Fault Mechanism and Improvement in the Augmented Railgun Excitation Circuit

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Abstract: The augmented electromagnetic railgun has demonstrated more potent electromagnetic force, a low excitation current, and less rail thermal damage, showing good potential in heavy load launch. However, the augmented railgun’s load characteristics differ from the conventional double-rail railgun. In the augmented railgun launching experiment, it was found that the fly-wheel diode was damaged, and the capacitive power supply could not discharge fully, which led to residual energy and lower energy utilization. This paper began with the characteristics of the sequential trigger circuit, followed by the causes of the above faults, as well as the corresponding solutions. Based on the conventional excitation circuit, fault detection experiments were carried out first, and the fault mechanism was clarified. Furthermore, according to the solutions proposed, the conventional excitation circuit was improved so that it can work normally when a heavy inductance was loaded. Finally, the sequential trigger experiment was carried out again with the same circuit parameters. The research results showed that the fly-wheel diode could work normally after the circuit was improved, and the problem of residual energy could also be solved effectively. Moreover, the output performance was almost unaffected.

Keywords: diode damage; railguns; pulsed power supplies

1. Introduction

Railguns are a new type of electromagnetic launch weapon. The typical simple railgun is composed of two parallel copper rails and a U-shaped aluminum armature, powered by a pulse forming network (PFN) composed of several capacitor pulse forming units [1,2]. When a strong current flows through the track and armature, the generated Lorentz force will drive the armature to accelerate and launch. The PFN system and launch schematic diagram of a railgun is shown in Figure 1.

Figure 1. The PFN system and launch schematic diagram of a railgun.
Different from the simple railgun, an augmented railgun has four or even more rails. It can strengthen the magnetic flux density inside the railgun bore without increasing the excitation current, thus providing a stronger driving force for the armature [3]. Therefore, the augmented railgun is not only a promising technology for launching heavy loads, but can also provide the same driving force with a smaller current, reducing the rail’s thermal damage and prolonging its life span [4,5].

At present, the excitation circuit topology of the augmented railgun is the same as that of the conventional double-rail railgun. Since the augmented railgun uses multiple rails in a series, the inductance of the augmented railgun is considerable, which significantly changes the discharge characteristics of PFN, and even leads to component damage [6]. Li reported the breakdown damage of the fly-wheel diode when the railgun inductance was large. He pointed out that the excessive reversal voltage on the fly-wheel diode was the root cause, and proposed the method of matching circuit parameters to avoid it [7]. Facing the same problem, Liu and Han adopted the fast recovery diode as the fly-wheel diode and added a resistor in parallel to the snubber circuits [8,9]. Jin added an inductor in series with the diode, decreasing the current change rate to suppress the reversal voltage [10]. The principle of the above methods is to limit the reverse voltage of the fly-wheel diode within a safe range. However, this method comes at a cost. The application of additional components not only makes the circuit more complex, but also changes the characteristics of the load current. The biggest deficiency is that the above methods are inflexible. When the load changes, the voltage suppression components must be replaced to limit the diode reverse voltage within a safe range.

Besides the damage to the fly-wheel diode, Li also reported that the electric energy could not be fully utilized when the railgun inductance is large. He pointed out that the high voltage at the tail of the railgun forced the thyristor to shut down prematurely, resulting in residual energy. To solve this problem, he proposed a secondary trigger method to release it [11]. In our experiment, breakdown damage to the fly-wheel diode and the problem of residual energy also occurred. The damaged fly-wheel diode and the voltage of the PFUs after launching are shown in Figure 2.

![Figure 2. Faults in augmented railgun launch experiment. (a) The damaged diode; (b) Residual energy of the power supply.](image)

In order to clarify the fault mechanism and solve the above problems with more general and flexible methods, this paper analyzed the discharge characteristics of the PFN considering the reverse recovery process of the diode. An improvement circuit was developed based on the conventional circuit. Unlike the previous method of suppressing the reverse voltage peak to protect the fly-wheel diode, the improved circuit prevents voltage spikes from occurring fundamentally. It does not add any components, nor does it affect the load current, and it is also suitable for any load. Furthermore, in the solution of residual energy, this paper presented a sequential trigger criterion to achieve the complete release of energy. Finally, the experiment platform was developed, and the verification
tests were carried out. The experimental results showed that the improved circuit could work normally, and the power supply could discharge fully based on the sequential trigger guideline.

