Analysis on the Influence of Breech Voltage on the Pulsed Discharge Characteristics of Capacitive Pulsed Power Supply in EML

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Abstract. Corresponding to the different gradient of the ideal working current, the movement process of the armature in the railgun bore can be divided into rising phase, stable phase and decreasing phase. Based on the load characteristic and the lumped-element equivalent circuit of the railgun, the characteristics of the railgun’s breech voltage in above three phases were analysed. Under the condition that the size of the launching system is close to the same, the change ranges of the breech voltage of the augmented railgun is much larger than that of the simple railgun, and the breech voltage of the augmented railgun is a very high forward voltage in the rising phase. The influence of the breech voltage on the discharge characteristics of the capacitive pulsed power supply was studied. In the rising phase, the high breech voltage of the augmented railgun has a significant adverse effect on the pulsed discharge characteristics of the capacitive pulsed power supply whose pulsed forming net consists of a large number of pulsed forming units with small energy storage and high resonance frequency. As a result, part of the stored energy of the capacitive pulsed power supply cannot be used effectively, which leads to the decrease of the working efficiency of the launching system. Using the launching system with a 13-MJ capacitive pulsed power supply and a medium calibre augmented railgun, the launching simulation and test were completed, and the analysis was verified. The research has important enlightenment for improving the match between the capacitive pulsed power supply and the railgun.

1. Introduction

Electromagnetic launch (EML) technology uses electromagnetic force to do work and converts the stored energy of high pulsed power supply (PPS) into the kinetic energy of payload, which can realize the hypervelocity launch of the projectile [1-2]. Electromagnetic railgun system mainly consists of rail launcher, armature and PPS. PPS is of great importance to the research and application of railgun technology [3-5]. Among all types of PPS used in railgun system, the most mature and widely used one is the capacitive pulsed power supply (CPPS). In recent years, due to the rapid technical progress of metallized film capacitor, the energy storage density of the CPPS has been greatly improved, which makes the CPPS have a good prospect of engineering application. The CPPS has many advantages on mature technology, operational reliability, and feasible financial condition, so it is predicted to be one of the main schemes of PPS for future engineering application [6-10].
Railgun, including rail launcher and armature, is a dynamic load in launching process. From the perspective of research on system matching, the dramatic change of dynamic load may have some impact on the power supply, which is worthy of attention and analysis. From the viewpoint of circuit, the load characteristics of railgun can be equivalent to a series circuit, which includes some components, such as variable resistance, variable inductance and controlled source that reflects the change of induced voltage. In the launching process, the port voltage of the series circuit can directly reflect the changing law of the load characteristics of railgun. The port voltage is also the breech voltage of railgun. Based on the ideal working current for launching, this paper analyzed the breech voltage characteristics of the simple railgun and the augmented railgun by using the lumped-element equivalent circuit of launching system. At the same time, the influence of the breech voltage variation of two kinds of railguns on the discharge characteristics of the CPPS was studied. Using the launching system with a 13-MJ CPPS and a medium caliber augmented railgun, the launching simulation and test were completed, and the analysis was verified.

2. Equivalent circuit of launching system
The rail launcher consists of rails, insulating supports and sealing devices. According to the different structure of launcher, railguns are usually classified as the simple railgun and the augmented railgun. The simple railgun consists of a pair of parallel rails, and the augmented railgun consists of multiple pairs of parallel rails. The armature is generally made of conductive metal or plasma material, which moves forward between the rails of the gun bore in the launching process.

Pulsed forming net (PFN), which consists of many pulsed forming units (PFUs) in parallel, is the key functional part of the CPPS. The working circuit of the PFU is a RLC circuit with crowbar circuit. The main components of the PFU include a pulsed capacitor, a pulsed switch, a pulsed inductor and a crowbar switch. Now, the pulsed capacitor is a metallized film capacitor; the pulsed switch is a thyristor switch that consists of several high-power thyristors in series or in parallel; the pulsed inductor is a dry-type air-core inductor; the crowbar switch is a high-voltage silicon stack that consists of several high-power rectifier diodes in series or in parallel.

Assuming that the armature moves smoothly in the gun bore, and ignoring some minute influence factors, such as air resistance, friction between the armature and the guide rail, the launching process of the railgun powered by the CPPS can be equivalent to the lumped-element circuit shown in figure 1.

