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Eleventh Progress Report
on
FUNDAMENTALS OF INTERRUPTION
IN VACUUM

MASTER

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1. SUMMARY

During the past three months effort has concentrated on formulating a method to predict the enhancement of electrode surface field and power input occasioned by the presence of a projection on the electrode surface, during the ion sheath development period which attends the scavenging a contact gap following current interruption in vacuum. In addition, experimental evidence has been obtained to support the theory, postulated earlier, of a turn-around interval for electrons left in the gap, which precedes the rise of the transient recovery voltage.

2. INTRODUCTION

The mathematical model which we have developed to interpret the events which occur when the current in a diffuse vacuum arc is suddenly brought to zero (1), successfully describes the formation and expansion of the positive ion sheath in front of the former anode and provides means for computing the energy input to that electrode by ion bombardment after current zero. It is believed that this energy input together with the electric field at the anode surface, if intense enough, produce conditions conducive to the emission of both metal vapor and electrons from that surface and the establishment there of cathode spots. This would constitute a reignition.

Although the transient recovery voltage concentrates across the ion sheath, the value of the surface electric field which it gives rise to is not as high as one might suppose, nor is the calculated energy input from the ions as great as one might expect if the electrode surface is to be elevated to boiling point. However, it has been assumed in the analysis that the surface of the electrode is flat, whereas in fact it is well known that contact surfaces are frequently scattered with debris. This can greatly enhance the local field in the vicinity of excrescences and cause focusing of the ions on such protuberances, thus greatly amplifying both the local field and the energy input. Until recently our work has been mainly concerned with events in the gap. During the last quarter attention has been turned much more specifically to the electrode itself. The rudiments of the methodology have been devised by which to take into account the presence of projections on the electrode surface.

3. MODELLING A PROTRUSION ON THE SURFACE OF THE FORMER ANODE

3.1 Outline of Proposed Method

Calculation of the electric field in the positive ion sheath and at the former anode surface becomes a complex task when the effects of surface protrusions are included. The following outline describes a tentative method for performing this computation. During the time period in question, the steps proposed are:

- 1) Select a protrusion geometry
- 2) Solve the Laplacian field in the ion sheath (including protrusion)
- 3) Introduce small charges one-by-one into the sheath and compute their trajectories under the influence of the field
- 4) Obtain the field in the sheath in the presence of charge (Poisson field), assuming that charges introduced simultaneously follow the same trajectories as they would individually
- 5) Iterate by repeating step 3 with the field obtained in step 4 and attempt to obtain a converging solution. Note: during the transit time of charges it is assumed the sheath boundary remains boxed.
- 6) Calculate the field at the protrusion. Calculate power input to protrusion.
- 7) Let sheath move a small distance and recompute steps 3 through 6.

The process is continued until the sheath boundary reaches the former anode or some other predetermined distance.

A discussion of each point in the above outline is included to clarify the procedure involved.

3.2 Selecting a Protrusion Geometry

Usually, protrusion geometry is selected in such a way as to facilitate the analysis. Several such geometries appear in the literature (1-3). These solutions are obtained for the case of a pair of parallel plate electrodes where the protrusion resides upon the surface of one of the electrodes. Our selection of protrusion geometry must reflect, as far as possible, conditions that would actually be encountered on a vacuum interrupter surface, the protrusion being the result of former arcing and the breaking of contact welds. The protrusions involved appear whiskerlike; their height is usually much greater than their base dimension.

The geometry chosen, that of a prolate spheroid, is shown in Figure 1 (4). The protrusion is located on the bottom plate of a parallel plate configuration.

Figure 1. Protrusion Geometry

3.3 The Laplacian Field in the Ion Sheath

The analysis of the electric field enhancement for the configuration in Figure 1 has been carried out previously (3-4). It was assumed in these analyses that the separation distance of the electrodes (ℓ) was much greater than the height of the protrusion (h). The results of these analyses can be applied to the ion sheath solution if the upper electrode surface is regarded as the plasma-sheath boundary. So, one may picture a moving electrode receding from a fixed electrode. "Snapshots" are taken in time sequence, like frames of a movie, freezing the moving electrode; Figure 1 represents one of these.

The electric field at the tip of the protrusion is calculated and compared to the electric field that would exist for the parallel plate combination without the protrusion. This results in an enhancement factor β , that is the ratio of the enhanced field to the parallel plate field. For the general case of a prolate spheroid (Figure 1).

$$\beta = \frac{2L^3}{(1-L^2) \ln \left\{ \left[\frac{1+L}{1-L} \right] - 2L \right\}} \quad (1)$$

where $L = [1 - (b/h)^2]^{1/2}$

The value of β ranges from 35 to 1000 for ratios of h to b of 10 to 100. This ratio can attain values of approximately $100^{(5)}$ for the whiskerlike protrusions found on the electrodes of a vacuum interrupter. Values of 100 for β would not be unusual.

