Arc Motion and Electrode Erosion in Rail Spark Gaps

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Abstract – Large capacitive energy storage systems are being implemented for powerful laser systems, electromagnetic launchers, and other pulsed power systems. Such MJ-class modularized capacitor banks individually require precise, reliable, cost-effective, and robust closing switches for synchronous operation. The closing switch, under intense mechanical and thermal shocks imposed by the high peak current, must tolerate high charge transfer, and provide long service life. The most popular closing switches up to date are spark gaps due to relatively simple design, robustness, easily field maintenance and repair. Main drawback of spark gaps is limited lifetime, which is related directly or indirectly to erosion of the electrodes. Various types of switches have been introduced, which utilize principle of arc motion in a magnetic field, thus effectively decreasing the current density on the switch electrodes. This report deals with numerical calculations of arc motion and electrodes erosion in rail spark gap. Results of numerical calculations are compared with experimental results in the report. Conditions for reduced electrodes erosion are defined.

1. Introduction

Many different closing switches have been developed for pulsed power applications. The major groups are vacuum switches, high-pressure switches, and solid-state switches. Papers [1, 2] provide review of extended tests (~3 years) of various types of switches for the National Ignition Facility, which have been performed on the test bed in the Sandia National Laboratory. Main criteria of evaluation were stable performance, low maintenance, long lifetime (ideally full laser duty time), environmental safety.

Three-electrode switches with electrodynamical acceleration of a spark channel have been developed at the Institute of High Current Electronics, Tomsk [3]. In such switches at a given current amplitude the diameter of the extended electrodes allows to control the spark velocity and hence the erosion of the electrodes providing the required lifetime.

2. Requirements to the high Coulomb switches

Main problems, which have to be solved in a high current, high coulomb transfer spark gap switch development include following:

1. Limit electrode erosion at minimum available level.
2. Exclude insulators spattering by discharge products and electrode debris.
3. Prevent mechanical damages, which arise due to cyclic high stress loads.

Although several factors limit the overall switch lifetime, the main reason for failure is usually related in one way or another to the electrodes erosion. Because of this, many studies have been conducted on electrode erosion in spark gaps (see [4–6] and references therein). It was shown in those studies that electrode erosion rate in spark gaps depends on many factors, namely: electrodes material, voltage, charge transfer, current through the switch, sort of gas and pressure, magnetic field, etc. As has been established with a high-speed optic-electronic registration system, the real spark electrode spot has a complex structure, with a number of microspots existing inside the integrated one [7, 8]. These microspots can aggregate or disaggregate, depending on the surface temperature and the current. For higher currents and higher temperatures, these microspots form close associations with the overlapping thermal fields. Two erosion regimes have been identified in [9, 10]: microerosion at interaction of individual spark filaments with the electrode surface (local evaporation, which always exists) and macroerosion with much high erosion rate, which starts when onset condition for melting is satisfied inside the integrated spark spot. This onset condition can be found at solution of one dimensional heat conductivity equation

\[ \rho c(\partial^2 T/\partial t^2) = \lambda(\partial^2 T/\partial x^2) \]  

subject to the boundary conditions

\[ \lambda \partial T/\partial x = -q(t), T(x,0) = T(\infty, t) = T_0, \]  

where \( \rho \) is the specific density, \( C \) is specific heat, \( \lambda \) is the thermal conductivity of an electrode material, and \( q(t) \) is the time dependent heat flux on the electrode surface. The solution of eq. (1) for a constant heat flux of duration \( t_p \) has been given by Belkin [12]. Onset condition for melting is given by

\[ q^* t_p = 0.5 \sqrt{\pi(T_{mp} - T_0) \rho c}, \]  

where \( T_{mp} \) is the melting point temperature, \( T_0 \) is the initial temperature of the electrode surface, \( \delta = \sqrt{\frac{\lambda T_e}{\rho c}} \) is the characteristic length of heat diffusion. Heat flux can be approximated by \( q \approx U J(t) \), where \( J(t) \) is the current density and \( U \) is the voltage drop in near elec-
trode region. Finally, one can calculate average current density in integrated arc spot for the melting initiation:

$$J^\ast = 0.5\sqrt{\pi(T_f - T_0)}pc\delta/(U_f l_f).$$ \hspace{1cm} (4)

For example for copper electrode ($U_c \sim 15\pm 20$ V) and at pulse parameters, given in Fig. 1, equation (4) results in $J^\ast \approx 10^4$ A/cm$^2$. It means that in a stationary arc melting and evaporation are unavoidable, because spark current density is more than order higher ($J \geq 10^5$ A/cm$^2$).

The principle of controlling a high current vacuum arc by magnetic field (external or self-induced field), forcing the constricted arc to move, has been utilized for long time in the design of vacuum interrupters [12, 13]. Linear rail geometry for vacuum interrupter was investigated in [14] at current up to 35 kA and arc velocity up to 3 km/s in self-magnetic field was registered in this work. Arc heaters for metallurgical and chemical processes [15], operating at atmospheric pressure, also employ magnetic field for arc motion, though at quite lower currents (up to 1 kA).

