AN EXPERIMENTAL INVESTIGATION OF NOZZLE ARCS UNDER TURBULENT CONDITIONS

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ABSTRACT

Turbulence cooling is an important energy removal mechanism for switching arcs. In the present work a two pressure system with an upstream stagnant pressure of up to 10 bar is used to generate low current arcs in a converging-diverging nozzle to obtain experimental results for the verification of turbulence models. Arc voltage and current measurement is taken for transient arcs with a maximum length of 60 mm in the current range of 100 A to 333 A. The repeatability of the results is discussed.

1. INTRODUCTION

Turbulence plays a dominant role in arc cooling at low current (< 10 kA), especially during the current zero period, in high voltage gas blast circuit breakers. Research has been ongoing to assess the applicability of existing turbulence models and their modifications when used for switching arc simulation [1, 2]. Progress in this aspect has however been hindered by a lack of reliable experimental results for comparison. This contribution aims at producing low current turbulent arcs under well-defined conditions and obtaining measurement of arc characteristics such as arc voltage and current.

2. EXPERIMENTAL SET UP

The arc is sustained by the electrical circuit shown in Fig. 1 with a slowly, nearly linearly decreasing direct current. The initial magnitude of the current can be controlled by the charging voltage of the capacitor bank (33 mF in total) and a high power resistor (4.5 Ω).

The two pressure system is shown in Fig.2. A tank of 0.02 m^3 supplies the gas flow with a filling pressure up to 10 bar. A magnetically valve controls the gas supply with an action time of 25ms. The arc is initiated by using a solenoid actuator to move a rod electrode which is originally in a closed position with the upstream electrode. The rod electrode finally withdraws into a downstream hollow electrode whose tip is 58 mm away from the fixed upstream electrode. This distance can be adjusted with an uncertainty of 1.5 mm due to measurement inaccuracy. Gas supply can be switched on and off at any time during the arcing process. The exhaust space has a volume of 0.017 m^3. Its volume can be increased by attaching another cylindrical container of volume 0.008 m^3. The travel of the rod electrode is measured by a displacement meter. The current is measured using a standard shunt resistor of 0.9 mΩ.

The shape and dimension of the nozzle is given in Fig. 3. The flat nozzle throat has a diameter of 12.5 mm and a length of 10 mm. The diameter of the rod electrode is 10 mm, giving a gap of 1.25 mm thick between the nozzle throat and the rod electrode. The upstream electrode has a flat tip with a diameter of 10 mm. Its tip is 8 mm away from the inlet of the flat nozzle throat. Both electrodes are made of 80% tungsten and 20% copper.

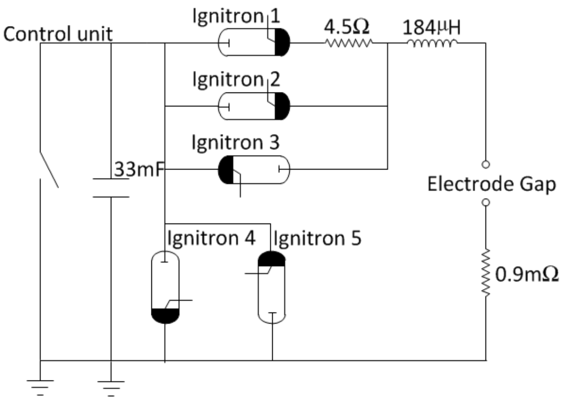

Fig. 1: Schematic diagram of the power supply

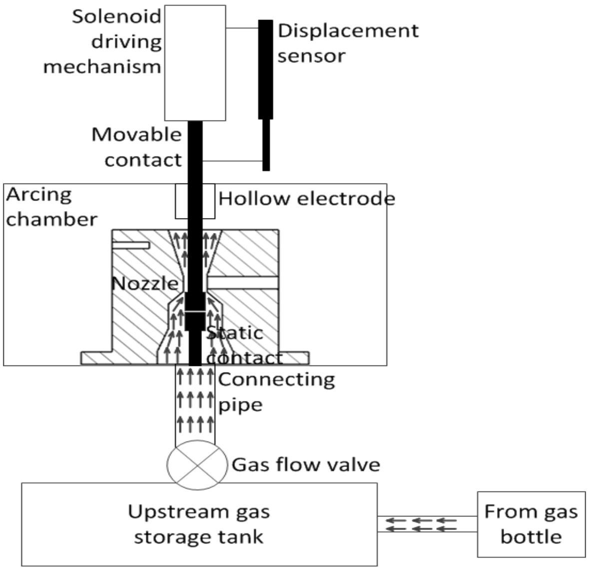

Fig. 2: Diagram showing the structure of a two pressure gas flow system.