![Figure 1. Lumped-element circuit of railgun system.](image)

The part (PFN) in the left discontinuous line frame is the lumped-element circuit of the PFN in figure 1. PFU_{k} is the PFU whose number is k (k=1, 2, ..., n), B is the bus bar, Circuit symbol C_{k}, T_{k}, L_{k}, D_{k}, i_{k}, u_{k} represent the pulsed capacitor, the pulsed switch, the pulsed inductor, the crowbar switch, the output current of the PFU_{k} and the voltage of the C_{k} in turn. The part (G) in the right discontinuous line frame is the lumped-element circuit of the railgun. Circuit symbol L_{0}, R_{0}, R_{r}, L_{r}, i_{g}, u_{g}, e_{v}, u_{a}, x represent the initial rail inductance, the initial rail resistance, the rail resistance gradient, the rail inductance gradient, the working current, the breech voltage, the induced voltage generated by the armature’s movement, the armature-rail contact voltage, the armature displacement in
the gun bore in turn. Rr'x and Lr'x respectively represent the variable resistance and the variable inductance changing with x.

The working current is:

\[ i_g(t) = \sum_{k=1}^{n} i_k(t) \]  

(1)

Supposing that the armature contacts well with the rails in the gun bore, that is \( u_a = 0 \), and then, the breech voltage is:

\[ u_g = (L_0 + L_r x) \frac{di_g}{dt} + (R_0 + R_r x) i_g + L_r v_i_g \]  

(2)

3. Breech voltage’s influence on pulsed discharge characteristics of CPPS

3.1. Ideal working current and its realization

In order to make the armature move forward smoothly at high speed, the CPPS is required to supply the railgun with a large amplitude pulsed current whose waveform is similar to the trapezoid shape. The ideal working current has a fast rising edge and a high platform value of wide duration. As the speed, displacement and acceleration of the armature are closely related to working current, the movement process of the armature in the gun bore can be divided into three working phases according to the different gradient of the ideal working current \( i_g \), as shown in figure 2.

1) Rising phase: \( di_g/dt > 0 \). \( T_F \) represents the rising phase, and its duration is \( t_F \).
2) Stable phase: \( di_g/dt = 0 \). \( T_p \) represents the stable phase, and its duration is \( t_p \).
3) Decreasing phase: \( di_g/dt < 0 \). \( T_D \) represents the decreasing phase, and its duration is \( t_D \).

![Figure 2. Ideal working current and its three phases.](image)

In figure 2, \( t_a \) is the moment when the armature moves out of the gun bore, and \( i_{ge} \) is an example current that is supplied by a CPPS. Generally, the working current is very large, its amplitude is about several MA and its pulse width is greater than 5 ms.

According to the circuit topology of the PFN, the greater the number of the PFUs is, the higher the resonance frequency of the PFU’s RLC circuit is, and the easier it is to realize the working current waveform close to the trapezoid by the sequential discharge. It is the normal design schemes of the PFN that the PFN contains a large number of the PFUs with small rated energy and high resonance frequency. For example, the PFN developed for the PEGASUS railgun included 200 PFUs, and the rated energy of its single PFU was only 50 kJ[11-12]. Under the normal design of the PFN, the following inequality holds:

\[ f > \frac{1}{2t_F}, \quad f > \frac{1}{2t_p}, \quad f > \frac{1}{2t_D} \]  

(3)
In inequality (3), f is the resonance frequency of the PFU’s RLC circuit. Inequality (3) shows that if the PFU was triggered at the beginning of TF (or TP, or TD), its discharge process would be ended in this phase generally. In order to make the waveform of the working current close to that of the ideal working current, a large number of the PFUs supply pulsed current to the launcher at each moment in the launching process, which means that the following inequality holds:

$$i_g(t) = i_e(t)$$  \hspace{1cm} (4)

From equation (2) and inequality (4), it is obvious that the output current of a single PFU has little influence on the breech voltage at any time during the launching process.

### 3.2. Characteristics of Breech Voltage

The circuit parameters of the simple railgun and the augmented railgun are quite different. The simple railgun has only one pair of rails and at its end the armature is installed, so its $L_0$ and $R_0$ are almost zero. The augmented railgun contains multi-pairs of parallel rails and the connecting structure between the rails is complex, so its $L_0$ and $R_0$ are much greater than that of the simple railgun. Generally, the order of $L_0$ of the augmented railgun with two-pairs of parallel rails is about $10^6 \, \text{H}$, and that of $R_0$ is about $10^{-4} - 10^{-3} \, \Omega$. In addition, under the condition that the rail size is similar, $L_0'$ of the augmented railgun is generally 1.5 times larger than that of the simple railgun.

