Research on Discharge Timing Control of Multi-Parameter Pulse Forming Network

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Abstract. To solve the complicated timing control caused by the mixed-use of multi-generation pulse power sources in the system, a timing trigger control system with a PID controller was designed. According to the nonlinear characteristics of the armature state during the launch process, the circuit model and the dynamic model of the electromagnetic launch system were established, and the PID controller and command processing and distribution system were designed. The results showed that the PID controller can precisely control the discharge timing of the multi-parameter pulse power module so that the armature acceleration can precisely track the set value.

1. Introduction

The launch speed of the solid armature electromagnetic launch system (EML) can reach 2-3km/s, which has great application potential in the military field [1]. The pulse shaping network (PFN) is an essential component that provides electrical energy to the electromagnetic launch device and plays the functions of energy compression and energy output.

The PFN is composed of multiple pulse power source modules (PPSs) according to a specific topology. Its working mode is that the PPSs trigger in sequence according to a certain timing. Therefore, in addition to the self-capacitance, resistance, inductance, and other parameters of the PPS, the trigger timing is also an essential factor. At the same time, to balance the force of the armature as much as possible, reduce the phenomenon of ablation in the bore, improve the launch efficiency, and control the muzzle velocity, it is expected that the discharge timing of the PFN can be easily controlled. Therefore, it is of considerable significance to study the trigger timing of the PPSs in the PFN.

At present, the trigger timing setting of the pulse power source module can be divided into the offline setting and the online control methods. Offline setting can be divided into the manual simulation and optimized design. Manual simulation refers to establishing the launching system model through virtual simulation software [2,3], observing the current waveform through the oscilloscope of the software, adjusting the trigger time of each pulse power source module multiple times, and obtaining the desired current waveform. The manual simulation requires high modelling accuracy, and the cumbersomeness of adjustment increases as the number of modules increases. The optimized design uses genetic algorithms, particle swarm optimization, and other optimization algorithms to optimize the discharge timing to achieve the purpose of the most stable current waveform, the maximum projectile initial velocity, and the highest launch efficiency [4,5], etc. This series of methods can automatically obtain the power module trigger timing of the desired current amplitude. Still, the
algorithm has high complexity and long calculation time, and it is easy to fall into the local optimal value. In terms of online control, the DSP-based PPSs trigger system outputs a current waveform by detecting the PFN, and when the current is less than a set value, it triggers the next PPS or several [6]. This method achieves control of the current waveform to produce a flat-topped current waveform. Still, there is a lack of research on the control of severely nonlinear launch systems and non-constant value current waveforms. The above-mentioned various timing control methods are all aimed at a single parameter PFN, and there is a lack of research on a PFN containing multiple parameters.

The research work in this paper establishes a simulation program for an electromagnetic emission system consisting of 20 PPSs with two parameters. A multi-parameter PPS trigger control system based on PID control is designed for this system. Verify the acceleration tracking effectiveness of the system under different expected accelerations.

2. Theoretical model of the PFN

2.1. structure of PFN
The pulse shaping network (PFN) of the electromagnetic launch system is composed of multiple pulse power source modules networked according to a certain topology. At present, the commonly used energy storage element of the electromagnetic emission system is capacitors. A PPS is mainly composed of the energy storage capacitor, silicon controlled rectifier (SCR), wave modulation inductor, freewheeling diode, and other parts. A PPS is also attached with auxiliary sub-modules such as sensors and control modules.

With the update of the test system and the increase of the kinetic energy requirements of the launch system, the multi-generation pulse power source module working together is a cost-effective method.

Figure 1 is a schematic diagram of the PFN of the multi-parameter power modules used in this experiment. The total number of type A and type B modules is 20. The capacity of the type A module is higher than the type B module. Group A contains only type A modules, which work in a synchronized trigger state. Group B is made up of type A and type B modules arranged alternately, and the group of modules works in the sequential triggering state. Group C is the remaining pulse power source modules. This time the remaining modules set as type A modules. Modules connect to the load in parallel.
Figure 1. Schematic diagram of the pulse forming network.

