Research on 100kJ pulsed power module for electromagnetic launch

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Abstract. With the development of the electromagnetic launch (EML) technology, the requirement of the pulsed power supply is increasing. Capacitor-based pulsed power supply usually consists of several hundred kilojoule level pulsed power modules (PPM) in parallel. The PPM for EML system requires the capability of continuous working ability, high energy storage density and high peak current. A 100kJ compact PPM with rated operational voltage 10kV was designed, the output peak current was about 90kA, and the continuous working ability was 6 times per minute. The design and selection of main components in the module were simulated. At last, the PPM was used in the testing of the coil gun. It provides transient pulse current test platform and technical support for the subsequent construction of megajoule level pulsed power supply.

1. Introduction

Pulsed power supply (PPS) is an important part of electromagnetic launch (EML) system, which provides the required power for emission. It can be used in electromagnetic rail gun, electromagnetic coil gun and electrothermal-chemical gun [1-4]. In order to meet the demands of launch frequency and installation space in EML system, the PPS designed for EML system must have compact structure and rapid energy storage. The capacitive PPS, one of the best power supply forms for EML system, has the advantage of quick charging and being suitable for modular integration [5].

In this paper, a 100kJ compact PPM with rated operational voltage 10kV was designed, the output peak current was about 90kA, and the continuous working ability was 6 times per minute. The thermal simulation of the design and selection of main components in the module was carried out. The PPM was used as a transient pulse current testing platform for the coil performance testing of the coil gun.
2. PPM and Components

2.1. Circuit topology

The PPM was designed to supply energy to the EML system. The circuit topology of PPM is shown in figure 1. The PPM consists of an energy storage capacitor $C$, a pulse-shaping inductor $L$, a pulse thyristor $SCR$ and a crowbar diode $D$. $R$ is the resistance of the electromagnetic launcher. $K_e$ and $K_d$ are a pair of normally open and closed contact switches, which are used for charging and energy release. $R_d$ is a protection resistance. The circuit structure of the thyristor in front of the diode is chosen, which has high discharge efficiency, no oscillation of capacitor and diode current, small energy consumption of thyristor and diode. It is beneficial to device protection and has advantages in multi-module parallel pulsed power supply [6].

![Circuit topology of PPM](image)

**Figure 1.** Circuit topology of PPM.

The simulation current waveform of the 100kJ PPM shows in figure 2. IPPM is the output current of the module. ISCR is the current flowing through the thyristor, and ID is the current flowing through the diode. At the moment of 0.3ms, the peak current of the PPM is about 90kA, meeting the design requirement and the inductance value in the PPM is about 20μH. After that, the thyristor is turning off, and the ISCR drops rapidly to 0 at 0.45ms. At this point the diode is turned to maximum current of 85kA.
2.2. Module structure

The structure of the PPM shows in figure 3. The locations of major components and related test equipment are marked in the figure. In order to integrate the PPM, we need to overcome some difficulties, such as electrodynamic force, temperature rise, electrical contact and electric insulating. In order to effectively improved the integration of PPM. We took a series of technical measures as follow: (1) Integrated package of the pulse thyristor and crowbar diode makes the semiconductor structure optimized. (2) According to the shape and structure of the semiconductor switch, the structure of the energy storage capacitor and pulse-shaping inductor were optimized and adjusted. The PPM dimension is $470\text{mm} \times 330\text{mm} \times 640\text{mm}$ and the energy storage density is about $1\text{MJ/m}^3$. 

Figure 2. Simulation current waveform of PPM.

Figure 3. Structure of the PPM.
2.2.1. Capacitor  The capacitor is an energy storage element which almost accounts for more than half of the volume and weight of the whole PPM. A metalized film capacitor (470mm×330mm×310mm) was employed, and the capacitor (2000μF/10kV) has the advantages of low inherent inductance, high utilization efficiency, self-healing property and good safety.

2.2.2. Inductor  The pulse forming inductor is applied to shape the output current waveform. In addition to the requirements of high through current capability, the pulse-shaping inductor (20μH/20kV) designed to sustain the violent mechanical impacts and thermal expansion has an epoxy casting dry-type air-core cylindrical structure, and is characterized by magnetic concentration, high specific energy and low resistance. The inductor has high flow capacity and can sustain the peak pulse current of 165kA and the width of the pulse current is about 10ms. The outside diameter and the height of the pulse forming inductor are 220mm and 312mm.