As stated, this value of β was calculated assuming the electrode separation to be much greater than the protrusion height. What if the separation distance is approximately the same as the protrusion height? This situation has also been analyzed (4) and results in a further enhancement factor dependent upon electrode separation. This additional enhancement factor is given as

$$\lambda \sim \frac{1}{1 - \frac{h}{\ell}} \quad (2)$$

In point of fact when the sheath first develops $h > \ell$, that is to say the sheath will initially cling to the profile of the protrusion. In the limit this tends to the one-dimensional condition that formed the basis of the original analysis. Thus one should really consider a sequence which passes from this condition, through the phase when $h \sim \ell$, to where $\ell \gg h$. This is depicted in Figure 2.

We conclude from these results that the local field at the protrusion can exceed the average field by two orders of magnitude at some stages during the sheath development. These results form the basis of the Laplace solution.

3.4 Introducing Charge into the Sheath

Charge (representing ion flow in the physical situation) is now introduced into the Laplace field as indicated in Figure 3. The charge enters at various annuli on the plasma sheath boundary in accordance with the known current density.

Charges are introduced individually so as to produce the minimum perturbation in the field. Their trajectories are then computed to determine their location at any instant in their transit across the sheath. It is then assumed, at least initially, that when the charges are introduced simultaneously, the trajectories do not interact, ie. coulomb forces are ignored. By this means it is possible to arrive at a first cut for the charge distribution in the sheath under "steady state" condition.

3.5 The Poisson Field in the Sheath

It is recognized that the presence of the charge in the gap will modify the field in accordance with Poisson's equation. Computer programs are being examined to determine how best to compute the Poisson field.

3.6 Checking the Field Solution

The most obvious way to check the basic assumption in step 3 (section 3.4) is by iteration. Once having found the Poisson field, charge is re-introduced as before and new trajectories are computed. If these and the new charge distribution they give rise to are very similar to those computed initially, they may be accepted. On the other hand, if they show a wide division, it will be necessary to iterate further until an acceptable solution is reached.

Figure 2. Sequential Forms of the Plasma - Sheath Boundary as it Expands into the Plasma

Figure 3. Injection of Ions into the Positive Ion Sheath

A guide to the likely rate of this convergence can perhaps be obtained by computing the radial field distribution produced by the charge. If this is small compared to the axial field, it is likely that the iteration procedure will converge quickly.

3.7 Power Input to the Protrusion

The field at the protrusion surface will be an output from the total field solution. The ion flux density should be comparable from the trajectories as should the energy which the ions convey (from their terminal velocity). Thus it should be possible to find out how these important parameters, field and power input are increased locally by the presence of the protrusion.

3.8 Sheath Movement

It has been tacitly assumed that the sheath boundary was fixed and that the field, ion trajectories, etc. could be computed on this basis. To obtain a complete picture as the sheath develops, it is necessary to repeat the series of computations described in steps 3 through 7 in section 3.1 at sequential instants after current zero. The critical items of field at the protrusion surface and power input to that surface, can then be plotted through time.

There is a basic assumption implicit in the above procedure, namely, the velocity of ions across the sheath is so much greater than the velocity of the sheath boundary itself, that the boundary can be considered fixed during the transit time of an ion. The validity of this assumption has been checked, as will be described in the next section.

4. Evaluation of Ion Transit Time Across Sheath

During the expansion of the ion sheath across the interelectrode space, ions pass from the quasineutral plasma through the sheath to the former anode. The ions approach the sheath boundary with an initial velocity and are accelerated through the sheath to the anode. As stated already, before a dynamic solution of the electric field and charge distribution in the sheath

can be attempted by the method previously discussed, it must be demonstrated that the velocity of the ions in the sheath is much greater than the velocity of the sheath boundary. Put another way, the growth of the sheath during the transit time of an ion, should be small compared with the sheath length itself.

The numerical model for current interruption in a dc vacuum arc was used to obtain data for calculations of the ion transit time. The program calculates and plots: ion density across the gap, ion velocity across the gap, post arc current, recovery voltage, sheath length, electric field at the anode surface and power input to the anode surface. The ion transit time was calculated as follows: the equation of motion of the ions as they pass through the sheath is

$$m_i \frac{dv_i}{dt} = q\bar{E} \quad (3)$$

$$v_i(0) = v_o$$

where v_o is the ion velocity as it leaves the sheath boundary. This differential equation represents the ion's "free fall" through the sheath to the anode. The distance travelled by the ion "t" seconds after entering the sheath is:

$$\ell = v_o t + \frac{1}{2} \frac{q}{m_i} \bar{E} t^2 \quad (4)$$

To calculate the transit time for an ion across the sheath the sheath length is substituted for ℓ and a quadratic equation in t is solved. Data from the numerical model can be used as input. The electric field in the sheath is really a function of position but can be approximated by

$$E = \frac{V_r}{\ell} \quad (5)$$

where V_r is the recovery voltage and ℓ is the sheath length. The transit time is then calculated by solving

$$\ell(t=0) = v_o \Delta t + \frac{1}{2} \left[\frac{q}{m_i} \frac{V_r}{\ell} \right]_{t=0} \Delta t^2 \quad (6)$$

