Research on high-rate and repeat frequency discharge lithium battery for electromagnetic launch primary power supply

Ren Ren, Dong Zhiqiang, Liu Jingang, Ye Weisheng and Su Zizhou

Northwest Institute of Mechanical & Electrical Engineering, Xian Yang, Shaanxi, China

Abstract. Lithium battery with excellent comprehensive performance can effectively improve the firing frequency of railgun, firing times of railgun, system integration and security of electromagnetic launch weapon system. The development of lithium-ion batteries were introduced in this paper, mainly from the material system of lithium battery, analyzes all kinds of lithium battery, combined with electromagnetic emission weapon system for high voltage cascade characteristics of primary lithium battery power supply demand, points out the advantages and disadvantages of the lithium battery materials system, determine the improved after optimization of high ratio of lithium iron phosphate battery as primary power battery components. Two kinds of lithium batteries have been tested by high power discharge test, which proves that the high power lithium iron phosphate batteries have better performance. The high power lithium iron phosphate battery with soft package, high discharge rate, high power density and good security, can meet the requirements of high power, high power density and good integration of the primary source of electromagnetic emission.

1. Introduction

In recent years, electromagnetic guns, laser weapons, microwave weapons and other directional energy weapons have become the focus of research at home and abroad. As a source of energy for directed energy weapons, the development of primary power sources has also progressed by leaps and bounds. From the mains - high voltage charger mode in the laboratory stage to the conventional generator - high voltage charger mode which can work in the field. However, due to the large volume, high weight and limited mobility of the above modes, new energy storage and power supply modes are needed to solve the on-board mobility problem. Lithium ion battery module series booster charging mode, its volume and weight decreased significantly compared with the above mode, so lithium ion battery primary power technology is more and more attention [1].

In spite of the rapid development of lithium battery primary power supply, its volume and weight are still too large. In order to realize the basic formation on land-based platforms, the primary power supply is required to be of high power, high power density, small size, light weight and conducive to integration.

To meet the above requirements, lithium battery primary power supply can be improved from two aspects: one is to develop and choose lithium battery with better comprehensive performance; The second is to optimize the charging strategy and topology of the system [2].

The first aspect is the most direct solution, because in the same circuit topology, the power density of lithium batteries with good performance can be increased by more than 10 times compared with conventional lithium batteries, and the system volume and weight can be greatly reduced by more than
Therefore, lithium batteries with excellent comprehensive performance can effectively improve the firing frequency (high power, short charging time) and the number of firing times (high energy storage) of the electromagnetic launch system, and reduce system volume & weight (high power density).

In this paper, aiming at the above requirements, several mainstream lithium batteries are studied, their material systems and comprehensive properties are analyzed, and finally a lithium battery with high power reproduction rate suitable for electromagnetic emission high-voltage cascade primary power supply is proposed.

2. Lithium battery development

Among many battery systems, lithium battery has the advantages of high energy density, low self-discharge rate, long cycle life, no memory effect, no pollution, no poison and so on. After commercialization, lithium battery has been widely used in consumer electronics, electric vehicles, national defense and other fields.

In the 1970s, the first lithium battery was developed successfully, titanium sulfide as a positive electrode material, lithium metal as a negative electrode material, but not large-scale application. Through the efforts of scientists, a series of anode and cathode materials with better performance were developed, and many scientific and engineering problems were overcome. Finally, SONY corporation of Japan launched the first generation of commercial lithium ion batteries in 1991, with graphite as the negative electrode and lithium cobalt acid as the positive electrode [3]. However, due to its high cost, lithium cobalt oxide is gradually replaced by lithium iron phosphate and ternary positive pole. Recently, lithium titanate batteries have been paid more attention for their good safety performance. These lithium batteries can be called second-generation lithium batteries. The cathode material is mainly graphite carbon. The energy density of a single cell is between 120Wh/kg and 250wh/kg, and the power density is up to 4000 W/kg. Already the highest of all commercial battery systems.

The third generation lithium ion battery will replace the cathode graphite carbon material of the existing lithium ion battery with the silicon cathode material, and develop a new cathode material at the same time. The specific energy of the single cell is expected to reach 300Wh/kg -- 350wh/kg. At present, some achievements have been made, but engineering application has not been realized.