A calibrated high voltage probe (Tektronix P6015A) is used to measure the voltage across the electrodes. The pressure near the nozzle surface at the midpoint of the flat nozzle throat is measured by a Kistler 601A piezoelectric sensor. It has a dynamic range of 0 – 250 bar with a response time of 6.7 µs. A charge amplifier is used to convert the electrostatic charges to a voltage signal which is recoded by a Tektronix 3034 oscilloscope with a bandwidth of 300 MHz and data acquisition rate of 2.5GS/s.

The solenoid takes 200 – 220ms to start to move after a DC voltage is supplied. The sequence of action of various parts of the system is given in Fig. 4. The time when the oscilloscope is triggered is referenced as time

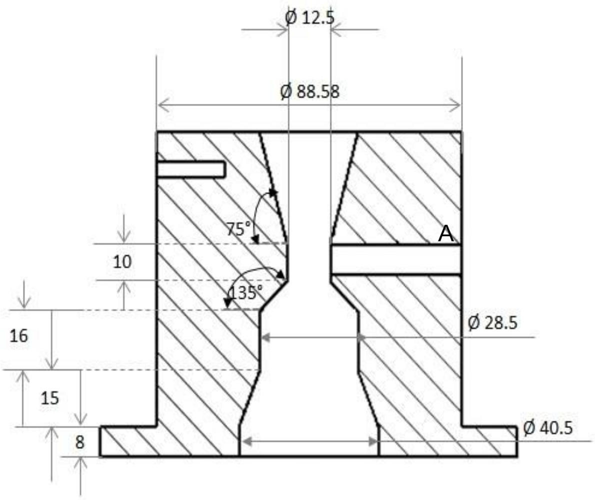

Fig. 3: Geometry of arc nozzle with dimensions. The pressure sensor is installed at Point A.

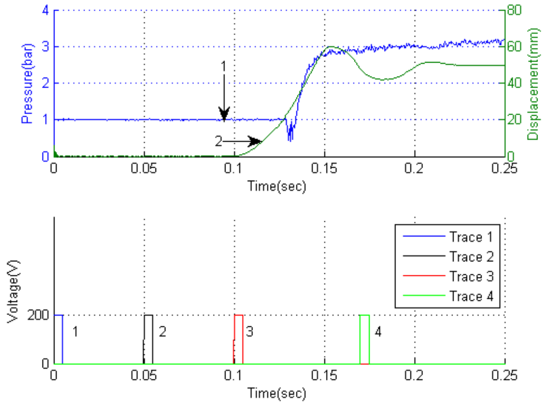

Fig. 4: Electrode travel curve (top) and sequence of triggering pulses (bottom) for different parts of the system. Curve(top): 1- Pressure in throat. 2- Downstream electrode displacement. Curve(bottom): 1 – Oscilloscope. 2 – DC current. 3 – Gas flow valve. 4 – Main current.

zero. Thus the time when the solenoid is powered to separate the electrodes is -100 ms. The current supply circuit is fired at 50 ms to force a low amplitude DC current through the closed electrodes. The magnetic controlled valve is powered at 100 ms to establish the flow field. A main current of one half-cycle can be supplied when the 4.5 Ω resistor is short circuited at a set time.

3. RESULT AND DISCUSSION

The upstream gas tank is filled with nitrogen at an initial pressure of 10 bar at room temperature. The downstream exhaust space is fixed at 1 bar. The change of voltage across the electrodes and the rod electrode tip position as a function of time is recoded for three capacitor bank charging voltages of 450 V (Case 1), 720 V (Case 2) and 1500 V (Case 3). For each case measurement is taken for two scenarios, one with the valve shut and the other opened at a specified instant. Results are given in Figs. 5, 6, 7, 8 and 9. Odd curves (1 and 3) indicate arc with gas flow while even numbered curves indicate arc without gas flow.

