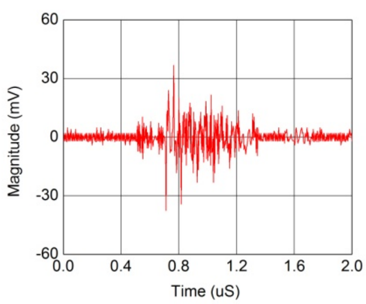
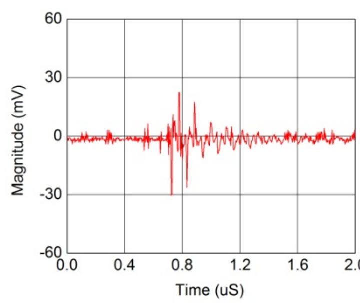


(c)

Figure 6. PD- Waveform at 4 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna (c). Square Loop Antenna



(a)



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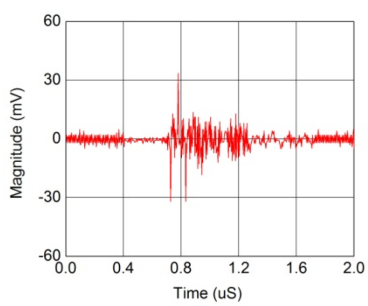


(b)

Figure 7. PD- Waveform at 4.8 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna (c). Square Loop Antenna

Figure 7 shows PD- waveform measurement result at 4.8 kV for each loop antenna.Vpp of the circle loop antenna is 74.4mV, whileVpp of the square and triangle loop antennasis 65.6 mV and 52.8 mV, respectively.

Figure 8 shows PD- waveform at 5.6 kV.Vpp of the circle loop antenna is104mV, while Vpp of the triangleand squareloop antennas is 74.4mVand81.6mV, respectively.

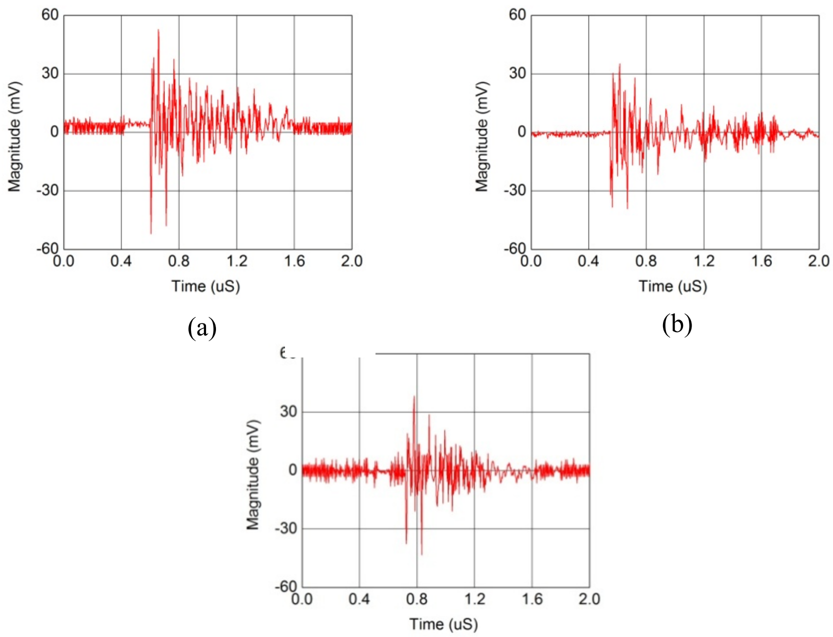


Figure8. PD- Waveform at 5.6 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna (c). Square Loop Antenna

Figure 9 shows the relation between Vpp and applied voltage for the circle, triangle, and square loop antennas. Vpp of PD induced EM wave measured by the circle loop antennas is the highest.

