On-line charging and discharging control of lithium ion battery

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Abstract. In order to use lithium battery as energy storage device in DC operating power supply system, and optimize the performances of lithium ion battery such as efficiency, etc., an on-line charging and discharging control scheme for lithium ion battery in DC operating power supply is proposed. Firstly, the internal equivalent state of lithium ion battery is estimated by the output voltage and current of lithium ion battery. Secondly, the expected charging and discharging state and current value of lithium ion battery is determined by the internal equivalent state of lithium ion battery. Finally, the output voltage of AC/DC converter is adjusted according to the internal equivalent state of lithium ion battery and the expected charging and discharging state and current value. The actual charging and discharging current of lithium ion battery is forced to tend to the expected current value, so as to optimize the performances of lithium ion battery. Theoretical analysis and case study show that the scheme is feasible.

1. Introduction
The advantages of lithium ion battery [1] make it an excellent energy storage device. In order to fully extend its life and give full play to its excellent performance, some appropriate control strategies should be adopted to manage and control its charging and discharging process [2]. The internal state and parameter estimation of battery is the basis of battery charging and discharging control. At present, a lot of work has been focused on battery modelling [3], state of charge (SOC) estimation and parameter identification [4-6], but most of them have the conflict between estimation accuracy and calculation complexity. Lithium ion battery has better energy storage characteristics [7-8], and is currently used in vehicle DC power supply system [9] as vehicle power battery. Compared with the lead-acid battery in the traditional DC operating power supply system [10], lithium ion battery has different operation modes. Generally, there are switching operation to realize the conversion of charging operation state and discharging operation state, which is not suitable to be directly used in the traditional DC operating power supply system. The state estimation algorithm of precise model of lithium ion battery is very complex [11-13], which can be used in battery performance evaluation and battery management system generally. But at present, it is not practical in the on-line charging and discharging control of lithium ion battery because of its high computational complexity, poor real-time performance and high implementation cost. This paper attempts to make the operation state of the battery in the DC operating power supply system similar to that of the battery in the vehicle power
system through appropriate control strategies, so as to investigate the feasibility of using lithium ion battery as energy storage device in the DC operating power supply system.

2. On-line charging and discharging system of lithium ion battery

2.1. System composition

The on-line charging and discharging lithium ion battery DC power system is composed of AC/DC converter, unidirectional isolation diode D, lithium ion battery pack (equivalent to electromotive force $e_c$ and internal resistance $r_c$), detection and control unit and electric load $r_{1d}$ / discharge load $r_{1d}$, as shown in Figure 1. In Figure 1, $u_{in}$ is the AC input voltage, $u_{dc}$ is the output voltage of AC/DC converter, $u_o$ is the output voltage of DC power system, $i_o$ is the output current of DC power system, $i_c$ is the charging and discharging current of lithium ion battery, and $i_{ld}$ is the load current. AC/DC converter can take use of the traditional DC operating power supply system with external controlling signal $u_g$.

2.2. System control scheme

The function of the AC/DC converter is to continuously output the DC voltage $u_o$ which fluctuates within a certain range around the rated voltage $u_{oc}$, namely $u_{omin} ~ u_{omax}$. In order to ensure the safe and reliable operation of AC/DC converter, the output current $i_o$ should be limited within its rated current $I_{oc}$. When using lithium ion battery as the energy storage device of DC power system, in order to optimize the cycle-life, safety and other performances of lithium ion battery, the operation state of lithium ion battery can be divided into cycle operation processes such as charging stage ①, static stage with charging ②, discharging stage ③ and static stage with discharging ④ in sequence, that is to say, the on-line charging and discharging current curve of lithium ion battery should be as shown in Figure 2 to optimize the comprehensive performance. Among them, charging stage ① and static stage with charging ② are the main states of lithium ion battery in DC operating power system, while discharging stage ③ and static stage with discharging ④ are the checking discharge behaviours with longer period. In Figure 2, the duration of each stage, as well as the expected charging and discharging current value during charging and discharging are related to the specific battery model, the battery state and the requirements for comprehensive performance optimization of battery, etc., which need to be set pertinently. This paper will not focus on it.