2. Study of the Fault Mechanism of the PFN with Inductive Load

Ideally, there is no transition process between the conduction state and the reverse blocking state of the diode. However, when the diode is conductive, many non-equilibrium carriers exist in the base region to store charges. They must be completely stripped or recombined so that the diode can restore the blocking capability. Therefore, when the conducting diode is instantaneously subjected to reversal voltage, the diode will conduct in reverse for a short time [12–15]. During this process, as the diode is almost short-circuited, leading to a significant current change rate, the parasitic inductance and branch stray inductance cannot be ignored because they may cause very high reversal voltage, which is a severe threat to the diode [16,17]. The recovery process of the diode must be fully considered in the fault mechanism analysis.

2.1. Analysis of the PFN Discharge Process

Although the PFN contains many PFUs, the whole discharge process can be regarded as the alternate discharge of adjacent capacitors. It is feasible to describe the discharge characteristics using the circuit model composed of two modules. Therefore, this paper develops a simplified PFN circuit, as well as an analytical model of the discharge process. The PFN circuit model is shown in Figure 3.

![Figure 3. The PFN circuit model includes two PFUs.](image)

In Figure 3, $L_{\text{load}}$ and $R_{\text{load}}$ are the inductance and resistance of the load, and $L_1$ and $R_1$ are the inductance and resistance of the electric reactor. The other symbols, $C_1$, $TH_1$, and $R_{\text{SL}}$, denote the capacitor, the thyristor switch, and the fly-wheel resistor. The components of the two PFUs are identical. The working process of this PFN is as follows: the control system sends the first trigger signal to $TH_1$, and the capacitor $C_1$ begins to discharge. This time is considered as the initial moment 0. After a period of time $\Delta t$, the control system sends the second trigger signal to $TH_2$, and the capacitor $C_2$ begins to discharge. The arrows in Figure 3 indicate the positive direction of the current in every branch, as well as the voltage direction.

The discharge process of PFU can be divided into two stages: the capacitive energy release stage and the fly-wheel stage. The key symbol to distinguish the two stages is whether the capacitor’s voltage reverses, thus a key parameter $t_0$ is introduced to indicate this moment. When PFU1 works in the capacitive energy release stage, the circuit can be regarded as an RLC circuit, and the voltage of the $C_1$ decreases gradually. According to the circuit equations, $t_0$ can be expressed as follows:

$$t_0 = \sqrt{(L_1 + L_{\text{load}})C_1} \tan^{-1}\left(\frac{\sqrt{(1 - d)/d}}{\sqrt{1 - d}}\right)$$  \hspace{1cm} (1)
where the \( d \) can be expressed as follows:

\[
d = \frac{(R_{\text{load}} + R_1)^2 C_1}{4(L_{\text{load}} + L_1)} \tag{2}
\]

According to Equations (1) and (2), the \( t_0 \) will be bigger as the \( L_{\text{load}} \) increases. It will take more time for the capacitor in PFU\(_1\) to discharge fully.

When PFU\(_1\) works in the fly-wheel stage, the voltage of capacitor \( C_1 \) reverses and the fly-wheel diode \( D_1 \) is conducted. The circuit in this stage can be regarded as an RL circuit since the thyristor \( TH_1 \) is turned off, and the output current \( I_{\text{load}} \) can be expressed as follows:

\[
I_{\text{load}} = I_m e^{-\frac{t}{\tau}} \tag{3}
\]

where \( I_m \) is the current intensity at time \( t_0 \). \( \tau \) is the time constant, and it can be expressed as follows:

\[
\tau = \frac{L_{\text{load}} + L_1}{R_{\text{load}} + R_{S1} + R_1} \tag{4}
\]

