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Partial Discharge Characterization of Gaseous Dielectrics for Gas-Insulated Applications

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Abstract: Partial discharge is a localized dielectric breakdown that can harm high-voltage equipment in electrical engineering. It occurs when there is a breakdown of insulation between two conductors under high voltage stress, resulting in sparks or arc flashes. These energetic electrons can age the insulation and lead to equipment failure. The objective of this project is to investigate partial discharge phenomena in gas-insulated systems and measure their intensity. The study refers to previous research to understand the topic and uses ultra-high frequency (UHF) and high-frequency current transformer (HFCT) sensors to measure partial discharge. Measurement circuits were designed for both methods, and MATLAB was used to analyze the partial discharge signals and calculate the pulse charge. The highest pulse charge recorded was 257.46 nC when CO_2 was used as the insulation gas, while the lowest was 4.2594 nC with free air as the insulation gas. This indicates that partial discharge is more intense when CO_2 is used. In conclusion, conducting partial discharge testing is crucial to assess the condition of high-voltage equipment and prevent failures.

Keywords: Partial Discharge Measurement, UHF Sensor, HFCT Sensor, Gas Insulation, Pulse Charge

1. Introduction

The term partial discharge refers to a discharge that does not completely bridge the space between the electrodes. The discharge may be in a gas-filled void inside an insulating material, or around an electrode in a gas. PD happens all the time in power systems but usually occurs in components that can withstand it (such as switchgear). It has yet not proved the relationship between partial discharges and long-term failure of electrical insulation. However, partial discharges are the major reason for aging and eventual failure of electrical insulation, so measurements of partial discharge activity are an item in the test program for most types of high voltage/radio frequency equipment. [1] There are several

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reasons that can cause partial discharge in high-voltage equipment. In some cases, surface contamination is where there is a lack of cleaning on the equipment. Other than that, workmanship which related to poor installation, material defects (manufacturing defects), salt spray or salt fog which can cause corrosion to the insulation, etc. [2].

A dielectric gas, or insulating gas, is a dielectric material in a gaseous state. Its main purpose is to prevent or rapidly quench electric discharges. Dielectric gases are used as electrical insulators in high-voltage applications, e.g., transformers, and circuit breakers. A good dielectric gas should have high dielectric strength, high thermal stability and chemical inertness against the construction materials used, non-flammability and low toxicity, low boiling point, good heat transfer properties, and low cost [3]. The most common dielectric gas is air, due to its ubiquity and low cost.

This project aims to investigate the partial discharge phenomenon in gas-insulated systems. Other than that, to measure the partial discharge in gas insulated system using HFCT and UHF sensor methods. Then, analyze the partial discharge signal with the different gas-insulated conditions. This project will analyze the intensity of partial discharge that occurs when conducting the testing.

2. Methodology

The methodology section describes all the necessary information that is required to obtain the results of the study.

A. Flowchart of the work progress

Figure 1 shows the overall flowchart of the work progress for measuring and analyzing the PD signal under different types of gas insulation. The first step before conducting the laboratory testing was to study the partial discharge phenomenon that occurred in gas-insulated applications. For example, previous studies were analyzed to clearly understand the project. After that, proposed the methods used in the testing to the supervisor. The most common methods used were using HFCT sensor and UHF sensor. While performing the laboratory testing, two conditions were set for the gas which were in free air as the insulation gas condition and CO_2 with 1 bar abs pressure as the insulation gas condition. The purpose of this laboratory testing was to analyze the intensity of the partial discharge by analyzing the PD signal obtained.