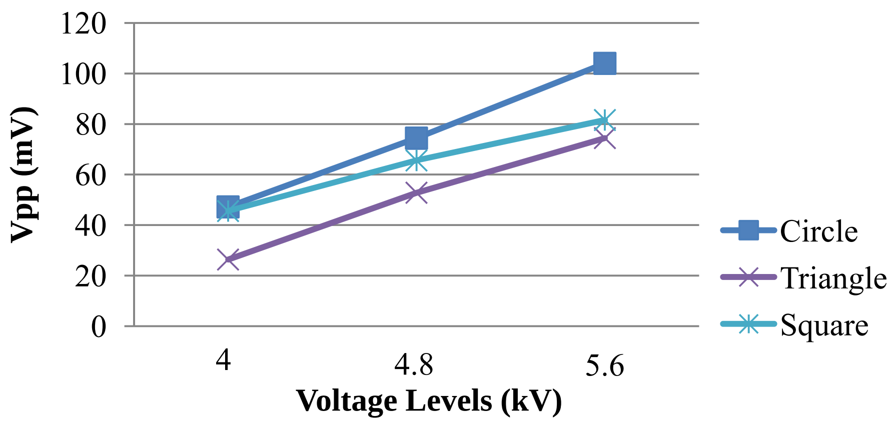
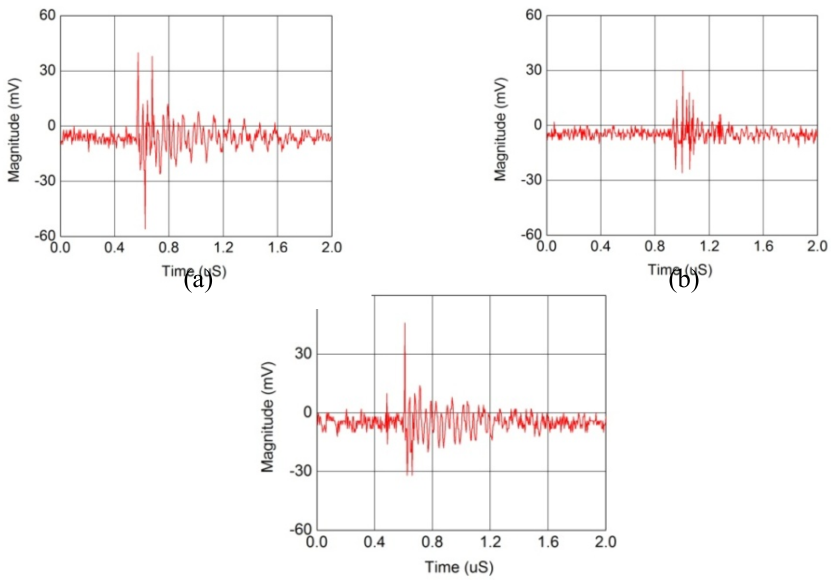


Figure 9. Relation of Vpp and Applied Voltage Level for Circle, Triangle, and Square Loop Antennas

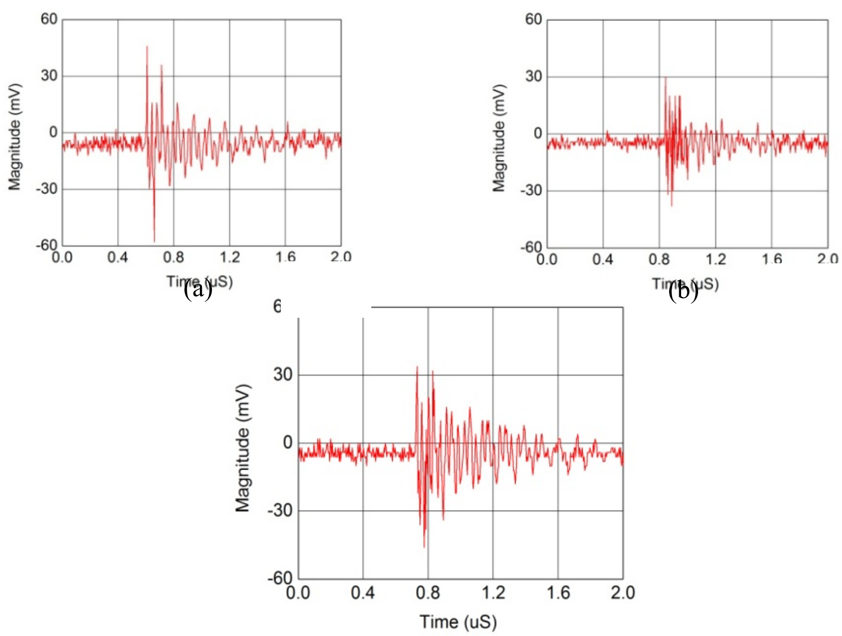
C.2. Positive PD Waveform

PD+ waveform in air (corona) measured by each antenna at 4 kV applied voltage is shown in Figure 10. Detection of circle loop antenna is 96 mV, while Vpp of the triangle andsquare loop antennas is 56mVand78 mV, respectively.



