Research on sequential fired 24MJ EML system

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***Abstract*—electromagnetic launch technology is intended to convert electric energy into armature's kinetic energy. To make the armature accelerated smoothly, PFN(pulse forming network) needs to generate a flattop wave by triggered sequentially. The thyristor in PFN is easy damaged under this condition. The thyristor's reverse recovery process is the critical reason for its damage. The paper expounds the thyristor's reverse recovery process and builds a macro model of thyristor describing this process. The thyristor damage reason when triggered in sequence is proposed by theoretical analysis. Assessment about the possibility of increasing the inductance to protect the thyristor has been made. The PSPICE model of a 24MJ EML(electromagnetic launch) system which is made up of PFN model and simplified barrel model is built. After increasing the inductance, the integral performance of the 24MJ EML system is evaluated. The result shows that the properly increasing of inductance can protect the thyristor effectively, and the efficiency of EML system will not significantly decrease at the meantime.**

***Keywords*—EML; thyristor; reverse recovery process; pulse forming inductor; PSPICE**

I. Introduction

The electromagnetic launch technology is one of the most important applications of pulsed power technology. It is the key technology for future long range precision attack. PFN is the channel that transfers the electric energy to the armature. Therefore, PFN(Pulse Forming network) is the research focus of electromagnetic launch technology. To make the muzzle speed of armature agree with design value, PFN is always asked to output high amplitude and flexible current waveform[1]. For EML system, a flattop current waveform is best for the acceleration of armature[2-3]. It means that pulse forming units should be triggered sequentially. Fig.1 shows the schematic diagram in which several PFU(Pulse Forming unit) discharge with load. PFN is triggered as the proposed timing sequence to get an quasi flattop current waveform[4]. Then, the armature will get smoothly accelerated and move out of the bore with high muzzle speed[5].

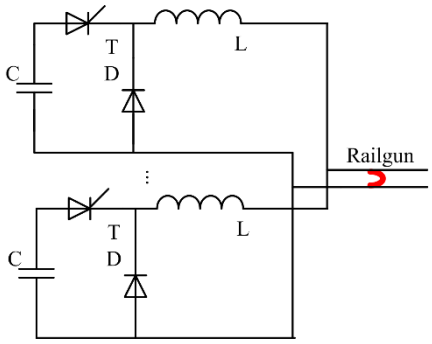

Figure.1. Application of PFN in EML

However, the thyristor is easily damaged when PFN is triggered sequentially, which seriously affect the stability and reliability of the EML system. Research shows that the failure of thyristor is always caused by the reverse recovery process[6]. The paper expounds the thyristor's reverse recovery process and builds a macro model of thyristor in which reverse recovery process is considered. The thyristor damage reason when triggered in sequence is proposed by theoretical analysis. When PFN is triggered sequentially, the paper present that thyristor can be protected effectively by increasing inductance, and the efficiency of EML system will not decrease significantly when the proper inductance is selected. Based on that, the paper calculate the 24MJ EML system's efficiency by building model in PSPICE. Result shows that the system runs reliably, and the efficiency decrease slightly from 27.2% to 24.4%.

The simulation and experiment in the paper is based on

104kJ PFU. The photo of the 104kJ PFU is as shown in Figure.2. The outline dimension of the module is 301×461×845mm. The overall energy density is 0.88MJ/m^3[7].

Figure.2. Photo of 104kJ PFU

II. Theoretical Analysis

A. *Reverse recovery process*

Pulse thyristors are solid-state semiconductor switches that structurally have three terminals and four layers[8]. A physical structure of pulse thyristor is shown in Fig.3. A is anode of thyristor; K is cathode and G is gate.

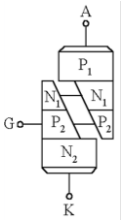

Figure.3. Physical structure of thysitor

When the thyristor turns from blocking to conducting, silicon is injected into a lot of nonequilibrium carriers. This carriers' conductivity modulation effect keeps the thyristor in a low-resistance state, so that a large surge current is allowed to flow through it. Before the thyristor turns from conducting to blocking, these carriers will dissipate through compositing, migration, and diffusion. It means that the thyristor will not turn off right after current zero. Contrarily, a reverse current will generate. Due to reverse recovery process of thyristor, inductor in series with the thyristor suffers relatively high voltage when reverse current sharply decreases[9]. Thus leading to the reverse overvoltage of the thyristor.

