Analysis of electric-heat characteristics and power storage capacity of emergency power supply in substation based on energy saving and environmental friendly materials

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Abstract. With the continuous increase of DC power system of substation, DC emergency power supply is needed for technical transformation and troubleshooting of DC power supply system. In order to study the ideal backup tool of DC power supply with light weight, small volume and easy to carry, and guarantee safety and stability of the renovation of substation dc system, this paper studies the ternary lithium ion battery with the advantages of large capacity and small volume. The paper intends to master the heating and cooling conditions of ternary lithium-ion batteries in charging and discharging process. Then, the feasibility application in substation emergency power supply of ternary lithium ion battery is analysed. The example results prove that the use of ternary lithium ion battery could meet the demand of using a variety of scenarios of transformer substation, and improve the reliability of dc power supply system.

1. Introduction
DC power supply system is the core of secondary equipment in substation. And the battery, which is an important part of DC system, is the last line of defense to guarantee the reliability of DC power system. Traditional DC emergency power supply usually relays on lead-acid battery, but its size and quality disadvantage make it difficult to realize the portability and mobility of DC emergency power supply. The development of mobile DC power supply system itself is a kind of innovation, but there are few researches on DC system specifically for substation.

At present, the new environmentally friendly material lithium ion battery is the important direction of modern substation high safety. However, few researches on high nickel 8112Li Ni Co Mn O. Most substations in China use lead-acid batteries, which leads to leakage, acid fog, pollution and maintenance difficulties. Ternary material, such as Xy Z2\Li Ni Co Mn O with high specific energy, has become a research and application hotspot. In order to solve the application problem of high-nickel ternary lithium ion battery in substation, it is very important to ensure the safety and operation of lithium ion battery with high storage capacity.

In this paper, the entropy variation characteristics of the anode and cathode of NCM811/C lithium ion battery are firstly analysed. Secondly, the electro-thermal coupling model of NCM811/C lithium ion battery was established, and the heat generation and exothermic characteristics of the battery during charging and discharging were discussed. Finally, the advantages of new material battery and conventional lead-acid battery in electric storage are obtained through experiments.
2. The Analysis of entropy heat change for ternary lithium ion battery

The reversible heat of the battery mainly depends on entropy change, which is shown in Equation 1:

\[ \Delta S = nF \left( \frac{dU}{dt} \right) \] (1)

where, the n of the lithium ion battery is taken 1;

The entropy change of the whole battery is the sum of the entropy change of the positive pole and the negative pole. The measured entropy change above corresponds to the reduction reaction of the positive pole and the oxidation reaction of the negative pole. Therefore, the inversion symbol is needed when the entropy change of the positive and negative pole is used to calculate the entropy change of the whole battery.

\[ \Delta S_{\text{full}} = \Delta S_{\text{NCM811, reduction}} + \Delta S_{\text{graphite, oxidation}} = \Delta S_{\text{NCM811, reduction}} - \Delta S_{\text{graphite, reduction}} \] (2)

It is necessary to reverse the symbol when calculating the change of battery life with the change of anode and cathode.

3. Thermoelectric coupling characteristics of ternary lithium ion batteries

3.1. Conservation of charge

3.1.1. The solid phase

The conservation equation of solid phase lithium ion charge is given by the following equation:

\[ \nabla \left( -\sigma_1^{\text{eff}} \nabla \phi_1 \right) = -S_\alpha j_{\text{loc}} \]

\[ S_\alpha = \frac{3\varepsilon_i}{r_p}; \sigma_1^{\text{eff}} = \sigma_1 \varepsilon_1^{n_1} \] (3)

where, \( \nabla \) is Laplace operator; \( \sigma_1 \) is the solid phase conductivity; \( \phi_1 \) is the solid phase potential; \( S_\alpha \) is the specific surface area of the porous electrode; \( j_{\text{loc}} \) is the local current density; \( \varepsilon_i \) is the volume fraction of solid phase; \( r_p \) is the particle radius of the active substance; \( \gamma_1 \) is the solid phase Bruggeman coefficient.

3.1.2. The liquid phase

The charge conservation of lithium ion in electrolyte is given by the following formula:

\[ \nabla \left[ -\sigma_2^{\text{eff}} \nabla \phi_2 + \frac{2RT \sigma_2^{\text{eff}}}{F} \left( 1 + \frac{\partial \ln f_z}{\partial \ln c_2} \right) \left( 1 - t_z \right) \nabla \left( \ln c_2 \right) \right] = S_\alpha j_{\text{loc}} \]

\[ \sigma_2^{\text{eff}} = \sigma_2 \varepsilon_2^{\gamma_2} \] (5)

where, \( \sigma_2 \) is the liquid phase conductivity; \( \phi_2 \) is the liquid phase potential; \( \varepsilon_2 \) is the liquid phase volume fraction; \( F \) is Faraday constant; \( t_z \) is the migration number of lithium ions; \( T \) is the thermodynamic temperature; \( f_z \) is the average molar activity coefficient; \( c_2 \) is liquid electrolyte concentration; \( \gamma_2 \) is the Bruggeman coefficient of liquid phase.