2.2.3. Semiconductor switch  Semiconductor switch is composed of a thyristor-stack and a diode-stack. The thyristor-stack has such advantages as quick switch on, low trigger power, flexible control mode, good anti-electromagnetic interference and good anti-vibration. As the main circuit discharge switch of the PPM, the thyristor-stack is composed of three six-inch thyristors in series. Each thyristor non-repetitive peak reverse voltage is 5.2kV. The turn-off delay times of the three thyristors are all less than 0.2μs. The output current of gate synchronization strong pulse trigger circuit is 8A/50μs. The pulse trigger circuit is encapsulated in the electromagnetic shielding box by means of optical fiber communication mode for remote control. The diode-stack is the crowbar switch of the PPM and has good one-directional conductivity, which is very suitable for limiting the reverse energy storage of the capacitor and improving the conversion efficiency of the system’s electric energy. The diode-stack consists of three six-inch diodes in series. The peak reverse voltage of each diode is 5.5kV.

3.  Thermal Simulation
In the process of continuous discharge, the temperature rise caused by excessive power becomes very serious. Continuous discharge means a doubling of the electrical action of the high-power components in a short period of time. It will make those high-power components with large heat, concentrated heat or poor heat dissipation characteristics heat up rapidly because of heat accumulation. Therefore, the thermal simulation of the main components is particularly important, especially in the process of continuous discharge. The inductor is made up of copper belt and insulating material. Since it has been continuously subjected to the current of $I_{PPM}$, the internal temperature rise of the inductor is an important concern.

Figure 4 shows the current density distribution of the inductor. Because of the transient skin effect and proximity effect, the current distribution of the copper belt is very uneven. The current mainly concentrates on the inner surface of the copper belt, while the current density on the outer surface is relatively small. At the 0.4ms, the maximum current density is $4.43 \times 10^3$A/m$^2$. 
At different time of discharge, the temperature distribution of the inductor is shown in figure 5. Because of the inside current density of the solenoid copper belt is much higher than outside, the inside of the copper belt temperature is higher. At the 1.8ms, the temperature reaches the highest value about 324K, and then the temperature begins to drop because of the influence of current drop and convection heat transfer. At the end of discharge, the maximum temperature is 316K.
3.0ms

Figure 5. Temperature distribution of inductor.

Figure 6 is the temperature curve of the inductor during continuous discharge. In the process of discharge, the temperature distribution of the copper strip is extremely uneven due to the skin effect of current. In the discharge gap, because of the good thermal conductivity of copper, the temperature of the copper strip drops rapidly. In the whole process, the highest temperature of the copper strip is no more than 350K.

4. Coil Performance Test
According to the structure diagram in figure 3, the 100kJ PPM was developed and its performance was tested discharging the artificial load. The selected test equipments are shown in table 1.
The coaxial coil electromagnetic propulsion devices have heavy load capacity, high efficiency and long repetition life, is one of the essential choices on battlefield in the future [7]. The performance of the designed coil directly affects the coil gun launcher. A coil design parameters and LCR measuring instrument test values are shown in the Table 2.

| Table 1. Test equipments |
|--------------------------|
| Equipment                | Model       | Parameter          |
| High voltage probe       | Pintech P6018A | DC 0-18kV          |
| Rogowski coil            | PEM CWT-LF1000 | DC 0-200kA         |
| Oscilloscope             | Tektronix DPO2012B | 100MHz,1GS/s    |
| LCR measuring instrument | HIOKI 3532-50 | Rs, Ls            |
| Artificial load          | Self developed | 3-10mΩ             |

| Table 2. Coil parameters |
|--------------------------|
| Coil | Resistance | Inductance |
| Design | 17.35mΩ | 0.174mH |
| Measurement(50Hz) | 17.57mΩ | 0.176mH |

Figure 7. The voltage waveform charging 5kV.
Figure 8. The 5kV experimental current waveform of coil.

The 100kJ PPM is a transient pulse current test platform, which can be used for coil performance test. The coil was tested for 1-5kV discharge performance to verify the reliability of the coil design. Figure 7 shows the charging voltage waveform of 5kV under similar half-power mode of the capacitor charging power supply, which takes about 5.5s. Figure 8 shows the 5kV discharge current waveform, and the current peak value is about 19.45kA. The experimental results were intact, the coil structure was not damaged, and the measured electrical parameters were not different from the measured values before the experiment, which verified the design rationality of the coil. It provided technical support for subsequent coil gun design.

5. Conclusion
Based on the topology of capacitor energy storage pulsed power supply, a 100kJ PPM with compact structure and continuous working capacity was designed in this paper. Rapid heat accumulation of continuous discharge operating conditions, which reduces the reliability of the situation, has carried on the thermal simulation. The PPM with energy storage density of about 1MJ/m³, has the ability of continuous short-time work. The constructed PPM was applied to test the performance of a coaxial coil which is used for subsequent electromagnetic propulsion. The following research work will be carried out.
1. Test the continuous discharge performance of the power module at the rated voltage.
2. Most of the simulation calculations are under ideal conditions, so it is necessary to further improve the simulation computing capacity.
3. Develop coils that can withstand higher discharge voltage.

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