Numerical simulation of spark channel dynamics in railgun switches

A V Kharlov
Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia
E-mail: akharlov@lef.hcei.tsc.ru

Abstract. Discharge of a capacitive storage on a load with unipolar pulse is employed for pumping of powerful lasers and also for feeding of electromagnetic launchers, and pulsed high magnetic field facilities. Spark gaps are often used to commute energy on a load. In some applications unipolar pulse is not feasible and oscillatory regime (underdamped sinusoidal) has to be realized for the capacitor bank discharge. Spark gaps, developed for unipolar discharge, cannot directly be employed in under-damped (oscillatory) regime, because at current transition through zero the arc channel could stop motion and ignite at initial place on the following half period. Two main objectives were pursued in this work: 1. develop and test simulation model of a the spark channel motion in linear rail geometry for the oscillatory regime of capacitor bank discharge; 2. Investigate arc motion and electrodes heating depending on the current and charge transfer in wide operation range.

1. Introduction
Discharge of a capacitive storage on a load with unipolar pulse is employed for pumping of powerful lasers [1, 2], and also for feeding of electromagnetic launchers [3], and pulsed high magnetic field facilities [4]. Spark gaps are often used to commute energy on a load. Triggered spark gaps with electrodynamical acceleration of spark channel were developed, investigated and thoroughly tested by Kovalchuk and colleagues [5] for LMJ facility [6]. Later two-electrode spark gap with inductive coupling in a triggering circuit [7] was introduced with sharp extension in operation range and charging voltage. In some applications unipolar pulse is not feasible and oscillatory regime (underdamped sinusoidal) has to be realized for the capacitor bank discharge. In particular, it is valid for a pulse magnetic method, which is used for assembling welding, cutting, and forming the details of products in various branches of industry [8-10]. In each of the aforementioned categories several machines were developed, divided mainly by energy storage from tens to a hundred kJ, working voltages of 6-40 kV, full pulse length from 100 µs to ms. Electromagnetic forming is a high-speed forming technology, using pulsed magnetic field. Due to extremely high velocities and strain rates in comparison to conventional quasi-static processes, forming limits can be extended for many materials. Additional advantages are: the process is environmentally friendly, because no lubricants are used, a high repeatability can be achieved at proper design of a pulse generator, the adjustment of the applied forces is provided via the charging energy and the voltage, respectively is very accurate, joining of dissimilar materials including material combinations of metals and glass, polymers, composites or...

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different metals is possible. Review [11] summarizes major publications and advances on electromagnetic forming. Spark gaps with electrodynamical acceleration of spark channel, developed for unipolar discharge, cannot directly be employed in under-damped (oscillatory) regime, because at current transition through zero the arc channel could stop motion and ignite at initial place on the following half period. Process of the arc ignition and motion became more complicated in the oscillatory regime of capacitor bank discharge. Prototype of a compact gas switch, intended for operation in oscillatory (low damping) regime of discharge, was introduced in [12]. It is two-electrode switch with electrodynamical acceleration of a spark channel and a matched series injection trigger generator. Two operations regimes have been investigated therein, namely “fast” regime with current amplitude $\sim 160$ kA, total charge $\sim 12$ C, period of oscillations 60 μs, full pulse length $\sim 400$ μs and “slow” regime with current amplitude $\sim 30$ kA, total charge 18 C, period of oscillations 360 μs, full pulse length $\sim 3$ ms. The spark gap is designed for 50 kV charging voltage, at a current up to 200 kA, and up to 20 C charge transfer. Two main objectives were pursued in this work: 1. To develop and test numerical simulation model for a rail-gun switch for the oscillatory regime of capacitor bank discharge with wide operation range in voltage and current; 2. To investigate arc motion and electrodes erosion depending on the current and charge transfer.

