Breakdown and Flashover in Compressed Gases : Effect of Gas Pressure and Insulator

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Abstract - The paper is aimed at the presentation of an experimental comparative study of breakdown of compressed CO_2 and surface flashover of PE solid insulator in compressed CO_2 gas medium. The discharge inception and breakdown voltage of the gas volume and the associated current are compared with the surface discharge inception and flashover voltage, and their associated current with the same experimental conditions (gas pressure, geometry of the electrodes and distance between active electrode and grounding)). Based on the analysis of the results, a qualitative explanation of the difference between breakdown and flashover mechanism has been suggested.

Keywords - SF_6 – Natural gases – CO_2 – Discharge – - Associated current – Inception voltage - Breakdown – Flashover.

I. INTRODUCTION

SF_6 is considered as the perfect gas for GIS and GIL) from dielectric view, and for GCB from interruption (thermal) view. Despite those exceptional characteristics, SF_6 is considered as an aggravating agent for the greenhouse gas effect with a high global (22800 for 100 years) and a very long lifetime in atmosphere (3200 years) [1], [2].

Recently, some solutions have been proposed for the SF6 replacement such as C3, C4, C5, etc. [1]-[4], which are mixed with other natural gases (CO_2, Dry Air or N_2). Studies are still ongoing for a better characterization of those gases even they are commercialized and used in HV electrical grids [5].

The advantage of this new generation of gases is that they exhibit equivalent performances as SF_6 with a close range of service pressure (8.8 bar abs for C4 and 5.5 bar abs for SF_6) and allowed to keep the same footprint. On the other hand, the mean inconvenient of those new gases are their behavior in extreme conditions (defect, metallic particles, voltage waveform and duration, ageing, partial discharges, etc.) [2] and the by-products created after the gas decomposition (breakdown or interruption) [1]-[5].

For this reason, research is performed to characterize and improve the natural gases to be as much as closer to SF_6 performances with acceptable footprint.

Despite the gas dielectric characteristics, the triple junctions are mainly the weakest area in high voltage equipment. When the electric field reaches a critical value, surface discharges are incepted and propagate along the insulator up to flashover.

On other hand, the physical mechanism responsible of the surface discharge propagation are not still now well knowledge because the complexity of the phenomena and the interaction of severe factors like:

- Interaction between the discharges, the kind of gas and the nature of the insulating material.
- Gas pressure.
- Surface charges and pollution (metallic particle).
- Geometrical parameters (insulator shape, electrodes form…).
- Etc.

Several studies have been done for the description and the analyze, the characterization, and modeling of creeping discharges and flashover in various compressed gases with different solid insulators and applied waveforms [6]-[13].

Some scholars showed that flashover voltage is not sensitive of gas pressure in opposition of volume gas breakdown [10]-[13]. No explanation was given.

In this paper, a comparative study of gas breakdown and flashover performance will be presented. The goal is to determinate the role of the insulator on the flashover process and to try to give answers concerning the charge injection during the process.

II. EXPERIMENTAL SETUP

The system (Fig. 1) consists of high voltage AC source (Transformer), a capacitive voltage divider, , High Frequency Current Transformer (HFCT), digital oscilloscope (Lecroy HDO6104), and a gas pressure vessel. Inside the vessel, a needle-plan electrodes system is installed, and which allows to insert a solid insulator with a metallic defect between them.