According to Equation (3), the voltage on the load can be expressed as follows:

\[
U_{\text{load}} = R_{\text{load}} I_{\text{load}} + L_{\text{load}} \frac{dI_{\text{load}}}{dt} \tag{5}
\]

According to Figure 3, the \( D_1 \) branch in the fly-wheel stage only exists if \( U_{\text{load}} \) is greater than 0. Otherwise, the fly-wheel diode \( D_2 \) will be subjected to reversal voltage and conduct ahead of time, which causes PFU\(_1\) and PFU\(_2\) to participate in the fly-wheel stage together. Substituting Equations (3) and (4) into Equation (5), it can be expressed as follows:

\[
U_{\text{load}} = I_{\text{load}} \left[ \frac{R_{\text{load}} L_1 - L_{\text{load}} (R_{S1} + R_1)}{L_{\text{load}} + L_1} \right] \tag{6}
\]

According to Equation (6), whether PFU\(_1\) and PFU\(_2\) participate in the fly-wheel stage together depends on the circuit parameters. Compared with the conventional double-rail railgun, the augmented railgun shows little difference in resistance, but much greater inductance. Therefore, when the augmented railgun is used as the load, the load voltage may be less than 0 according to Equation (6), resulting in a common fly-wheel.

\( TH_2 \) receives a trigger signal after a while (\( \Delta t \)). If \( \Delta t < t_0 \), the PFU\(_2\) will discharge in the energy release stage of PFU\(_1\), and the capacitor \( C_1 \) has not discharged fully at this time. As the voltage of \( C_2 \) is higher than \( C_1 \), the discharge of \( C_1 \) is suppressed, and the output current of \( C_1 \) drops dramatically. According to the working principle of the thyristor, the \( TH_1 \) will recover to the blocking state if the current reverses. Furthermore, the thyristor’s trigger signal is usually an unimodal pulse. It will not open again once the thyristor recovers to the blocking state. Therefore, the residual energy of the capacitor \( C_1 \) cannot be released.

If \( \Delta t > t_0 \), the PFU\(_2\) will discharge in the fly-wheel stage of PFU\(_1\). Due to the great inductance of the augmented railgun, the voltage on the load reverses during the fly-wheel stage, leading to the premature conduction of \( D_2 \). Therefore, the powerful voltage of the capacitor \( C_2 \) will be applied to the conductive diode \( D_2 \) directly when the thyristor is triggered. Ideally, the diode \( D_2 \) will turn off instantly. However, the transition time is unavoidable, during which the diode can be regarded as a good conductor. Therefore, the capacitor \( C_2 \), the diode \( D_2 \), and the fly-wheel resistor \( R_{S2} \) form an RC circuit loop. Since the fly-wheel resistor \( R_{S2} \) is very small and the voltage of capacitor \( C_2 \) is very high, the current change rate and the reverse peak current are enormously significant. Considering the branch stray inductance and the parasitic inductance of the diode, the fly-wheel diode \( D_2 \) will be subjected to strong reversal voltage, which may cause breakdown damage to the fly-wheel diode.
2.2. Experiment Platform and Data Measuring Methods

To verify the analytical model proposed above, a PFN experiment platform consisting of six identical PFUs was developed. The main components of PFU were as follows: a capacitive power supply including six metalized film capacitors (10 kJ/10 kV), a high-voltage and high-power thyristor switch (70 kA/18 kV), a fly-wheel diode composed of four fast recovery diodes (70 kA/20 kV), a wave modulator embed by epoxy resin, and an inductive load which was used to simulate the augmented railgun. The experiment platform and the components are shown in Figure 4. The specific circuit parameters of the experiment platform are shown in Table 1.