2. Arc motion
Motion of a canal channel through the switch electrodes naturally decreases erosion of the electrodes, which, in turn, decreases sputtering of the insulators and their decontamination by erosion products. Decrease of the erosion also leads to constant form of the electrodes and, hence stable breakdown voltage will be guaranteed and, respectively, time delay stability in the switch operation. Velocity of a plasma channel is defined by equilibrium in magnetic force and air drag force, acting on a plasma channel [13]. Plasma channel forms bridge between the rails, and is accelerated along the electrodes due to $\mathbf{j} \times \mathbf{B}$ force exerted by the discharge current $I(t)$. Figure 1 demonstrates schematic of the arc motion.

![Figure 1. Schematic of the arc motion.](image)

The arc motion produces a shock wave that exerts retarding pressure $P_2$ on the accelerating plasma channel. Magnetic force can be written as product of current, average magnetic field through the channel length and the channel length: $F_{m}(t) = I(t) \cdot B(t) \cdot d$.

Air drags force, acting on a plasma channel is $F_{p}(t) = P_2(t) \cdot S$ where $S = bd$ – channel area at normal motion, $P_2(t)$ – pressure between shock wave and plasma piston, providing retarding pressure on the plasma channel.

$$P_2(t) = \frac{\gamma + 1}{2} \cdot \rho_1 \cdot v^2$$  \hspace{1cm} (1)

where $v$ is the plasma channel velocity, $\gamma$ is adiabatic index, i.e. the ratio of the specific heat capacity at constant pressure to that at constant volume (1.4 for atmospheric air at the temperature of 293 K) and $\rho_1$ is air density at atmospheric pressure and the temperature of 293 K, i.e. 1.21 kg/m³.
In order to increase average magnetic field through the channel length it is desirable to both decrease diameter of the electrodes and decrease channel length, but both these actions tend to increase maximum electric field in the inter-electrode gap and limit maximum operational voltage. It is possible to raise operational voltage by increase in pressure. But retarding air drag force would be risen in the same way, decreasing arc velocity and increasing erosion. Preliminary experiments on choose of electrodes diameter and gap were provided with electrodes diameters 12, 16, 20, 30 mm with gap 30-40 mm. Based on those experiments, 20 mm electrodes were accepted for developed switch as optimal.

3. Experimental layout

Picture of principal electrical circuit is given in figure 2. Capacitor bank $C$ is assembled from 14 capacitors IK50/3 (50 kV, 3 µF), connected in parallel. Measured capacitance of the bank is 39.9 µF. The body of the main switch is connected with ground through the saturable inductor 4. Additional resistor $R$ and inductance $L$ define required pulse shape and current amplitude. After the main spark gap breakdown the inductor 4 cores are quickly saturated, and the switch body is getting connected with ground through very low resistance. Bank $C$ is discharged and the current pulse is formed.

![Figure 2. Electrical scheme: Rch – charging resistor, L, R – pulse shaping elements, C – capacitive storage, 1, 2 – switch electrodes; 3 – discharge channel; 4 – inductor, 5 – triggering generator.](image)

The switch has been investigated in two regimes, so called “fast” and “slow” regimes. Transfer between regimes requires modest change in the discharge circuit. For realization of the fast regime additional resistor $R_3=0.0125$ Ω and inductance $L_2=0.54$ µH are included in the discharge circuit. Experimental current waveform (1) and calculated absolute charge curve (2) are given in figure 3a. Current amplitude is 162 kA, total charge – 12.3 C. Period of oscillations is equal to 60 µs. Total inductance and resistance of the discharge circuit, calculated from period and damping of the oscillations, are $L=2.0\div2.2$ µH and $R=0.03\div0.034$ Ω. For realization of the slow regime additional resistor $R=0.1$ Ω and inductance $L=82$ µH are included in the discharge circuit. Experimental current waveform (1) and calculated absolute charge curve (2) are given in figure 3b. Current amplitude is 27 kA, total charge – 18.5 C. Period of oscillations is equal to 360 µs. Total inductance and resistance of the discharge circuit, calculated from period and damping of the oscillations, are $L=80.5\div83$ µH and $R=0.132\div0.142$ Ω. All tests for fast and slow regimes were carried out at charging voltage 40 kV.
4. Numerical simulation

