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Analysis of overcharging characteristics of a new type lithium iron phosphate battery for dc system of substation

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Abstract. In recent years, the number of DC power system in substation has been increasing. And the technical transformation of DC power system, fault maintenance and other workload is also on the rise, therefore dc emergency power emerged. The lead-acid battery is usually adopted for traditional DC emergency power supply. The disadvantage of lead-acid battery in volume and quality makes it difficult to realize the portability and mobility of dc emergency power. Lithium iron phosphate battery technology is the frontier technology in the rapid development period. However, the characteristics are not studied clearly. This paper studies the characteristics of lithium iron phosphate battery in different ambient temperature, operating conditions, and current of charge and discharge, analyses and summarizes the characteristics of battery charge and discharge, so as to improve the maintenance of station DC power supply system and the reliability of power supply network.

1 Introduction

As an emergency power supply after ac interruption, battery provides power for substation protection, control, accident lighting and so on, and is the guarantee of substation safe operation. At present, most substations use "maintanance-free" valve-controlled lead-acid batteries. From the point of view of operation, valve-controlled lead-acid batteries only do not add water, accident specific gravity; Its daily maintenance workload is still large. Moreover, valve-controlled lead-acid batteries have a high requirement for ambient temperature and a risk of short-term collapse [1].

Compared with lead-acid batteries, lithium iron phosphate batteries have higher rated voltage, which can reduce the number of batteries in series with the same capacity. With better temperature characteristics and lower requirements for ambient temperature [2-3], lithium iron phosphate batteries are regarded as an ideal substitute for lead-acid batteries with further improvement in performance and further decline in price[4-5].Although lithium iron phosphate batteries have many advantages, their characteristics such as overcharge and discharge and poor consistency are objective facts [6]. There are still many problems to be further studied when they are applied to substations as backup power.

In this paper, through analysis of the lithium iron phosphate battery power supply reliability when it is applied in substation of overcharging and small capacity battery group the advantage of parallel application, analysis on the operation mode, the lithium iron phosphate batteries work over charging voltage, the size of the over charge current, the features of accident is discharging, long battery life under the over features, for the application of lithium iron phosphate batteries in the substations promotion to provide technical support.

2 The lithium iron phosphate battery electrochemistry - thermal coupling model

In the normal operation of the NCM(111) cells, it involves the mutual transformation between chemical energy and electric energy, as well as the generation of heat energy and heat exchange with the external environment. Therefore, in order to study the temperature field of the battery under different working conditions more accurately, it is necessary to understand the mutual coupling mechanism between the electrochemical field and the temperature field of the battery, and build a more detailed electrochemical and thermal coupling model on this basis.

2.1 Control equation of the electrochemical model

This Li^+ electrolyte transport process involves the diffusion and migration of Li^+, and the concentration gradient determines the diffusion process, and the potential distribution and concentration gradient determine the migration process of Li^+. Fick's second law is used to solve the transport of Li^+ in the electrolyte:

$$\frac{\partial C_l}{\partial t} + \nabla \cdot J_l = 0 \quad (1)$$

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where, J_l is the flux of Li^+ in the electrolyte, which includes two terms. The first term is the diffusion of Li^+, which satisfies Fick law; The second is electromigration.

$$J_l = -D_l \nabla C_l + \frac{i_l t_+}{F} \tag{2}$$

where D_l represents the effective diffusion coefficient of Li^+, t_+ is the number of Li^+ transfers, and vis the concentration of Li^+.

Taking positive extreme as an example, the boundary condition of Equation 3 is:

$$D_l \left.\frac{\partial C_l}{\partial x}\right|_{x=x_{L,p}} = 0,\ D_l \left.\frac{\partial C_l}{\partial r}\right|_{r=R_{s,p}} = i_{\mathrm{int},p} \tag{3}$$

In the pore space of the active layer filled with electrolyte, the current density is controlled by the migration and diffusion of charged particles. Assuming that the electrolyte inside Li^+ is the only material motion, is:

$$i_l = -\sigma_l \nabla \phi_l + \frac{2RT\sigma_l}{F}(1 + \frac{\partial \ln f_\pm}{\partial \ln C_l})(1 - t_+)\nabla(\ln C_l) \tag{4}$$

As you can see, i_l is made up of two parts, the first part is Ohm's law, and the second part is the concentration gradient Li^+ .And, σ_l refers to the ionic conductivity of the effective electrolyte, and $f_\pm$ is the average molar activity coefficient.