In addition, lithium-metal batteries with negative electrodes (lithium metal batteries) have a higher theoretical energy density and a cathode material that does not contain lithium, thus reducing costs. However, due to obvious defects, no good products have been developed in the previous 50 years. With the progress of technology, lithium metal battery is also expected to become the next generation of lithium battery technology. Lithium metal batteries are mainly developed in solid metal lithium batteries, lithium sulfur batteries and lithium air batteries.

To sum up, the lithium battery monomer suitable for the primary power source of electromagnetic launch should still be developed on the basis of the second-generation lithium battery with the most mature technology and the highest degree of commercialization.

3. Comparison of lithium battery material systems

3.1. Comparison between energy-type lithium batteries and power-type lithium batteries

The discharge current value is given when the battery capacity is expressed. In order to facilitate the comparison of batteries with different material systems, it is usually expressed as a multiplier (unit, C), which refers to the current output by releasing the rated capacity within a specified period of time. If the rated capacity of a lithium battery is 2Ah and the discharge rate is 2C, it means that the battery can discharge continuously for 1 hour at the current of 2A and 0.5 hour at the current of 2A at the maximum.

Lithium batteries can be divided into energy type and power type in terms of energy characteristics. Energy-type batteries have higher specific energy (Wh/kg), larger capacity and discharge rate generally within 3C. They are mainly used in electric vehicles, consumer electronics and other fields.
that require more energy and long battery life. Power type battery is designed for short term large current discharge. It can discharge at high discharge rate in short term. It is mainly used in start-stop system or hybrid power system. The current mainstream power battery can achieve a discharge rate of 30C.

Since the pulse power supply of directional energy weapons such as electromagnetic railguns and microwave weapons is short-time operation, the power of primary power supply is required to improve the firing rate of weapons. The high power primary power source composed of energy-type batteries is bulky and heavy, and cannot be moved; However, the power lithium battery has a large short-term discharge rate and the store energy can be used for multiple times. In addition, the power lithium battery can also be charged in the form of larger charge rate, with a short charging time. Therefore, it is the first choice for the primary power source of directional energy weapon lithium battery such as electromagnetic launch.

3.2. Comparison of material systems in power lithium batteries
As shown in table 1, according to the different material systems, three representative power lithium batteries with better performance were selected from the second-generation lithium batteries, namely ternary lithium battery, high-ratio lithium phosphate battery and lithium titanate battery, for comparative analysis.

As can be seen from table 1, the performance of lithium batteries in different systems is different, which needs to be comprehensively evaluated based on the core index requirements of lithium battery primary power supply.

**Table 1.** The comparison sheet about three kind of material system lithium battery.

| Part                        | voltage  | Work temperature range | Discharge rate | The theory Specific capacity mAh/g | The actual Specific capacity mAh/g | Power density kW/kg | security   |
|-----------------------------|----------|------------------------|----------------|-----------------------------------|-----------------------------------|---------------------|------------|
| Ternary lithium battery    | 3.8V     | 0℃～50℃                | 30C            | 280                               | 155                               | 4.0                  | general    |
| Lithium iron phosphate battery | 3.2V   | -10℃～55℃              | 40C            | 170                               | 110                               | 3.3                  | good       |
| lithium titanate battery   | 2.3V     | -40℃～60℃              | 30C            | 175                               | 91                                | 1.6                  | excellent  |

3.2.1. Advantages and disadvantages of ternary lithium batteries. Ternary lithium battery Li(NiCoMn)O₂ is the general name of lithium battery with cathode material system of lithium nickel-cobalt manganate. In the new ternary system cathode materials, the synergistic effect of the three elements is obvious. Cobalt element can stabilize the layered structure and inhibit cationic mixing. Manganese can greatly reduce the cost and effectively improve the safety performance of materials [4]. Its comprehensive performance is significantly better than that of lithium batteries with nickel, cobalt and manganese as cathode materials. Currently, it has the largest market in the field of energy batteries.

The ternary system has a single battery with high voltage and large specific capacity, so it needs the least number of batteries in the primary power supply system, reducing the complexity of the battery management system and high reliability. Also has the highest energy storage, can support the maximum number of launches.