4.1. Magnetic field simulation

Figure 4 shows example of DC magnetic field simulation in typical experimental geometry (Radius of the electrode 10 mm, distance between centers 50 mm, outer grounded cylinder with diameter of 210 mm). Table 1 summarizes results for dependence of magnetic field between electrodes on distance D between centers of electrodes. It can be seen from the table 1 that the electrode radius defines mainly the magnetic field values, while distance D between centers of electrodes affects slightly. Increase in distance D between centers of electrodes slightly reduces average magnetic field \( B_{av} \) between electrodes. It is also important to note that external grounded cylinder (210 mm diameter) provides critical impact on magnetic field and it differs significantly from the 2 wires field in free space.

| Distance (mm) | \( B_{max} \) (T) \( \frac{R10}{R15} \) | \( B_{av} \) (T) \( \frac{R10}{R15} \) |
|---------------|-----------------|-----------------|
| 40            | 3.86/3.07       | 2.9/2/21        |
| 50            | 3.6/2.7         | 2.35/2/24       |
| 60            | 3.36/2.47       | 2.01/1.82       |

It may be seen from table 1 that electrodes radii provide predominant affect on maximum magnetic field, which is obtained at the electrodes surfaces.

4.2. Arc motion in two regimes

Appropriate equations of motion could be written as:

\[
\frac{d(mv)}{dt} = I(t)B(t)i - P_zS
\]  

(2)

\[
\frac{d(m)}{dt} = \alpha I(t)^2
\]  

(3)
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), \( P_2 \) is the pressure in area between shock wave, moving ahead of plasma in a stationary gas with \( V_1 \) velocity, and plasma volume, \( S \) is the effective cross-section area of the plasma channel.

![Graph](image)

**Figure 4.** Left: magnetic field between electrodes; right: 2D map (HV–HV electrode, LV–LV electrode, 1 – outer grounded cylinder).

**Table 2.** Arc velocity and displacement S of the spark channel.

| Regime  | \( V_{\text{max}} \) (m/s) | \( S \) (m) Sim/exp |
|---------|--------------------------|------------------|
| Fast    | 3500                     | 0.27/0.18        |
| Slow    | 600                      | 0.35/0.25        |

Equations (2), (3) are coupled with electric circuit equation, which provides \( I(t) \) waveform (figure 3). Ablation parameter \( \alpha \) takes into account for mass, involved in motion together with the accelerated plasma. Its value depends weekly on current in range 50-200 kA and could be approximated as \( \alpha=(4-6)\cdot10^{-12} \) kg/(A²s). The ablation leads to the state of plasma as mixture of gas and metallic vapor.

![Graph](image)

**Figure 5.** Calculated time dependent velocities of the spark channel for fast (a) and slow regime (b).
In the plasma channel, the presence of metal vapors not only increases the amount of radiated power: it also increases the electrical conductivity in the zones surrounding the arc. These two effects both tend to decrease the axis temperature of the arc. Initial conditions for the equations (2), (3) are clear: \( v(0)=0, m(0)=m_0 \). Substituting Eq. (1) into Eq. (2) and (3) we obtain a nonlinear differential equation. This equation can be solved numerically for arc velocity and mass of the plasma channel. Figure 5 shows calculated velocities of the spark channel for fast regime (a) and slow regime b). Table 2 shows calculated results for maximum arc velocity \( V_{\text{max}} \) and effective displacement \( S \) of the spark channel both for fast and slow regimes. Obtained values of the displacement \( S \) are somewhat higher than the experimental ones (shown in table 2 also). It may be attributed to the fact that velocity tail provides in the calculations contribution to the displacement \( S \), though actually the arc is already dissipated to this moment. It may be clear seen by comparison of figure 3 and figure 5. Ratio of the displacement \( S \) for the slow and fast regimes in the experiment and simulation correspond well to each other (approximately as ratio of charged transfer, as it follows from the developed theory).

5. Summary
Numerical simulation model was developed for a rail-gun switch for the oscillatory regime of capacitor bank discharge. Arc motion and electrodes heating was investigated depending on the current and charge transfer. Reasonable agreement with experiment has been demonstrated.

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