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

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INTRODUCTION

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. 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 analysed 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 calibre augmented railgun, the launching simulation and test were completed, and the analysis was verified.

Equivalent Circuit of Launching System

The launching process of the railgun powered by the CPPS can be equivalent to the lumped element circuit shown in Figure1. The working current is:

$$i_g(t)=\sum_{k=1}^{n} i_k(t) \quad (1)$$

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

$$u_g=(L_0+L_r'x)\frac{di_g}{dt}+(R_0+R_r'x)i_g+L_r'vi_g \quad (2)$$

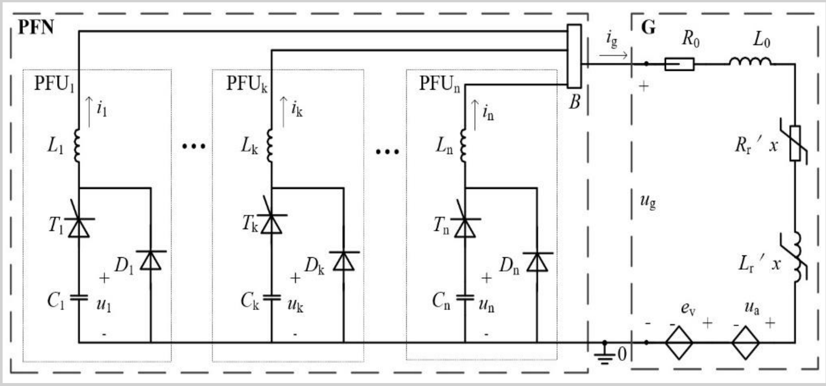

Fig. 1 Lumped-element circuit of railgun system

Breech voltage's influence on pulsed discharge characteristics of CPPS

■ Ideal working current and its realization

The ideal working current for railgun 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 Figure2.

1) Rising phase T_F : $di_g/dt>0$ its duration is t_F.

2) Stable phase T_P: $di_g/dt=0$ Its duration is t_P.

3) Decreasing phase T_D: $di_g/dt<0$ its duration is t_D.

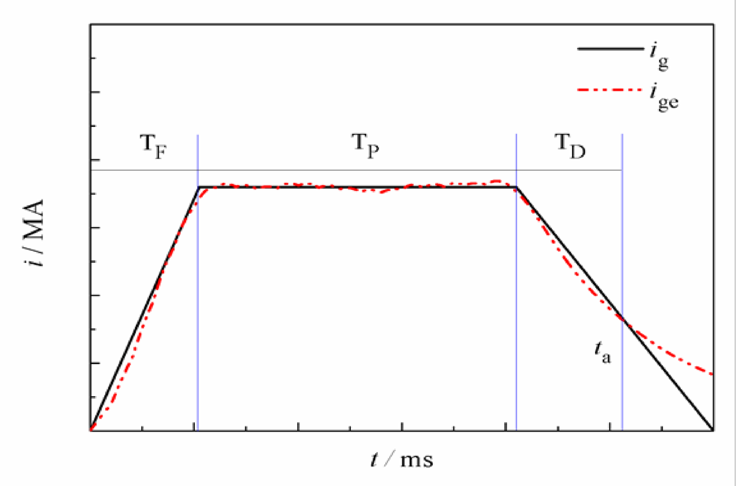

Fig.2 Ideal working current and its three pahses

In Figure2, t_a is the moment when the armaturee 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. Under the normal design of the PFN, the following inequality holds:

$$f>\frac{1}{2t_F},\quad f>\frac{1}{2t_P},\quad f>\frac{1}{2t_D} \quad (3)$$

In the inequality(3), f is the resonance frequency of the PFU's *RLC* circuit. The inequality (3) shows that if the PFU was triggered at the beginning of T_F (or T_P, or T_D), its discharge process would be ended in this pahse 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:

$$i_k(t)\ll i_g(t) \quad (4)$$

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.

■ Characteristics of Breech Voltage

The simple railgun has 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} H, and that of R_0 is about 10^{-4}~10^{-3} Ω. Under the condition that the rail size is similar, L_r' 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:

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

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 breach voltage of the simple railgun is relatively small and close to zero; b) R_0 and L_0 are large, so the breach 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:

$$u_g\approx(R_0+R_r'x)i_g+L_r'vi_g \quad (6)$$

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 breach 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 breach voltage of the augmented railgun is usually much smaller than that in the rising phase, but because of the larger R_0 and L_r ', the breach 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:

$$u_g\approx-(L_0+L_r'x)\left|\frac{di_g}{dt}\right|+(R_0+R_r'x)i_g+L_r'vi_g \quad (7)$$

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 di_g/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, 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. 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.

■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_k (as shown in Figure1), 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_g, so according to the Substitution Theorem in circuit, u_g 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 PFU_k under the action of u_k and ug respectively, then the output current of the PFU_k is:

$$i_k(t)=i_{k1}(t)+i_{k2}(t) \quad (8)$$

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, ik and di_k/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_k:

$$L\frac{di_k(t)}{dt}+R_e i_k(t)+u_g>0 \quad (9)$$

Inequality (9) means that D_k alway operates in shutdown mode during the discharge of the PFU_k. When i_k 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 Ck wasteful. That is to say, the phenomenon that the PFU_k 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 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 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.