Taking positive extreme as an example, the boundary condition of Equation 5 is:

$$\sigma_l \left.\frac{\partial \phi_l}{\partial x}\right|_{x=x_{L,p}} = 0,\ \sigma_l \left.\frac{\partial \phi_l}{\partial r}\right|_{x=x_{s,p}} = \frac{I}{A} \tag{5}$$

2.2 Governing equations of the thermal model

Direct cause of the battery temperature change for battery internal raw heat and heat exchange with the outside world, in this article, considering the battery internal materials of the differences between the layers, for any single material layer, the conservation of energy is as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q \tag{6}$$

where, ρ represents the material density of the layer, C_p represents the specific heat capacity of the layer, T represents the material temperature of the layer, t represents the time, and $q$represents the heat generation rate of the layer. When the material is located inside the cell, q represents the heat generation rate calculated by 3D electrochemical model q_b . When the material is positive and negative ears, q represents the heat generation rate calculated by Joule's law $q_{tab.p.}$ and $q_{tab.p}$; The heat generation rate in the rest of the cell is 0.

The heat generation rate of the cell is composed of reversible heat generation rate and irreversible heat generation rate, and its calculation expressions are equations (7) and (8) respectively.

$$q_{rev} = \frac{\iiint_V \mathrm{int}(\phi_S - \phi_l - U_{eq})dV}{V} \tag{7}$$

$$q_{irrev} = \frac{\iiint_V \sigma_s(\frac{\partial \phi_S}{\partial V})^2 + \sigma_l(\frac{\partial \phi_l}{\partial V})^2 + \sigma_l(\frac{\partial \ln C_l}{\partial V})(\frac{\partial \phi_l}{\partial V})}{V} dV \tag{8}$$

where, V is the volume of the cell.

Joule's law is applied to obtain $q_{tab.p.}$ and $q_{tab.p}$:

$$q_{tab.p} = \frac{Q_{tab.p}}{V_{tab.p}} = \frac{I^2 R_{tab.p}}{V_{tab.p}} \tag{9}$$

$$q_{tab.n} = \frac{Q_{tab.n}}{V_{tab.n}} = \frac{I^2 R_{tab.n}}{V_{tab.n}} \tag{10}$$

where, $Q_{tab.p}$ and $Q_{tab.n}$ represent the total heat generation rate, $R_{tab.p}$ and $R_{tab.n}$ represent the resistance, $V_{tab.p}$ and $V_{tab.n}$ represents the volume, and the subscript p, n represents the positive and negative poles respectively.

The process of heat exchange with the outside world:

$$-\lambda(\frac{\partial T}{\partial n}) = h(T_{amb} - T_\infty) \tag{11}$$

where, T_{amb} is the external temperature, T_∞ is the temperature at the direct contact of LIB with the outside, λ is the thermal conductivity of the external material of the NCM(111) cells, n is the normal direction of the outer surface of the battery, and h is the convective heat transfer coefficient with the outside.

3 Analysis of working characteristics of lithium iron phosphate batteries

At present, the application of large-capacity lithium iron phosphate batteries is still in its infancy. The single capacity of large-scale production in the market is 50AH, and larger batteries with 100AH or above can also be customized. However, the larger the single capacity, the lower the safety factor. The capacity of single battery modules designed by the substation according to the regulations is generally above 300AH. Compared with the direct series application of single cells above 300AH and the 18650 or 26650 battery cell series and parallel application, the topology structure of series and parallel combination of single cells with relatively stable performance of 50AH battery has higher security. In this paper, 50AH lithium iron phosphate battery was used for analysis.

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3.1 Operating voltage characteristics of lithium iron phosphate batteries

The characteristics of multiple test curves of lithium iron phosphate batteries were analyzed from different cases. And, the operating characteristics and operating voltage characteristics of the battery were analyzed. The working voltage of a battery refers to the potential difference between positive and negative electrodes of the battery when charging and discharging. The operating voltage has two key values which are the charging cut-off voltage and the discharge cut-off voltage. Both of them are designed to prevent the decomposition of active substances in the battery or to prevent the chemical structure inside the battery from being damaged, which could lead to life loss or safety accidents.

(1) Discharge ratio characteristics of working voltage of lithium iron phosphate battery

Fig. 1 shows the characteristic curve of the working voltage of lithium iron phosphate battery at different discharge ratios. The minimum discharge rate is 0.2c, the maximum discharge rate is 20C, and nine different discharge rates form a set of curves. It can be seen from the figure that, no matter which kind of discharge rate curve, the voltage in the discharge process is relatively flat, only when it is close to the termination voltage, it bends down quickly, indicating that the discharge characteristics of the battery is good.

