Cold-electrode voltage fall for impulse arcs in argon between copper electrodes

O Diaz and V Cooray
Lightning Research Group, Division for Electricity, Uppsala University
Ångströmlaboratoriet Box 5234, 751 20, Uppsala, Sweden
E-mail: oscar.diaz@angstrom.uu.se

ABSTRACT: The full electric arc discharge in gases for short gaps in homogeneous electric field and pressure-distance (pd) below 150 Torr·cm, can be described as a transition between different discharge mechanisms such as: Townsend, glow, and arc. Once the arc is achieved the measured voltage drops to some volts and the current density increases several orders of magnitude. Depending upon the type of gas used, the electrode surface characteristics and type of electrical excitation, the cathode and anode voltage fall might change. The present work is directed to study the electrode fall (sum of anode and cathode falls) during a current impulse arc discharge between copper electrodes in ceramic tubes filled with argon between 0.01 and 6.5 Torr·cm. The copper electrodes were cleaned, degassed and hydrogen reduced. The arc voltages were measured with fast/slow rise times and short/long duration current impulses produced by a RLC circuit. An increasing variation of the electrode fall was found at the pressure-distance range analyzed.

1. Introduction

The discharge in gases for low pd < 150 Torr·cm can be explained as a transition between different mechanisms, from Townsend, to glow and finally arc. When the arc stage has been achieved, one can observe different phenomena at the cathode in comparison with the preliminary glow stage: the voltage fall changes from some hundreds of volts to some tens, the current density at the arc spot might increase from $10^2$ to $10^6$ A/cm$^2$ approx. and the discharge channel light emission begins to contain spectrum lines from the electrode material due to the presence of active electrode vapour in the cathode vicinity. The arc has a voltage drop at the cathode in the order of minimum ionizing or minimum exciting potential of the gas or electrode vapour, and a capability of withstand large currents by means of its own mechanism of electron emission from the cathode (field and/or thermoionic) [1, 2].

Several methods have been used in order to determine the electrode fall in glow and arc discharge stages. One of them consisted in measuring the voltage fall by changing the interelectrode distance in a constant current arc, similar to a circuit breaker opening process [3]. Other method consisted in establishing the arc by melting a thin wire between fixed separated electrodes; then the anode fall was estimated by measuring the current and amount of electrode mass eroded during one single full arc discharge [4]. An interesting method consisted in measuring arc voltages for different constant electrode distances and then to extrapolate the measured values to zero interelectrode distance, so the minimum possible voltage to be measured was approximately the sum of the anode and cathode fall.
[5]. Depending upon the type and the characteristics of the gas used (electronegative, noble, impurity content, pressure), the electrode surface chemical composition (amount adsorbed gas, oxide layers, erosion), and the characteristics and type of electrical excitation, the cathode and anode voltage fall might change, being commonly reported to have a higher cathode fall [1, 3, 6].

During the first half of the 20th century, a lot of efforts were addressed to study in detail the different stages of the glow discharge and many authors have achieved good results while measuring the potential distribution inside the different glow regions [7]. Most of the studies related to electrical arcs were done after the 50’s, with the improvement of experimental techniques and numerical/theoretical models. For the arc discharge the potential is distributed on the anode and the cathode falls, the transition regions between the electrode and the gas and along the positive column. The positive column is characterized by having an almost constant voltage drop along its length. The electrode fall (anode + cathode) have been also measured for different electrode materials and gas types, pressures close to 760 Torr (1 atm) and interelectrode distances of some millimetres [3-5]. For this work different current impulses were applied to ceramic gas filled tubes with copper electrodes in order to create a full arc discharge. Arc voltage and current were registered for the estimation of the electrode fall.

2. Experimental Setup

2.1. Gas tubes

The gas tubes were made of a pair of copper electrodes and cylindrical ceramic tubes of 3 mm internal radius, having interelectrode distances of 0.6 and 3 mm. Four tube samples for each pressure and interelectrode gap distance were tested. The electric field inside the tube assured enough insulation between the discharge area and the tube walls and a homogeneous distribution over the discharge area (better for the shorter gap); as it is shown in figure 1, where the light colours represent the high electric field intensity regions between the electrodes.

![Figure 1. Electric field distribution for the 3 mm (left) and 0.6 mm gaps (right).](image)

Argon with impurity concentrations lower than 2 ppb was used for filling the tubes at pressures between 0.21 and 21 Torr. Oxygen-free copper electrodes were first washed with acetic acid, rinsed in deionised water, dried, degassed in low vacuum (700 °C and 7.6·10^{-7} Torr) and finally were reduced in a hydrogen atmosphere at 700 °C. These different tasks aimed to reduce the amount of impurities on the electrode discharge surface. However, the authors are aware that not all the copper oxide layers were completely removed, different situation to other works where more complex processes as ion bombardment or controlled/localized glow sputtering were used (see effects of clean and dirt surfaces in discharges in argon [6]). Once the tubes were sealed with eutectic welding, they were conditioned by applying of current impulses of ca. 100mJ in rounds of 1 s, five shots each tube side.
2.2. Current impulse generator

Two different RLC series circuits were used to produce the full arc discharge. The circuits were charged with a DC source at different voltages until a maximum of 5kV. The fast circuit had a main capacitance of 10 µF and an output current impulse of 1.5/40 µs and 130 A peak. The slow circuit main capacitance was 60 µF and its current impulse was 15/500 µs and 700 A peak (current impulse times: time to peak time / half amplitude time).