In Case 1, both scenarios start with a current of 100 A. It decreases with a rate of 0.64 A/ms as a result of power consumption in the circuit, especially in the resistor. Electrode separation takes place at 92 ms and 100 ms respectively. It is clear that in both scenarios there is a sudden increase in voltage across the electrodes, from 2.69 V to 22.91 V for the scenario with the valve opened later. The current has a corresponding drop of 4.39 A. The value of 2.69 V at 71.65 A corresponds to a resistance of

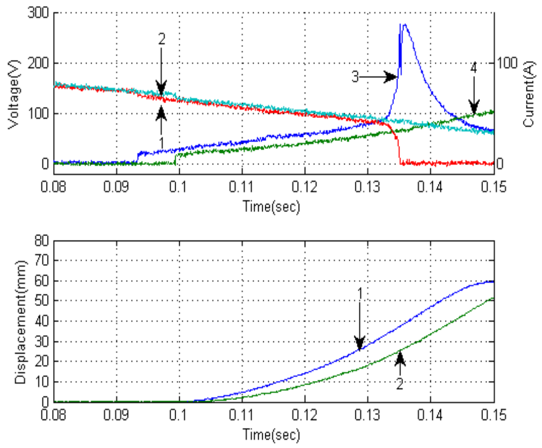

Fig. 5: Arc voltage and current with/without gas flow for a charging voltage of 450 V. Curves 1 and 3 are arc current and voltage respectively with nitrogen gas flow. Curves 2 and 4 are arc current and voltage respectively without nitrogen gas flow (keys also apply to other figures).

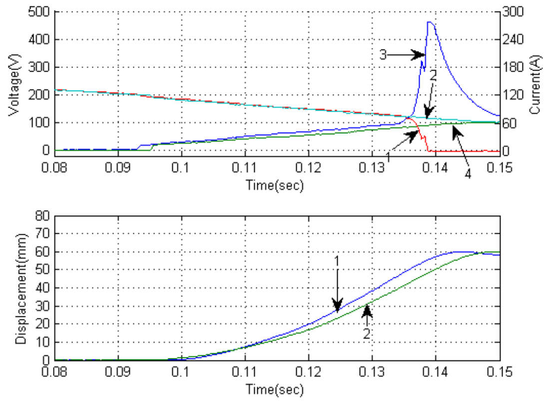

Fig. 6: Voltage and current records for a capacitor bank charging voltage of 720 V

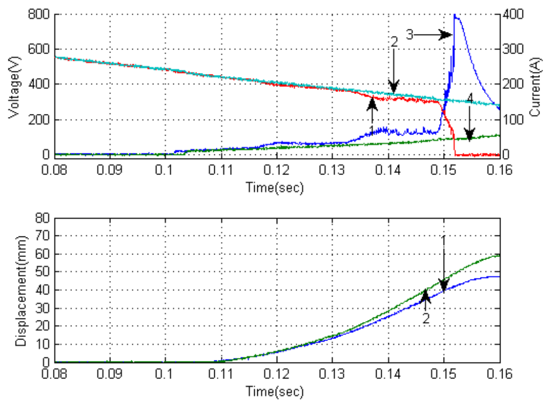

Fig. 7: Voltage and current records for a capacitor bank charging voltage of 1500 V.

37.54 mΩ, which is dominated by the electrode contact resistance between the two electrode surfaces.

When an arc is struck between the two electrodes, this electrode contact resistance is replaced by the electrode sheath layers. Therefore, the value of 22.91 V is the sum of the anode and cathode sheath drops at a current of 71.65 A without externally forced gas flow because the valve only starts to open at 100 ms. The voltage of the arc column should therefore be derived by taking the initial voltage rise at electrode separation from the recorded voltage.

In contrast with the measurement with the valve opened at 100 ms, the arc without forced gas flow continues to burn beyond 150 ms. Because the rod electrode in this scenario starts to move at 98 ms, its arc length is smaller (bottom diagram of Fig. 5) and convection cooling is weaker in comparison with the scenario where the valve is opened. This gives a lower arc resistance, which explains the higher arc current and lower arc voltage for this scenario, as clearly shown in Fig.5.

The arc current starts to decrease rapidly at 134 ms with an instantaneous value of 37.87 A in the forced gas flow scenario and extinguishes at 135 ms, as a result of the capacitor bank being no longer able to sustain the arc at a current of 37.87 A (curve 1 in Fig.5). The arc takes 1 ms to extinct. The voltage across the electrodes increases rapidly and reaches the voltage of the capacitor bank (275 V) when the current ceases to flow.

Case 2 follows a similar pattern to Case 1. The current starts at a value of 160 A. Electrode separation takes place at 95ms and 105 ms for the two scenarios. Because of the increased initial current, the sudden current drop corresponding to electrode separation is no longer apparent and the power consumption in the arc column is negligible. The voltages cross the electrodes at their separation are respectively 2.23 V and 2.18 V. The arc starts to extinguish at 136 ms with a current of 69.53 A.