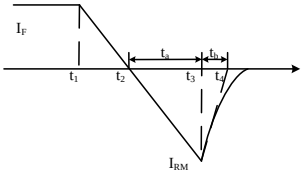

Figure.4. Turn-off process of thyristor

B. *The damage reason of thyristor*

The schematic diagram of PFU is as shown in Fig.5. The capacitor C is 1785μF/10.8kV. The inductor L is 10μH. The thyristor T is connected in parallel whose rated voltage is 5.6kV. D is the crowbar diode. All the PFUs in the paper adopt the Fig.5 structure whose thyristor is put behind the diode. Under this condition, thyristors needs to endure the whole pulse current, and thyristor is easily damaged when PFN is triggered in sequence.

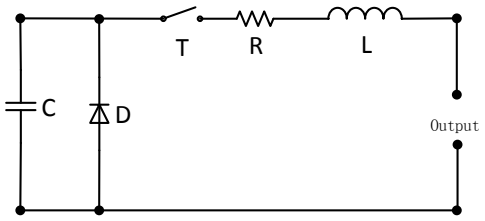

Figure.5. Schematic diagram of PFU

The paper analysis the damage reason through PFN which is made up of 2 PFUs. In Fig.6, PFU_1 is the first triggered, and PFU_2 is the next. R_o,L_o is the load resistance and load inductance. R_1,L_1,R_2,L_2 is the pulse inductance. C_1,C_2 is the storage capacitor. Fig.7 is the current waveform through T_1 and T_2. When T_1 in PFU_1 turns on, current will flow through the load. Crowbar diode D_1 will turn on after the voltage across C_1 decrease to 0 as shown in Fig.7. Then, PFU_2 is triggered in t_2. Under the influence of PFU_2, a reverse voltage will generate across the load and the reverse voltage will force the current through T_1 decrease rapidly. That's why the thyristor is easily damaged when PFN is triggered in sequence.

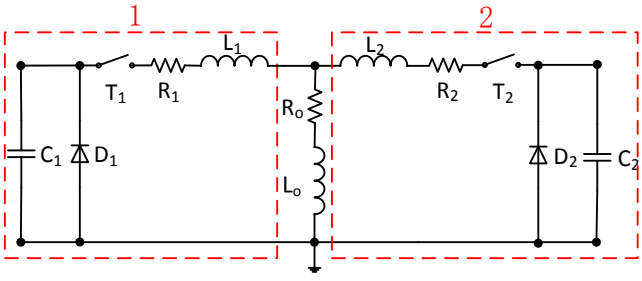

Figure.6. PFN triggered in sequence

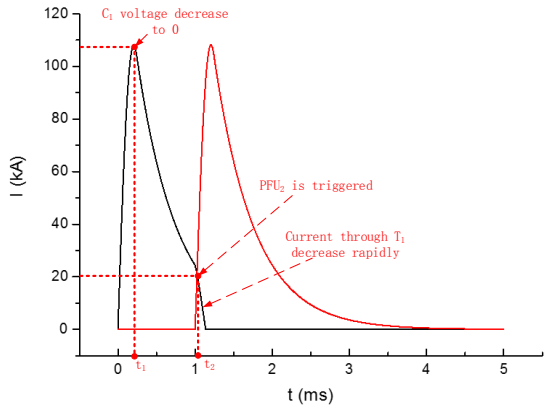

Figure.7. Current waveform through thyristor

C. *pulse forming inductor*

Pulse forming inductor and thyristor are in one branch. It can limit the peak current and di/dt of the current through the thyristor, so that the thyristors are protected[10]. When the inductance of PFU increase from 10μH to 30μH, the waveform parameter is as shown in Table.1. The efficiency of EML system is always believed to be significantly correlated with the inductance. The paper present that the efficiency is not so correlated with the inductance, when a large amount of PFUs discharge sequentially in parallel.

TABLE. I. Current Parameters

1#	*10uH*	*20uH*	*30uH*
Peak Current(kA)	83.5	66.5	57.2
Pulse Width(uS)	430	563	670
di/dt(kA/uS)	0.348	0.218	0.158

III. Simulation Modeling

A. *thyristor*

Based on PSPICE, the paper builds a macro model of thyristor in which reverse recovery process is considered. The macro model uses conventional devices to emulate the external behavior of the thyristor. A piecewise function (1) with 3 stages is proposed to describe the reverse current of thyristor[11].

$$I_R(t)=\begin{cases}-t\cdot di/dt, t\le t_2\\ -I_{RM}\cdot \sec h[(t-t_c)/\tau_\alpha], t_2\le t\le t_c\\ -I_{RM}\cdot \sec h[(t-t_c)/\tau_b], t\ge t_c\end{cases} \quad (1)$$

τ_a and τ_b are time constants; As shown in Fig.8. t_c is the moment that current rate changes; t_2 is the moment that reverse current reaches maximum.