![Figure 4. The PFN experiment platform. (a) Overall sight of the experiment platform; (b) Fly-wheel diode; (c) Inductive load; (d) Capacitive pulsed power supply; (e) Thyristor switch; (f) Wave modulator.](image)

Table 1. The specific circuit parameters of the experiment platform.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{load}$</td>
<td>Load resistance</td>
<td>17 mΩ</td>
</tr>
<tr>
<td>$L_{load}$</td>
<td>Load inductance</td>
<td>530 uH</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Resistance of the current wave modulator</td>
<td>2 mΩ</td>
</tr>
<tr>
<td>$L_i$</td>
<td>Inductance of the current wave modulator</td>
<td>20 uH</td>
</tr>
<tr>
<td>$C_i$</td>
<td>Capacitance</td>
<td>2 mF</td>
</tr>
<tr>
<td>$R_{S_j}$</td>
<td>Fly-wheel resistance</td>
<td>2 mΩ</td>
</tr>
<tr>
<td>$u_0$</td>
<td>Initial charging voltage of PFU</td>
<td>2000 V</td>
</tr>
</tbody>
</table>

According to Figure 3, two PFUs were sufficient to verify the fault mechanism, thus only two PFUs were used in the fault mechanism verification test. The current and voltage can describe the discharge process most intuitively, so they are mainly collected in the experiment. Since the current and the voltage were powerful, the Rogowski Current Coil (100 kA) and the High Voltage Differential Probe were applied (3 kV). The schematic diagram of the testing system is shown in Figure 5.

As shown in Figure 5, to avoid confusion, only the partial data measuring method and equipment were displayed in a single PFN. However, the data measuring method and equipment were identical in the corresponding location of another module. The voltage of thyristor $TH_i$ and fly-wheel diode $D_j$ were directly measured using the High Voltage Scoring Probe. The current flowing through the capacitor $C_i$ and the load were also directly
measured using the Rogowski Current Coil. After obtaining the current data, the voltage of the capacitor and the load can be calculated as follows:

\[ U_c = U_0 - \frac{1}{C_1} \int_0^t I_c(t) \, dt \]  \hspace{1cm} (7)

\[ U_{load} = I_{load}R_{load} + L_{load} \frac{dI_{load}}{dt} \]  \hspace{1cm} (8)

Figure 5. The schematic diagram of the testing system.

2.3. Acquisition and Analysis of the Experimental Data

The mechanism of the residual energy proposed in Section 2.1 is verified first. According to Table 1 and Equation (3), \( t_0 \) could be calculated as 1.6 ms, so \( \Delta t \) was set to 1 ms, which indicated that the PFU_2 was triggered when the PFU_1 was in the capacitive energy release stage. The current and voltage data measured in the experiment are shown in Figure 6.

![Schematic diagram of the testing system](image)

Figure 6. Current waveform and voltage waveform when \( \Delta t \) was 1 ms.

According to Figure 6, PFU_1 was in the capacitive energy release stage, and the voltage of PFU_1 was still 1170 V when the time was 1 ms. However, the output current of capacitor \( C_1 \) decreased significantly and dropped to less than 0 slightly as the PFU_2 was triggered. The thyristor was also turned off under the reverse current. Since the process from the
PFU₂’s triggering to the TH₁’s blocking lasted about 60 ms, the energy released by capacitor $C_1$ was very little, thus the voltage of capacitor $C_1$ decreased slightly. In addition, the thyristor TH₁ no longer received the trigger signal even if the voltage of TH₁ became positive, and it could not recover to the conduction state. Therefore, the voltage of capacitor $C_1$ was maintained at 1160 V, and the residual energy of 1345.6 J could not be released.

Based on Table 1 and Equation (6), it could be calculated that the load voltage would be reversed during the fly-wheel stage. Therefore, $\Delta t$ was set as 3 ms, which indicated that the PFU₂ was triggered when PFU₁ was in the fly-wheel stage. The current and voltage waveforms measured in the experiment are shown in Figure 7.

