Post-arc Dielectric Recovery Characteristics of Free-burning Ultrahigh-Pressure Nitrogen Arc

F. Abid[1]*, K. Niayesh[1], and N. Støa-Aanensen[2]

[1] Norwegian University of Science and Technology, Trondheim, Norway
[2] SINTEF Energy Research, Trondheim, Norway
* fahim.abid@ntnu.no

***Abstract*—This work contributes to the fundamental understanding of post-arc dielectric recovery characteristics of free-burning nitrogen arcs as a function of gas filling pressure. Arc peak current of 425 A at a frequency of 925 Hz is used throughout the experiment. The arc burns freely between two fixed electrodes without any forced gas flow. Three different filling pressures are investigated: 1 bar (atmospheric pressure), 20 bar, and 40 bar, the latter being in the supercritical region. To investigate the effect of inter-electrode gap on the recovery process, two different gap distances are used: 20 mm and 50 mm. A 10 kV high voltage pulse with a rate of rise of 150 V/µs is applied across the electrodes after current zero. To evaluate the recovery process, the time between current zero and the start of the pulse is varied from 10 µs to 10 ms. Experimental results show that the dielectric recovery performance improves with the filling pressure even in the absence of a forced gas flow. The breakdown strength is observed to recover faster for a longer electrode gap.**

I. Introduction

Nitrogen undergoes phase transition to a supercritical state (SC) above a critical pressure (33.5 bar) and a critical temperature (126 K). An SC fluid exhibits properties of both the liquid (high dielectric strength, high heat capacity) and the gaseous phase (self-healing, no vapor bubbles). Current interruption medium in power switching devices must hold a specific set of properties; such as high insulation strength during off time, low resistance during on time, fast recovery after switching, long lifetime etc. For gas circuit breakers, the properties of SC fluids are believed to enhance the current interruption performance [1], [2].

At present, the gas circuit breakers are filled at the atmospheric pressure or slightly elevated pressure. It is well known that the dielectric strength is high at high filling pressures. Nonetheless, there are few publications reported on gas discharge at extremely high filling pressure and in supercritical region. Among the published works, none of them covers high energy arc discharges typical for power switching applications [1], [2]. Recently, some efforts have been made to investigate arc discharges in SC N_2 at tens of bars filling pressure. Nitrogen is chosen due to its environmentally benign nature, good insulation strength and low critical pressure. It has been reported that the free-burning arc voltage increases with filling pressure of nitrogen, without any abrupt change during the transition from gas to SC state [3], [4]. A higher arc voltage results in a higher energy deposition in the arc channel.

Current interruption can be described as a race between the cooling of the arcing channel and the voltage that builds up across the contacts [5]. To have a successful current interruption, the dielectric strength between the electrodes should be higher than the transient recovery voltage stress imposed by the network. Hence, the post-arc dielectric recovery characteristics of the arcing medium is of importance. To the knowledge of the authors, no work has been reported on the post-arc dielectric recovery characteristics of supercritical nitrogen for switchgear applications.

This study focuses on the influence of filling pressure on the dielectric recovery characteristics of free-burning nitrogen arcs in a fixed electrode arrangement. Three different filling pressures are investigated in this study: 1 bar (atmospheric pressure), 20 bar, and 40 bar (supercritical region). To evaluate the recovery of dielectric strength as a function of time, a 10 kV high voltage (HV) pulse with a rise time of approximately 70 µs is applied across the electrodes after CZ. The time between CZ and the pulse is varied from 10 µs to 10 ms. Finally, to investigate the effect of inter-electrode gap on the recovery process, the gap distance between the electrodes is varied. The breakdown voltage as a function of time after current zero crossing is reported to evaluate the dielectric recovery characteristics of the arc channel at different filling pressures.

II. Experiment Setup

The test circuit is shown schematically in Fig. 1. It consists of a charging and a discharging section of a 4.8 µF high voltage (HV) capacitor bank, *C*. The capacitor, *C* is charged from the HV source and through the diode-resistor unit (R_C-D_C). Once the capacitor, *C* is fully charged to a predefined charging voltage, the switch S_C is opened to disconnect the rest of the circuit from the grid. The inductance, *L*, is chosen in such a way that a fixed current amplitude of 425 A at a frequency of 925 Hz can be generated. Once the triggered vacuum switch (*TVS*) is closed, the current flows through the inductor and further through a copper ignition wire (40 µm diameter) inside the arcing chamber. After the current starts flowing, the ignition wire melts due to adiabatic heating and an arc is initiated. The arc burns freely between the electrodes without any forced N_2 flow.