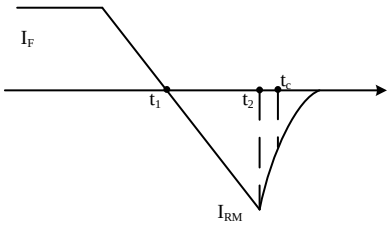

Figure.8. Turn-off process of thyristor

B. *load*

The model of load is as shown in Fig.9. It's a simplified load model in which the load resistance and load inductance change linearly with the armature position changing.

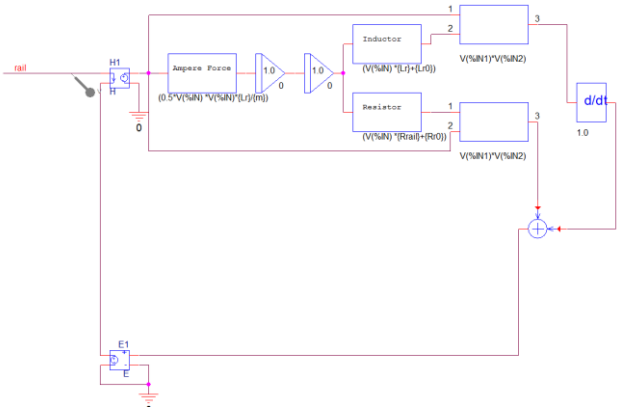

Figure.9. Model of load

C. *24MJ electromagnetic launch system*

The photo of 8MJ pps system is as shown in Fig.10. 24MJ PPS is made up of three 8MJ power devices. Every 6 PFUs consist of a PFN. Thirteen PFN inform an 8MJ power device. In order to protect the thyristor, the inductance of PFU is increased from 10μH to 120μH. According to overall parameters of the system, a simulation model shown in Fig.11 is built in PSPICE[12]. The whole system is divided into four parts and the four parts are triggered in the time sequence shown in Table.2.

Figure.10. Photo of 24MJ EML system

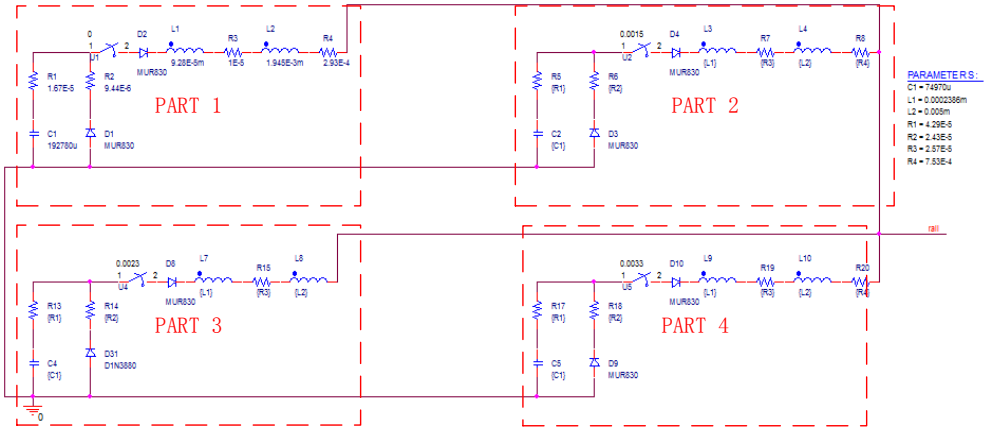

Figure.11. PSPICE model of 24MJ EML system

TABLE. Ⅱ. The Sequence Of Triggering

Group	*1*	*2*	*3*	*4*
Time Sequence(ms)	0	1.5	2.3	3.3

IV. Simulation Parameters Calibration

In order to ensure the accuracy of simulation model, it's necessary to check the simulation parameters through experiment. Therefore, thirteen PFUs were triggered in sequence, and the load parameter is 19.2mΩ/0.154μH. When the voltage is charged up to 2kV, the experimentally measured current waveform through thyristor is as shown in Fig.12, and the simulation current waveform is as shown in Fig.13. Table.3 shows the waveform parameters of Fig.12 and Fig.13. It can been seen that the simulation current waveform is almost the same as the experimental one. Thus, the simulation parameter is accurate.