2.2. Working characteristics of PPS

The working model of the PFN is divided into synchronous triggering and sequential triggering. Synchronous triggering is to meet the high current requirements of the first discharge of the pulse forming network, and multiple PPSs are triggered at the same time. The number of trigger modules \( n \) is calculated by equation (1-3) [7].

\[
\hat{I} = \frac{\arctan \left( 2\omega \left( \frac{L_n}{n} + L_r \right) \left( \frac{R_n}{n} + R_l \right) \right)}{\omega} \tag{1} \]

\[
\omega = \left( \frac{L_n}{n} + L_r \right) \cdot C \cdot n - \frac{\left( \frac{R_n}{n} + R_l \right)^2}{4 \left( \frac{L_n}{n} + L_r \right)^2} \frac{1}{2} \tag{2} \]

\[
\hat{I} = \frac{U}{\omega \left( \frac{L_n}{n} + L_r \right)} \sin \left( \omega \cdot \hat{t} \right) \cdot e^{-\frac{1}{2} \left( \frac{R_n}{n} + R_l \right) \left( \frac{L_n}{n} + L_r \right) \left( \frac{R_n}{n} + R_l \right)} \tag{3} \]

Where \( L_n \) is the inductance value of wave modulation inductance, \( L_r \) is the inductance value of electromagnetic railgun, \( R_n \) is the resistance of the pulse power source module, \( R_l \) is the resistance value of electromagnetic railgun, \( C \) is the capacitance value of energy storage capacitor, \( \hat{I} \) is the peak value of the synchronous discharge current of the type A module.

The sequential triggering is that the pulse power source module is triggered sequentially at a specific time interval. This mode mainly works after the output current of the pulse shaping network reaches the set current value. The purpose is to track the set value of the controlled objectives, such as current and acceleration.

Figure 2. Circuit model of pulse power supply.

The working characteristics of the pulse shaping network are very complicated because the discharge state of each module is determined by the working state of the SCR and freewheeling diode [8]. Figure 2 shows the circuit model of a single pulse power source module. In figure 2, RL and LL are the resistance and inductance of the wave modulation inductance, \( R_c \), \( U_c \), and \( C \) are the storage capacitor resistance, voltage, and capacitance, \( R_b \) and \( L_b \) are the resistance and inductance of the cable, \( R_s \) is the resistance of the SCR, \( R_o \) is the resistance value of the freewheeling diode and \( U_{ao} \) is the voltage value across the rail.

The operating characteristics of a single pulse power source module can be expressed as
\[
\left\{(L_e + L_n) \frac{di}{dt} + (R_e + R_n) i_n + (R_e + R_h) i_n + \left( \int \frac{1}{C} \, di \, dt \right) \varepsilon(t - t_n) \right\} = -U_{ao} \varepsilon(t - t_n) \quad U_i > 0
\]
\[
\left\{(L_e + L_n) \frac{di}{dt} + (R_e + R_h) + R_s i_n = -U_{ao} \varepsilon(t - t_n) \right\} \quad U_i \leq 0
\]

\* MERGEFORMAT (4)

Where \( i_n \) is the current in the \( n \)th module and \( \varepsilon(t - t_n) \) is the unit step function.

Therefore, the output current \( i \) of the pulse forming network is
\[
i = \sum_{j=1}^{n} i_j \quad \* MERGEFORMAT (5)
\]

### 3. Dynamic process modelling of electromagnetic railgun

In order to simulate an electromagnetic rail gun system, the dynamic process of the electromagnetic rail gun was modelled. During the launch of the electromagnetic rail gun, various parameters will change with the movement of the armature, and the influence of these parameters on the current waveform cannot be ignored. The circuit model and the dynamic model of the load is established below.