(c)

Figure 10. PD+ Waveform at 4 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna (c). Square Loop Antenna

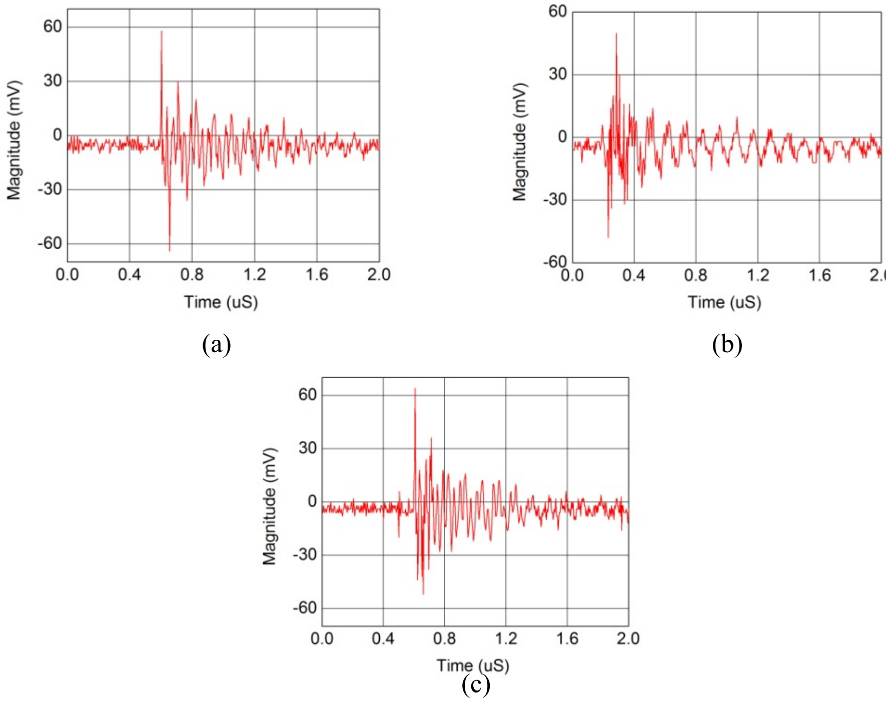


(c)

Figure 11. PD+ Waveform at 4.8 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna (c). Square Loop Antenna

Figure 11 shows PD+ waveform measurement result at 4.8 kV for each loop antenna. Vpp of the circle loop antenna is104 mV, while Vpp of the triangle andsquare loop antennas is 68 mVand80 mV, respectively.

Figure 12 shows PD+ waveform at 5.6 kV. Vpp of the circle loop antenna is122mV, while Vpp of the triangleand square loop antennas is 98 mVand116 mV, respectively.



(a) (b) (c)

Figure 12. PD+ Waveform at 5.6 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna (c). Square Loop Antenna

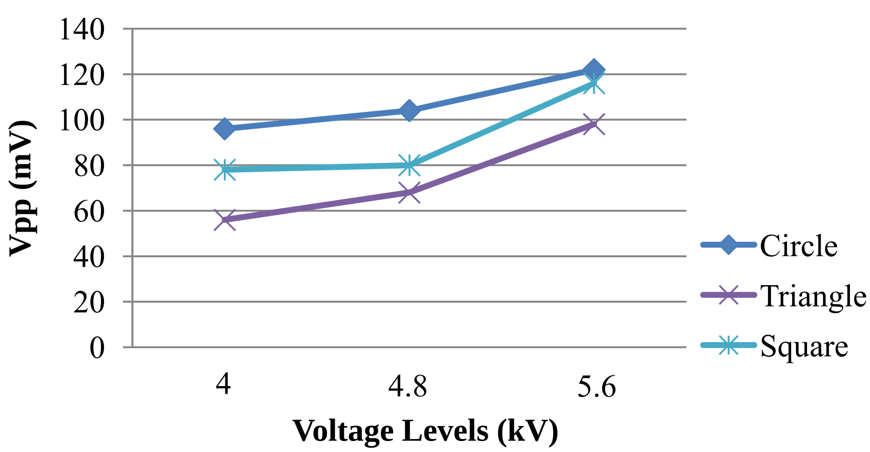
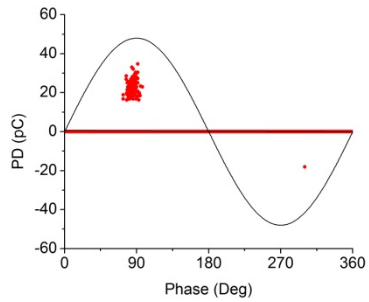