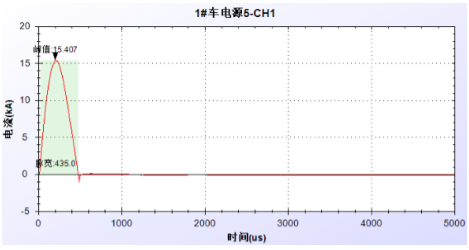

Figure.12. Experimental current waveform

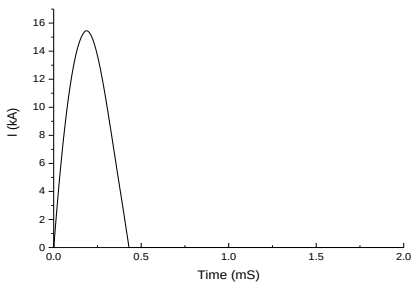

Figure.12. Simulated current waveform

TABLE. Ⅲ. Current Waveform Parameters

1#	*Experiment*	*Simulation*
Peak Current(kA)	15.407	15.447
Pulse width(μs)	435	430.3
di/dt(kA/μs)	0.0656	0.0643

V. Simulation Results

Simulation results is shown in Fig.14 and Fig.15. The curve in Fig.15 describes relationship between armature position and time. According to the known rail length, the muzzle-leaving time can be got from Figure.13. The rail length is 8m[13]，and the muzzle-leaving time is 0.00618s. The black curve in Fig.15 describes the relationship between current and time, and the blue one describes relationship between current and time. The muzzle speed and muzzle current can be read according to the known muzzle-leaving time. Muzzle speed is 2439m/s, so that the efficiency of 24MJ EML system can be calculated.

The total energy storage of system:

$$E=\frac{1}{2}CU^2=234\times0.5\times1785\times10^{-6}\times(10800)^2=24.36MJ$$

The muzzle energy of armature:

$$E_k=\frac{1}{2}mv^2=0.5\times2\times2439^2=5.95MJ$$

Efficiency of system:

$$\eta=\frac{E_k}{E}=\frac{5.95}{24.36}=0.244=24.4\%$$

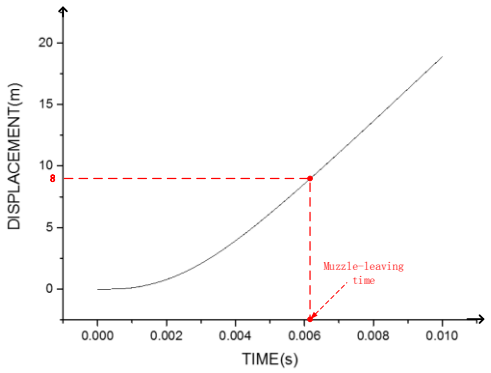

Figure.14. Relationship between displacement and time

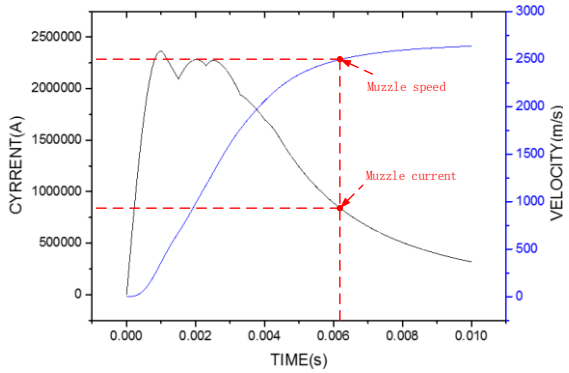

Figure.15. Muzzle current and muzzle speed

Conclusion

The paper show the 104kJ PFU and the 24MJ EML system which is made up of 234 PFUs. The subsequent experiment shows that the 24MJ system work reliably after increasing the inductance, and the thyristor don't damage anymore when the system is triggered in sequence. Meanwhile, efficiency of system decrease slightly from 27.2% to 24.4%. It means that increasing inductance properly can protect the system effectively, and the efficiency will not be affected significantly.

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