3.2. Conservation of mass

3.2.1. The solid phase

The mass conservation law of lithium ions in intercalated particles of active materials of lithium ion batteries can be described by Fick’s Second Law, and the mass transfer in solid phase can be expressed
by the following formula:
\[
\frac{\partial c_i}{\partial t} + \frac{1}{r_2} \frac{\partial}{\partial r} \left(-r^2 D_i \frac{\partial c_i}{\partial r} \right) = 0
\]  
where, \(c_i\) is the solid phase lithium ion concentration; \(D_i\) is the diffusion coefficient of lithium ion in solid phase; \(r\) is the radial distance of particles.

3.2.2. The liquid phase
The liquid mass conservation equation of lithium ion battery is given by the following equation:
\[
\varepsilon_2 \frac{\partial c_{z^2}}{\partial t} + \nabla \cdot \left(-D_{z^2}^{\text{eff}} \nabla c_{z^2} \right) = \frac{S_{\text{a,loc}}}{F} \left(1 - t_+ \right)
\]  
(8)
\[
D_{z^2}^{\text{eff}} = D_{z^2} \varepsilon_2
\]  
(9)
where, \(D_{z^2}\) is the diffusion coefficient of lithium ion in the liquid phase.

3.3. Electrode process dynamics
The local current density is solved by the Bulter-Volmer equation:
\[
j_n = j_0 \left[ \exp \left( \frac{\alpha_a F}{RT} \eta \right) - \exp \left( -\frac{\alpha_c F}{RT} \eta \right) \right]
\]  
(10)
where, \(\alpha_a\) and \(\alpha_c\) are the transfer coefficients; \(\eta\) is overpotential; \(j_0\) is the exchange current density. The exchange current density can be calculated by the following formula:
\[
j_0 = F k_0 \varepsilon_2 \alpha_a \left( c_{1,\text{max}} - c_{1,\text{surf}} \right)^{\alpha_a} c_{1,\text{surf}}^{\alpha_a}
\]  
(11)
\[
\eta = \varphi_1 - \varphi_2 - U_i
\]  
(12)
where, \(k_0\) is the reaction rate; \(c_{1,\text{max}}\) is the maximum concentration of solid lithium ion; \(c_{1,\text{surf}}\) is the surface concentration of solid lithium ion. Electrode overpotential is shown as the difference between electrode potential and equilibrium potential, which can be given by the following formula. where: \(U_i\) is the equilibrium voltage of the solid phase electrolyte.

3.4. Conservation of energy
The heat generating part of the battery is simplified into three parts, namely, reversible electrochemical reaction heat, irreversible polarization heat and irreversible ohm heat, which are expressed as follows:
\[
\rho C_p \frac{\partial T}{\partial t} = \lambda \nabla^2 T + q
\]  
(13)
\[
q = q_{\text{rea}} + q_{\text{act}} + q_{\text{ohm}}
\]  
(14)
\[
q_{\text{rea}} = S_{\text{a,loc}} \frac{\Delta S}{F}
\]  
(15)
\[
q_{\text{act}} = S_{\text{a,loc}} \eta
\]  
(16)
\[
q_{\text{ohm}} = -i_1 \nabla \varphi_1 - i_2 \nabla \varphi_2
\]  
(17)

4. The Boundary conditions
Convection heat transfer exists outside the battery and in the environment. The boundary conditions are as follows:
(18)

where, the heat transfer coefficient is set at 10W/ \((m^2 \cdot K)\), and the ambient temperature was set at 298.15K (25℃). The outer boundary of the positive electrode is set as constant working current, and the outer boundary of the negative electrode is defined as 0 potential in the discharge process, and the outer boundary of the positive electrode is 4.3V.