#### 3.1. Load circuit model

![Figure 3. Circuit model of an electromagnetic rail gun.](image)

Figure 3 shows the load circuit model of the electromagnetic rail gun launcher, where \( L_r \) is the track inductance, \( R_r \) is the track resistance value, \( R_{\text{vesc}} \) is the contact resistance between the armature and the track, \( R_a \) is the armature resistance, \( R_c \) is additional contact resistance, and \( R_0 \) represents the spurious parameter of the cable line. The load circuit model is expressed as

\[
U_{ao} = (R_r + R_a + R_{\text{vesc}} + R_0) i + L_r \frac{di}{dt} + L_v i v
\]

\* MERGEFORMAT (6)

Where \( i \) is the circuit flow value, and \( v \) is the armature movement speed.

The track resistance \( R_r \) can be described as [9]
\[
R_r = R_{r0} + R_e x
\]
\* MERGEFORMAT (7)

\[
R_e = \frac{8}{3h_e} \sqrt{\frac{\pi \rho \mu_{r0}}{2t}}
\]
\* MERGEFORMAT (8)

\[
\rho_r = \rho_{r0} + \beta_r \frac{i}{h_e}
\]
\* MERGEFORMAT (9)

Where \( R_{r0} \) is the initial resistance value of the track, \( R_e \) is the track resistance value per unit length, \( x \) is the armature displacement length, \( t \) is the energizing time, \( \rho_r \) is the instantaneous resistivity, \( \mu_{r0} \) is the track permeability, \( h_e \) is the track thickness, \( \rho_{r0} \) is the initial resistivity of the track, \( \beta_r \) is the thermal effect constant of resistivity. From equation (7–9), it can be seen that due to the existence of the current skin effect, the value of \( R_e \) is related to the working time \( t \), the instantaneous resistivity \( \rho_r \),
the track permeability $\mu_0$ and other factors.

The rail inductance $L_r$ can be described as

$$L_r = L_{r0} + L_r x$$  \hspace{1cm} \text{MERGEFORMAT (10)}$$

Where $L_{r0}$ is the initial inductance value of the track, $L_r$ is the gradient of the track inductance.

$R_{\text{vec}}$ produced by the speed skin effect can be described as [10,11]

$$R_{\text{vec}} = R_{\text{vec}} v^2$$  \hspace{1cm} \text{MERGEFORMAT (11)}$$

where $R_{\text{vec}}$ is a proportional coefficient, usually in the range of $1 \times 10^{-9}$ to $2 \times 10^{-9}$.

During the launch, the contact between the armature and the track is a non-ideal electrical contact. When the current passes through the contact area, the actual contact point will form a contraction effect, resulting in contact resistance. The following formula is commonly used to estimate the contact resistance $R_c$.

$$R_c = \frac{k}{(0.102 F_c)^n}$$  \hspace{1cm} \text{MERGEFORMAT (12)}$$

Where $k$ is a constant related to the material. For copper-aluminum materials, $k$ is usually taken as 0.98, $m$ is often taken as 1, and $F_c$ is the contact force between the track and the armature.

3.2. Load dynamics modelling

During the launching process of the electromagnetic railgun, the armature will receive Lorentz force $F_p$, air resistance $F_u$, and friction force $F_f$. According to Newton's second law, we have the following formula

$$ma = F_p - F_f - F_u$$  \hspace{1cm} \text{MERGEFORMAT (13)}$$

Where $m$ is the armature mass.

Lorentz force $F_p$ can be described as

$$F_p = \frac{1}{2} L_r i^2$$  \hspace{1cm} \text{MERGEFORMAT (14)}$$

Air resistance $F_u$ can be described as [12]

$$F_u = c_{p1} \rho_0 2 A v_x x \left( \frac{x}{2} \right) + c_{p2} A v_x x$$  \hspace{1cm} \text{MERGEFORMAT (15)}$$

Where $\gamma$ is the specific heat of the air in front of the armature, $\rho_0$ is the density of the air in front, $A$ is the sectional area of the armature, $a$ is the acceleration of the armature, $c_{p1}$ is the viscosity coefficient of the air, and $P$ is the length of the contact surface between the rail and the armature.