![Figure 7. Current waveform and voltage waveform collected when $\Delta t$ was 3 ms.](image)

According to Figure 7, in the fly-wheel stage, the load voltage was negative, and the voltage of the fly-wheel diode $D_2$ was positive, which indicated that it was conducted in advance. This was also confirmed by the current-$D_2$ waveform, which increased to 340 A during the fly-wheel stage. The PFU₂ was triggered when the time was 3 ms. The current flowing through $D_2$ increased in reverse significantly, reaching 20 kA. According to the analysis in the above sections, this resulted from the short-circuit discharging of capacitor $C_2$ and fly-wheel branch $D_2$. Besides, the voltage of the fly-wheel diode $D_2$ also increased considerably in reverse and was up to 5.3 kV, far exceeding the initial charging voltage of the PFU. The peak voltage occurred at the beginning of the diode reverse recovery, which is caused by significant current change rate, parasitic inductance, and branch inductance. Although the reversal voltage of 5.3 kV was less than the diode’s breakdown voltage of 20 kV, the initial charging voltage of the PFU was only 2 kV, which was far lower than the actual charging voltage of the practical augmented railgun. According to the experimental results, the root cause of the damage of the fly-wheel diode was premature conduction, which led to a dangerous current change rate and reversal voltage.
3. Improvement in the Excitation Circuit

Based on the conventional railgun excitation circuit, solutions for fly-wheel diode damage have been proposed by many researchers. According to Equation (6), Li increased the inductance of the electric reactor to prevent the load voltage from reversing [7]. Other researchers adopted a fast recovery fly-wheel diode. With shorter reverse recovery time, the reverse peak current and the reverse peak voltage were smaller [8,9]. However, the above methods are all based on the current circuit. Changing the circuit parameters or adopting more advanced components is inevitable. For different augmented railgun loads and high-energy augmented railgun launching, these methods are not easy to implement. Therefore, in order to propose a more robust solution, the current excitation circuit is improved and the verification test is carried out.

3.1. Solution of the Fly-Wheel Diode Damage

According to the above analysis, premature conduction is the fundamental reason for fly-wheel diode damage. Therefore, the purpose of circuit improvement is to prevent the fly-wheel branch from common fly-wheel. The excitation circuit is redesigned based on the above principle. The improved excitation circuit is shown in Figure 8.

![Figure 8. The improved excitation circuit.](image)

As shown in Figure 8, the fly-wheel branch and the capacitor are paralleled directly, and the thyristor is moved behind the fly-wheel branch. Through the above improvement, whether the fly-wheel diode is conducted only depends on the voltage of the paralleled capacitor. Therefore, the fly-wheel diode \(D_2\) maintains a blocking state when the PFU_1 is in the fly-wheel stage, and premature conduction is avoided since the voltage of capacitor \(C_2\) is positive. Besides the above advantage, the thyristor can completely isolate all PFUs. When the PFU_2 is in the capacitive energy release stage, the current flowing through \(TH_1\) will decrease rapidly, and the thyristor \(TH_1\) will restore the blocking capability. Therefore, when the PFU_2 is in the fly-wheel stage, the fly-wheel branch in the PFU_1 cannot form a loop with the load. The common fly-wheel is thoroughly avoided.

3.2. Verification Test of the Improved Excitation Circuit

The experiment platform was developed again, based on the circuit in Figure 8. When the PFU_1 was in the capacitive energy release stage, the circuit was still an RLC circuit and \(t_0\) was still 1.6 ms. First, the performance of the fly-wheel diode was verified under the improvement circuit. We set \(\Delta t\) to 3 ms, indicating that the PFU_2 was triggered when the PFU_1 was in the fly-wheel stage. The other circuit parameters remained unchanged. The current and voltage waveforms collected in the experiment are shown in Figure 9.