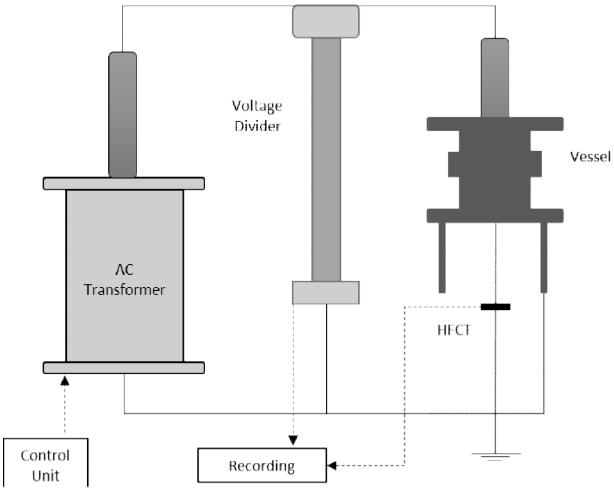
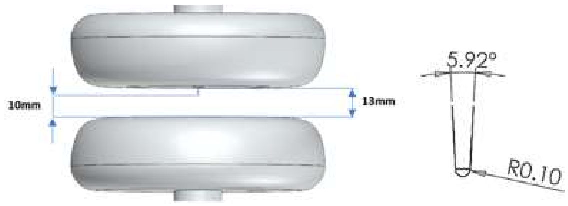


Fig. 1. Test setup.

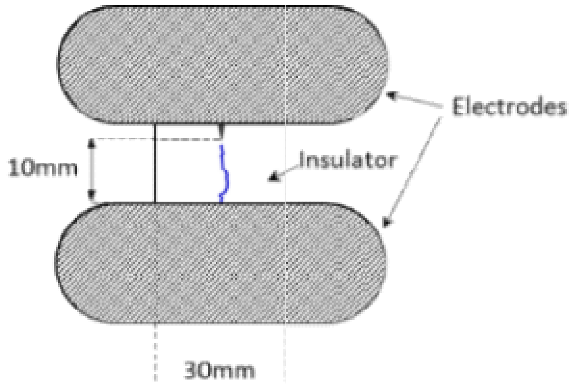
The insulation defect model consists of a needle (radius, R~100 μm) -plane electrode arrangement (Fig. 2). The tungsten needle is placed between two Bruce-shaped aluminium plane electrodes of 102mm diameter and a flat area of 60mm to provide a homogeneous background field. For each flashover and breakdown measurement series of 5 and 10 individual discharges are performed, this allows us to have exploitable values without rapidly degrading the state of insulators and electrodes.

The average of the measured values is taken as the flashover voltage VFO or the breakdown voltage VBD. For breakdown and flashover measurements, the AC voltage increase rate is 2kV/s till the 90% of the presumed electrical discharge is reached, and then 0.1 kV/s. Three minutes were kept in between the individual electrical discharges.

For flashover tests, a cylindrical PE insulator is used which measures 13 mm in height and 30 mm in diameter (Fig.2). A 3mm needle with 0.1mm in radius is fixed at the insulator surface and connected to the HV electrode with conductive aluminium tape. The effective gap between the needle tip and the ground electrode is 10 mm.



(a): non-uniform configuration without insulator.



(b): non-uniform configuration with insulator.

Fig. 2. Electrodes configuration.

III. RESULTS AND DISCUSSION

A) Inception and Gas breakdown

Figure 3 illustrates the variation of both positive and negative inception voltage and breakdown voltage with gas pressure. The breakdown characteristic of CO_2 shows a strong nonlinear behaviour with the gas pressure increasing under AC voltage as opposed to the uniform field configuration that exhibits a linear trend [14]. This effect can be attributed to the space charge created in the gas volume where the needle tip is covered with a cloud of charge carriers which will be stabilized by negative ions formed by attachment of electrons. Thus, the negative space charges generate a reduction of the electric field on the side of the tip. This causes an increase in the breakdown voltage.

The breakdown voltages increase with the gas until 5 bar abs and then stabilize between 6 bar abs and 8.8 bar abs : VBD is between 44 kV and 48 kV. On the other hand, except the range between 3 bar abs and 6 bar abs, the positive inception voltage is close to the breakdown voltage. For a critical pressure, the positive half-cycle becomes decisive, and the dielectric breakdown occurs at its peak value.

Figure 4 shows the instantaneous voltage and current during a breakdown event for different gas pressure. The positive and the negative inception voltages were measured at various pressures in the needle-plane configuration for a gap distance d = 10 mm and corresponding to a field utilization factor of 0.0375.