Considering the characteristics of AC/DC converter and lithium ion battery, the output voltage $u_{dc}$ of AC/DC converter is adjusted properly by the control of detection and control unit, and the timely switching of electric load/discharge load, so as to force the actual charging and discharging process of lithium ion battery and the actual charging and discharging current of lithium ion battery to follow the expected charging and discharging current curve. The detection and control unit determine the output voltage of AC/DC converter in different stages according to the output voltage and current of DC power system and the output voltage and current of lithium ion battery, and then convert it to the
external control signal $u_k$ which given to AC/DC converter. The AC/DC converter adjusts its output voltage $u_{o_1}$ to the expected output voltage according to the external control signal $u_k$, so as to force the actual charging and discharging process of lithium ion battery and the actual charging and discharging current of lithium ion battery to the expected charging and discharging current curve when the comprehensive performance is optimized.

3. On-line charging and discharging control algorithm of lithium ion battery

3.1. Charging control
In the charging stage of lithium ion battery, AC/DC converter charges lithium ion battery as fast as possible under the premise of ensuring its own safety and improving comprehensive performance of lithium ion battery. The output voltage of AC/DC converter should make the charging current of lithium ion battery tend to the expected value of charging current as far as possible, but it is limited by the rated output current of AC/DC converter. In order to force the AC/DC converter to output the expected voltage, the detection and control unit gives corresponding control signal $u_k$ to control the output voltage of AC/DC converter according to Formula (1) in the charging stage of lithium ion battery.

$$u_{o_1}(k+1) = \begin{cases} e_c(k) + U_{dth}, & \text{if } u_o(k) < e_c(k) \\ \min \left\{ I_{cm} r_c(k) + e_c(k), \frac{I_{oe} + e_c(k)}{r_c(k)} \right\} + U_{dth}, & \text{if } e_c(k) \leq u_o(k) \leq U_{o\text{max}} \\ U_{o\text{max}} + U_{dth}, & \text{if } u_o(k) > U_{o\text{max}} \\ u_{o_1}(k), & \text{others} \end{cases}$$

Where, $k$ is the discrete value of time $t$, $U_{dth}$ is the dead zone voltage of unidirectional isolated diode $D$, and $I_{cm}$ is the maximum charging current value allowed for lithium ion battery charging.

3.2. Control of static stage with charging
In the static stage with charging of lithium ion battery, the output voltage of DC power supply system should be within the allowable fluctuation range around rated output voltage, namely $U_{o\text{min}} \sim U_{o\text{max}}$, and the charging and discharging current of lithium ion battery should be zero. In order to make the lithium ion battery in the static stage with charging, the detection and control unit outputs corresponding control signal to control the output voltage of the AC/DC converter according to Formula (2).

$$u_{o_1}(k+1) = \begin{cases} U_{o\text{max}} + U_{dth}, & \text{if } u_o(k) > U_{o\text{max}} \\ U_{o\text{min}} + U_{dth}, & \text{if } u_o(k) < U_{o\text{min}} \\ u_{o_1}(k) - I_c(k)r_c(k), & \text{if } U_{o\text{min}} \leq u_o(k) \leq U_{o\text{max}} \\ u_{o_1}(k), & \text{others} \end{cases}$$

3.3. Discharging control
In the discharging stage of lithium ion battery, there are two kinds of discharging state according to whether the AC/DC converter is needed to intervene the discharging. When the electromotive force of lithium ion battery is high and the discharge current of lithium ion battery may exceed the maximum allowable discharging current, the AC/DC converter outputs a relatively high voltage to suppress the discharging current of lithium ion battery. When the electromotive force of lithium ion battery is low and the discharging current of lithium ion battery is impossible to exceed the allowable maximum discharging current, the AC/DC converter exits the intervention, the lithium ion battery will discharge naturally according to the discharging load, and the output voltage of AC/DC converter only follows the output voltage of lithium ion battery, so as to improve the quick response ability when the charging and discharging system switches to the next new stage. In the discharging stage of lithium ion battery,
the detection and control unit outputs corresponding control signal to control the output voltage of AC/DC converter according to Formula (3).

