MASTER

Eighth Progress Report

on

FUNDAMENTALS OF INTERRUPTION

IN VACUUM

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Division of Electric Energy Systems

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1. SUMMARY

In analysing the behavior of a vacuum arc during interruption a mathematical model has been set up to describe the events occurring in the interelectrode gap during interruption. The reliability of the results obtained using such a model depends on the accuracy of the initial assumptions made in setting up the model equations.

In our last report [1] the results obtained from the model analysis were compared to experimental data and it was found that there was a discrepancy close to current zero. To improve our model results some of the original model assumptions have been reconsidered in order to make the model more closely represent the physical reality of a vacuum arc.

2. INTRODUCTION

A theoretical model of the extinction of a metal vapor arc in a vacuum interrupter was described in the last report [1]. The post-arc data calculated using the model was in reasonable agreement with experimental data except that the calculated post-arc current was discontinuous at current zero whereas the observed current is continuous. The model has now been improved, resulting in a smooth transition of the interrupter current from the commutating period to the post-arc period.

3. MODEL OF INTERRUPTION

3.1 Review of Commutation Model and Post-Arc Model

The time span encompassed by the complete interruption model includes two very different regimes. The first regime covers the time period from the steady state condition to current zero, i.e. commutation, and the second regime continues from current zero until interruption is complete.

During commutation the arc is still burning and the corresponding arc voltage is of the order of tens of volts. The current is predominantly carried by the electrons which are moving rapidly from the cathode to the anode through the ions and neutrals. As the current is commutated to zero the source of the metal vapor, the cathode spots, is reduced, resulting in a decline of the interelectrode plasma density. By modelling the plasma as an ion-neutral fluid through which the electrons are moving, the density, velocity and temperature of the ions and neutrals during commutation can be calculated, enabling the conditions in the gap at current zero to be determined.

At current zero the cathode spots have all been extinguished and a negative recovery voltage is quickly impressed upon the gap by the external circuit. As the voltage builds up a positive ion sheath grows into the quasi-neutral plasma from the anode sweeping up ions in its path. The electrons are repelled by the electric field in the ion sheath and move in the opposite direction towards the old cathode where they are collected. Using the 'transition model' of Andrews and Varey [2] to describe the positive ion sheath, and the ion-neutral fluid model to describe the quasi-neutral plasma, the post-arc current, the power input to

the old anode and the electric field at the same surface can be calculated as a function of the recovery voltage.

3.2 Electron-Reversal Period

The difficulty with the model so far described is that it results in a discontinuity in the current at current zero. The cause of this discontinuity is the assumption that the electrons instantaneously reverse direction at current zero. To improve the model the interaction of the external circuit with the gap at current zero has been taken into account by the addition of an 'electron-reversal' period between current zero and the initiation of the positive ion sheath.

The assumption that the electrons immediately reverse their direction at current zero was justified by considering the electron plasma frequency. This frequency is a measure of how quickly an electron can respond to an applied electric field and it is dependent on the electron density. For a typical vacuum arc the electron concentration is in the order of $10^{19}/\text{m}^3$, giving an electron plasma frequency of 30 GHz, (an electron response time of 3×10^{-11} s). Thus the assumption that the electrons immediately reverse direction as the negative recovery voltage builds up seems at first sight to be reasonable.

If, as we have assumed, the recovery voltage starts to build up directly at current zero, the electrons would immediately be 'halted in their tracks' and would start to accelerate back towards the old cathode as the ion sheath began to grow into the plasma. Although the net current at current zero must be zero, there are two equal and opposite components of the current at that time, the ion current and the electron current. Before commutation the electron current is an order larger than the ion current, but as the arc current is reduced to zero the electron velocity drops more quickly than the ion velocity until at current zero the ions and electrons are moving at the same speed towards the anode. If the electrons are then immediately halted the electron current will go to zero and the net current in the gap will be equal to the ion current. In other words the net current would immediately jump from zero to a value equal to the ion current, introducing a discontinuity.