According to the circuit parameters and the variable relation given by equation (2), the change and difference of both breech voltages of two kinds of railguns in three working phases were analyzed.

1) Rising phase. The armature is in the state of motion from rest to low speed, $x$ and $v$ are very small, so the product terms related to $x$ and $v$ in equation (2) can be ignored. Therefore, equation (2) is simplified as:

$$u_g \approx L_0 \frac{di_g}{dt} + R_0 i_g$$  \hspace{1cm} (5)

The rapid rise of $i_g$ makes $di_g/dt$ very large, which is several kA/μs generally. It can be seen from equation (5):

a) $R_0$ and $L_0$ are very small, so the breech voltage of the simple railgun is relatively small and close to zero.

b) $R_0$ and $L_0$ are large, so the breech voltage of the augmented railgun has a large amplitude.

2) Stable phase. The acceleration of the armature is large, and both $x$ and $v$ are increasing. Because $i_g$ reach and maintain stable value, the term related to $di_g/dt$ in equation (2) can be ignored. Therefore, equation (2) is simplified as:

$$u_g \approx (R_0 + R_0' x) i_g + L_0' v_i_g$$  \hspace{1cm} (6)

The stable value of $i_g$ is very large, generally several MA, and at the end of this phase $v$ also has a higher value which is often close to 2000 m/s. Therefore, it can be seen from equation (6):

a) With the increase of $x$ and $v$, the breech voltage of the simple railgun increases gradually from small to large, and the maximum value is obtained at the end of this stage.

b) As the value of $di_g/dt$ is zero, the breech voltage of the augmented railgun is usually much smaller than that in the rising phase, but because of the larger $R_0$ and $L_0'$, the breech voltage of the augmented railgun is still larger than that of the simple railgun.

3) Decreasing phase. The acceleration of armature decreases gradually, $x$ and $v$ continue to increase, $i_g$ decreases rapidly and $di_g/dt$ becomes negative. Equation (2) can be rewritten as:

$$u_g \approx -(L_0 + L_0' x) \left| \frac{di_g}{dt} \right| + (R_0 + R_0' x) i_g + L_0' v_i_g$$  \hspace{1cm} (7)

In this phase, $x$ and $v$ are the largest, usually $x$ is greater than 5 m and $v$ is not less than 2000 m/s. The absolute value of $di_g/dt$ is also very large, generally several kA/μs. Therefore, it can be seen from equation (7):
a) Because \( \frac{d\phi}{dt} \) is negative, the breech voltage of the simple railgun changes from large to small, or even negative.

b) Because \( L_0 \) is large, the breech voltage of the augmented railgun has a negative voltage generally.

According to the previous analysis, there are differences in changes of the breech voltage between the simple railgun and the augmented railgun, and the reason of the differences is mainly due to the different structure of the two kinds of railguns. Under the condition that the size of the two launching system are close to the same, the breech voltage change of the augmented railgun is much larger than that of the simple railgun during the launching process. It is a typical phenomenon in the launching process of the augmented railgun that the breech voltage is a high positive voltage in the rising phase.

3.3. Influence of breech voltage on CPPS

The influences of the breech voltage on a single PFU was discussed as follow. In the working circuit of the PFU, as shown in figure 1, \( u_k \) can be regarded as a power supply because \( C_k \) has initial energy. Equation (4) shows that \( i_k \) has almost no effect on \( u_k \), so according to the Substitution Theorem in circuit, \( u_k \) is also regarded as a power supply at a short time. Due to the same circuit structure, the resonant frequencies of \( u_k \) and \( u_{g} \) are the same. Let \( i_{k1} \) and \( i_{k2} \) be the pulse current of \( RLC \) circuit of the PFUs under the action of \( u_k \) and \( u_{g} \) respectively, then the output current of the PFUs is:

\[
i_k(t) = i_{k1}(t) + i_{k2}(t)
\]

(8)

When the polarity of \( u_g \) is opposite to that of \( u_k \), the actual directions of \( i_{k1} \) and \( i_{k2} \) are opposite. As seen from equation (8), in such case, \( i_k \) and \( \frac{d\phi}{dt} \) will decrease simultaneously with the increase of \( u_{g} \). When the value of \( u_k \) is certain, once the value of \( u_{g} \) is larger than a threshold value, the following inequality will always hold in the discharge process of the PFU:

\[
L \frac{d\phi(t)}{dt} + R i_k(t) + u_{g} > 0
\]

(9)

Inequality (9) means that \( D_k \) always operates in shutdown mode during the discharge of the PFU. When \( \phi \) decreases to near zero, \( T_k \) turns off at once. If \( u_{g} \) is relatively large, \( u_k \) may also be a high voltage at the moment when \( T_k \) just turns off. According to the switching characteristics of thyristor, \( T_k \) will keep the off state until the end, which makes some residual electric energy of \( C_g \) wasteful. That is to say, the phenomenon that the PFUs cannot fully release the stored electric energy occurs.

