ARC CURRENT, VOLTAGE, AND RESISTANCE IN A HIGH ENERGY, GAS FILLED SPARK GAP

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Abstract

A spark gap was designed and constructed to measure its time dependent arc resistance. The arc current was measured and the resistance calculated using the current waveform and the circuit parameters. Operating parameters were: Unipolar pulses, breakdown voltage 35 kV, peak current 30 kA, toal energy per shot 1 kJ. The energy dissipated in the arc was found to be 5 % to 10 % of the total energy. Arc resistance vs. time curves were obtained for the electrode materials Stainless Steel, Copper-Tungsten, and Graphite; for the gases air, Nitrogen, and SF_6; and the gas pressures 1, 2, and 3 atm. Statistical analysis was performed on the resultant data. Essential results are: Within the statistical and measurement errors, the resistance is independent of the electrode material. For each gas, the resistance, R, is proportional to pd (p-pressure, d-gap distance). The constants of proportionality for the temporal minimum value of the resistance are: 31 ± 7 m Ω/cm-bar (air), 47 ± 14 m Ω/cm-bar (N_2), and 76 ± 16 m Ω/cm-bar (SF_6).

Introduction

In relation to spark gap erosion studies it is important to obtain information about the energy or power dissipated in an arc discharge. The main energy sources for electrode erosion are Joule-heating of the electrodes and the power dissipated in the arc itself. In order to investigate the dependence of the erosion rate on physical parameters, such as the power dissipated in the arc, it is desirable to have information on the arc current and voltage as a function of time, with the voltage separated into resistive and inductive components. Whereas current measurements are straightforward, the measurement of the arc voltage, and especially the separation into resistive and inductive parts, is difficult at best. The first problem in measuring the voltage is the neccessarily high dynamic range of the sensor and recorder, from 10's of kilovolts before breakdown to several 10's V during current maximum. Furthermore, direct measurements at the arc (i.e. voltage measurement at the electrode tips) are virtually impossible.

Several authors have reported arc voltage measurements in the past. Barannik et al. [1] used capacitive dividers in a coaxial arrangement, Braudo and Craggs [2] used a resistive divider and a biased diode to overcome the problem of the high initial voltage. Common problems for these arrangements are, among others, stray capacitances of the probes, use of nonlinear elements, and the impossibility to distinguish beween resistive and inductive voltage drops. Measurements of the spark gap resistance has also been reported by Sorenson and Ristic [3] and by Ristic and Dubois [4[for very short pulses ($\tau < 2$ ns) where the arc drop is relatively large and predominantly resistive in nature.

In the present paper a pragmatic approach was chosen to overcome the mentioned difficulties. In the circuit equation

$$V_0 = \frac{1}{C} \int i dt + Ri + \frac{d}{dt}(Li), \qquad (1)$$

with $R = R_0 + R_e(t) + R_a(t)$, $L = L_0 + L_e(t) + L_a(t)$ (R_0, L_0 circuit parameters, R_e, L_e electrode parameters, R_a, L_a arc parameters, and V_0 breakdown voltage), the essential unknown quantities are the arc resistance, R_a, and the arc inductance, L_a. All the other parameters or functions can be either measured easily ($i(t)$, C, L_0, R_0) or estimated within a sufficient accuracy (R_e, L_e using the geometry of the device and equations describing the time dependent skin effect [5]). If the arc inductance $L_a(t)$ is known within reasonable accuracy, Eq. (1) can be solved for the arc resistance $R_a(t)$ obviating the need for making explicit arc voltage measurements.

Experimental Set-Up

The spark gap arrangement is sketched in Fig. 1. It was designed to facilitate changing of electrodes (electrode materials used were Graphite, Stainless Steel, and Copper-Tungsten), to withstand up to three atmospheres of gas pressure, and to provide easy access for diagnostics. In order to obtain a unipolar pulse in accordance to other experiments on electrode erosion conducted at Texas Tech University, the current was overcritically damped, using a load resistor of 0.8 Ohm.