The fallacy with the argument is that we have assumed that the recovery

voltage is unaffected by the processes occurring in the gap. In fact the recovery voltage is in part determined by the gap current, or put another way by the gap resistance which momentarily remains low. Consider the circuit shown in Figure 1. This is a simple representation of the experimental circuit during and after commutation. At current zero $I_1 = I_2$ and $I = 0$. The capacitor C_2 is charged to a voltage V_2 at current zero and for the period of interest, the few microseconds after current zero, the capacitor voltage remains essentially constant. C_2 can then be replaced by a voltage source V_2 for this analysis. The circuit should also include the stray capacitance and resistance of the equipment as shown in Figure 2. The recovery voltage, V_R , can now be found from equation (1):

$$\frac{V_R}{R_S} + C_S \frac{dV_R}{dt} + \frac{1}{L_1} \int V_R dt + I = - \frac{1}{L_2} \int (V_2 + V_R) dt \quad (1)$$

which reduces to

$$C_S \frac{d^2 V_R}{dt^2} + \frac{1}{R_S} \frac{dV_R}{dt} + \frac{V_R}{L} = - \frac{V_2}{L_2} - \frac{dI}{dt} \quad (2)$$

where:

$$L = \frac{L_1 L_2}{(L_1 + L_2)}$$

From equation (2) it can be seen that as long as the dI/dt in the gap is equal to $-V_2/L_2$ the recovery voltage will be zero.

The behavior of the recovery voltage after current zero will be as follows. Initially the voltage will be just large enough to slow down the electrons arriving at the anode so that the gap current increases at a rate of V_2/L_2 . The energy of the electrons at current zero is of the order of 10^{-5} eV, so the recovery voltage during this period will be approximately 10^{-5} V which is negligibly small. During this period there will be no ion sheath formed since electrons will still be arriving at the old anode albeit at an increasingly slow rate.

The electrons will continue to slow down until the gap current is equal to the ion current, at which time no electrons will be reaching the anode. The

Fig. 1 Simplified experimental circuit during and after commutation of arc current

Fig. 2 Post-arc circuit

gap can no longer maintain a dI/dt without a significant recovery voltage building up as the region adjacent to the old anode becomes depleted of electrons and the ion sheath begins to grow into the plasma. The post-arc sheath equations can now be applied with the addition of equation (2) which adds the circuit constraints to the model.

Figure 3 illustrates the two different regimes in the post-arc period. In region 1 the recovery voltage is zero and the post-arc current is given by:

$$\frac{dI}{dt} = \frac{-V_2}{L_2}$$

At point (a) the post-arc current is equal to the ion current I_i . Beyond (a) the recovery voltage starts to increase as the ion sheath forms in the gap. At first the recovery voltage will rise slowly since the gap dI/dt is still significant but as the gap current begins to decrease the voltage rises rapidly until it is essentially determined by the external circuit.

3.3 Additional Model Modifications

Two modifications have been made to the model to improve the ion-neutral fluid density and velocity calculations. These are to include the random loss of particles from the gap to the shields and the expansion of the flow from the cathode to the anode.

The model has assumed a one-dimensional flow which is approximately true when the interelectrode length, l , is much smaller than the electrode diameter, D , but due to the random motion of the ions and neutrals there will be some particles which will have a large enough velocity perpendicular to the gap axis to escape from the gap altogether. To account for the escape of the particles from the flow a loss term has been added to the ion-neutral fluid equations as follows:

$$\text{rate of particles escaping/unit volume} = n_f \bar{v}/D$$

where $\bar{v}$ is given by:

$$\bar{v} = (8kT_f/\pi M)^{1/2}$$

Fig. 3 Post-arc current and recovery voltage

Continuity Equation

$$\frac{\delta n_f}{\delta t} + \frac{\delta (n_f v_f)}{\delta x} = - \frac{n_f \bar{v}}{D} \quad (3)$$