As shown in Figure 9, the voltage of \(D_2\) was almost \(-2000\) V before the PFU_2 was triggered \((t < 3\) ms\), indicating that the fly-wheel diode \(D_2\) was always blocked. Different from the unimproved excitation circuit, since the \(TH_2\) had not received the trigger signal, the \(D_2\) could not be turned on even if the load voltage reversed. After the PFU_2 was triggered, the current flowing through \(TH_1\) decreased rapidly and dropped to zero, indicating that the thyristor \(TH_1\) was turned off. Therefore, the PFU_1 would no longer participate in the circuit discharge process. Furthermore, the voltage of \(D_2\) decreased gradually, which was
consistent with the voltage of $C_2$. The voltage of $D_2$ was almost 0 V, and the current flowing through $TH_1$ was 0 A when the PFU$_2$ was in the fly-wheel stage. This showed that the $D_2$ fly-wheel branch only existed in this stage; the common fly-wheel was avoided.

![Figure 9](image.png)

**Figure 9.** Current waveform and voltage waveform collected in the experiment.

Furthermore, this paper compared the output performance before and after the circuit improvement. The comparison result of the load current is shown in Figure 10.

![Figure 10](image.png)

**Figure 10.** Load current comparison result before and after the circuit improvement.

According to Figure 10, the load current waveform was almost the same before and after the circuit improvement, except for the slightly faster current drop in the fly-wheel stage. This is because the $D_1$ and $D_2$ branches were paralleled in the fly-wheel stage before the circuit was improved, resulting in a smaller total impedance. There only existed one
fly-wheel branch after the circuit was improved, thus leading to a larger impedance. As a result, the current decreased faster in the fly-wheel stage.

According to the experimental results, the improved circuit can prevent the diode from conducting prematurely, as well as the common fly-wheel by isolating all the PFUs. The current flowing through $D_2$ would not reverse, and the reversal voltage of $D_2$ would not exceed the voltage of $C_2$. The reliability of the circuit was greatly improved. Since the circuit parameter matching need not be considered when using different loads in the improved circuit, this method was more robust and did not change the output performance.

3.3. Solution of the Residual Capacitive Energy

According to the above research, if the latter PFU is triggered when the former PFU is in the capacitive energy release stage, the thyristor switch in the former PFU will be turned off, leading to residual energy. Since it takes longer for the PFU to discharge completely when the inductance of the load is heavy, this problem is more evident in the application of the augmented railgun. Li proposed the secondary trigger method to solve this problem [7]. He sent a trigger signal to PFUs with residual energy again after the last PFU was fully discharged. Indeed, the excitation current of the railgun is generally adjusted to the approximate square waveform to accelerate the armature stably. The flat-top current is formed by many continuous current pulses [18]. The typical excitation waveform of the railgun is shown in Figure 11.

![Figure 11. Typical excitation current waveform of railgun.](image)

As shown in Figure 11, the discharge of each PFU will ideally generate a current pulse. The current increases in the capacitive energy release stage and decreases in the fly-wheel stage. The capacitive energy is fully released when the current increases to the extreme. Therefore, it is crucial to set an appropriate trigger sequence so that each PFU can discharge completely to form a pulse. Otherwise, the flat-top current cannot be formed.

Therefore, a PFN circuit including six PFUs was developed based on the improved circuit, and the experiments were carried out under two trigger sequences. One was the tight trigger sequence, and another was the loose trigger sequence. The trigger sequences are shown in Table 2. The current and voltage waveforms measured in the experiment are shown in Figures 12 and 13.

According to Figure 12, the voltage of the first four PFUs did not drop to zero in the tight trigger experiment. The voltage of the PFU$_1$ and PFU$_2$ was about 1160 V, and the voltage of the PFU$_3$ and PFU$_4$ was about 430 V. Furthermore, since the PFU$_1$ and PFU$_2$ were in the capacitive energy stage when the PFU$_3$ and PFU$_4$ were triggered, there was no current extreme nor a complete current pulse. The same process also happened after the
PFU₅ and PFU₆ were triggered. The load current in the tight trigger experiment did not meet the requirements of the excitation current of the railgun.

According to Figure 13, the voltage of all PFUs dropped to zero in the loose trigger experiment, indicating that all the capacitive energy had been released. Furthermore, since the latter group of the PFU discharged in the fly-wheel stage of the former group of the PFU, the complete current pulse was generated, which was beneficial in forming the flat-top current.