The friction force $F$ can be described as [13]

$$F_f = \mu F_c$$  \hspace{1cm} \text{MERGEFORMAT (16)}$$

$$F_c = F_0 + F_e$$  \hspace{1cm} \text{MERGEFORMAT (17)}$$

$$F_e = K_e j^2$$  \hspace{1cm} \text{MERGEFORMAT (18)}$$

$$K_e = \frac{1}{3} \frac{L_e}{d}$$  \hspace{1cm} \text{MERGEFORMAT (19)}$$

Where $\mu$ is the friction coefficient, $F_0$ is the structural force caused by the deformation of armature tail during the loading stage, $F_e$ is the normal electromagnetic force during the armature launching process, $L_e$ is the length of armature tail, and $d$ is the armature width.

To make the armature get as much thrust as possible in the early stage of the launch and reduce the start delay, the armature usually chooses the initial position at four times the caliber position, which is recorded as $x_0$, so the displacement formula of the armature relative to the gun tail can be expressed as
\[ x = x_0 + \int_0^t \dot{x} \, dt = x_0 + \int_0^t adt \, \tau \]  
\[ \text{\* MERGEFORMAT (20)} \]

4. Control system

4.1. PID controller

The controllers based on proportional, integral, and derivative are simply called PID controllers. PID controllers occupy a dominant position in industrial process control. The core idea of PID control is to determine the control strategy by the error between the control target and the actual behavior. The schematic diagram of a conventional PID control system is shown in figure 4, where \( R \) is the set value, \( y \) is the system output, \( u \) is the controller output, and \( e \) is the error.

![PID control system schematic diagram](image)

**Figure 4.** PID control system schematic diagram.

The input value of the PID controller is the difference between the set value \( a_d(t) \) and the actual system output value \( a(t) \)

\[ e(t) = a(t) - a_d(t) \]  
\[ \text{\* MERGEFORMAT (21)} \]

The ideal algorithm of the PID controller is

\[ u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int_0^t e(t) \, dt + T_d \frac{de(t)}{dt} \right] \]  
\[ \text{\* MERGEFORMAT (22)} \]

This time the controller selects the square of the output current \( I \) of the pulse shaping network as the controller output variable. The armature acceleration \( a \) is the desired control variable, then the control object model can be described as[14]

\[ a = \frac{1}{2} L_s I - \mu(F_0 + \frac{l L_s}{3d} I) - (\gamma + 1) \rho \left( A v^2 + A x^2 + \frac{1}{2} c_f v^2 x \right) \]  
\[ \text{\* MERGEFORMAT (23)} \]

At the instant, when the electromagnetic rail gun starts to work, there may be a case where the set acceleration value differs greatly from the actual acceleration value. Since the integrator will record a large error at the start, which will affect the subsequent control, the PID controller will only start to control the launch process after the acceleration reaches the set value.
Figure 5. Schematic diagram of the PID control system of an electromagnetic rail gun

Figure 5 is a closed-loop control system of an electromagnetic rail gun based on the PID controller. The control system mainly includes the PID controller, instruction processor, instruction distributor, and so on. The instruction processor is responsible for determining the type of pulse power source according to the actual output current of the pulse shaping network and the output signal of the PID controller. The instruction distributor is used to find the next pulse power source and handle various exceptional situations.

The actual current value output by the pulse shaping network to the electromagnetic track transmitter can be measured by the Rogowski current transformer, but the directly measured current data contains a large amount of noise information [15]. So the current signal needs to be filtered. In this design, the sliding average filtering algorithm is selected, and the calculation formula is as shown in equation (24). The continuous current sampling values are regarded as a queue, and the length of the queue is fixed to \( k \). Each time, a new data \( i_j \) is put into the queue head, and the original data \( i_j \) (first in first out principle) is discarded, and the \( k \) data in the queue are averaged to obtain a new filtering result \( \bar{I} \).

\[
\bar{I} = \frac{i_j + i_{j-1} + \cdots + i_{j-k+1}}{k} \tag{24}
\]