Simulation and test of augmented railgun system

■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. The launching simulation and test were carried out to verify the conclusion using a medium calibre augmented railgun system. 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 10kV, 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 2000m /s.

Table.1 Main technical parameters of augmented railgun

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

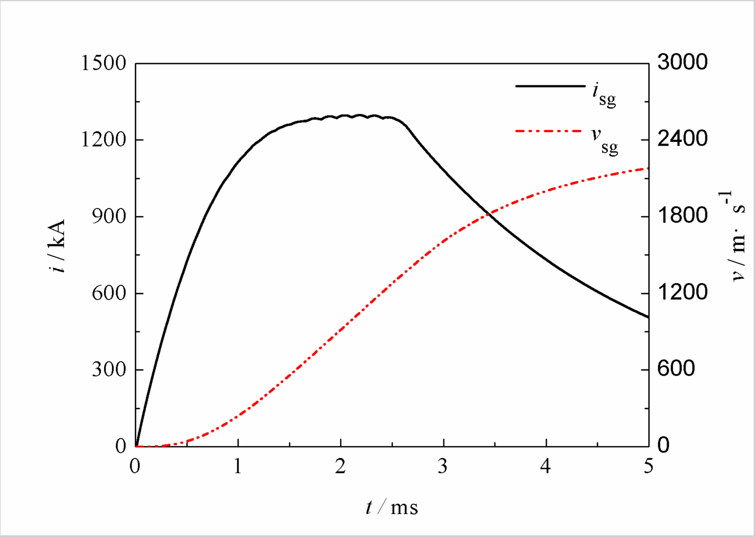

Fig.3 Simulation working current and simulation velocity of armature

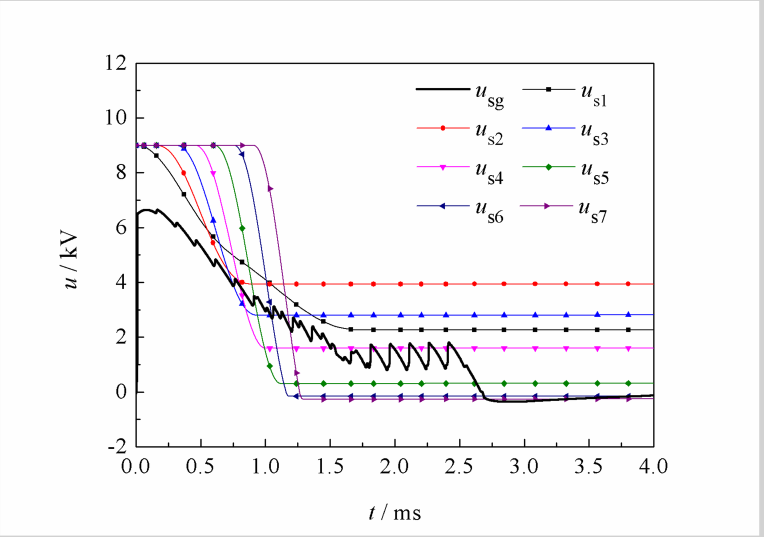

Fig.4 Simulation waveforms of breech voltage and pulsed capacitor voltage

The simulation results show that: a) The maximum value of the breech voltage in the rising phase is about 6.64kV; b) 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; c) 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.

■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. 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, Obviously, the experimental results support the conclusions.

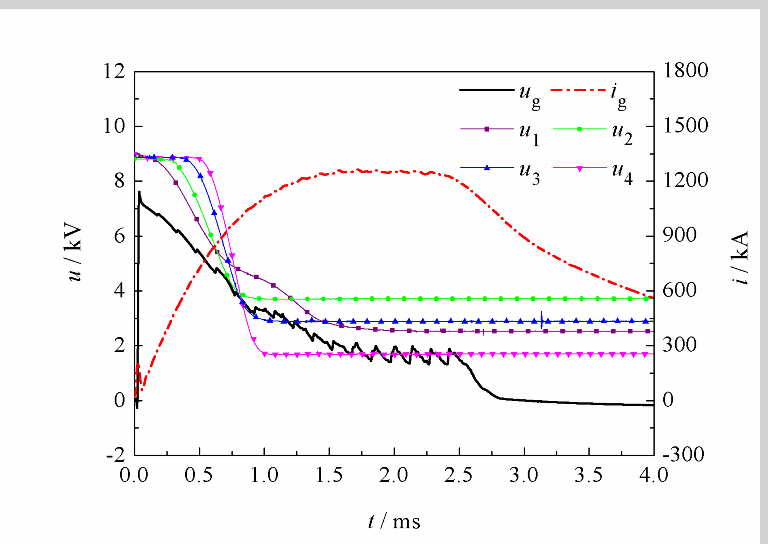

Fig.5 Measured waveforms of breech voltage and pulsed capacitor voltage

CONCLUSION

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.

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