Table 2. The trigger sequence adopted in the experiment.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Charging Voltage</th>
<th>Trigger Sequence in Tight Trigger Experiment</th>
<th>Trigger Sequence in Loose Trigger Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFU₁</td>
<td>2000 V</td>
<td>0 ms</td>
<td>0 ms</td>
</tr>
<tr>
<td>PFU₂</td>
<td>2000 V</td>
<td>0 ms</td>
<td>0 ms</td>
</tr>
<tr>
<td>PFU₃</td>
<td>2000 V</td>
<td>1 ms</td>
<td>3 ms</td>
</tr>
<tr>
<td>PFU₄</td>
<td>2000 V</td>
<td>1 ms</td>
<td>3 ms</td>
</tr>
<tr>
<td>PFU₅</td>
<td>2000 V</td>
<td>1.8 ms</td>
<td>5 ms</td>
</tr>
<tr>
<td>PFU₆</td>
<td>2000 V</td>
<td>1.8 ms</td>
<td>5 ms</td>
</tr>
</tbody>
</table>

Figure 12. Experimental data in tight trigger experiment.

Figure 13. Experimental data in loose trigger experiment.
According to the above analysis, the problem of the residual capacitive energy only occurs under the tight trigger sequence. It can be easily avoided by loosening the trigger sequence. Previous researchers proposed many optimization methods for the trigger sequence of the railgun [19–21]. They all show the characteristics of the loose trigger criterion, and that the problem of residual capacitive energy does not occur.

3.4. Launch Experiment of the Augmented Railgun Conducted on the Improved Circuit

To ensure the effectiveness of the improved circuit when applied to the augmented railgun, the launch experiment was also conducted. In the experiment, the number of PFUs is expanded to nine, and they are charged to 7000 V, which caused damage in the previous experiment, providing a more convincing result in terms of the effectiveness of the improved circuit. The augmented railgun applied in the experiment is shown in Figure 14. The power supply current and voltage measured after the launch experiment are shown in Figure 15.

![Figure 14. The augmented railgun.](image1)

![Figure 15. The current measured and voltage of the power supply after the launch experiment.](image2)

As shown in Figure 15, the pulsed power supply discharged sequentially, leading to the breakdown of the fly-wheel diode in the previous experiment. However, the pulsed power supply can work normally in these experiments by improving the circuit. The current waveform is smooth and up to 171.45 kA. The results show the effectiveness of the improved circuit. Furthermore, the voltage after the launch experiment also proves that loosening the trigger sequence is an effective solution for the residual energy. By simply preventing the latter power supply from being triggered before the energy of the former power supply is completely released, residual energy will not occur.
4. Conclusions

In view of the practical problems in the application of the augmented railgun, this paper mainly studies the fault mechanism of the fly-wheel diode and the causes of the residual capacitive energy, as well as the solutions. The above problems are clarified through theoretical analysis and experimental verification, and the solutions are proven to be effective. Our research conclusions are as follows:

(1) Premature conduction is the fundamental cause of fly-wheel diode damage. Since the inductance of the augmented railgun is heavy, the load voltage will reverse in the fly-wheel stage, causing the premature conduction of the fly-wheel diode. Once the latter PFU is triggered, the conductive fly-wheel diode will be short-circuited to the capacitor and subjected to a dangerous current change rate and reversal voltage, resulting in its damage.

(2) Tight trigger is the root cause of residual capacitive energy. This problem will occur when the latter PFU is triggered in the capacitive energy release stage of the former PFU. Therefore, loosening the trigger sequence is an effective solution. Furthermore, this method is favorable for forming the square current waveform.

(3) The improved excitation circuit can prevent the fly-wheel diode from damage. By isolating each PFU, the premature conduction of the fly-wheel diode does not occur even if the load voltage is reversed. Moreover, there is little influence on the output current characteristic when the improved excitation circuit is adopted. Compared with the present augmented railgun excitation circuit, the improved excitation circuit is more robust.

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References


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