Due to the complicated process and complicated steps of the industrial preparation of the ternary material system, the change of the ratio of three elements has a significant impact on the properties of
the cathode material, especially at high temperature, its structure is unstable. However, in the case of high power use, because the output current is large, the battery energy loss is large, and the internal temperature of the battery rises significantly. Without considering the heat dissipation system, in the middle of high-power refrequency operation, the battery is already in a high temperature environment, and its complex ternary system has poor thermal stability, which may cause adverse effects. For example, Mn$^{2+}$ can be generated, while Mn$^{3+}$ is soluble in the electrolyte, which will cause the loss of active substances. In addition, Mn$^{2+}$ has a strong catalytic effect, which will catalyze the electrolyte decomposition and deposit on the negative electrode, leading to the increase of battery impedance, and these reactions can be carried out faster at high temperature [5]. In addition, the cathode material has a strong oxidation after lithium removal, which is easy to exothermic decomposition and release oxygen. Exothermic reactions occur between oxygen and the electrolyte, or between positively active substances and the electrolyte. These exothermic reactions may cause the battery to explode. Because at present the commercial battery mainly USES the organic liquid electrolyte, the battery quantity is numerous, once a single explosion fire, will cause the chain reaction, the rapid combustion. Tesla cars, for example, use ternary lithium batteries and have more than 7,000 single batteries. There have been reports of tesla batteries burning around the world. As shown in the picture, on April 21, 2019, a tesla MODEL S parked in an underground garage in Shanghai was engulfed by fire in a short time, less than 8 seconds from smoke to flame.

![Figure 1. Ternary lithium battery spontaneous combustion in a Tesla car.](image)

The safety of the ternary lithium battery is its biggest weakness, even in primary level power supply system, through the battery management system, the structure of the active thermal management, fuse protection, improve the multiple security measures such as improving the security of the system, but because of its characteristics of material itself, especially in high power output occasions such as electromagnetic launch, the safe hidden trouble that there should not be ignored.

3.2.2 Advantages and disadvantages of lithium iron phosphate batteries. Lithium iron phosphate battery(LiFePO$_4$)is a lithium battery that uses lithium iron phosphate as a cathode material. Its operating voltage is moderate (3.2v), and its specific capacity is slightly lower than that of a ternary lithium battery. Its advantages are high discharge rate, fast charging and long cycle life, good stability and safety in high temperature and high thermal environment. In addition, since batteries do not contain valuable elements such as cobalt, phosphorus and iron are abundant and cheap.

The charging and discharging process of lithium battery can be regarded as the removal and insertion of lithium ions in the lattice at the micro level. However, there are P-O covalent bonds in the lattice of lithium iron phosphate to form delocalized three-dimensional chemical bonds with strong stability, which makes LiFePO$_4$ have strong thermodynamic and kinetic stability [6]. During the charge and discharge process, the lithium ions are deembedded and embedded to make the material transition between FePO$_4$ and LiFePO$_4$. Because the structure of the two molecules is the same, the structure stability of the material is good and the cycling performance of the material is excellent.

The disadvantage of lithium iron phosphate battery lies in its poor conductivity, low vibration density and low energy density. In order to improve its performance, researchers conducted a series of
doping and modification studies. Its electrical conductivity and electrochemical performance were significantly improved, and its high multiplier performance was also significantly improved. The lithium iron phosphate battery selected in this paper has a maximum discharge rate of 60C. As shown in figure 2, the battery discharges at multiple discharge ratios from 30C to 60C, and has a stable discharge platform. At 60C, the voltage of the discharge platform is slightly lower, but the output can still be stable.

**Figure 2.** The discharge chart about one kind of high-rate discharge LiFePO₄ battery.

As shown in the figure, in the early stage of high-multiplier discharge, the voltage of the high-multiplier lithium iron phosphate battery drops rapidly, and the voltage is stable after reaching a certain discharge platform. On the output platform, the output power fluctuation is small, and the control difficulty is low. When the battery capacity is released by 40%, the voltage platform is broken and the voltage drops rapidly, making it impossible to maintain a high rate of discharge. Therefore, when lithium iron phosphate battery is discharged at a high rate, as long as it is within the range of the corresponding discharge platform, it can ensure stable power output, reduce the control difficulty of the primary power control system, and reduce the volume, weight and cost of the control system hardware. The platform exists until the battery power is released by 40%, which is enough to meet the energy requirements of multiple re-frequency operation of electromagnetic emission.

3.2.3. Advantages and disadvantages of lithium titanate batteries. The biggest difference between lithium titanate batteries and the previous two types of batteries is that the cathode material is lithium titanate instead of carbon. Lithium titanate is the only negative electrode material that belongs to the phase transition reaction mechanism. Lithium titanate battery has almost no effect on the molecular structure when charging and discharging, so it has incomparable advantages over other negative electrode materials. For example, charging more times, charging process faster, safer. Lithium titanate battery is chosen as the primary power source for electromagnetic launch and other directional energy weapons, which has two advantages. The second is safety. The charging and discharging platform has a high voltage, and under the condition of high-ratio charging and discharging, no lithium dendrites will be produced, which is better than that of ternary lithium battery and lithium iron phosphate battery.