The measuring system consisted of a Lecroy PPE6kV voltage probe, a Pearson current transformer and a digital store oscilloscope (DSO) Tektronix TDS1002. The bandwidth of the measurement system was limited to 20MHz because the fast transients during the initiation of the discharge were not of interest of this work. Since the desired voltage value to be measured is in the order of some volts, the DSO 8-bit vertical resolution was set to obtain the best results while measuring. For circuit 1, the minimum recorded voltage resolution was 620 mV and for circuit 2 was 220 mV. Typical voltage and current waveforms recorded for both circuits used are presented in figure 2.

![Waveforms for Circuit 1. pd = 1.32 [Torr-cm]](image1)

![Waveforms for Circuit 2. pd = 1.32 [Torr-cm]](image2)

Figure 2. Typical current and voltage measured for the same pd product. Note for both cases the time scales and the current amplitude on the left vertical axis.

3. Results

Some general characteristics can be pointed out from the results obtained:

- **Arc voltage stability.** The measured arc voltage reached a noticeable stable value with the long time impulse from circuit 2, after the half amplitude time (~ 500 µs). For the fast impulse circuit 1, the arc voltage tended to stability as the current impulse was close to its minimum value (t ~ 200 µs), making it difficult to determine an arc voltage value.

- **Arcs at low pressure.** For both circuits and the lowest pressure analysed 0.21 Torr, the arc voltage was unstable for the current values below 10A. This behaviour is opposite to what was observed for higher pressures where the arc voltage did not deviate much from a mean value at lower currents values.

![Arc Voltage measurements. The bars represent the standard deviation obtained for each pressure value](image3)
The arc voltages reported correspond to the average and standard deviation of four different measurements for each circuit and pd value. It was observed that the arc voltages for pd below 0.2 Torr·cm were close to a mean value of 14.5 V, and tend to deviate to a higher voltage value as presented in figure 3.

4. Discussion

Some authors have done measurements of the electrode fall for configurations similar to the ones used in this work (copper anode/cathode electrodes, argon at a pressure \( \leq 760 \) Torr, maximum current \( \sim 100 \) A for \( t < 1 \) ms): a) \( V_{\text{fall}} = V_{\text{anode}} + V_{\text{cathode}} = 5 + 12 \) V [3]; b) \( V_{\text{fall}} = 16.5 \) V [5], where both the values were measured in Argon at 760 Torr (1 atm). Given that not all authors include information related with the electrode cleaning, setup dimensions or detailed characteristics of the electrical circuit used, a direct comparison in the same conditions from preliminary works is not possible.

Considering that: a) the values of pressure and current amplitude used in this work do not affect drastically \( V_{\text{fall}} \), as concluded in [5]; b) the value of the positive column potential distribution is uniform and is approx. 10 V/cm for Argon, as it was measured in [8] and c) the transition regions from the electrodes to the gas are concentrated in the cathode and anode fall (with lengths in the orders of magnitude of \( 10^{-7} \) m and \( 10^{-4} \) m respectively [3]); it is possible to assume that the measured arc voltage corresponds to the electrode fall. One can observe in figure 3 that values for electrode fall below \( pd = 1 \) Torr·cm are in the vicinity of 14.5 V, showing a slight increment for the interval 1 < \( pd \) < 10 Torr·cm reaching a maximum of 19.5 V. The measured electrode fall values were more stable tendency for the 0.6 mm gap.

5. Conclusion

The measured electrode fall value showed an increasing tendency (from \( \sim 14 \) V at 0.2 Torr to \( \sim 17 \) V at 21 Torr) for argon discharge between copper electrodes under the conditions of this work.

6. References

[1] von Engel A 1965 Ionized gases (Oxford: Oxford University Press) chapter 9 pp 259-289
[2] Holmes R 1978 Electrode Phenomena (Electrical Discharges in Gases) ed J Meek and J Craggs (Norwich: John Wiley & Sons) chapter 11 pp 839-867
[3] Dickson B and von Engel A 1967 Proc. Roy. Soc. Lon. A 300 1462
[4] Hemmi R Yokomizu Y and Matsumura T 2003 Anode-fall voltage of air arcs between electrodes of copper, silver and tungsten at currents up to 1500A Technical meeting on electrical discharges IEE Japan 2003
[5] Yokomizu Y Matsumura T Henmi R and Kito Y 1996 J. Phys. D.: Appl. Phys. 29 1260
[6] Phelps A V and Petrović Z L 1999 Plasma Sources Sci. Techn. 8 (1999) R21-R44
[7] Francis G 1956 The glow discharge at low temperature (Encyclopedia of Physics vol. XXII Gas Discharges II) ed Flügge S (Berlin: Springer-Verlag) chapter 2 pp 53-203
[8] Busz-Peuckert and Finkelnburg W 1956 Z. für Phys. 144 244