4.2. Instruction processor

Let \( e_i \geq 0 \) and \( \dot{e} \geq 0 \) are state P, \( n_1 < e < m_1 \) and \( n_2 \leq \dot{e} < m_2 \) are state NS, \( e < n_1 \) and \( \dot{e} < n_2 \) are state NB, output ZE means no output, output A means trigger type A module, and output B means trigger B module. \( n_1 \), \( m_1 \), \( n_2 \) and \( m_2 \) are the upper and lower limits. The specific value is set according to the actual control system. The rule design of the control table is shown in Table 1, where the rules are set according to the inference conditions of ‘if A and B then C.’

| \( e \)   | \( \dot{e} \)   | \( \bar{I} \) |
|---------|----------------|-------------|
| NB      | A              | A           | ZE          |
| NS      | B              | B           | ZE          |
| ZE      | ZE             | ZE          | ZE          |
| P       | ZE             | ZE          | ZE          |

**Table 1.** Control table

4.3. Instruction distributor

After obtaining the instruction of the type A module or type B module through the instruction system, the instruction distribution system shown in Figure 6 is used to send the trigger instruction to the type A or type B module of a specific group. The instruction distribution system mainly has the following functions:

1) Synchronous trigger function. Generally, the current value required to reach the set acceleration
of the armature is very high. The energy provided by a single module is insufficient to achieve the set acceleration value, and multiple modules need to be triggered synchronously.

2) Force trigger function. After the synchronous triggering is completed, the acceleration peak value (the acceleration peak value is considered to be reached when $\frac{da}{dt} > 0$ changes to $\frac{da}{dt} \leq 0$) still does not reach the set acceleration value. The forced trigger function is started. Under this function, the untriggered power modules are triggered one by one until the acceleration value reaches the set value.

3) Instruction distribution function. After obtaining valid instructions (only one module is triggered and different from the previous instruction), if the module corresponding to the instruction is not triggered, the module will be triggered, and the used module information will be updated. If all the modules in the group are triggered, the used group information will be updated and the retrieval operation will be repeated from the next group. If there is an untriggered module in the group, but the module corresponding to the instruction has been triggered, the instruction distribution function will jump out.

4) Exceptional circumstances handling function. The purpose is to intervene in special situations. There are currently two exceptional cases

a) The module is not working correctly. After the command is sent, the output current of the module is wrong. Report the module number and enter the forced trigger function.

b) Repeated command. The trigger instruction points to a triggered power module many times, and the current value has a large deviation. Report the module number and enter the forced trigger function.
5. Simulation and verification

This paper uses Matlab / Simulink to build the electromagnetic railgun system model and design the instruction processing and distribution system. The pulse forming network is composed of 20 pulse power source modules. The topology of the pulse power source is shown in figure 1. Some key parameters used in the electrical and dynamic models are shown in table 2.

![Diagram of PID control system](image)

**Figure 6.** Schematic diagram of the PID control system of an electromagnetic rail gun.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $R_{L}/m\Omega$ | 2.4 | $R_{oL}/m\Omega$ | 0.1 |
| $L_{L}/\mu H$ | 20 | $R_{c}/m\Omega$ | 0.11 |
| $R_{e}/m\Omega$ | 1.2 | $R_{w}/(m/s)^{2} \times 10^{-9}\Omega$ | 1.5 |
| $U_{c}/V$ | 10000 | $m/kg$ | 0.5 |
The set acceleration value and the actual acceleration curve are shown in figure 7 and figure 8. When the set value is constant at $1.4 \times 10^6$, Figure 7 is the waveform of armature acceleration and pulse shaping network current output value. When the acceleration setting value is shown in equation 25, Figure 8 is the waveform of the acceleration value of armature and the current output value of the PFN. The maximum positive error, the maximum negative error and the average error of the upper part of the curve of the maximum negative error are selected as the evaluation indexes. Table 3 is the evaluation index of the current effective working waveform tracking set value.

\[
a = 1.8 \times 10^5 - t \times 4 \times 10^5
\]

\* MERGEFORMAT (25)

![Figure 7. Acceleration and current waveform at constant acceleration](image-url)
Figure 8. Acceleration and current curve at decreasing acceleration.