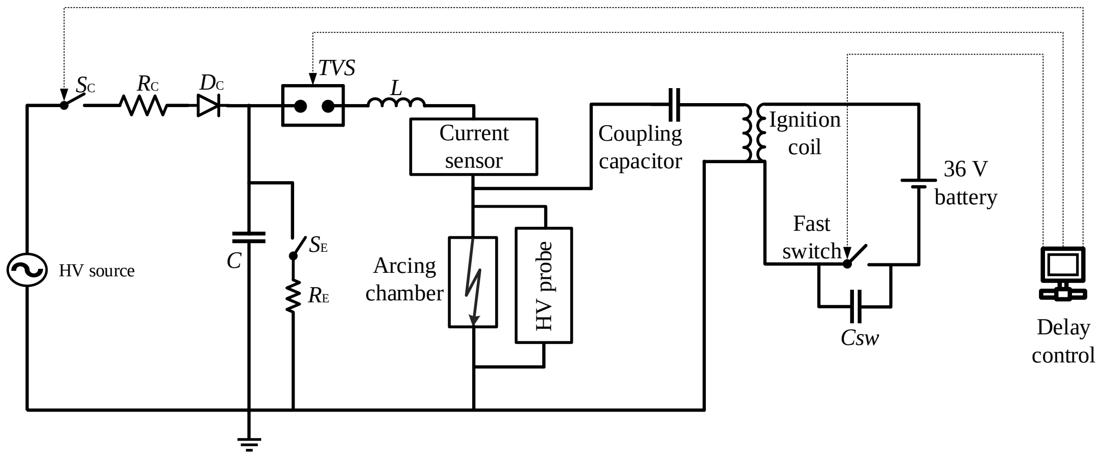

Fig. 1. Test circuit.

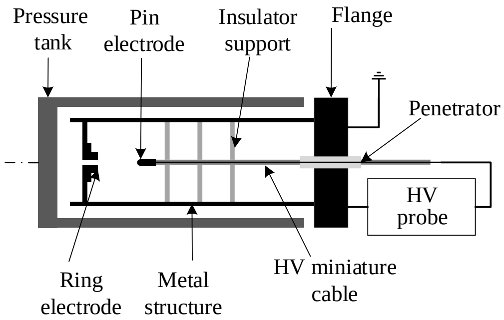

Fig.2. Interior connection of the pressure tank.

The arc current continues to flow until current zero crossing (CZ), when the TVS interrupts the current. A 10 kV high voltage (HV) pulse is applied between the arcing electrodes after a predefined time delay. The HV pulse is generated from a car ignition coil by opening the current flowing through its primary windings. A coupling capacitor is connected between the high current circuit and the ignition coil. The time delay of the pulse after CZ can be precisely controlled in the order of few microseconds by a computer-controlled synchronization unit. In this paper, the time between CZ and the start of the HV pulse is varied from 10 µs to 10 ms. When the dielectric strength of the electrode gap is not high enough to withstand the HV pulse, a breakdown occurs, marked by a collapse of the applied pulse voltage.

A pressure tank of 15.7-liters rated for 500 bars, shown schematically in Fig. 2 is used as arcing chamber. A 24 kV HV cable is fed through the flange of the pressure tank. The HV cable is terminated to the pin electrode, and held in position inside the pressure tank by insulators. The experimental setup is put inside an explosion-safe room. All the operations are controlled from a separate room located at a safe distance.

A high voltage (HV) probe is used to measure the arc voltage and voltage pulse after CZ across the electrodes. The HV probe is connected outside the pressure tank. A shunt resistor is used to measure the arc current. The current sensor is connected on the high voltage side of the arcing chamber on a floating potential. All the data are sent to the control room via optical fiber and stored in a digital oscilloscope for further analysis.