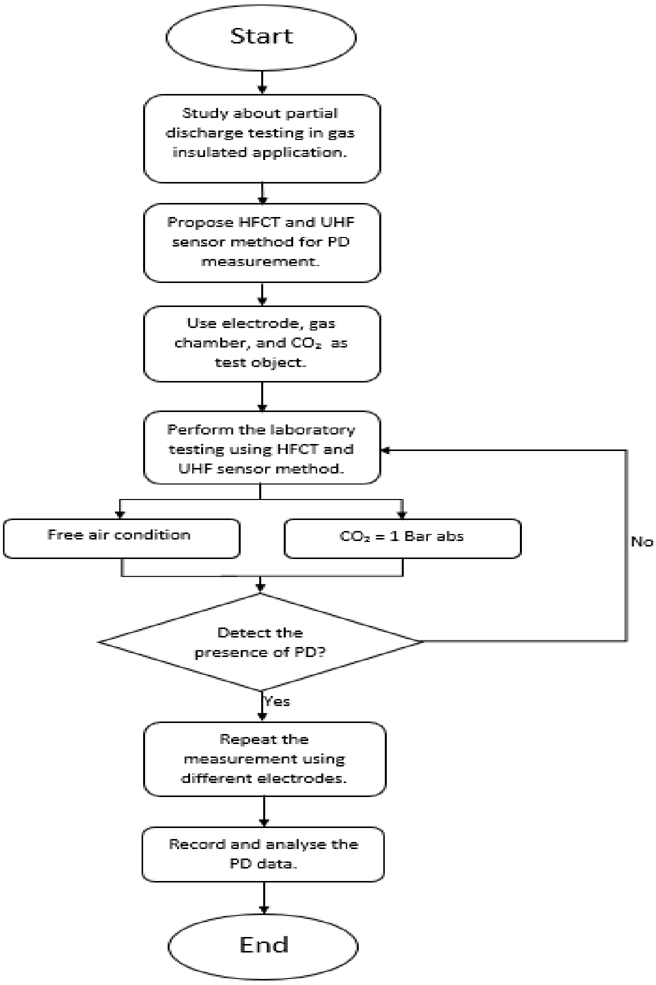


Figure 1: Overall flowchart of the project.

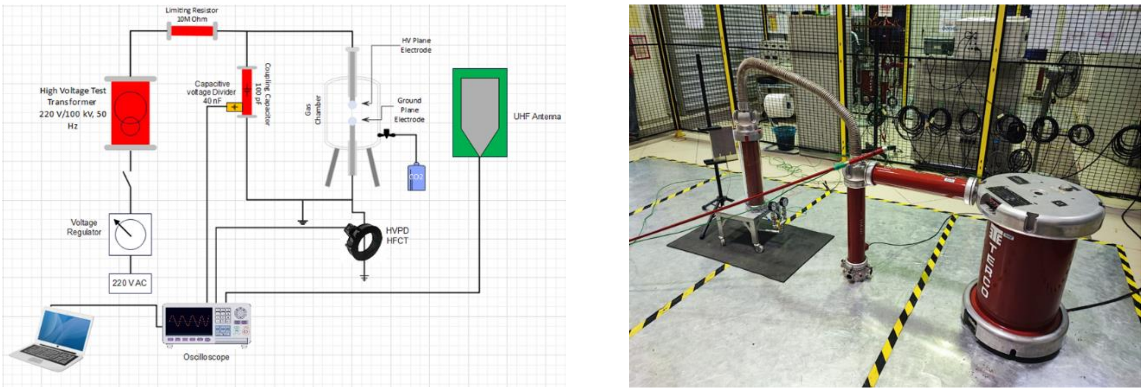
B. Measurement of PD signal using HFCT and UHF sensor

For this project, UHF and HFCT sensors were used to capture the PD signal. For the HFCT sensor, the clamped type was used where the sensor will be clamped on the ground wire of the testing equipment. As for the UHF sensor, the type of UHF sensor used was ultra-wideband antenna and it will be placed 25 cm from the test equipment for better sensitivity and accuracy. Both sensors will be connected to an oscilloscope to display and record the PD signals. Figure 2 shows the sensors used.

