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**DOI**
10.1109/CEIDP61707.2025.11218308

**Publication date**
2025

**Document Version**
Final published version

**Published in**
Proceedings of the 2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)

**Citation (APA)**
Plantfeber, T., Saleem, M. S., Muñoz, F. M., Born, D. V. D., Lathouwers, A., & Vaessen, P. (2025). A Novel Measurement Setup for Dielectric Characterization of Alternative Gases: Applied to Partial Discharge Behaviour in CO2/O2 Mixtures. In *Proceedings of the 2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (pp. 416-419). IEEE. https://doi.org/10.1109/CEIDP61707.2025.11218308

# A Novel Measurement Setup for Dielectric Characterization of Alternative Gases: Applied to Partial Discharge Behaviour in $CO_2/O_2$ Mixtures

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2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) | 979-8-3315-8902-8/25/$31.00 ©2025 IEEE | DOI: 10.1109/CEIDP61707.2025.11218308

***Abstract*—As the world moves towards $SF_6$-free insulation technologies, understanding the dielectric behaviour of alternative gas mixtures is becoming increasingly important. Detailed characterization of partial discharge (PD) behaviour within conventional measurement circuits is constrained by distortion of the fast transient signal, limiting the effective measurement bandwidth. This study presents a novel measurement circuit that omits the traditional coupling capacitor and instead leverages the inherent capacitance of the gas-insulated structure to establish a more compact and sensitive detection path. The improved setup enables detailed time-domain acquisition of fast-rising PD pulses using a high-frequency current transformer (HFCT).**

**Using this system, the corona discharge characteristics of a $CO_2/O_2$ (70%/30%) gas mixture are experimentally investigated at pressures of 0.2, 0.3 and 0.4 MPa. Phase-resolved PD patterns are analysed to assess the influence of gas pressure on PD inception voltage, charge magnitude, and pulse repetition behaviour.**

***Index Terms*—Partial discharge (PD), PD inception voltage (PDIV), high frequency current transformer (HFCT), phase resolved PD (PRPD), gases, $CO_2/O_2$.**

## I. INTRODUCTION

The promising arc quenching and dielectric insulation characteristics of $SF_6$ made it a valuable choice for gas-insulated equipment. Therefore, it has dominated the market for the past few decades. Despite the numerous advantages of $SF_6$, its global warming potential (GWP) is 22.5k times that of $CO_2$, and its atmospheric lifespan is 850 years [1], [2]. The power sector dominates the usage of $SF_6$ and results in 80% of $SF_6$ emissions globally [1]. TenneT, a transmission system operator (TSO), is also working to reduce $SF_6$ to achieve its sustainability goals. It aims to ensure uninterrupted power supply while minimizing the carbon footprint by preventing $SF_6$ emissions. To achieve this, 17 km of 380 kV gas-insulated line (GIL) will be installed using an eco-friendly alternative gas [3], [4].

Earlier studies on $CO_2$ and $CO_2/O_2$ mixtures prove that it can be an alternative to $SF_6$ [5]. Previous research [6] examines the breakdown strength of pure $CO_2$ and $CO_2/O_2$ mixtures at various pressures with different voltage shapes. In another study [7], the mixture of $CO_2$/ $O_2$ (70%/30%) is considered a promising alternative.

While previous studies have examined the partial discharge (PD) behaviour of pure $CO_2$ [8], the behaviour in $CO_2/O_2$ mixtures remains unexplored. This paper investigates the PD behaviour in a $CO_2/O_2$ (70%/30%) mixture under varying pressure conditions. To enable this experimental study, a novel PD detection method is employed using the HV bushing as a coupling capacitor, together with a high-frequency current transformer (HFCT). This setup improves the sensitivity of the measurement system and allows for a more accurate detection of PD activity in alternative gases such as $CO_2/O_2$ and C4-FN gas mixtures.

## II. EXPERIMENTAL SETUP

### A. Electrode Arrangement and Test Compartment

This paper investigates the PD behaviour of a protrusion with a smoothing sphere, as recommended by [9]. It consists of a sharp needle made of tungsten with a tip approximately 0.25 mm in diameter, protruding 3 mm from a smoothing sphere of 40 mm diameter connected to a high-voltage bushing. There is a plane electrode with a 200 mm diameter which is connected to ground. The gap distance between the tip of the needle and the plane electrode is 15 mm. This geometry can be seen in the enlarged section of Fig. 1.

To contain the pressurised gas, a vessel was manufactured from a GIS and has a volume of approximately 0.11 $m^3$. The maximum voltage rating of the compartment is 145 kV AC. The total combined height of the compartment, including the base and the bushing, is 3.9 m.

