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Study of partial discharge and breakdown phenomena at triple junctions under various conditions of pressure and temperature

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Abstract. The presence of a triple junction constitutes a potential source of failure in many industrial applications. The reinforcement of the local electric field due to differences in relative permittivity facilitates the formation of partial discharges (PD) which weaken the insulation system and eventually lead to complete breakdown. Additionally, severe environmental conditions (temperature, pressure) associated with certain applications (e. g. nuclear or aeronautical sector) should be considered because of their influence on discharge phenomena occurring at triple junctions. In this study, the behaviour of partial discharge inception voltage (PDIV) and of breakdown (flash-over) voltage (BIV) is compared in the case of a triple junction with an aluminium oxide disc as a solid insulator when the system is heated up to 400 °C. While the PDIV decreases strongly for temperatures above 300 °C, this effect disappears for the BIV. It is proposed that this behaviour is due to the fact that relative permittivity of the aluminium oxide disc increases with temperature at low frequencies, but remains relatively stable at high frequencies, regardless of the temperature.

1. Introduction

The junction between a solid insulator, a solid conductor and the surrounding gas constitutes a triple junction which could be the starting point for electrical breakdown in case of overvoltages. Since the local electric field at the triple junction is reinforced due to differences in relative permittivity of the solid insulator and the surrounding gas, voltages below the threshold for electrical breakdown lead to the inception of partial discharges (PD). PD can lead to an accelerated aging of the insulation system and cause low-level damage which could accumulate and finally end up in complete breakdown [1], [2].

These triple junctions are often present in industrial applications where high voltage conductors are isolated from other system components using solid insulators. In some circumstances, the solid insulator and the surrounding gas are exposed to severe environmental conditions in terms of pressure and temperature, as for example in the nuclear or the aeronautical sector where temperatures up to 500 °C and pressures down to 100 *mbar* are reached, respectively [3], [4].

This work aims to come to a more detailed understanding of phenomena taking place at triple junctions at various temperatures and pressures. Measurements of PDIV (Partial Discharge Inception Voltage) and BIV (Breakdown Inception Voltage) were made using a device consisting of an aluminium oxide disc (Al_2O_3) placed between a grounded stainless-steel disc and a cylindrical tungsten electrode connected to an AC power supply (50 *Hz*) for gas pressures (N_2) between 50 *mbar* and 1000 *mbar* and temperatures between 20 °C and 400 °C.

2. Theoretical Background

Gas discharges can be initiated under the condition that seed electrons are accelerated by an external electric field. If the electrons gain a sufficiently high energy during their free path and come into an ionising collision with other gas atoms/molecules, an electron avalanche can be formed, and a self-sustaining discharge can be initiated provided that a secondary emission mechanism enables the regeneration of electrons.

The effect of gas temperature on breakdown can be described using the equation of the ideal gas law, see (1), of the free mean path, see (2), and of the electric field strength, see (3), which is considered to be constant near the triple junction:

$$N = \frac{p}{k_B \cdot T} \quad (1) \quad \lambda = \frac{1}{\sigma \cdot N} \quad (2) \quad E = \frac{\varepsilon}{q_e \cdot \lambda} \propto \frac{V}{d} \quad (3)$$

where N is the gas density, p the gas pressure, k_B the Boltzmann constant, T the gas temperature, λ the mean free path, σ the collision cross section for electron-gas ionisation, E the electric field strength, ε the ionisation potential, q_e the elementary charge, V the breakdown voltage and d the distance between the electrodes.

As can be seen in the above equations, an increase in temperature leads to a decrease in gas density which in turn leads to a greater value for the mean free path. Consequently, for a given ionisation potential, the electric field strength and thus the voltage needed to provoke a discharge decrease.

3. Experimental setup and procedure

To test the triple junction at high temperature and different gas pressure / density, an experimental setup as pictured in figures 1 and 2 was constructed.

The triple junction assembly was constituted of a cylindrical tungsten electrode (diameter: 30 mm, Rogowski profile) (3) connected (1) to a high voltage power supply (50 Hz AC), an aluminium oxide disc (99,7 % α -Al₂O₃, diameter: 50 mm, thickness: 1 mm) (4) as dielectric test object, a grounded steel electrode (diameter: 50 mm) (5), a ceramic (silicon nitride) heating element (6), separately connected to a DC power supply, which was in this work operated up to 400 °C (measured near the triple junction) and a thermocouple (7) measuring the temperature inside the stainless steel disc and serving as input for the regulation of the heating element realised within LabVIEW using a PI controller. All elements were placed in a refractory box (2) consisting of porous aluminium oxide with low thermal conductivity to homogenise the temperature around the triple junction and to protect the vacuum chamber which was made of PMMA.