(a) (b)

Figure 2: Sensors used in measurement. (a) HFCT sensor, (b) Ultra-wideband UHF sensor

Figure 3 shows the measurement circuit for the PD test. To study the partial discharge breakdown of the gas insulation, plane, spherical, and needle rods were utilized as defect models. The electrodes were placed on HV and ground side to provide homogenous background electric field conditions.[4] The electrodes were placed inside the gas chamber. The high voltage side of the electrode that was connected to the bushing was removable and connected to a high voltage AC source with a maximum output voltage of 100 kV rms. The ground side of the electrode, however, was vertically removable within the gas chamber so that the desired gap length could be achieved with an accuracy of 0.1 mm. Current sensing was performed by coupling a high-frequency current transformer (HFCT), of 60 MHz upper cutoff frequency, to the lower (grounded) plane electrode, while the recording of the generated signals was performed through a 500 MHz, 2GS/s oscilloscope. While the UHF sensor was placed outside of the gas chamber at a distance of 25 cm. The recording of the generated signal was also performed through the same oscilloscope.



(a) (b)

Figure 3: Measurement test setup. (a) Experimental circuit, (b) Implementation of experimental circuit inside HV lab

C. Analysis of PD data

For analysis, PD data recorded will be compared and the area under the curve of the signals will be calculated using MATLAB. Figure 4 shows the typical PD signal. shows a typical PD pulse as viewed on an oscilloscope, in which the charge is determined by integrating the current signal. As determined by the integrated pulse charge, the discharge magnitude, q differs from one PD pulse to another because the discharge size depends, in part, on the composition of the gas in the gap that is altered by the presence of ions, metastables, and radicals created by the previous pulse [5]. In essence, the size of this prior pulse depends indefinitely on the influence of its previous pulse, and so on. In general, the time separation from the previous pulse, t also moves non-deterministically from one PD pulse to another, depending on how the initiatory electrons are generated and how quickly the space charge is cleared.

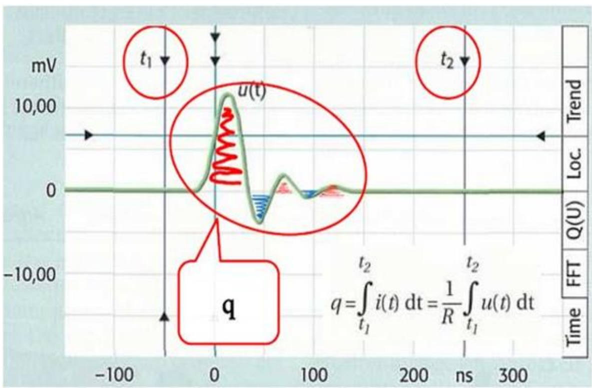


Figure 4: Typical PD pulse as viewed on an oscilloscope.

3. Results and Discussion

A. PD Data Collected from The Testing

Before starting the testing, even when the control panel is not turned on, a peak-to-peak voltage of 2.4 mV was obtained which shows the noise level inside the lab. After energizing the control panel in order to check and validate if the UHF sensor is working, the peak-to-peak voltage behavior was calculated, and 22.5 mV peak-to-peak voltage was obtained at 0 V supply. So, the signal with a peak-to-peak voltage value under 22.5 mV is not considered a PD signal.

Tables 1 to 4 display the PD data collected from the measurement using different gas insulations and different pairs of electrodes. The gap between electrodes on the HV side and ground side was set to 5 cm. The data were divided into two which were frequency and peak-to-peak voltage. The measurement was conducted until a complete breakdown of the insulation gas happened.