\[
    u_{o1e}(k + 1) = \begin{cases} 
        e_c(k) + U_{dth}, & \text{if } u_o(k) > e_c(k) \\
        \frac{r_fz(k)}{r_c(k) + r_fz(k)} e_c(k) + U_{dth}, & \text{if } u_o(k) \leq e_c(k) \text{ and } \frac{e_c(k)}{r_c(k) + r_fz(k)} \leq -I_{dm} \\
        I_{cmin} r_c(k) + e_c(k) + U_{dth}, & \text{if } u_o(k) \leq e_c(k) \text{ and } \frac{e_c(k)}{r_c(k) + r_fz(k)} > -I_{dm} \\
        \frac{I_{oee} e_c(k)}{r_c(k) + r_fz(k)}, & \text{if } I_{dm} r_c(k) + e_c(k) \leq \frac{I_{oee} e_c(k)}{r_c(k) + r_fz(k)} \\
        u_{o1}(k), & \text{others} 
    \end{cases}
\]

Where, \( I_{dm} \) is the maximum allowable discharging current value of lithium ion battery during discharge.

When the discharge of lithium ion battery reaches the residual EMF \( u_{cmin} \) according to the discharge depth, the discharge is stopped, and the corresponding control signal is given by the detection and control unit to control the AC/DC converter to limit the output voltage according to Formula (4).

\[
    u_{o1e}(k + 1) = U_{cmin} + U_{dth}, \text{if } e_c(k) < U_{cmin}
\]

3.4. Control of static stage with discharging

In the static stage with discharging of lithium ion battery, the charging and discharging current of lithium ion battery should be zero, and the detection and control unit outputs corresponding control signal to control the output voltage of AC/DC converter according to Formula (5).

\[
    u_{o1e}(k + 1) = \begin{cases} 
        u_{o1}(k) - i_c(k) r_c(k), & \text{if } i_c(k) \neq 0 \\
        u_{o1}(k), & \text{if } i_c(k) = 0 
    \end{cases}
\]

3.5. Control signal determination of detection and control unit

After determining the voltage \( u_{o1e}(k+1) \) that should be output in the next step of each phase by AC/DC converter, the external control voltage signal \( u_g(k) \) should be supplied by the detection and control unit according to Formula (6).

\[
    u_g(k) = \frac{u_{o1e}(k+1) - u_{o1}(k)}{K_u}
\]

Where, \( K_u \) is the ratio coefficient of the output voltage \( u_{o1} \) regulated by the external control voltage signal \( u_g \) of AC/DC converter.

3.6. State and parameter estimation of lithium ion battery

In the process of lithium ion battery charging and discharging control, when the detection and control unit outputs appropriate control signal to control the output voltage of AC/DC converter, the equivalent electromotive force \( e_c(k) \) and the equivalent internal resistance \( r_c(k) \) of lithium ion battery are required, which can’t be obtained directly through detection. It can be estimated approximately according to the detection values of the output voltage and current of lithium ion battery. In order to improve the feasibility and reduce implementation costs, the \( e_c(k) \) and \( r_c(k) \) can be approximately estimated according to Formula (7) and Formula (8), respectively.

\[
    r_c(k) \cong \frac{u_c(k) - u_o(k-1)}{i_c(k) - i_c(k-1)}
\]

\[
    e_c(k) \cong \frac{i_c(k) u_o(k-1) - i_c(k-1) u_o(k)}{i_c(k) - i_c(k-1)}
\]
4. Example analyses
Aiming at the DC operating power supply system with on-line charging and discharging of lithium ion battery for transformer substations, the controllability of on-line charging and discharging current of lithium ion battery is verified through case analysis, which proves the feasibility of optimizing the comprehensive performance of lithium ion battery by controlling the actual charging and discharging current of lithium ion battery, and this provides a basis for using lithium ion battery as energy storage device in DC operating power supply system. The main parameters of the example system are shown in Table 1, and the analysis results of the example system are shown in Figures 3-7.

Table 1. Main parameters of the example system.

| rated voltage (V) | Voltage accuracy | rated charging current (A) | discharging current (A) | discharging load (Ω) |
|-------------------|-----------------|---------------------------|-------------------------|----------------------|
| 300               | ±0.2%           | 30                        | 30                      | -30                  | 10                   |

Figure 3 shows the load of DC power system in the example analysis, considering the conditions of gradual loading, sudden loading, gradual unloading, sudden unloading, switching to discharging load, low frequency fluctuation of load, high frequency fluctuation of load, etc., almost involving various load conditions that may occur in the actual operation of DC power system, so as to comprehensively inspect the effect of the on-line charging and discharging control of lithium ion battery.