Table 3. Acceleration tracking evaluation index.

| Acceleration waveform     | Average error/A | Maximum positive error/A | Maximum negative error/A |
|---------------------------|-----------------|--------------------------|--------------------------|
| Constant acceleration     | -2.1868×10³     | 3.9654×10⁴               | -6.9384×10⁴              |
| Decreasing acceleration   | 3.2891×10³      | 1.2431×10⁴               | -5.5178×10⁴              |

It can be seen from figure 7-8 that the control system proposed in this paper can accurately control the trigger sequence of the power module to make the armature acceleration track the set value. It can be seen from Table 3 that the maximum value of positive and negative error and the average value of the error of armature acceleration are less than two orders of magnitude of the set value, so it can be considered that the designed control system can effectively control the armature acceleration tracking set value.
6. Conclusion

Aiming at the timing setting and armature acceleration control of the PFN, a trigger control system based on PID control is proposed. The system includes a PID controller, an instruction processing system, an instruction distribution system and other subsystems. By analyzing various physical phenomena during the launching process, the launching process of the electromagnetic launching system is mathematically modelled from the two directions of the load circuit model and load dynamics model.

Simulation proves that the control system proposed in this paper can effectively control the trigger timing of the pulse power source module to ensure that the armature acceleration follows the set value. For the actual device, there are more influencing factors and uncertainties in the launch process. The modelling in this paper is only the theoretical abstraction of the actual device, which cannot fully reflect all physical phenomena and effects. However, the control method proposed in this paper is universal, and it is still applicable when the theoretical model and actual system parameters changed.

All in all, the control system can obtain the trigger timing required for the actual launch in the simulation system. And with the development of sensor technology, this control method can be used for online control systems.

References

[1] Li Baoming and Lin Qinghua. 2018 Defence Technology 14(05) 134-45
[2] Coffo M and Gallant J. 2007 16th IEEE International Pulsed Power Conference. Albuquerque, NM, US:IEEE 1814-17
[3] Xue Fei and Zhang Jiange. 2010 Electrical Engineering. (S1) 16-8
[4] Ma Ping, Hu Yuwei, Yang Ming, Liu ZZ and Wang ZC. 2014 Journal of Ballistics 26(03) 104-10
[5] Hu Yuwei, Ma Ping, Yang Ming, Lu Linyun and Wang Zicai. 2014 Systems Engineering and Electronics 36(07) 1232-37
[6] Hu Nan, Yuan Weiquan, Liu Kun, Ma Jin and Yan Ping. 2020 Advanced Technology of Electrical Engineering and Energy 39(03) 67-73
[7] Zhang Xiao, Lu Junyong, Dai Yufeng, Wu Wenxuan, Wang Xin and Ma Tao. 2019 22nd International Conference on Electrical Machines and Systems (ICEMS). Harbin, China:IEEE 2019 1-4
[8] Hu Yuwei, Ma Ping and Yang Ming, et al. 2012 16th International Symposium on Electromagnetic Launch Technology. Beijing, China:IEEE 2012:1-6
[9] Hu Yuwei. 2014 Research on simulation and performance optimization for electromagnetic railgun Harbin Institute of Technology
[10] Liu Xukun, Yu Xinjie and Liu Xiucheng. 2016 Transactions of china electrotechnical society 31(11) 186-93
[11] Yu Xinjie, Fan Zhaoran. 2011 IEEE Transactions on Plasma Sciences 39(1) 405-10
[12] Rolader G E and Batteh J H. 1991 IEEE Transactions on Magnetics. 27(1) 120-5
[13] Zhou Yuan, Zhang Dongdong, Yan Ping. 2015 IEEE Transactions on Plasma Science 43(5) 1516-22
[14] Ang KH, Chong G and Li Y. 2005 IEEE Transactions on Control Systems Technology 13(4) 559-76
[15] Tian Hui, Xia Yan and Li Baoming. 2014 High voltage Engineering 40 (04) 1153-58