### B. Limitation of a Conventional Measurement Circuit

Traditional PD measurement setups often use a coupling capacitor to create a path in which the apparent charge can be measured. The self-inductance resulting from this current loop, in combination with the capacitance of the coupling capacitor and the capacitive test object, results in a series LC circuit. The resonance circuit distorts the signal, limiting the effective bandwidth of the measurement circuit. By injecting a fast pulse according to the procedure proposed in [10], the parameters of the detection circuit can be evaluated based on the resonance frequency. After connecting an external coupling capacitor of 1 nF, the measurement circuit had a resonance frequency of 3.5 MHz with the test compartment and 1.63 MHz without. From this, it was derived that the capacitance of the test compartment is approximately 276 pF.

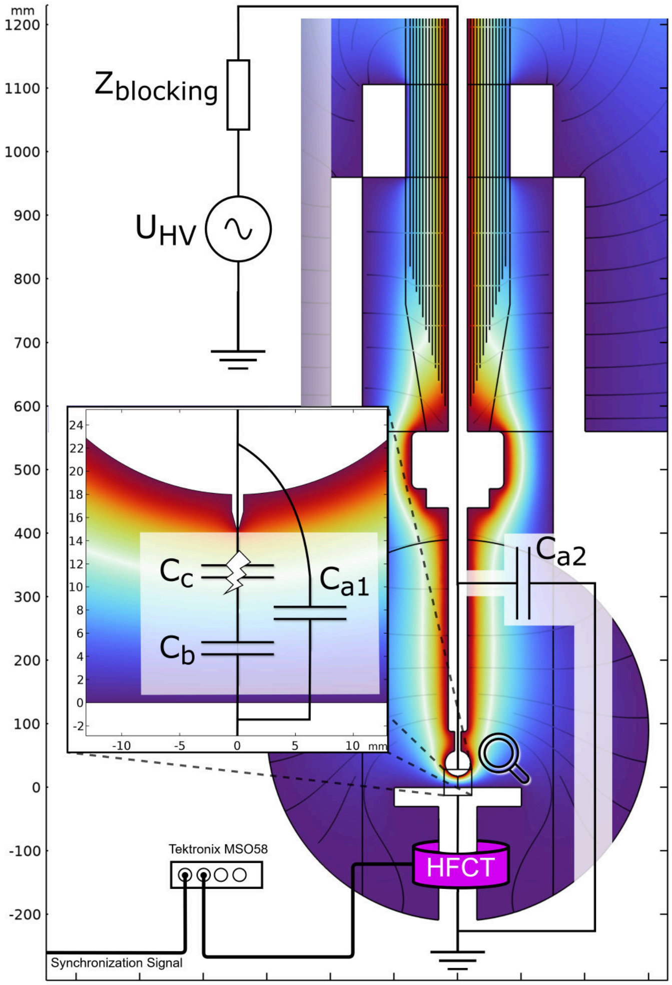

Fig. 1: Schematic and diagram of the measurement circuit which uses the coupling of the high-voltage bushing to the grounded enclosure ($C_{a2}$) as an alternative to a coupling capacitor

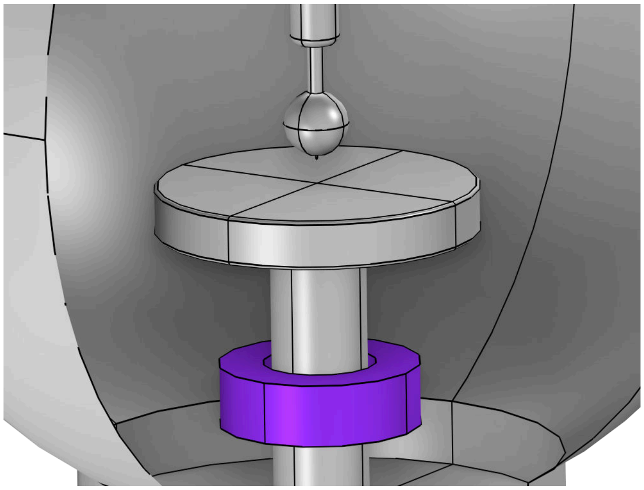

Fig. 2: Simplified 3D model of test compartment with the HFCT highlighted in purple

### C. Improved Measurement Circuit

A simplified 3D model (Fig. 2) of the test compartment was developed to estimate its capacitance using finite element method (FEM) simulations. To identify the dominant contributors to the capacitance, a study was performed where the grounded enclosure of the compartment was electrically isolated from the ground plane of the electrode arrangement. The objective is to split the $C_a$ component from the ABC model [11] into two separate capacitances $C_{a1}$ and $C_{a2}$.