In general, the working voltage of the battery drops rapidly at the beginning of discharge. The higher the discharge ratio, the faster the decline. There is then a longer and slower period of descent, known as the platform area of the battery. The lower the discharge ratio, the longer the duration of the platform area, the higher the platform voltage and the slower the voltage drop. When the battery is about to run out of power, the voltage starts to drop again.

As can be seen from Figure 1, the operating voltage of the battery is different at different discharge ratios. With the increase of the discharge ratio, the working voltage platform of the battery shows a downward trend. The higher the discharge ratio, the more obvious the decline will be. Meanwhile, the proportion of flat area decreases, and the available discharge duration decreases.

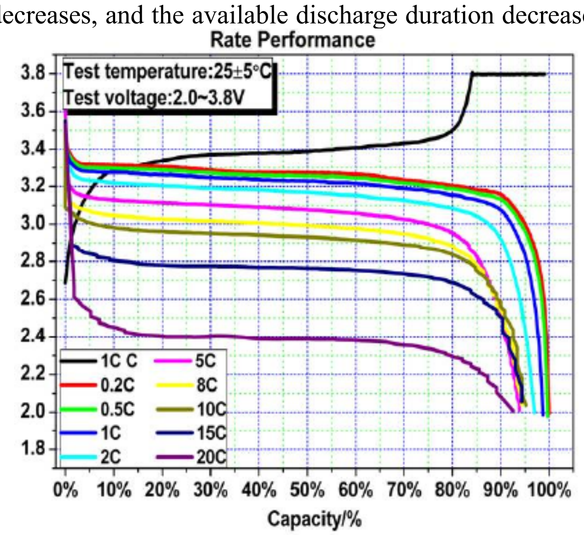

Fig. 1 Discharge ratio characteristic curve of working voltage

(2) Ambient temperature characteristics of working voltage of lithium iron phosphate battery

Figure 2 shows the characteristic curve of the operating voltage of lithium iron phosphate battery at different ambient temperatures. The operating voltage, discharge capacity and the ambient temperature of the battery are related closely. With the increase of the ambient temperature, the voltage of the battery platform increases slightly and the ratio of the discharge station area increases, and the discharge time also becomes longer.

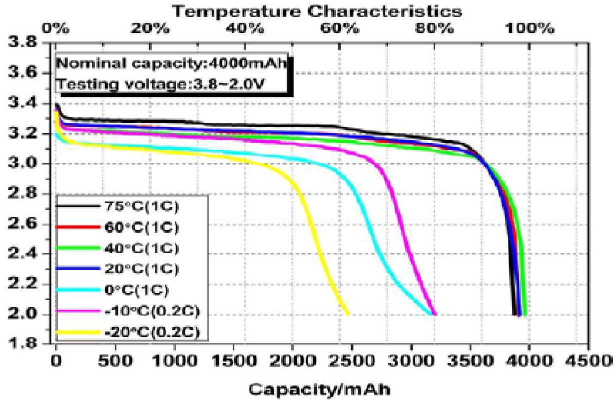

Fig. 2 Ambient temperature characteristic curve of working voltage

3.2 Capacity characteristics of lithium iron phosphate batteries

The capacity of a battery could be divided into nominal and actual capacity. Nominal capacity, also known as rated capacity, refers to the amount of electricity that should be provided when the battery is discharged at a rate of 10h to the termination voltage at an ambient temperature of 25 ° C ±2 ° C. The actual capacity is greatly affected by discharge ratio and ambient temperature.

(1) Discharge ratio characteristics of the capacity of lithium iron phosphate batteries

Fig. 3 shows the changes of discharge capacity of lithium iron phosphate battery under different discharge ratios. The discharge capacity of the same battery decreases with the increase of discharge ratio. This is because with the increase of discharge current, the polarization trend of the battery is more obvious, which leads to the increase of internal resistance of the battery and the decrease of the output capacity. But the multiplier discharge characteristics of lithium iron battery is good, even if the figure of 20C discharge, still can give off more than 92% of the electric quantity, the production process of mature manufacturers discharge proportion is greater. This is one area where lithium iron phosphate batteries have an advantage over lead-acid batteries.