Figure 13. Relation of Vpp and Applied Voltage Level

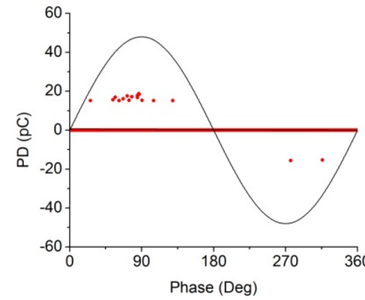
Figure 13 shows the relation between Vpp and applied voltage for the circle, triangle, and square loop antennas. Vpp of PD induced EM wave measured by the circle loop antennas is the highest.

C.3. PD Pattern $(\varphi - q - n)$

PD Pattern $(\varphi - q - n)$ in air (corona) measured by each antenna at 4 kV applied voltage is shown in Figure 14. The number of PD occurrence detected by circle, triangle, and square loop antenna is 108, 17, and 40, respectively (Figure 5a-c).



(a)



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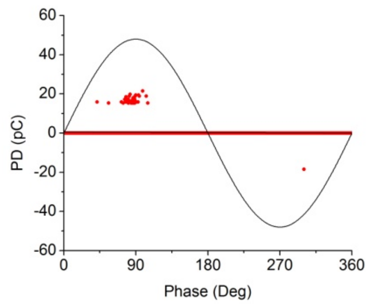
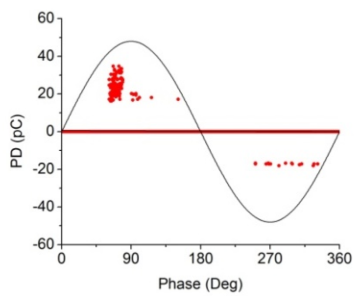
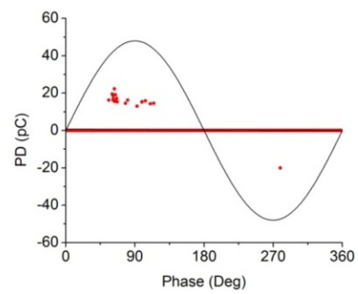


(c)

Figure14. PD Pattern $(\varphi - q - n)$ at 4 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna(c). Square Loop Antenna



(a)



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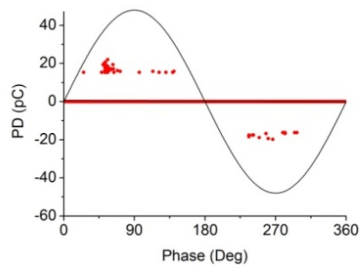

(c)

Figure 15. PD Pattern $(\varphi - q - n)$ at 4.8 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna(c). Square Loop Antenna

Figure 15 shows PD measurement result in the form of $(\varphi - q - n)$ at 4.8 kV. The number of PD occurrence detected by circle, triangle, and square loop antenna is 135, 20, and 53, respectively (Figure 6a-c).

Figure 16 shows PD measurement result in the form of $(\varphi - q - n)$at 5.6 kV. The number of PD occurrence detected by circle, triangle, and square loop antenna is 322, 126, and 182, respectively (Figure 7a-c).