When the sheath length and recovery voltage at a given time are substituted in equation (II-6), Δt is obtained. The distance moved by the sheath in Δt is then compared with the distance the ion travels in the same time interval. The data used for the calculations is shown in Figures 4 and 5. Values of ℓ and V_r at $t = 0.5, 1.0, 1.5$ and 2.0 microseconds were substituted into equation (6) while using a value of $v_o = 2.0 \times 10^3$ m/sec. The ion transit time so calculated was used to find the distance the sheath boundary moved into the plasma. This was accomplished by using a linear approximation of $d\ell/dt$ from the plot in Figure 4; ie.

$$\Delta \ell = \frac{d\ell}{dt} \Delta t \quad (7)$$

The results of the computations are shown in Table II-1.

Table II-1

t_o	V_r (v)	ℓ (m)	v_o (m/sec)	$\Delta \ell$ (m)	Δt nsec
0.5 μ sec	2.06×10^3	4.71×10^{-4}	2×10^3	1.3×10^{-5}	8.3
1.0 μ sec	9.70×10^3	1.77×10^{-3}	2×10^3	5.27×10^{-5}	20.3
1.5 μ sec	14.12×10^3	3.118×10^{-3}	1×10^3	8.0×10^{-5}	30.1
2.0 μ sec	13.24×10^3	3.922×10^{-3}	1×10^3	6.3×10^{-5}	39.0

It is apparent from Table II-1 that to an ion traversing the sheath, the sheath boundary appears to stand still, indicating that a quasistatic numerical approach to the calculation of the electric field and charge distribution is acceptable.

5. EXPERIMENTAL WORK

A previous report (6) describes the "electron reversal period". This was introduced into the mathematical model to explain events occurring in the gap immediately following current zero. It was shown how the external circuit interacts with the residual plasma in the gap, producing a short

Figure 4. Sheath Length and Recovery Voltage used to Calculate Ion Transit Time

ION VELOCITY ACROSS GAP

POWER INPUT TO SURFACE

Figure 5. Ion Velocity and Power Input to Former Anode Surface from Theoretical Model

period after current zero during which the electrons in the plasma are brought to rest. There is no ion sheath during this time and the recovery voltage is negligible. Although this makes for a consistent model it is nevertheless a theoretical development, which, until recently, was unconfirmed experimentally. We have now obtained clear experimental evidence of the existence of the electron reversal period, it is shown in Figures 6, 7 and 8.

Figure 5 shows the arc current and the voltage across the test interrupter. In the bottom trace, we see the arc current commutated to zero approximately 7.8 ms after the trace begins. Figure 6 shows the post-arc current and voltage for the interrupter. This oscillogram clearly shows that at the time of current zero passage the recovery voltage is approximately zero and remains so for a period between 200 and 400 nsec. Figure 7 shows the post arc current and recovery voltage with a time scale of 1 μ sec per division. This shows an electron reversal period of approximately 250 nsec. In addition Figure 7 shows a sharp change in the slope of the post arc current. This coincides with the rise in recovery voltage, as was predicted theoretically. It also signals the beginning of the ion sheath formation of the former anode.

Figure 9 shows results of the numerical model developed to determine post arc currents and recovery voltages. It will be seen that it compares most favorably with the experimental results of Figure 7.

Figure 6. Interrupter Current and Voltage (2.5 kA Arc Current at Commutation)

$t = 2 \text{ } \mu\text{sec/div}$

Figure 7. Post Arc Current and Recovery Voltage (2.5 kA Arc Current at Commutation).

Figure 8. Post Arc Current and Recovery Voltage
(2.5 kA Arc Current at Commutation).

POST-ARC CURRENT

RECOVERY VOLTAGE

Figure 9. Model Predictions of Post-Arc Current and Recovery Voltage for a Commutated Current of 2.5 kA.

REFERENCES

- (1) T. J. Lewis, "High Field Electron Emission from Irregular Cathode Surfaces", Journal of Applied Physics, Vol. 26, No. 12, December 1955, pp 1405-1410.
- (2) M. Mason and W. Weaver, "The ELECTRO-MAGNETIC FIELD", University of Chicago Press, 1929.
- (3) L. D. Landau and E. M. Lifshitz, "ELECTRODYNAMICS OF CONTINUOUS MEDIA", Pergamon Press, 1960, pp 24-26.
- (4) G. N. Fursei and P. N. Vorontsov - Velyaminov, "Qualitative Model of Initiation of a Vacuum Arc I. Breakdown Mechanism", Sov. Phys. - Tech. Phys., Vol. 12, No. 10, April, 1968, pp 1370-1376.
- (5) G. A. Farrall, Private Communication.
- (6) Allan Greenwood and Susan Childs, "Fundamentals of Interruption in Vacuum", DOE Contract ET-78S-5013.A000, Eighth Progress Report, May 1980.