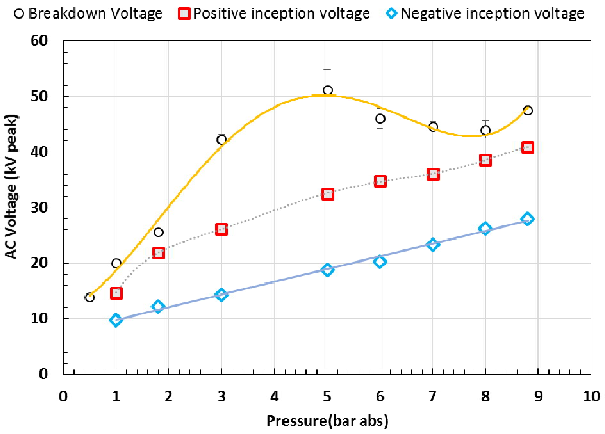
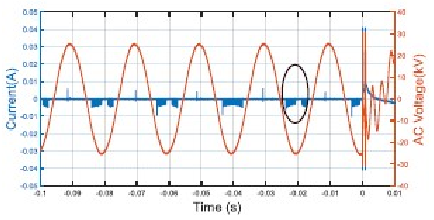


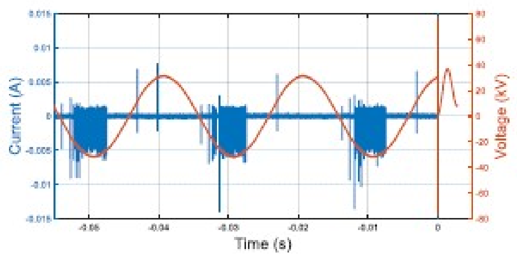
Fig. 3. Positive and negative voltage inception, and voltage breakdown vs gas pressure.

B) Inception and Surface flashover

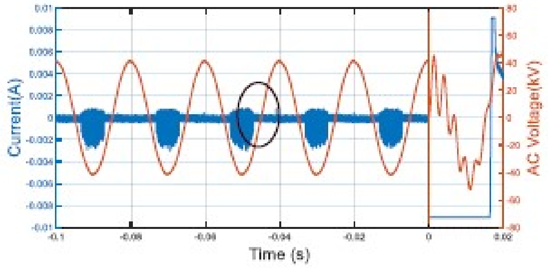
For flashover tests, the gap distance is d = 10 mm and corresponding to a field utilization factor equal to 0.025. As for breakdown, a strong nonlinear behavior as a function of gas pressure is observable. The flashover occurs in AC voltage on both positive and negative peaks. For a critical pressure, flashover occurs at the peak value of the positive half-cycle. As for breakdown, the negative inception voltage increases linearly with the gas pressure, as shown in Figure 5. By increasing the pressure, the negative inception curve and the flashover curve reach close voltage levels at a critical pressure, PC = 8 bar abs. On the other hand, Figure 6 shows that flashover voltage increases with the gas pressure until 3 bar abs, and then becomes approximately constant with an average value of 32 kV.



(a) Gaseous Breakdown on negative half cycle (2 bar abs).



(b) Gaseous Breakdown on positive half-cycle (3 bar abs).



(c) Gaseous Breakdown on positive half cycle (8 bar abs).

Fig. 4. Voltage-current waveform of discharge inception and breakdown voltages.