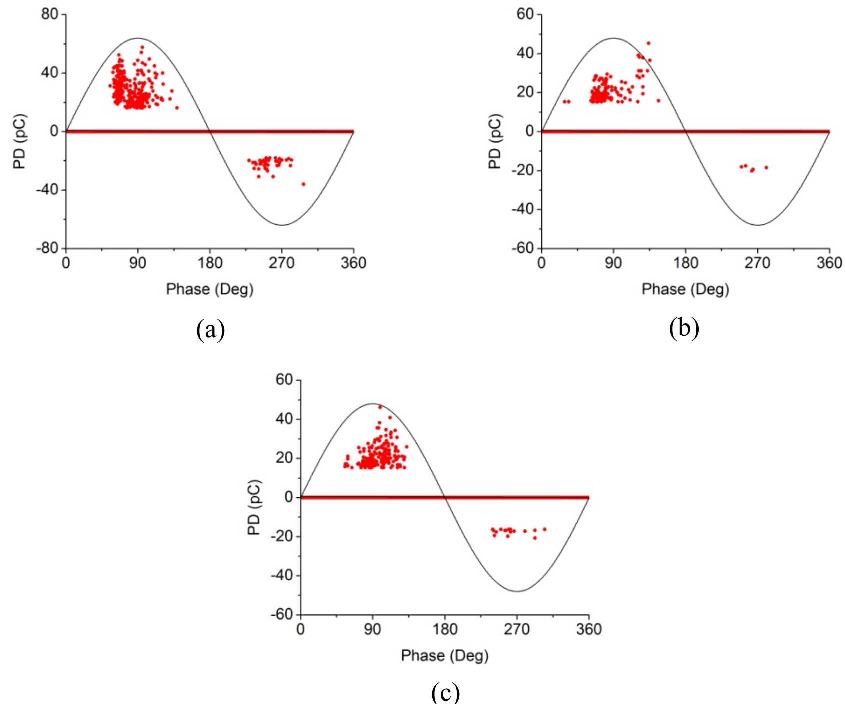

Figure 16. Pattern $(\varphi - q - n)$ at 5.6 kV
(a). Circle Loop Antenna (b). Triangle Loop Antenna(c). Square Loop Antenna

Figure 17 and Figure 18 show the average charge and the number of PD occurrence at 4 kV, 4.8 kV, and 5.6 kV. The charge and the PD number measured by the circle loop antenna were higher than one measured by the triangle and the square loop antennas. The circle loop antenna is the best PD sensor among the three sensors.

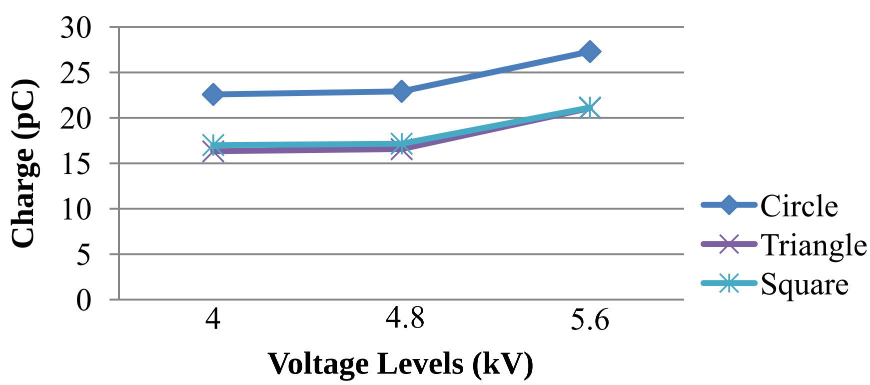

Figure 17. Average Charge Measured by Loop Antenna

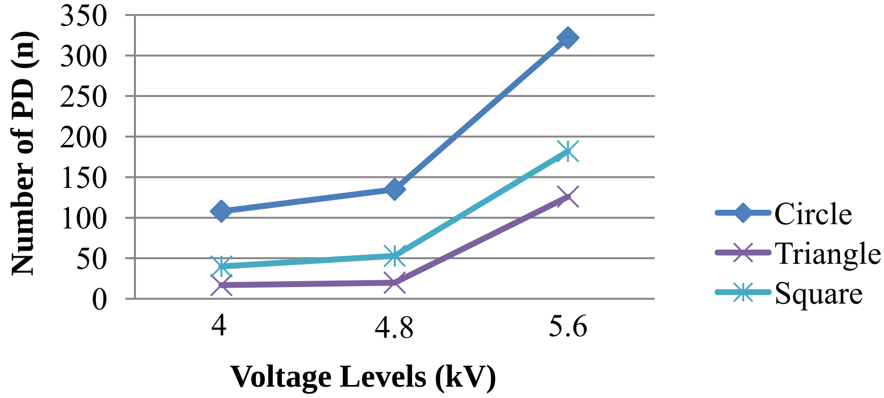

Figure 18. Number of PD Measured by Loop Antenna

Figure 19 shows theeffect of the antenna distance to PD source on PD magnitude measured by loop antennas.If the distance of the loop antenna to PD source is further, the sensitivity of the loop antenna reduces.