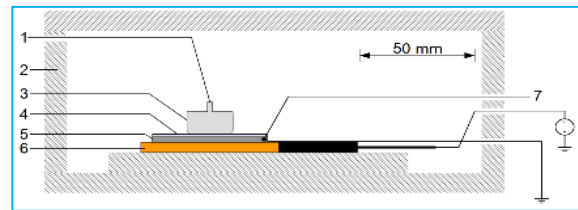


Figure 1. Schematic of the triple junction assembly including the heating plate inside the refractory box.

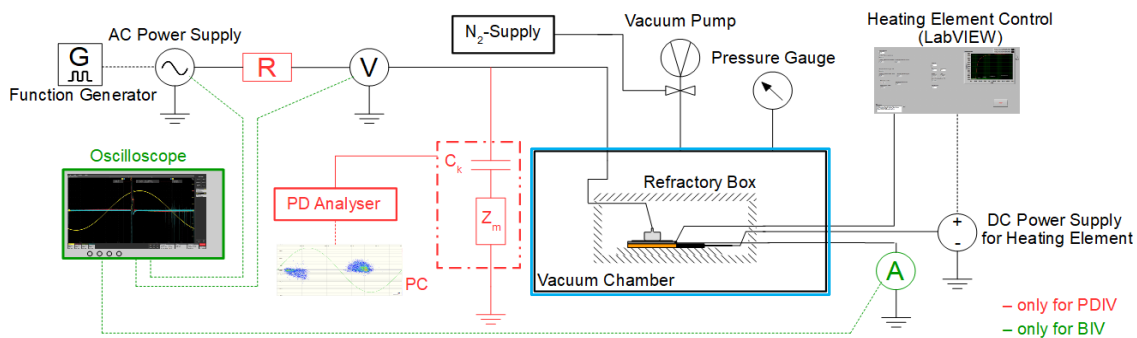


Figure 2. Schematic of the experimental setup

The triple junction assembly was connected to a high voltage power supply, controlled by a function generator (50 Hz AC), which was placed in series with a 10 M Ω resistance (only present for PDIV

measurements). The PDIV was determined corresponding to the standard IEC 60270 using a commercial partial discharge analyser (OMICRON MPD 600) which was connected in parallel to the triple junction assembly via a 250 pF coupling capacitor whereas for BIV measurements only a current probe connected to an oscilloscope was used. The applied voltage was measured with a high voltage probe.

All the experiments were made inside a vacuum chamber using nitrogen thus preventing undesirable oxidation of the electrodes at high temperatures. A vacuum pump, a nitrogen supply, and a Pirani type sensor to monitor the pressure were connected to the vacuum chamber.

Precise temperature surveillance and appropriate regulation of the heating element were essential for this work. Temperature measurement at the triple junction and in its near vicinity in the gas showed only a slight temperature difference. Hence, the gas density at the triple junction where the discharges are expected to take place and its near proximity can be considered as homogeneous allowing the analysis of the results only as a function of gas density.

PDIV and BIV were determined in range from $20\text{ }^{\circ}\text{C}$ up to $400\text{ }^{\circ}\text{C}$ and 1000 mbar down to 50 mbar . For the PDIV determination, a voltage of approximately 100 V below the expected PDIV was first applied, then raised by steps of 10 V and maintained during 10 s . The voltage was raised again by 10 V if no discharges were detected (detection threshold: 3 pC). Otherwise, the voltage was maintained for 30 s and in the case of more than 30 detected discharges, the PDIV value was retained. A similar procedure was applied for the BIV determination whereas a voltage of 1 kV below the expected BIV was first applied and then raised every 10 s by 100 V until breakdown was reached.

Additionally, the relative permittivity of the aluminium oxide disc was determined in the same temperature range and in a frequency range from 20 Hz up to 1 kHz using the same test circuit and a commercial LCR-Meter (Wayne Kerr LCR Meter 4300).

4. Results and discussion

Figures 3 and 4 respectively show the results for the PDIV and BIV depending on temperature as a function of gas density. To ease the lecture, all points belonging to the same temperature experiments are connected with a trendline.