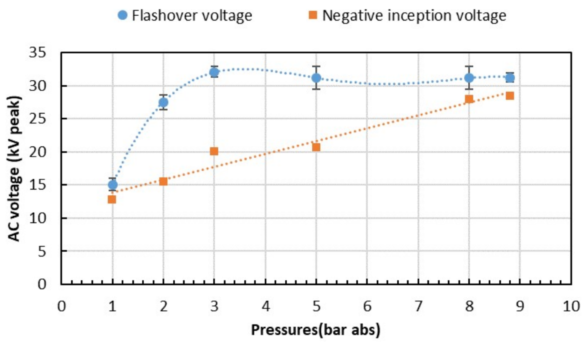


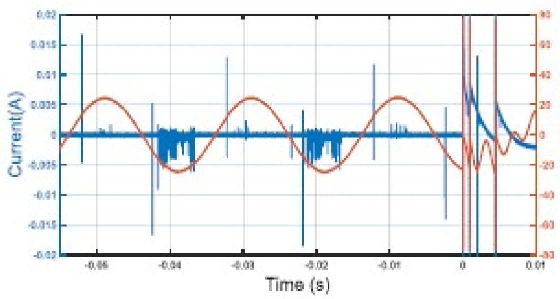
Fig. 5. V50% Flashover and Negative inception voltages as a function of gas pressure.

Figure 6 illustrates the instantaneous leakage current during the surface discharge (corona/streamer) inception and the flashover. Different modes are observed in the nonlinear flashover voltage behavior with the filling pressure. When the gas pressure is between 1 bar abs and 2 bar abs, flashover occurs on the negative half-cycle peak. The positive pre-breakdown discharge is stopped to transit to breakdown, influenced by the shielding effect produced by the positive glow corona. The negative pre-discharge modes are as follows: streamer, glow discharge and leader discharge, associated currents are shown in Figures 6-a, negative half cycles. When the gas pressure is over 2 bar abs, flashover occurs on a positive half-cycle peak: positive glow corona appeared for pressures up to 5 bar abs.

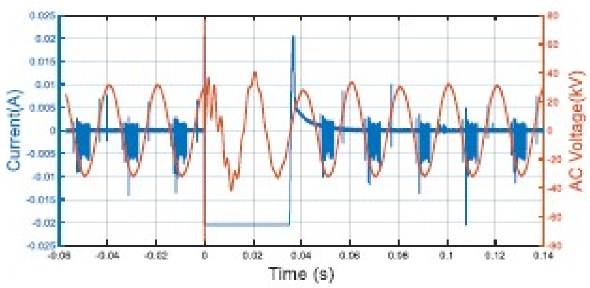
C) Discussion

The flashover voltage is lower than the breakdown voltage, for the same electrode configuration, and gap, and gas pressure. As the voltage increases, partial discharge appears at the interface between the HV electrode and the solid insulator. With the increase of the applied voltage, the discharge activity is more intense, and the leader propagates along the insulator surface until the ground electrode -flashover- as observed by [8][9][13].

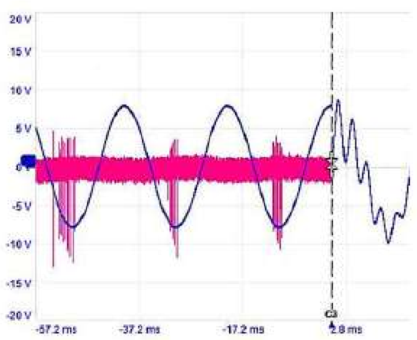
On the other hand, the surface discharge current is greater than for the discharge gas pre-breakdown for the same configuration (gas pressure, electrodes configuration and gap distance), but the number of the current pulses is less. This observation makes it possible to highlight the effective charge injection from the solid insulator along the discharge propagation. Indeed, photoemission and electrical field emission from the solid insulator are possible supplementary charge injection mechanisms that can explain the increase of the magnitude of the current pulse. The electrical field emission is usually governed by the intensity of the tangential electrical gradient at the insulator surface [15]. For the photoemission, the mechanism is more complex as the photoemission of the solid dielectric usually needs less energy than the photoionization of the gas [16]. The extraction of the electrons from the solid insulator leaves a positive charge at the surface that interacts with the discharge head, and generates:



(a) Flashover on negative half cycle (2 bar abs).



(b) Gaseous Breakdown on positive half-cycle (3 bar abs).



(c) Gaseous Breakdown on positive half cycle (8 bar abs).

Fig. 6. Voltage-current waveform of surface discharge inception and flashover voltages.