III. Experimental Results and Discussions

A typical measurement of the arc voltage, arc current and the HV pulse after CZ at 1 bar filling pressure is shown in Fig. 3. The initial voltage peak at approximately 0.5 ms before CZ marks the melting of the ignition wire and initiation of the arc. The current continues to flow until CZ, where the TVS interrupts the current. Just after the CZ, the temperature of the arc channel is still high. As a result, some of the charged carriers are present between the arcing contacts. When a HV pulse is applied between the contacts, a breakdown may occur.

Two different cases, with one breakdown and one without breakdown, are shown in Fig. 3. The red line represents a test where the HV pulse was applied approximately 700 µs after CZ, resulting in a breakdown. The breakdown is recognized by a voltage collapse at 7.8 kV. The test without a breakdown (pulse applied at 2 ms after CZ) shows the full HV pulse and following oscillations from the ignition coil (green line). For the cases where a breakdown occurred, the value of the breakdown voltage is considered for further analysis. For the cases without having a breakdown due to the pulse, it

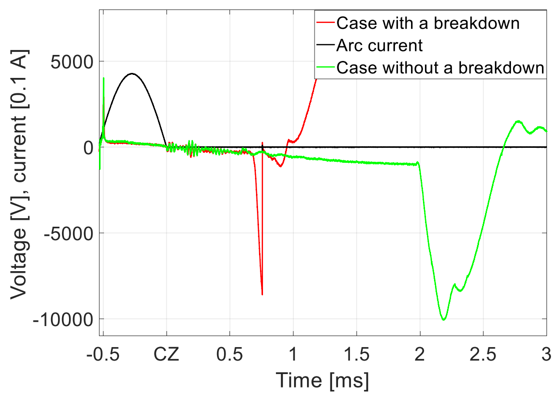

Fig. 3. Typical measurement showing a case of a breakdown (red line) and a case of not breakdown (hold) occurs (green line).

is termed as a hold voltage. Due to the stray capacitance in the setup, there are voltage oscillations with a voltage peak of approximately 400 V just after CZ, which are not part of the applied HV pulse. The rate of rise of these voltage oscillations are 125 V/µs, which is comparable to the rate of rise of 10 kV HV pulse. When the breakdown strength of the medium is less than the voltage oscillations then breakdown occurs. In this paper the breakdown caused by the voltage oscillations are also considered to evaluate the recovery characteristics.

A. Effect of filling pressure

The effect of gas filling pressure on the dielectric recovery performance of free-burning nitrogen arcs is illustrated in Fig. 4. The filled markers indicate a not breakdown (hold voltage) due to the HV pulse, while the empty markers indicate the breakdown voltage. At 1 bar filling pressure and 50 mm gap distance, the withstand voltage is approximately 330 V from 10 µs up to approximately 400 µs after CZ. After 400 µs, the gap gradually recovers its dielectric strength, which can be seen by the increase of the breakdown voltage for pulses starting later than 500 µs. After approximately 2 ms, no breakdowns were observed for the applied pulse at 1 bar gas pressure.

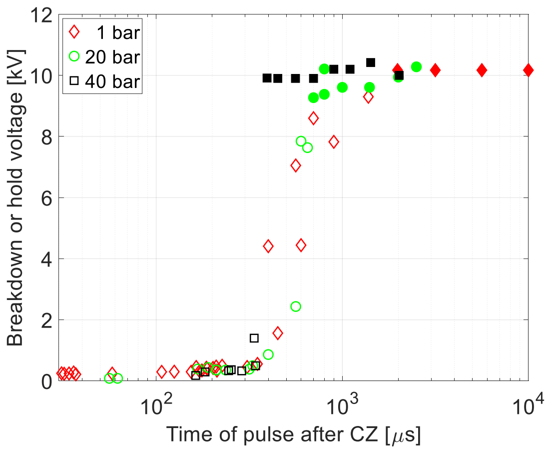

Fig. 4. Breakdown or hold voltage as a function of time to pulse after CZ for 50 mm inter-electrode gap distance. The filled marker represents the withstand voltage whereas the empty marker represents the breakdown voltage.

For 20 bar and 40 bar at an inter-electrode gap of 50 mm, the breakdown voltage after CZ from 10 µs to approximately 300 µs is approximately 100 V, which is low compared to 1 bar filling pressure during that time. However, after 300 µs the gap recovery process was observed to be faster as the filling pressure increases. Compared to the case with 1 bar filling pressure; no breakdowns occurred for 50 mm gap distance for pulses after 800 µs and 400 µs for 20 bar and 40 bar filling pressures, respectively.