The PFN contains a large number of the PFUs with small storage energy and high resonance frequency, so the above research shows that if the railgun has a high breech voltage during launching process, the situation that many PFUs cannot fully release the stored electric energy may occur. Such situation would have an impact on the pulsed discharge characteristics of the CPPS, and it leads to the inevitable decrease of launching efficiency of the railgun system.

Based on the actual situation of the two kinds of railguns, the possible influence of the breech voltage on the CPPS in three working phases was analyzed as follows:

1) The simple railgun. The maximum value of the breech voltage appears in the later period of the stable phase, and it is relatively small, which generally cannot make inequality (9) hold, while the breech voltage in other phases is smaller. Therefore, when the simple railgun is launching, the phenomenon that the CPPS cannot completely release the stored electric energy usually does not occur.

2) The augmented railgun. The breech voltage is very high in the rising phase, which makes inequality (9) hold in the PFUs triggered at the beginning of the rising phase. As known from equation (3), the phenomenon that the CPPS cannot completely release the stored electric energy occurs. The breech voltage is greatly reduced at the beginning of the stable phase, and inequality (9) cannot hold in the subsequent launching process, so the electric energy of the PFUs triggered in the stable phase is released completely. The PFUs, which are triggered to discharge in the later period of the rising phase, maybe keep working to the stable phase, so the electric energy of these PFUs is released completely.
4. Simulation and test of augmented railgun system

4.1. Launching simulation

The breech voltage of the augmented railgun in the rising phase is high, so part of the stored electric energy in the CPPS cannot be effectively utilized, which leads to the decrease of the launching efficiency. In this paper, the launching simulation and test were carried out to verify the conclusion using a medium caliber augmented railgun system. The augmented railgun adopts two-pair parallel rail structures and its main technical parameters are shown in Table 1. The rated energy storage of the CPPS used for the augmented railgun is 13 MJ. Its PFN consists of 260 PFUs and the rated energy storage of the PFU is 50 kJ, so the CPPS has an excellent performance of the precise control of the output current. The rated voltage of the PFU is 10 kV, and its RLC circuit resonance frequency is 1125.6 Hz. The main parameters of the RLC circuit are as follows: the capacitance of the pulse capacitor is 1.0 mF, the inductance of the pulse inductor is 20 μH and the internal stray resistance is about 5.0 mΩ. Another important research goal of the launching test is to make the muzzle velocity of a 1-kg armature exceed 2000 m/s.

| Name                        | parameters |
|-----------------------------|------------|
| Initial rail inductance/ \(L_0\) | 4.20 μH    |
| Initial rail resistance/ \(R_0\)  | 0.60 mΩ    |
| Rail inductance gradient/ \(L_r'\) | 0.79 μH/m  |
| Rail resistance gradient/ \(R_r'\) | 0.11 mΩ/m  |
| Rail quantity/ \(N\)          | 4          |
| Rail effective length/ \(l_R\) | 6 m        |

The electromechanical dynamics simulation model is developed by Matlab/Simulink, which consists of the CPPS equivalent circuit, the railgun equivalent circuit, the armature motion equation, etc. In order to obtain a pulsed discharge scheme that meets the target expectation, the launching process was simulated. A feasible pulsed discharge scheme is as follows: The working voltage of the CPPS is 9.0 kV, all PFUs are divided into 17 groups for sequential discharge and the time interval between each group is 150 μs. That is to say, in order to obtain a trapezoidal working current, the first group includes 52 PFUs, and the other groups include 13 PFUs. The simulation working current (\(i_{sg}\)) and the simulation velocity of armature (\(v_{sa}\)) obtained by the scheme are shown in Figure 3.