- A repulsion effect in the case of positive space charge at the head that pushes the discharge to move away to catch other photoelectrons (photoionization and photoemission). Those photoelectrons are responsible for the positive current pulses and the heating of the leader/spark channel.
- An attraction effect of negative space charge from the solid insulator and from the gas that contribute to the increase of the local attachment and/or recombination at the interface. This can explain the presence of electronegative elements at the arced insulator surface.

The heating of the leader channel interacts also with the insulator surface and may generate supplementary electrons by a thermo-emission effect which, in turn contributes to the creation of a preferential path across the surface. On the other hand, depending on the polarity, the efficiency of the charge injection from the solid insulator or the attachment/recombination process will govern the propagation path. The attachment and recombination processes mainly occur at the solid/gas interface.

Based on the previous explanations, the description of the surface discharge inception and propagation can be clarified too, depending on the gas pressure:

(a)1 < P ≤ 2 bar abs: The flashover occurs on the negative half-cycle peak where the negative leader current pulses are observed at the beginning of the negative half-cycle. The leader current pulses are the result of charge accumulation left by the previous activity. During the positive half-cycle, the density of the current pulses is less than is typical for positive streamers and presents some leader current peaks after charge injection at the beginning of the positive half-cycle. The negative half-cycle just before flashover shows that the leader propagates quickly (final jump) because, at this stage, the critical length was achieved and the unbridged gap between the discharge head and the ground electrode is partially ionized, as suggested in [6].

(b)P > 2 bar abs: The flashover occurs on the positive half-cycle peak where positive streamers currents and leader pulse current are observable for pressures up to 5 bar abs. During the positive half cycle, at P = 3 bar abs and as the voltage increases, the stages to discharges are streamer onset, glow corona onset and the leader channels bypass the positive glow corona volume and follows the same process as described in (a). Whereas, during the negative half cycle, the streamer mode is involved before the flashover on the positive half-cycle.

(iii)For pressures P ≥ Pc, the gas breakdown (and the surface flashover occur on the positive half-cycle peak. The transition from streamer discharge to leader discharge is immediate and breakdown is immediately after streamer onset, with only a small increase of voltage.

Comparing the current activities, the surface discharge peak current is 4 times higher than the gas partial discharge one. In fact, the surface discharge includes supplementary mechanisms for discharge development as described previously. Furthermore, no current pulses were detected preceding surface flashover. Ions generated during the pre-discharge phenomenon on negative half-cycles may not be removed before polarity reversal occurs, resulting in a space-charge induced field distortion. This results in a reduction of the surface flashover voltage.

On the other hand, it was observed that the surface discharge trends to stick the insulator surface with the increasing of the gas pressure [8][9][13]. This can explain the relative stability of the surface flashover voltage for high pressures: the main electrical charges are collected from insulator caused by the increase of the attachment process with the gas pressure rising. Moreover, according to [17][18], the discharge velocity increases with the energy increase. The more is energy injected or applied, the more the discharge is faster. For higher pressures, the inception voltage is higher resulting in a higher velocity of electrons and ions. Resulting in a faster avalanche growth and faster discharge development, and the corona initiation curve and the flashover curve reach closer voltage levels.

IV. CONCLUSION

In this paper, a comparative experimental study between compressed CO_2 gas breakdown and flashover of PE insulators in compressed CO_2 medium have been presented.

The results showed that a polarity reversal appears for both breakdown and flashover depending on the gas pressure. The inception discharge voltage of the gas increases with the gas pressure and becomes close to breakdown voltage when pressure is over the critical pressure. The same observation has been reported for flashover.

The recorded current showed a difference between partial discharge in the gas and creeping discharge at the insulator surface. The main difference are the magnitude and the number of pulses; the magnitude of the current of the surface discharges are higher than the partial discharges in the gas while the number of the pulses are less.

The main mechanism suggested for the explanation of the difference between breakdown in the gas and flashover in the injection of charges from the solid insulator with different manners (photoemission, photoionization, thermo-emission).

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