The main disadvantage of lithium titanate as a cathode material for lithium ion batteries is that it has poor electronic conductance and is outdated in charge and discharge under the condition of large multiplier. The material has severe polarization and reduced reversible capacity, resulting in poor multiplier performance [7]. In addition, lithium titanate has a high negative potential. Although it brings many benefits, the output voltage of the battery is only 2.3V. Compared with ternary lithium battery and lithium iron phosphate battery, the battery voltage is 60% and 39% lower. This means that the same voltage level of the primary power supply system, the number of lithium titanate battery can be compared with other two kinds of battery have greatly increased, at the same time increase the battery management system in the primary power supply system, enclosure, switch, such as the number of main components, the system size, weight and unfavorable impact of reliability.
3.2.4. Comprehensive performance evaluation of lithium batteries

Table 2. The comprehensive performance evaluation about different material system lithium battery.

| Name                        | Complexity of system | System power density | System volume & weight | System security | Total score |
|-----------------------------|----------------------|----------------------|------------------------|-----------------|-------------|
| Ternary lithium battery     | 8                    | 8                    | 8                      | 5               | 29          |
| Lithium iron phosphate battery | 10                   | 10                   | 10                     | 8               | 38          |
| Lithium titanate battery    | 6                    | 6                    | 6                      | 10              | 28          |

As shown in Table 2, the main performance of the primary power supply system composed of three lithium batteries is scored separately, and the scores of each performance are added to reflect its comprehensive performance level. The main performance is divided into system complexity, system power density, system volume weight and system security. In each category, it is better to score 10 points for the three lithium batteries, while the other two will score relatively high. Finally, the lithium battery with the highest comprehensive score will be selected.

The complexity of system, the lower the complexity of the system, the higher of the score, which is related to the single battery voltage, operating temperature, specific capacity. Although the voltage and specific capacity of ternary lithium battery are the highest, its operating temperature is limited, so it needs to add a thermal management system, which not only heats up the battery unit at low temperature, but also cools the battery unit at high temperature. The whole primary power supply system is more complicated. Lithium titanate, on the other hand, due to the low voltage of single batteries and the large number of batteries in series in the system, leads to a large increase in the corresponding battery management system and battery cells, which makes the system the most complex. The operating temperature range of high multiplier lithium iron phosphate battery is large, and it can be charged with multiple refrequency and high power without thermal management system, with the lowest system complexity.

The higher the power density of the system, the better the integration of the system. It is related to battery voltage, discharge rate, material system and so on. As far as the battery itself is concerned, the power density of ternary lithium battery is the highest. However, due to the poor high temperature characteristics of ternary lithium battery, the power density of the system is significantly reduced after the addition of thermal management. Lithium titanate battery has the lowest power density because of its low voltage and discharge ratio.

The volume and weight of the primary power supply system are affected by the specific capacity of the battery and the power density of the system. Lithium iron phosphate battery with high multiplier is the smallest, followed by lithium ternary battery, and lithium titanate battery has the highest volume and weight.

In terms of safety, lithium titanate battery cathode uses lithium titanate material, which has higher safety than the other two batteries. However, the high-multiplier lithium iron phosphate battery improves the material and preparation technology, and optimizes the high-current output structure, so the temperature rise is small and the safety performance is good. Compared with the above two lithium batteries, ternary lithium batteries have the worst safety.

To sum up, the primary power supply of high voltage lithium battery is required to be integrated, high-power and high-power density, small in volume and weight, and good in safety. Based on the above core requirements, among the three types of power lithium batteries listed and analyzed in this section, lithium iron phosphate battery with high power ratio has the highest comprehensive performance score, which is the first choice for the primary power source of electromagnetic gun high-
voltage cascade lithium battery pack.

4. Lithium battery performance test
Through theoretical analysis, it is determined that lithium iron phosphate battery with high ratio is the first choice for lithium battery of primary power source of electromagnetic launch. In order to verify its performance, three lithium iron phosphate batteries and three lithium titanate batteries were selected for the comparison test of large-rate discharge, while the ternary lithium battery was not tested due to its safety.