It was found that the compartment's capacitance is dominated by the coupling of the conductor in the bushing to the surrounding grounded GIS enclosure, which will further be referred to as $C_{a2}$. Since the geometry of the electrode arrangement is very well defined, its capacitance contribution of approximately 5 pF, represented $C_{a1}$ as in Fig. 1 is used in Equation 1 to evaluate $C_{a2}$. $C_{a1}$ represents the coupling of the conductor to the ground plane.

$$C_{a2} = C_{\text{COMPARTMENT}} - C_{a1} = \sim 271\text{pF} \tag{1}$$

By placing a sensor between the electrode arrangement and ground, the current through $C_{a2}$ can be measured, and the external coupling capacitor can be omitted altogether. The diagram of this circuit can be seen in Fig. 1. This configuration has a much smaller current loop, shifting the resonance frequency of the measurement circuit to 144 MHz. The sensor installed is a HFCT, highlighted in purple in Fig. 2. The output of the HFCT is connected to an oscilloscope through a gas-tight connection. The HFCT has a bandwidth of 10 kHz - 500 MHz, which lacks the 50 Hz power frequency. Therefore, a separate source is used to synchronize the PD's to the AC phase, based on a phase synchronized sawtooth wave [12].

## III. METHODOLOGY

Prior to testing, the gas compartment was vacuumized to 0.01 mbar and held at this pressure for 5 minutes. After vacuumization, the chamber was filled with a $CO_2/O_2$ (70%/30%) mixture to a pressure level of 0.4 MPa. After letting the gas settle for at least 15 minutes, the PD test was performed. Two additional tests were conducted at pressures of 0.3 and 0.2 MPa by repeating the tests after releasing some of the gas.

AC voltage was applied to the needle-to-plane electrode arrangement and increased until the partial discharge inception voltage (PDIV) was reached. This voltage level was recorded for each pressure condition. Further measurements were then performed at 1.2 and 1.5 times the PDIV to study the evolution of PD behaviour under increased electric field stress. At each of these voltage levels, 10,000 consequential pulses were recorded in the oscilloscope operating at a sampling rate of 1.5625 GS/s. Each detected pulse was recorded over a 1 $\mu$s time window, which includes 300 ns of data before the trigger event of the pulse.

Apparent charge magnitudes were estimated using a quasi-integration method based on IEC 60270. A calibration pulse of known charge was injected between the needle and ground plane. After digital bandpass filtering, a calibration factor was derived from the filtered peak. The same filtering and scaling were applied to all PD pulses. This method follows the approach described in detail in [13].

To ensure that all discharges measured belong to the electrode arrangement, a verification test was performed in which the test voltage was applied without the needle present.

## IV. RESULTS

Figs. 3, 4 and 5 show the phase-resolved partial discharge (PRPD) patterns for the $CO_2/O_2$ (70%/30%) mixture at pressures of 0.2 MPa, 0.3 MPa, and 0.4 MPa, respectively. None of the samples have been discarded, so each plot contains 10,000 PD pulses. As pressure increases, a corresponding increase in PDIV is observed, reflecting the enhanced dielectric strength due to higher gas density. At voltage levels of 1.2 and 1.5 times PDIV, the repetition rate increases because the electric field becomes stronger, increasing the probability of discharge.

## V. DISCUSSION

The PD behaviour observed in the mixture deviates from typical air behaviour, where Trichel pulses form regular, horizontal PRPD patterns. In contrast, the mixture shows a greater variation in charge magnitudes. A similar scattering in pulse magnitude is also noted in pure $CO_2$ at 0.8 MPa in [8].

Additionally observed is a triangular-shaped distribution in charge magnitude, which is voltage-related. It is most pronounced at 0.2 MPa, as shown in Fig. 3.

## VI. CONCLUSION

A measurement setup was developed to perform detailed measurements of partial discharges in alternative insulating gases. By eliminating the traditional coupling capacitor and utilizing the inherent capacitance of the gas-insulated compartment, the setup enables more detailed acquisition of fast PD pulses in the time-domain by using a HFCT.

The system was applied to study the partial discharge behaviour of a $CO_2/O_2$ (70%/30%) mixture at pressures from 0.2 MPa to 0.4 MPa. The results showed that PD inception voltage increases and apparent charge magnitude decreases with an increase of pressure, while discharge repetition rate rises at higher voltage levels. Additionally, unusual PD behavior, such as widely varying pulse magnitudes, was observed, highlighting the importance of dedicated studies on alternative gases.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge Wim Termorshuizen for his valuable contribution to the development of the experimental setup.