Table 1: Data obtained from the measurement for free air as gas insulation. (Needle – Plane Electrode)

PDIV (kV)	Frequency (MHz)	Peak to Peak (mV)
15	10.47	85.2
20	22.7	37.4
25	4.57	36.6
30	2.028	45
35	2.268	273
40	5.10	257

Table 2: Data obtained from the measurement for free air as gas insulation. (Needle – Needle Electrode)

PDIV (kV)	Frequency (MHz)	Peak to Peak (mV)
15	2.116	28.1
20	3.248	33.5
25	2.116	62.7
30	0.572	102
35	2.286	143

Tables 1 and 2 show differences in peak-to-peak voltage and frequency value for each PDIV increment. Collectively, the peak-to-peak voltage value of Table 1 is higher than Table 2. Frequency values also show the same for both tables. For Table 1, the peak-to-peak voltage increased by 67% from 85 mV to 257 mV. Whereas the frequency value decreased by 105% from 10.47 MHz to 5.10 MHz. For Table 2, the peak-to-peak voltage increased by 80% from 28.1 mV to 143 mV. Whereas the frequency just increased slightly by 7% from 2.116 MHz to 2.286 MHz.

Table 3: Data obtained from the measurement for CO_2 = 1 Bar abs. (Spherical – Plane Electrode)

PDIV (kV)	Frequency (MHz)	Peak to Peak (mV)
15	2.123	41
20	3.115	351
25	2.336	320
30	2.2	181

Table 4: Data obtained from measurement for CO_2 = 1 Bar abs. (Needle – Plane Electrode)

PDIV (kV)	Frequency (MHz)	Peak to Peak (mV)
15	28.2	119
20	56	168

Tables 3 and 4 show differences in peak-to-peak voltage and frequency values for each PDIV increment. Collectively, the peak-to-peak voltage value of Table 3 is higher than Table 4. But, for frequency values, it is vice versa. For table 3.3, the peak-to-peak voltage increased by 77% from 41 mV to 181 mV. Whereas the frequency value increased slightly by 3.5% from 2.123 MHz to 2.2 MHz. For Table 3.4, the peak-to-peak voltage increased by 29% from 119 mV to 168 mV. Whereas the frequency just increased by 50% from 28.2 MHz to 56 MHz.

From the tables, it can be concluded that the usage of the electrode with a larger surface area will trigger high peak-to-peak voltage because, for a larger surface area, it will be hard for energy to concentrate and bridge the gap between electrodes. Besides, using CO_2 as insulation gas made the complete breakdown occur faster than using free air as insulation gas. This can be seen because the highest PDIV increment before the complete breakdown occurred for CO_2 was 30 kV and the highest PDIV increment for free air was 40 kV.

B. Pulse Charge from PD Signal 3

Table 5 to 8 shows the pulse charge calculated for both insulation, free air and CO_2 using different electrodes. Pulse charge can be calculated using MATLAB from the data collected from the PD signal.

Table 5 shows the pulse charge calculated using MATLAB for needle-to-plane electrodes. Initially, the pulse charge increased from 4.4528 nC for PDIV 15 kV to 7.5547 nC for PDIV 25 kV. After that, it slightly decreased to 7.3548 nC for PDIV 30 kV before increasing again to 8.8501 nC for PDIV 35 kV and 9.6692 nC for PDIV 40 kV.

Table 5: Pulse charge, q of free air as gas insulation. (Needle – Plane Electrode)

PDIV (kV)	Pulse Charge, q
15 kV	4.4528 nC
20 kV	6.6043 nC
25 kV	7.5547 nC
30 kV	7.3548 nC
35 kV	8.8501 nC
40 kV	9.6692 nC

Table 6 shows the pulse charge calculated using MATLAB for the needle-to-needle electrode. The pulse charge increased as the PDIV increased without any decrease. For PDIV 15 kV the pulse charge recorded was 11.892 nC. For PDIV 20 kV, 25 kV, 30 kV, and 35 kV the pulse charge recorded was 36.644 nC, 43.569 nC, 66.457 nC, and 75.284 nC respectively. The pulse charge increased by 34% for each increment on average.