The test samples were 3 lithium iron phosphate batteries with soft cover and high multiplier, 3.2V8ah, and 40C discharge multiplier. Three lithium titanate batteries with soft cover and high rate, 2.3V8.5ah, discharge rate 30C.

![Figure 3. Two types of soft-packed lithium batteries.](image)

As shown in the figure, single discharge experiment and repeated discharge experiment of lithium battery can be carried out after NHR5600 electronic load is used to connect lithium battery, discharge current and other parameters are set. The HIOKI 8861 recorder was used to record the discharge waveform, and FLUKE F63 infrared thermometer was used to measure the multi-point temperature of the battery surface.

First, a single discharge experiment was conducted, the discharge time was 30s, the voltage was measured during the discharge process, and the minimum value was recorded. After the discharge, the temperature of multiple points was measured and the mean temperature rise was calculated. The specific data are shown in table 3, in which the measured discharge waveform of 2# lithium titanate battery is shown in figure 5.
### Table 3. Single discharge record of lithium titanate battery and lithium iron phosphate battery.

|                  | Discharge rate | Pre-discharge voltage | Discharge voltage | Output current | Discharge time | Mean temperature rise after discharge |
|------------------|----------------|-----------------------|-------------------|----------------|----------------|----------------------------------------|
| 1# lithium titanate battery | 30C            | 2.58V                 | 1.89V             | 255A           | 30s            | 1.1°C                                  |
| 2# lithium titanate battery | 30C            | 2.59V                 | 1.92V             | 255A           | 30s            | 1.0°C                                  |
| 3# lithium titanate battery | 30C            | 2.62V                 | 1.91V             | 256A           | 30s            | 1.1°C                                  |
| 1# lithium phosphate battery | 40C            | 3.31V                 | 2.79V             | 322A           | 30s            | 1.7°C                                  |
| 2# lithium phosphate battery | 40C            | 3.35V                 | 2.81V             | 323A           | 30s            | 1.6°C                                  |
| 3# lithium phosphate battery | 40C            | 3.32V                 | 2.80V             | 322A           | 30s            | 1.8°C                                  |

As can be seen from Table 3, the discharge rate and discharge voltage of lithium iron phosphate battery are higher than that of lithium titanate battery, which is determined by the performance of the two material systems. For the same discharge time, the temperature rise of lithium titanate battery is lower, while that of lithium iron phosphate battery is higher, but the difference is not large.

### Figure 5. Single discharge curve of 2# lithium titanate battery.
By setting the parameters, the two batteries were subjected to re-frequency discharge experiments, and the re-frequency high-multiplier discharge was achieved. Among them, the re-frequency discharge curve of 40C of lithium iron phosphate battery with high multiplier is shown in figure 6.

![Graph showing discharge characteristics](image)

**Figure 6.** The repeat frequency discharge chart about high-rate discharge LiFePO₄ battery.

In figure 6, the abscissa is the number of sampling points, and the ordinate is the battery voltage. It can be seen that the battery voltage is basically on the 2.75v discharge platform during the 5 times of large-ratio discharge. When the discharge is stopped, the voltage can quickly recover to 3.2v, and the measured temperature rises to 2.6℃ after discharge. It can be seen that the battery works well under the condition of high ratio and frequency reproduction.

It can be seen from the test results that both types of lithium batteries can discharge at a large rate of single and repeated frequency for a short time. In the case of similar volume and weight of the two types of lithium batteries, lithium iron phosphate batteries have higher discharge rate, stable discharge platform and small absolute value of battery temperature rise compared with lithium titanate batteries.

5. Conclusion

The primary power supply technology of high voltage cascade lithium batteries are analyzed and studied which is one of Key technologies in electromagnetic emission field. first of all, from the material system of lithium battery, analyzes kinds of lithium battery, combined with electromagnetic emission weapon system for high voltage cascade characteristics of primary lithium battery power supply demand, points out the advantages and disadvantages of the lithium battery materials system, determine the improved after optimization high-magnification lithium iron phosphate batteries as electromagnetic emission of primary power supply battery components. Then, through experiments, the excellent performance of lithium iron phosphate batteries with high multiplier was verified.

To sum up, this paper proposes that high power lithium iron phosphate batteries can be used in the primary power source of electromagnetic launch. This battery has high discharge rate, good safety, and can meet the requirements of high power, high power density and good integration of the primary power source of electromagnetic launch.

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