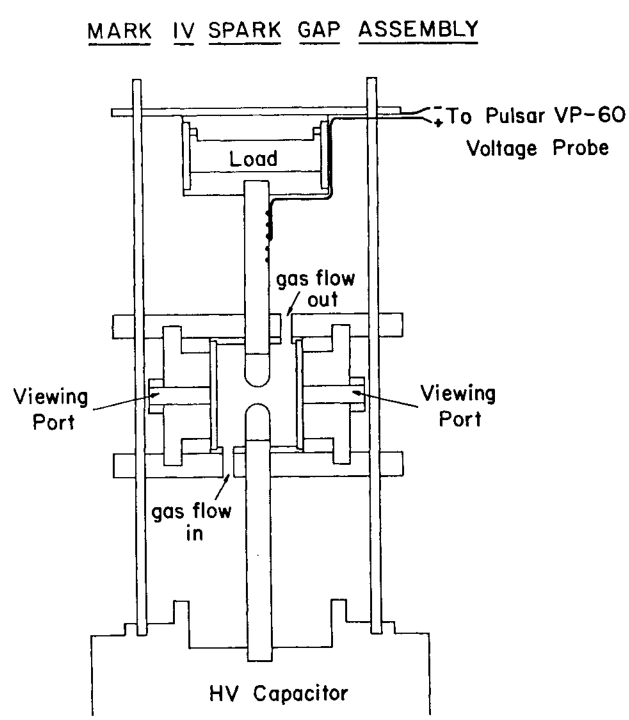

Fig. 1 Experimental Arrangement

The current has been measured using a Pearson Coil (model 110) around one of the eight current return rods of the system. In order to increase the accuracy of the current measurement, the dI/dt signal

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was also measured with a calibrated pick-up coil. Output signals were registered with a transient digitizer and stored in a computer.

For estimation of the arc inductance, $L_a(t)$, the self luminance of the arc channel was recorded simultaneously at three axial positions with a streak camera. The arc inductance was calculated from the channel radius as a function of time, taking a homogeneous current distribution within the luminous channel as basis for the maximum inductance value and a surface current distribution as basis for the minimum value. Both values have been considered to estimate the total error for the final calculation of the arc resistance.

Results

Figure 2 shows, as an example, the arc current, resistance, and resistive arc voltage, including the range of uncertainty for the resistance. Inductive

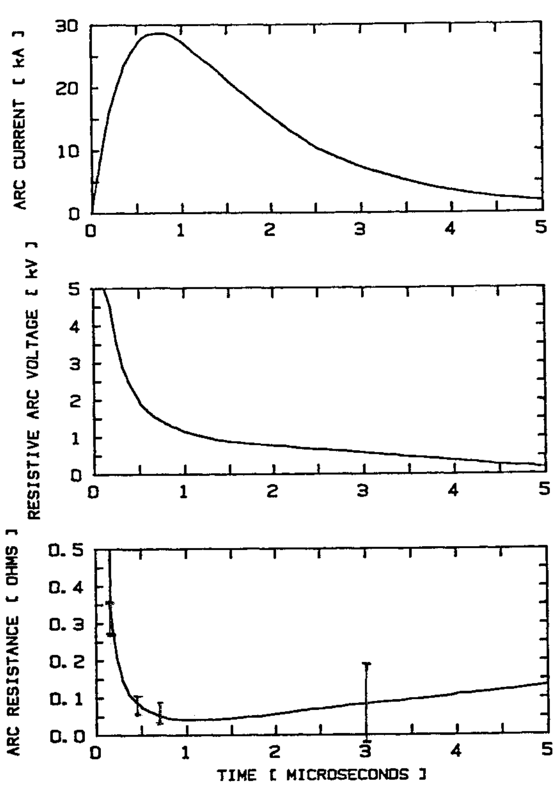

Fig. 2 Arc Current, Voltage, and Resistance for Graphite Electrodes in N_2 at 1 Atmosphere.

parts of the arc voltage are in the same order of magnitude during the current maximum (Fig. 3). Measurements have been performed for all combinations of electrode material (stainless steel 304, Graphite AFC-100, Copper-Tungsten 3W3), gases (air, N_2, SF_6), and pressures (1, 2, and 3 atm). The breakdown voltage has been kept fixed for all cases to 35 kV in order to provide comparable peak current amplitudes of approximately 30 kA by adjusting the gap distance.