The open circuit voltage of a battery is a function of temperature and SOC:

\[
U_{\text{eq}} = U_{\text{ref}} + \frac{dU}{dt} \left( T - T_{\text{ref}} \right)
\]

(19)

The solid phase diffusion coefficient conforms to the Arrhenius equation:

\[
D_1(T) = D_{1,\text{ref}} \exp \left[ \frac{E_{\text{ah}}}{R} \left( \frac{1}{T_{\text{ref}}} - \frac{1}{T} \right) \right]
\]

(20)

The liquid phase diffusion coefficient is a function of concentration and temperature:

\[
D_2(c_2, T) = 10^{[-4.43-\frac{54}{T-229-5.0.001c_2}-0.22+0.001c_2]-4}
\]

(21)

The reaction rate constant conforms to the Arrhenius equation:

\[
k_0(T) = k_{0,\text{ref}} \exp \left[ \frac{E_{\text{ah}}}{R} \left( \frac{1}{T_{\text{ref}}} - \frac{1}{T} \right) \right]
\]

(22)

5. Simulation analysis

The experimental system used in this paper is a self-built experimental system using a combination of high and low temperature test box, charge and discharge test system and temperature meter.

5.1. Test Methods

As shown in Figure 1, the main function of this experimental system is to control the test temperature by using a high and low temperature test box, and test the battery's current, voltage and capacity and other parameters during the charging and discharging process by using a charge-discharge tester. Then, the battery's temperature is measured during the test process by using a channel temperature recorder. The control temperature range of high and low temperature test chamber is from -30℃ to 300℃.

![Experimental system structure diagram](image)

Figure 1. Experimental system structure diagram: (a)Physical map; (b)Schematic diagram

5.2. Determination of single entropy heat coefficient of ternary lithium ion battery

By analysing the experimental data, the entropy heat coefficient diagrams are shown in Fig. 2. As shown in Figure 2(a), the change range of entropy heat coefficient of graphite/ Li semi-cell is from -
0.215 to 0.38 m V/K. The entropy heat coefficient (D U/ D T) is closely related to SOC. The entropy heat coefficient of the battery is positive between 0%SOC and 20%SOC, indicating that endothermic reaction occurs in the battery within this area, and negative between 30%SOC and 100%SOC, indicating that exothermic reaction occurs in the battery within this area. At 50%SOC, an obvious exothermic peak appears and reaches its maximum value. The reason for this phenomenon is mainly related to the structural transformation of graphite. As shown in Fig. 2(b), the entropy heat coefficient of 8112Li Ni Co Mn O/ Li half battery ranges from 0.05 to -0.04 m V/K. The battery entropy heat coefficient is positive between 0%SOC ~ 30%SOC, indicating that the battery has endothermic reaction within this area, and negative between 40%SOC ~ 100%SOC, indicating that the battery has exothermic reaction within this area. It can also be seen that the change range of entropy heat coefficient is small compared with Graphite/Li, which shows that the positive electrode materials have little influence on temperature.

Figure. 2 Entropy heat coefficient of positive and negative half-cells under different SOC conditions: (a) Negative electrode; (b) Positive electrode

5.3. Effect of multiplier on heat generation and heat transfer of ternary lithium ion battery

Fig. 3 shows the change curves of reaction heat, polarization heat, Ohm heat and total heat of the battery in the discharging process. Fig. 3 (a) and (b) show the heat release curves at 0.2C and 0.5C ratios. It can be seen at this stage, because of the small current, battery ohm heat and heat of reaction is small. At this case, the battery heat of reaction is occupied the main part of the heat change battery, and heat release trend of batteries and batteries also change heat of reaction is consistent. The cause of this phenomenon is the battery temperature change is small, which causes the battery internal
resistance is affected by the temperature change is lesser also. When increasing ratio of battery, as shown in figure 3 (c) and (d), the battery of irreversible heat or ohm heat and polarization hold on the battery thermogenesis, most battery of reversible heat the heat of reaction occupies smaller part of the heat production.

5.4. Discharge characteristics of lithium batteries

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.

![Figure 4](image)

Figure 4 Comparison of discharge characteristics of lead acid battery and lithium battery at different temperatures

As can be seen that 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, environmentally friendly, easy maintenance, good charging characteristics, discharge characteristics and cycle performance. So, it is very suitable for small energy storage system. Therefore, it is imperative to popularize the application of ternary lithium ion battery in substation power supply.

6. Conclusion

i. Taking the advantages of the high-power density of ternary lithium battery, the product is light in weight, easy to carry, could achieve large current impact, and more convenient for maintenance. The application of new material concepts of energy saving, economy, convenience and reliability is of great significance to realize the maintenance of station DC power supply system and improve the power supply reliability of power grid.

ii. During the charging process of rechargeable battery components, heat release is the inverse process of partial discharge. The influence on the surface temperature of the battery is that surface temperature as the environment gradually reduces the influence of convection, which may explain why the battery charging process of the highest temperature is lower than the highest temperature in the process of discharge.

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