Ring type high pressure switches with rotating arc channel have been introduced by analogy with vacuum devices. Paper [16] presents theoretical model for such switches both with external and self-induced magnetic field. Experimental investigations of the rotating arc switch at atmospheric pressure are given in [17] at current up to 200 kA in ringing discharge with current transfer ~ 200 C per pulse. Paper [18] presents detailed investigation of the rotating arc gap coaxial switch (26 kV, 250 kA, 75 Coulomb), specifically developed for multi-MJ capacitor banks by Titan Pulse Science Division.

3. Arc motion

Typical discharge current for conditions of the paper [3], which will be mainly used for comparison with experiment, is given in Fig. 1. Arc motion in a rail gap channel in general can be described as moving current contour under action of accelerating magnetic force and drag of the medium, which acts on the rear plasma bridge surface. The arc motion produce a shock wave that exerts retarding pressure $P_z$ on the accelerating plasma channel.

Under these conditions appropriate equations of motion becomes:

$$\frac{d(mv)}{dt} = I(t)B(t)l - P_zS;$$ \hspace{1cm} (5)

$$\frac{d(m)}{dt} = \alpha I^2,$$ \hspace{1cm} (6)

where $I$ is the circuit current; $B$ is the magnetic field in the arc area; $l$ is the arc length (height of the rail channel); $P_z$ is the pressure in area between shock wave, moving ahead of plasma in a stationary gas with $V_i$ velocity and plasma volume; $S$ is the effective cross-section area of the plasma channel. The ablation parameter $\alpha$ takes into account only mass, involved in motion together with the accelerated plasma. Initial conditions for equations (5), (6) are clear: $v(0) = 0$, $m(0) = m_0$. $P_z$ is much higher than atmospheric pressure for parameters of interest and it can be written as strong-shock approximation, namely

$$P_z = \frac{V + 1}{2}p_0v^2,$$ \hspace{1cm} (7)

where $\gamma$ is the ratio of the specific heat at constant pressure to that at constant volume and $p_0$ is the atmospheric density, i.e., 1.29 kg/m$^3$.

Substituting Eq. (7) into Eq. (5) we obtain a nonlinear differential equation for the velocity $v$. This equation can be solved numerically, but for small masses good approximation can be obtained by taking left side of Eq. (1) as zero, which results in:

$$v(t) = \sqrt{\frac{2IB}{\gamma + 1}p_0S}. \hspace{1cm} (8)$$

Indeed, at motion with uniform acceleration time of formation of the shock wave and characteristic length can be written as:

$$t_0 = \frac{2c_0}{(\gamma + 1)\alpha_0}, x_0 = c_0t_0^2/2, \hspace{1cm} (9)$$

where $\alpha_0$, $c_0$ represent initial acceleration and non-perturbed sound velocity in air.

Taking into account initial mass of the arc column and erosion rate, measured in [18], as 100 $\mu$g/C, plasma mass can be estimated as $m \leq 0.02$ g for 250 kA current, and $t_0 \sim 0.2$ $\mu$s, $x_0 \sim 0.003$ cm are derived from formulas (9). These time and space scales are much less than characteristic values of the problem, so formation of the shock wave can be considered as instant at formation of the plasma channel.

Figure 2 presents comparison of arc velocity, derived from formula (8), with numerical solution of equation (1) at different plasma mass. One can see here that for mass $m \leq 0.1$ g approximation is quite satisfactory and estimations remains good even at larger masses.
Fig. 2. Arc velocity vs time at different plasma mass

Mean velocity varies in range 16.7±1.9 km/s for curves in Fig. 2. Note that experimental mean velocity of arc motion, measured in [3], was ~ 1.8 km/s, so there is really good agreement between theory and experiment. Comparison with results of the paper [19], where the motion of plasma channel in linear rail geometry was investigated, also provides good agreement.

4. Heating of electrodes

At motion of the plasma channel along the electrodes (z coordinate) heat flux at position z can be written as

\[ \delta Q(z(t)) = UcI(t)\delta z / v(t) \]  \hspace{1cm} (10)

and

\[ \delta Q(z) / \delta z = Uc(t)I(t) / v(t) \]  \hspace{1cm} (11)

One can see from formula (1) that heating of the electrodes can be considered as uniform along the electrodes, because, as follows from formula (8), velocity is proportional to the current. It makes simple and straightforward calculation of temperature distribution on the electrodes. Steel and copper have been considered here, because they are mostly used as electrodes materials.

Figure 3 shows electrode temperature on the surface for steel and copper \((T_0 = 293\text{ K} \text{ is accepted as initial temperature here})\). Fig. 4 presents temperature distribution vs depth at time moment \(t = 600\ \mu\text{s}\). One can see here that temperature distribution is almost relaxed in copper at that time and remains sharp in steel. So, copper can be considered as favorable material for electrodes in comparison with stainless steel due to high thermal conductivity of copper, in spite of larger melting temperature for steel.

5. Summary

Simple and effective model is suggested for the consideration of arc motion in linear rail geometry in high pressure gas at high current and high charge transfer pulses. Good agreement with the experiment is observed in considered range of parameters.

References