Within the measurement and statistical errors, no dependence of the resistance on the electrode material has been found. The value of the resistance at its temporal minimum depends on the gas type, pressure, and gap distance according to

$$R_{a,min} = C_g p d$$

where C_g describes the dependence on the gas. This constant has the values 31 ± 7 for air, 47 ± 14 for N_2, and 76 ± 16 mΩ/cm bar for SF_6. Due to the measurement errors, a dependence on pressure as proportional to $p^{1/2}$, as mentioned by Mesyats [6], cannot be excluded.

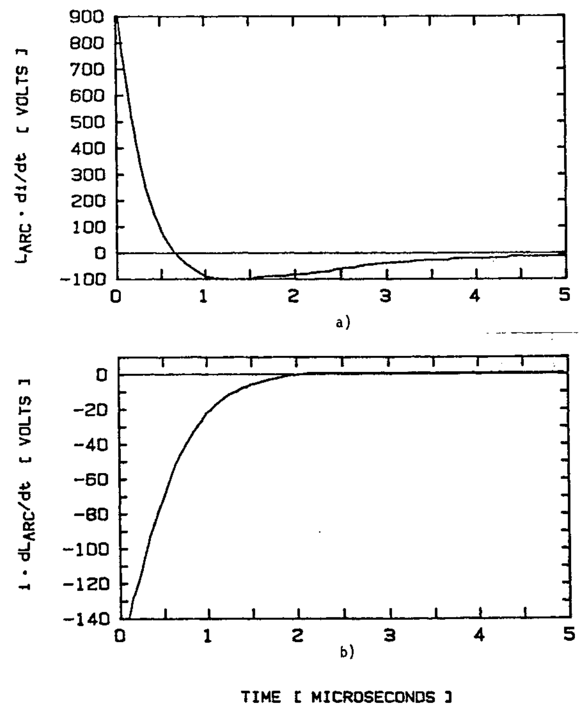

Fig. 3 Inductive Arc Voltage Drops
a) $L_{arc} \cdot di/dt$, b) $i \cdot dL_{arc}/dt$

The time dependence of the measured arc resistance has been compared with different models for the case of the filling gas being air. Whereas the older models of Toepler [7] and Weizel/Rompe [8] show discrepancies of up to a factor of 10, excellent agreement is found with the model of Mesyats [6] and Vlastos [9] for times up to the current maximum (Fig. 4).

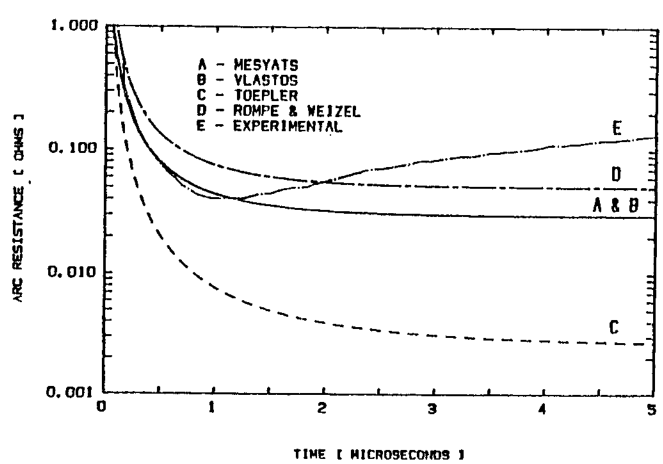

Fig. 4 Comparative Arc Resistance Plot

Discussion

By careful design and analysis of a spark gap and its circuit geometry, it is possible to find the power dissipated in the arc (including the electrode fall regions) within reasonable accuracy without performing an explicit voltage measurement. Relatively simple diagnostical methods, such as current measurements and optical diagnostics using a streak camera to determine the arc radius as a function of time, reveal sufficient information to determine the arc resistance and the power dissipated in the arc with an accuracy of approximately 20 %.

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