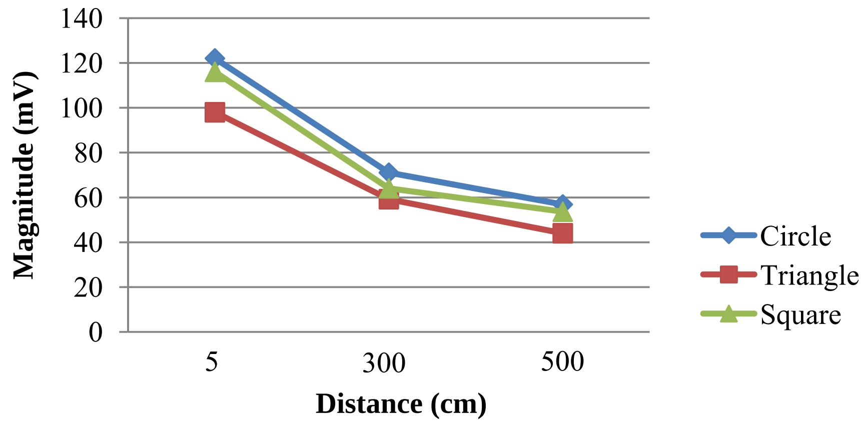

Figure 19. PD Source to Loop Antenna

Table 2 showspropagation properties of PD induced EM wave detected by the loop antennas. At the distance of PD source to the antenna in the range less than λ/2π, PD induces EM wave, whileat the PD source to the antenna more than λ/2π, PD radiates EM wave.

Table 2. Propagation Properties of PD Emitted EM Wave Measured by Loop Antennas

Shape Antenna	PD Source to Antenna (cm)	Wavelength (cm)	Induction/ Radiation
Circle	5	300	Induction
	200		Radiation
	500		Radiation
Triangle	5	300	Induction
	200		Radiation
	500		Radiation
Square	5	300	Induction
	200		Radiation
	500		Radiation

D. Discussion

The experimental results showed that the circle loop antenna is the best in measuring PD compared with the other sensors. It is explained as follows. Based on the Faraday law and equation 1 and 2, a time-varying magnetic field over a surface bounded by a closed loop induces a voltage around the loop. The magnetic flux flows through the antenna increases if the area increases. The area of circle loop antenna is 71.58 cm^2. Circumference square loop antenna and triangle loop antenna is equal to circle loop antenna, but both loop antenna has an area of 56.25 cm^2 and 37.5 cm^2. The best sensitivity loop antenna is the circle loop antenna because it has the widest area among the loop antennas.

The distanceof PD source to antenna affects thesensitivity ofthe loop antenna. If the distance of loop antenna to PD source is further, the sensitivity of the loop antenna reduces. This is due to EM wave attenuation. Intensity of EM wave reduces when EM waves passes through a certain distance.The cause ofthe attenuationarescattering, absorption, diffraction, reflection. Path lossor pathattenuationis obtainedfromthe equation:

$$L = 10\, n \log_{10}(d) + C \tag{4}$$

where L is the path loss (dB), n is the path loss exponent (2 for free space, 4 for lossy environment, 4-6 for building, stadium, or indoor environment), d is the distance between transmitter and receiver (m), and C is a constant which accounts for system losses.

4. Conclusion

This paper discusses the design and implementation of loop antena to measure partial discharge (PD). Severalconclusions are suggested as follows:

1. The loop antenna is designed to measure PD induced EM wave in the frequency up to 100 MHz.
2. The form, the circumference, the number of rounds of loop antenna affect the frequency response of the antenna. In the design, the circumference of a loop antenna is set to be a tenth of a wavelength of PD induced EM wave. The conductor wire length of loop antenna is set to be 30 cm to achieve 100 MHz bandwidth.
3. Various forms of the loop antenna: circle, square, and triangle have been designed and implemented. The designed loop antennas were applied to measure PD in high voltage laboratory. The needle-plate electrodes in air is used as a PD source. The test results showed that the new designed loop antennas were able to detect and measure PD.
4. The sensitivity ofthe circle loop antenna is the best among the new designed loop antennas.

5. References

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Umar Khayam was born in Indonesia in 1975. He received B.Eng. with honor (cum laude) and M.Eng. degrees in electrical engineering from Bandung Institute of Technology (ITB), Indonesia, in 1998 and 2000, respectively. He received Doctor Degree in Electrical Engineering from Kyushu Institute of Technology (KIT), Japan in 2008. He was a researcher at Hikita Laboratory, KIT, Japan, during 2008-2009 and 2010-2012. Since 2008, he is a Lecturer at School of Electrical Engineering and Informatics ITB, Indonesia. Dr. Umar Khayam received Best Paper Award in 2005 KJ Symposium on Electrical Discharge and High Voltage Engineering. His research interest is partial discharge measurement and phenomena in electric power apparatus. Dr. Umar Khayam is a member of IEEE.