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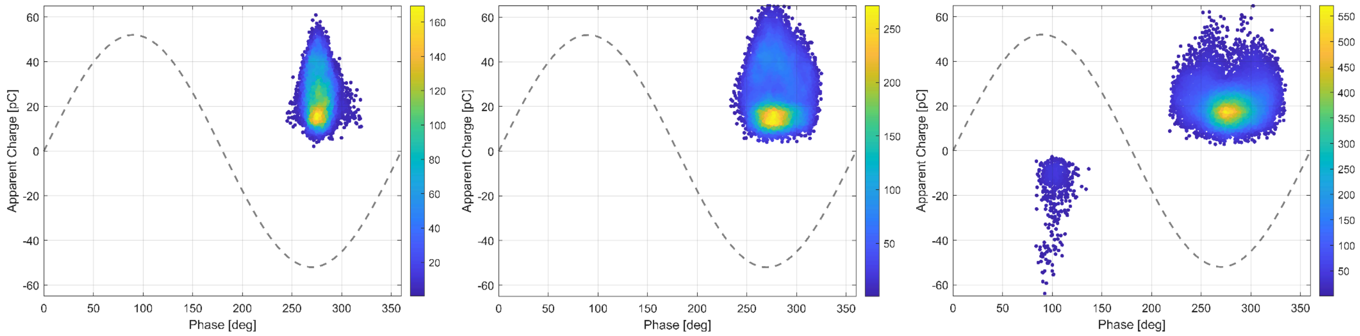
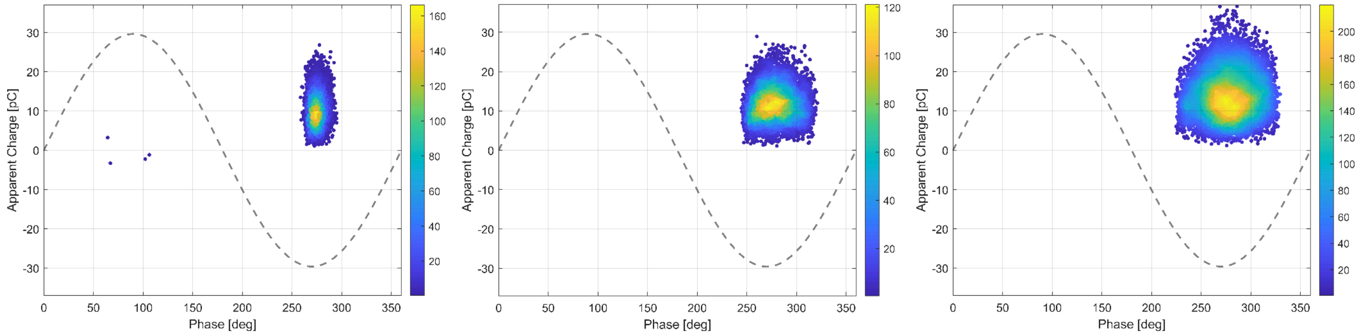


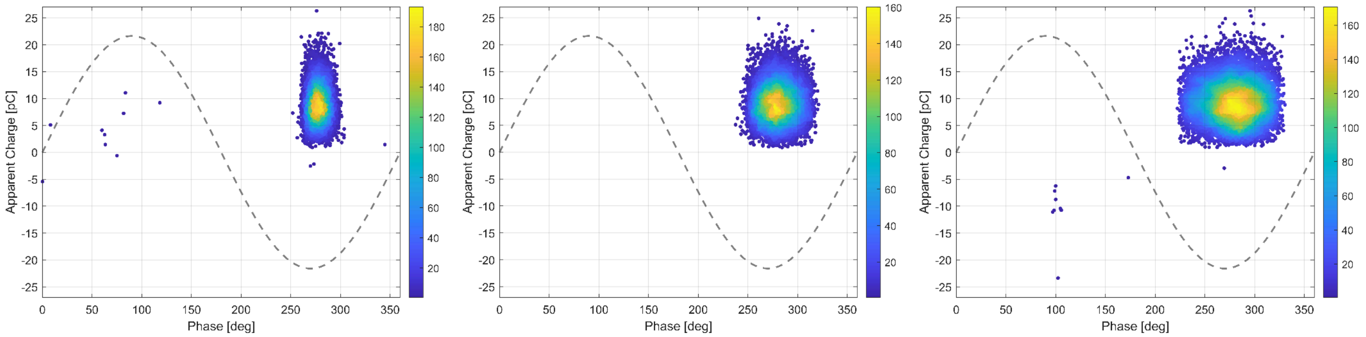
(a) (b) (c)

Fig. 3: PRPD patterns for $CO_2/O_2$ mixture at 0.2 MPa, measured at PDIV of (a) 100%, (b) 120% and (c) 150%.



(a) (b) (c)

Fig. 4: PRPD patterns for $CO_2/O_2$ mixture at 0.3 MPa, measured at PDIV of (a) 100%, (b) 120% and (c) 150%.



(a) (b) (c)

Fig. 5: PRPD patterns for $CO_2/O_2$ mixture at 0.4 MPa, measured at PDIV of (a) 100%, (b) 120% and (c) 150%.