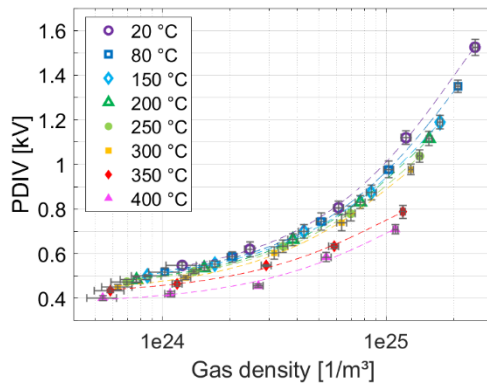


Figure 3. PDIV as a function of gas density for different temperatures.

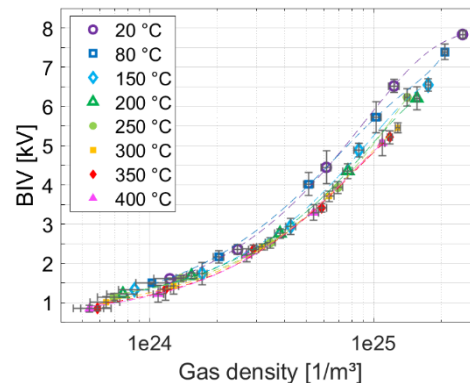


Figure 4. BIV as a function of gas density for different temperatures.

On the one hand, as expected, both the PDIV and BIV decrease with temperature when plotted as a function of gas pressure. For a given gas at constant pressure, increased temperature leads to a drop in gas density, and therefore to a proportional increase in the mean free path of free electrons. If the applied electric field is of the same intensity, the average energy of the free electrons is higher. Hence, it is expected to measure a lower PDIV/BIV at higher temperature than at ambient temperature.

On the other hand, assuming that the gas density is homogeneous in the vicinity of the triple junction, it should be expected that all the trendlines merge together when plotted as a function of gas density. However, as can be seen in figure 3, with increasing temperature up to $300\text{ }^{\circ}\text{C}$, all the curves for the PDIV are slightly below their precedent ones whereas a bigger gap between $300\text{ }^{\circ}\text{C}$ and $350\text{ }^{\circ}\text{C}$ can be observed. Consequently, for a given pressure, the increase in the mean free path in the gas due to increase

in temperature does not alone explain the decrease in PDIV. However, this effect disappears for the BIV, see figure 4.

Thus, attention was then directed towards the role that the aluminium oxide disc could play on the PDIV/BIV since studies showed that temperature may alter the dielectric properties such as relative permittivity [5]. Figure 5 shows the dependence of the relative permittivity of the aluminium oxide disc on temperature and for different frequencies.

As can be seen, the relative permittivity of the aluminium oxide disc increases with temperature, especially at low frequencies (50 Hz highlighted by a trendline). This results in an increased local electric field near the triple junction. It is therefore logical that the PDIV drops with temperature even more than may be expected simply due to the decrease in gas density.

However, BIV seems to be unaffected by the increase in relative permittivity with temperature (in particular, 300 °C, 350 °C and 400 °C characteristics are strongly merged). This effect may be explained by the velocity of the discharge propagation. Since the propagation of the streamer discharge occurs at a speed of approximately 10^5 m/s and the distance between the high voltage and the grounded electrode is about 1 cm, the breakdown takes place within 10^{-7} s corresponding to a frequency of 10 MHz. As can be seen in figure 5, at high frequencies the relative permittivity remains relatively stable no matter the temperature. Hence, the discharge propagation for BIV is too fast to be influenced and, in contrast to the PDIV, all curves tend to merge when plotted as a function of gas density.

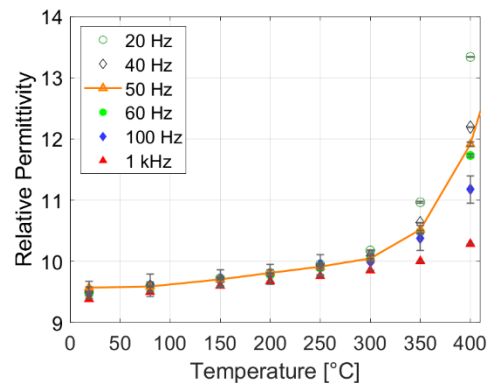


Figure 5. Relative permittivity of 99,7 % aluminium oxide disc for different temperatures and frequencies

5. Conclusions

The present work reports on the influence of temperature and different gas pressures/densities on PDIV and BIV at a triple junction. It was observed that both the PDIV and BIV decrease with temperature when plotted as a function of gas pressure, and that the influence of the evolution of the dielectric properties of the solid insulator leads to a decrease in PDIV whereas BIV seems to be unaffected because discharge propagation is too fast to be influenced by changes in the ceramic insulator's permittivity.

These results are of interest for industrial applications featuring triple junctions exposed to high temperature conditions under various pressures.

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