Figure 4 shows the expected charging and discharging process of lithium ion battery, the charging and discharging current curve $i_{cq}(t)$ and the actual charging and discharging current $i_c(t)$. It can be seen from the figure that under the control of detection and control unit, the charging and discharging process of lithium ion battery is carried out in strict accordance with the expected order of charging stage, static stage with charging, discharging stage and static stage with discharging. The start-up time of each stage is strictly consistent with the expected time. The charging and discharging stage is carried out according to the limit conditions of charge and discharge until the charge and discharge reaches the completion state. In the static stage, the charging and discharging current is very small. In the charging stage, the charging current is sometimes smaller than the expected maximum charging current because of the limitation of the rated output current of the AC/DC converter. In the discharging stage, the partial discharging current is less than the expected maximum discharging current, which is caused by the lower equivalent electromotive force of lithium ion battery and the relatively large load during discharge. If want to discharge more quickly, the load can be switched to a corresponding discharging load.

![Figure 3. Load of DC power system.](image1)

![Figure 4. Charging and discharging current control of lithium ion battery.](image2)

Figure 5 shows the output current $i_d(t)$, charging and discharging current $i_c(t)$ and load current $i_{ld}(t)$ of the DC power supply system with the on-line charging and discharging control of lithium ion battery. It can be seen from the figure that the results are consistent with the expected values and limiting conditions of lithium ion battery charging and discharging control, and can reach the purpose of approaching the expected charging and discharging current curve as much as possible under the
condition of not exceeding the limiting conditions. It shows that the comprehensive performance of lithium ion battery can be optimized as much as possible under the condition of ensuring the normal output voltage of DC power system.

Figure 6 shows the output voltage of AC/DC converter and DC power system when the lithium ion battery is charged and discharged according to the expected current curve. It can be seen from the figure that the difference between the two is the dead zone voltage value of an isolation diode, and the changing process of the voltage is completely consistent with the whole process of charging stage, static stage with charging, discharging stage and static stage with discharging of the expected current curve, and the actual output voltage value of each stage is consistent with the expected output value, which is in line with the demand of the DC operating power supply system controlled by the on-line charging and discharging of lithium ion battery.

Figure 5. Current situation in the system. 

Figure 6. Output voltage of AC/DC converter and DC power system.

Figure 7 shows the efficiency of lithium ion battery with or without the control of on-line charging and discharging. In Figure 7, \( \eta(t) \) is the efficiency with the control of on-line charging and discharging, and \( \eta_N(t) \) is the efficiency without the control of on-line charging and discharging. It can be seen from the figure that the efficiency \( \eta(t) \) is higher in other periods except for the start-up phase of DC power system. It shows that the charging and discharging efficiency of lithium ion battery and the efficiency of DC power supply system can be improved by controlling the charging and discharging current of lithium ion battery in the static stage to zero. This is because in the on-line charging and discharging system of lithium ion battery, as an energy storage device, lithium ion battery works in the static stage with charging most of the time, and the charging and discharging current tends to zero, so the electric energy consumed by the internal resistance of lithium ion battery is very small, so the system efficiency is high.

Figure 7. Efficiency of lithium ion battery in the DC system.

5. Conclusions
Through the on-line charging and discharging control of lithium ion battery, the charging and discharging process of lithium ion battery and the charging and discharging current of lithium ion battery can be forced to run according to the expected charging and discharging current curve, so that
the operation state of lithium ion battery can be flexibly controlled on-line. Not only can lithium ion battery be used as the energy storage device in the DC operating power supply system, but also the comprehensive performance of lithium ion battery can be optimized on-line, so as to ensure the safe operation and prolong the cycle-life of lithium ion battery. The battery in DC operating power supply system mainly runs in the state of charging stage and static stage with charging. As long as the appropriate control scheme is applied, lithium ion battery can obviously be used as the energy storage device. The on-line charging and discharging control of lithium ion battery and the determination of the expected charging and discharging current curve need to use the real-time equivalent state of lithium ion battery, and the accurate state estimation algorithm is often complex, which affects the system's feasibility and realization cost. The high cost-effective optimization strategy of comprehensive performance and on-line control algorithm of charging and discharging for lithium ion battery are expected by the engineering community, and will be the next research content.

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