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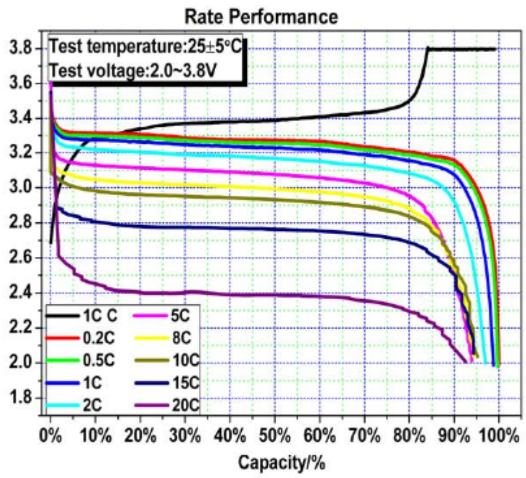

Fig. 3 Discharge ratio characteristic curve of capacity

(2) Environmental temperature characteristics of the capacity of lithium iron phosphate batteries

Fig. 4 shows the characteristic curve of discharge capacity of lithium iron phosphate battery with the change of ambient temperature. It can be seen that the actual discharge capacity of lithium iron phosphate batteries increases with the increase of ambient temperature. This is mainly because with the increase of ambient temperature, the viscosity of electrolyte inside the battery decreases, the activity increases, the ion diffusion ability increases, and the actual capacity of the battery increases. However, it can also be seen that the low temperature performance of lithium iron phosphate batteries is poor, the discharge voltage drops at low temperature, the discharge time becomes shorter, and especially the discharge capacity is greatly reduced. Battery capacity is positively correlated with temperature.

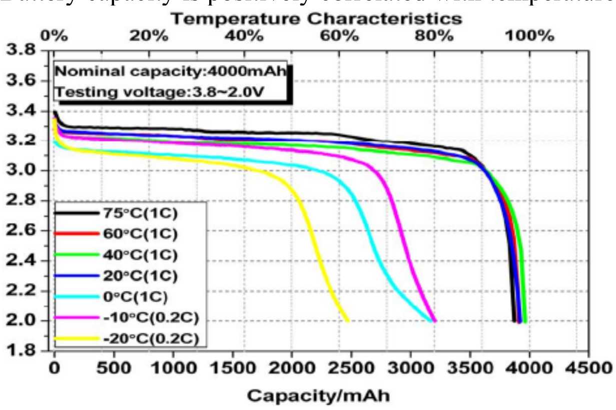

Fig. 4 Ambient temperature characteristic curve

4 Simulation analysis

Comparison of temperature characteristics between lead-acid battery and lithium battery: At 55℃, 100 Ah lead-acid battery cycled by 0.1C(10A) current for 130 times, and the remaining capacity of the battery accounted for 65.2% of the initial capacity. The 100 Ah lithium battery is charged and discharged 1062 times with 0.4C(40A) current, and the remaining capacity of the battery accounts for 74.7% of the initial capacity. Nine times the size of a lead-acid battery.

Tab. 1 Comparison results of discharge characteristics of lead-acid and lithium batteries at different temperatures

discharge temperature	Discharge capacity of lead-acid battery	Discharge capacity of lithium batteries
50℃	78%	101.80%
20℃	68%	100%
10℃	62%	96.80%
0℃	58%	86.30%
-10℃	50%	50.00%
-20℃	40%	31.60%
10℃	62%	96.80%
0℃	58%	86.30%
-10℃	50%	50.00%
-20℃	40%	31.60%

As can be seen from the table, at room temperature, the same discharge temperature, lithium battery discharge capacity is much higher than lead-acid battery. Therefore, lithium ion battery has obvious advantages, such as small size, light weight, high energy ratio, environmental protection, easy maintenance, good charging characteristics, discharge characteristics and cycle performance, and is very suitable for small energy storage system. In contrast, traditional lead-acid batteries have a small energy-to-weight ratio, large internal resistance, large self-discharge current, complex maintenance, good ventilation (in case of fire caused by the accumulation of hydrogen released), and poor seismic performance. So, it is imperative to popularize the application of lithium iron phosphate battery in substation power supply.

5 Conclusion

It is an inevitable trend for substation to use backup power for maintenance, especially for dc power system with high power supply requirements. Commercial lithium-ion batteries so far has more than 40 years, compared with the mature technology of lead-acid battery, more than 170 years of its many aspects still need development and progress, represented by the lithium iron phosphate battery of new type of lithium battery energy saving, economy, convenience, and the application of the concept of reliability stand with dc power supply system maintenance and improve power supply reliability of the power grid is of great significance. With the maturity of lithium iron phosphate battery technology and the decrease of its price, it is expected to replace lead acid battery as the preferred battery for substation backup power supply.

Acknowledgments

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