B. Inter-electrode gap

To investigate the effect of inter-electrode gap distance on the recovery process, similar experiments were conducted at a gap distance of 20 mm at two different

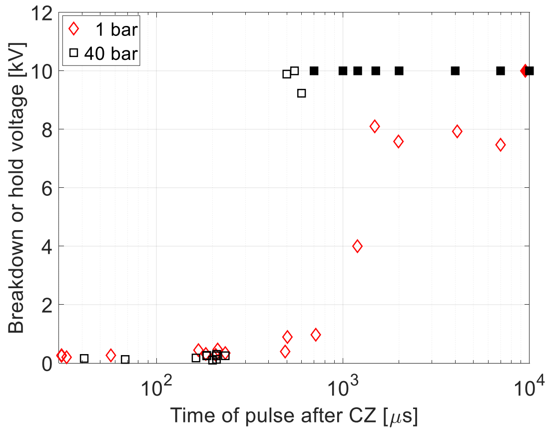

Fig. 5. Breakdown or hold voltage as a function of time to pulse after CZ at an interelectrode gap of 20 mm. The filled marker represents the hold voltage whereas the empty marker represents the breakdown voltage.

filling pressures: 1 bar and 40 bar. The breakdown or hold voltage as a function of the time of the start of the pulse after CZ are plotted in Fig. 5. The observed trend of a faster recovery of the post-arc channel for 40 bar in contrast to 1 bar filling pressure is also observed at 20 mm gap distance. When compared between the two inter-electrode gap distances, it is observed that the smaller gap distance takes longer time to recover, see Fig. 4 and Fig. 5. For 1 bar at 50 mm gap distance, no breakdown is observed when a pulse is applied after 2 ms of CZ. However, when the gap distance is 20 mm, the gap recovers slowly, resulting in a minimum time to hold the pulse at 10 ms. At 40 bar, the minimum time after CZ for having a not breakdown (hold) of the pulse is 400 µs and 700 µs for 50 mm and 20 mm, respectively.

C. Discussions

The post arc dielectric recovery performance of free-burning nitrogen arc indicates that after a certain time (several hundreds of microsecond) the recovery performance improves with the filling pressure. However, just after CZ, the breakdown voltage measured for high filling pressure arcs is lower than that for the atmospheric pressure arcs. Thermal interruption performances of the free-burning nitrogen arc also show a reduced breakdown voltage for high filling pressure (i.e., 20 bar, 40 bar) in comparison to atmospheric pressure. When the filling pressure is high, the energy deposition in the arc channel also increases because of increased arcing voltage. The arc at high filling pressure gets constricted due to the filling pressure and the temperature of the arc core increases as a result. In free burning arc, in the absence of forced cooling, the arc core fails to dissipate the stored thermal energy. As a result, the breakdown voltage just after CZ is found to be low at high filling pressure in comparison to atmospheric pressure. The time just after CZ is hence very crucial for free-burning arc at an extremely high filling pressure.

For power switching applications, to cool the arc effectively near CZ, some sort of forced gas flow is applied as a form of puffer or self-blast principle. A forced gas flow at a high filling pressure can increase the mass flow rate and hence, the cooling can be enhanced. But as was seen, increasing the distance did not lead to significant changes in the recovery rate (up to 10 kV, at least). The difference was much greater for 1 bar, which indicates that faster moving contacts are perhaps more important at low pressures. As the dielectric recovery characteristic improves at a high filling pressure, with forced cooling and moving contact arrangement, the ultrahigh-pressure nitrogen has the potential to be used as a current interrupting medium.

IV. CONCLUSIONS

The post-arc dielectric recovery performance of free-burning nitrogen arcs as a function of filling pressure is reported in this paper. A 10 kV HV pulse is applied with a controlled time delay after CZ. Based on the experimental investigations, the following conclusions have been drawn:

- The dielectric recovery performance of free-burning arcs improves with the filling pressure, and a faster dielectric recovery is observed as the filling pressure is increased. However, just after CZ (in the thermal phase) the withstand voltage is lower for higher filling pressures.
- As the inter-electrode gap distance is decreased, the recovery process takes more time, as expected.

ACKNOWLEDGMENT

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