The starting current in Case 3 is much higher than the other two cases with a value of 330 A at 50 ms (Fig. 8). The increases in voltage across the electrodes corresponding to electrode separation are respectively from 2.5 V to 22.44 V and from 1.4 V to 17.2 V for the two scenarios with and without the valve opened. The arc current and voltage behave differently at the stage when gas flow is established. There are two distinct voltage increases starting at 117 ms and 134 ms, respectively. The valve in this case is scheduled to open at 100 ms with a full opening time of 25 ms. The first voltage increase is expected to be the effect of arc confinement by gas flow from the tank following the opening of the valve. The effect is modest because the rod

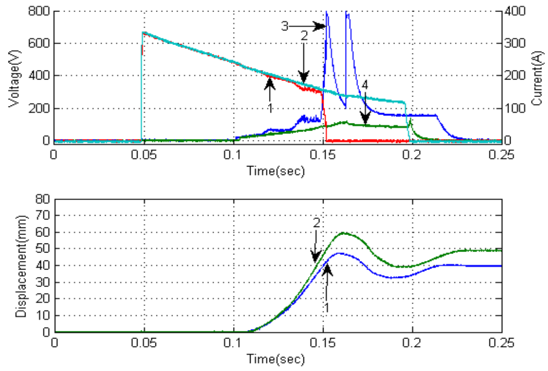

Fig. 8: Complete voltage and current records for a capacitor bank charging voltage of 1500V.

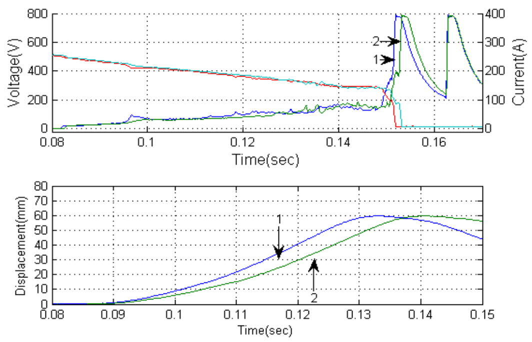

Fig. 9: Voltage and current records of two shuts for a capacitor bank charging voltage of 1500 V.

electrode still blocks the nozzle and gas can only exhaust into the downstream space through the gap between the rod electrode and the nozzle throat with a thickness of 1.25 mm. The second increase of nearly 100 V is a consequence of the rod electrode clearing the nozzle throat and the establishment of high speed gas flow. The flow leads to enhanced arc cooling and increases the arc resistance.

Corresponding to the voltage climbing, there is an apparent drop in arc current. Despite the increased travel speed of the rod electrode, the arc voltage and current after 138 ms experiences a temporary change in the opposite direction. This is believed to be caused by the rapid change of flow field downstream the nozzle throat when the rod electrode continues to move away from the nozzle throat and causes the arc resistance to increase. It is highly likely that a shock is formed in the diverging section of the nozzle causing broadening of the arc column [3].

The arc current starts to decrease again from 141 ms with a rate of 1.54 A/ms until 149 ms when the current with an instantaneous value of 149.8 A begins a rapid drop at a rate of 37.63 A/ms leading to arc extinction at 152 ms. The corresponding rate of increase of voltage between 149 ms and 153 ms is approximately 217.9 V/ms. There are voltage fluctuations immediately before arc extinction due to possible instability of the arc column. The electrode gap length varies from 26.17 mm to 37.62 mm over the period of 141 ms to 149 ms. The arc with no forced flow continues to burn beyond 160 ms. The arc voltage varies between 130.2 V at 141 ms and 134.7 V at 149ms. A more complete picture of the arcing process is given in Fig. 8 where the electrode movement is also given.

For each case experiment was repeated for a few times to check the reproducibility of the results. Results from two shuts are given in Fig. 9. It can be seen that the voltage across the electrode does fluctuate during the arcing process, leading to temporary changes to the arc current. The maximum change (130 V ~ 150 V) in voltage between the two shuts can reach 15% of the average value. The current has more or less the same value between 140 ms and 148 ms with a value of 155 A.

5. CONCLUSIONS

An experimental investigation was carried out on transient nozzle arcs sustained by a slowly decreasing low magnitude direct current supplied by a capacitor bank. Gas flow is provided by a two pressure system. Current and voltage across the electrodes are measured for three initial currents of 100A, 160A and 333A. The changing features in current and voltage are analysed. The effect of gas flow is observed by comparing the difference in voltage across the two electrodes for two scenarios with and without forced convection. The scattering in voltage is also given. Work is ongoing to measure the pressure variation at key locations to provide more information for the verification of turbulence models.

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