Table 6: Pulse charge, q of free air as gas insulation. (Needle – Needle Electrode)

PDIV (kV)	Pulse Charge, q
15 kV	11.892 nC
20 kV	36.644 nC
25 kV	43.569 nC
30 kV	66.457 nC
35 kV	75.284 nC

Table 7 shows the pulse charge calculated using MATLAB for spherical–plane electrode. For PDIV 15 kV, the pulse charge generated was 16.858 nC. As for PDIV 20 kV, 25 kV, and 30 kV, the pulse charge generated was 36.644 nC, 43.569 nC and 66.457 nC respectively. The value of the pulse charge increased as the PDIV value increased with an average percentage of 34.48% for each increment of PDIV.

Table 7: Pulse charge, q of CO_2 = 1 bar abs. (Spherical – Plane Electrode)

PDIV (kV)	Pulse Charge, q
15 kV	16.858 nC
20 kV	36.644 nC
25 kV	43.569 nC
30 kV	66.457 nC

Table 8 shows the pulse charge calculated using MATLAB software. For PDIV 15 kV, the pulse charge was 115.97 nC and for PDIV 20 kV, the pulse charge recorded was 257.46 nC. The pulse charge increased by 55% when increasing the PDIV from 15 kV to 20 kV.

Table 8: Pulse charge, q of CO_2 = 1 bar abs. (Needle– Plane Electrode)

PDIV (kV)	Pulse Charge, q
15 kV	115.97 nC
20 kV	257.46 nC

The value of the pulse charge depends on the PD signal. To calculate the pulse charge, the data from the PD signal will be inserted in MATLAB software. The PD pulse charge depends on the signal obtained. The higher increment of PDIV the higher the pulse charge will be.

Figure 5 depicts the signal for the highest pulse charge calculated for free air as gas insulation. The pulse charge calculated was 75.284 nC, from a PDIV increment of 35 kV using needle to needle electrode.

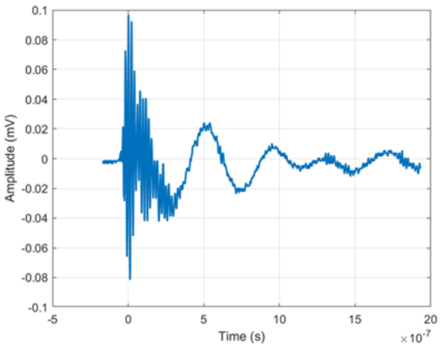


Figure 5: PD signal for PDIV 35 kV using free air and needle to needle electrode.

Figure 6 shows the signal for the highest pulse charge calculated for CO_2 as gas insulation. The pulse charge calculated was 257.46 nC from a PDIV increment of 20 kV using a needle-to-plane electrode.

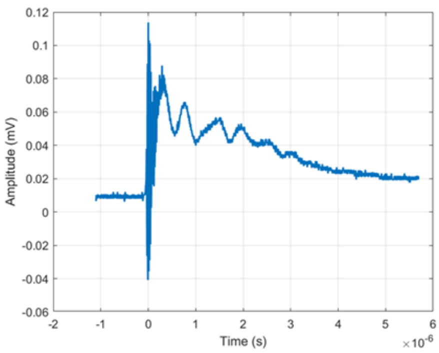


Figure 6: PD signal for PDIV 20 kV using CO_2 and needle to plane electrode.

4. Conclusion

From the result obtained, the types of electrodes used affect the peak-to-peak voltage and the complete breakdown time of gas insulation. The smaller surface area causes the complete breakdown to occur faster than the larger surface area. The peak-to-peak voltage using a spherical electrode was considered the highest with a value of 351 mV whereas the highest peak-to-peak voltage using a needle electrode was recorded at 273 mV. Lastly, comparing the results on both insulation gases shows that CO_2 as gas insulation generates a higher pulse charge than free air as gas insulation. CO_2 as insulation generates the highest pulse charge which is 257.46 nC whereas the highest pulse charge generated using free air as insulation is 75.284 nC. A higher pulse charge can contribute to a higher localized stress level, but it is not the only determining factor of PD occurrence. Other factors, such as the insulation condition and material properties, also play a significant role. For example, degraded insulation or impurities within the material can create more favorable conditions for PD initiation, regardless of the pulse charge.

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