Momentum Equation

$$M n_f \left(\frac{\delta v_f}{\delta t} + v_f \frac{\delta v_f}{\delta x} \right) = - \frac{\delta P}{\delta x} - n_1 e z E + n_1 e z \frac{J}{\sigma} - \frac{n_f \bar{v}}{D} v_f \quad (4)$$

Energy Equation

$$\begin{aligned} \frac{3kn_f}{2} \left(\frac{\delta T_f}{\delta t} + v_f \frac{\delta T_f}{\delta x} \right) = & -P \frac{\delta v_f}{\delta x} + \frac{\delta}{\delta x} \left(k_c \frac{\delta T_f}{\delta x} \right) - P_r - v_f n_1 e z E \\ & + v_f n_1 e z \frac{J}{\sigma} - \frac{n_f \bar{v}}{D} \left(\frac{1}{2} M v_f^2 + 2kT_f \right) \end{aligned} \quad (5)$$

The second modification allows for the expansion of the flow as it crosses the gap. The model has previously only allowed for initial ion and neutral velocities parallel to the gap axis. If the particles have any initial component of velocity perpendicular to the gap axis the cross-sectional area of the flow will increase as it travels towards the anode, as shown in Figure 4. When the change in cross-section is small compared to the total cross-section the flow can still be analysed using one-dimensional equations with addition of an expansion term [3].

4. NUMERICAL ANALYSIS OF THE MODEL

The model improvements described in section 2 have now been incorporated into the numerical analysis of the model. The improvements are:

- (a) Addition of the electron reversal period after current zero.
- (b) Addition of the circuit equation, (equation (2)), to the post-arc differential equations.
- (c) Addition of the random loss of particles from the ion-neutral flow.
- (d) Introduction of the ion-neutral flow expansion due to the radial component of velocity.

The results from the improved model are shown in Figures 5 and 6. It can be seen in Figure 6 that the discontinuity at current zero has been removed from

Fig. 4 Conical expansion of the ion-neutral fluid flow due to the radial velocity

(a) No loss of particles,
no expansion of flow

(b) Random loss of particles,
no expansion of flow

(c) Random loss of particles
and expansion of flow

Fig. 5 Ion-density at current zero.
2 kA arc current commutated
in 10 microseconds

POST-ARC CURRENT

RECOVERY VOLTAGE

POWER INPUT TO SURFACE

ELECTRIC FIELD

SHEATH LENGTH

Fig. 6 Post-arc results. 2 kA arc current commutated in 10 microseconds

— with electron reversal period
 - - - without electron reversal period

the post-arc current. Figure 5 shows the normalised ion density at current zero for the following three conditions:

- (a) No loss of particles from flow and no expansion of flow.
- (b) Random loss of particles, but no expansion of flow.
- (c) Random loss of particles and expansion of flow due to initial neutral radial velocity of 500 m/s.

The results show that the random loss of particles from the flow is not significant in determining the flow density at current zero, but that the expansion of the flow does reduce the density close to the anode.

Using the model a study will now be made of the post-arc behavior of different electrode materials under various circuit conditions.

5. EXPERIMENTAL WORK

Three months ago it was reported that the experimental circuit had been dismantled and moved to a new laboratory in the engineering center at RPI. The equipment has been reassembled and the final connections to the 4 kV capacitor bank and the associated power supplies and controls are being made. Once these connections are complete the test circuit will be operational again and further experimental work will be carried out.

6. CONCLUSIONS

The model of current interruption in a diffuse vacuum arc, described in this and previous reports, now includes the complete period from steady state arcing, through commutation to current zero and the post-arc period with no discontinuities in the current. This has been accomplished by the introduction of an 'electron reversal' period between current zero and the initiation of the positive ion sheath. The model has been further improved to allow for the expansion of the ion-neutral fluid and the loss of particles from the fluid flow due to the random motion of the particles. The model can now be used to study interruption in vacuum arcs.

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