![Figure 3. Simulation working current and simulation velocity of armature.](image-url)
According to the simulation results, the waveform of $i_g$ is approximately trapezoidal, and the value of $di_g/dt$ is about 1.66 kA/μs at the beginning of the rising phase. If $t_t$ is taken as 1.1 ms, the average value of $di_g/dt$ is about 1.1 kA/μs. The relevant parameters of the PFU were brought into the pulsed discharge circuit, and the influence of the breech on the PFU was analyzed. The calculation shows that when $u_g$ maintain about 4.87 kV, the PFU cannot release the stored electric energy completely. According to the parameters of the railgun and the simulation results, it can be estimation by equation (5) that the average value of $u_g$ is about 6.97 kV at the beginning of the rising phase, and the average value of $u_g$ is about 5.21 kV in middle period of the rising phase. It can be estimation by equation (6) that the maximum value of $u_g$ is about 2.13 kV in the stable phase. Obviously, the phenomenon that the PFUs cannot completely release the stored electric energy will occur inevitably. In addition, according to the above pulsed discharge scheme, the triggering time of the PFUs in Group 7 is at 900 μs, which means that these PFUs enter the relatively small value of $u_g$ in a short time. Based on the rough estimate above, we judged that the PFUs that would not fully release the stored electric energy during the launching process of railgun should appear before Group 7. The voltage of the pulse capacitors of the PFUs and the breech voltage were simulated, and these simulation waveforms are shown in figure 4, $u_{gs}$ is the breech voltage of the railgun, and $u_{gk}$ (k=1, 2, ..., 7) is the voltage of the pulse capacitors of the PFUs in group k.

![Figure 4](image)

**Figure 4.** Simulation waveforms of breech voltage and pulsed capacitor voltage.

The simulation results show that:

1) The maximum value of the breech voltage in the rising phase is about 6.64kV.
2) The PFUs in the first four groups cannot fully release the stored electric energy, and the residual voltage of the pulsed capacitors is 2.27 kV, 3.94 kV, 2.81 kV and 1.60 kV in turn.
3) The residual voltage of the PFUs in the second group is the highest, and the electric energy failed to release accounts for about 19.16% of the stored electric energy of these PFUs.

### 4.2. Launching Test

According to the above pulsed discharge scheme, the launching test of the augmented railgun system was carried out. The measured waveforms of the breech voltage and the voltage of the pulsed capacitors of the PFUs in first four groups are shown in figure 5. $u_g$ is the breech voltage, $i_g$ is the working current, and $u_k$ (k=1,2,3,4) represents the voltage of the pulsed capacitor of the PFUs discharged in Group k. Obviously, the experimental results support the conclusions of this paper.
By comparing figure 3, figure 4 and figure 5, it can be found that the waveforms obtained from the simulation and the test have a good consistency, but there are still slight differences as follows:

1) The amplitude of the measured breech voltage is slightly higher than that of simulated voltage in the rising phase.
2) The amplitude and pulse width of the measured working current are slightly lower than that of the simulated current.

The analysis shows that the main reasons for these differences are as follows:

1) The actual launching process is a dynamic process, and the parameters of the simulation model, such as stray resistance and stray inductance, cannot be completely consistent with the actual parameters.
2) The initial voltages of the PFUs have some certain dispersion in the actual launching process.
3) The eddy loss of the metal parts on the railgun and the contact loss between the armature and the rails were not considered in the simulation launching process.

5. Conclusions

Based on the ideal working current and the lumped-element equivalent circuit of the railgun launching system, the characteristics of the breech voltage of the simple railgun and the augmented railgun were analyzed. At the same time, the influence of the breech voltage on the discharge characteristics of the CPPS was studied. Using the launching system with a 13-MJ CPPS and a medium caliber augmented railgun, the launching simulation and test were carried out to verify the research conclusions. The results show that:

1) The breech voltage of the simple railgun and the augmented railgun have obviously different characteristics. Under the condition that the size of the launching system is close to the same, the change ranges of the breech voltage of the augmented railgun is much larger than that of the simple railgun. Especially, in the rising phase, the breech voltage of the augmented railgun is a very high forward voltage.
2) In the rising phase, the high breech voltage of the augmented railgun has a significant adverse effect on the pulsed discharge characteristics of the CPPS whose PFN consists of a large number of PFUs with small energy storage and high resonance frequency. At the beginning of the rising phase, the PFUs triggered to discharge cannot completely release the stored electric energy to the launcher. As a result, part of the stored energy of the CPPS cannot be used effectively, which leads to the decrease of the working efficiency of the launching system.

With the development of EML, the size of the railgun system and its launcher will be larger and the working current will be higher, which will lead to higher breech voltage. Therefore, the next step is to carry out the countermeasures research to reduce or eliminate the influence of high breech voltage on the discharge efficiency of the CPPS.
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