Research on Equalization Control Strategy of Marine Lithium Battery Pack

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Abstract. With the widespread use of clean energy in ship electric power systems, marine lithium battery systems are becoming more and more popular. Aiming at the problems between the individual cells in the lithium battery pack, such as inconsistency in voltage, capacity, and internal resistance, the state of charge (SOC) of battery is selected as the equalization control variable, an equalization topology structure based on SOC for battery connecting or bypassing is designed. The equilibrium control strategy fusing model predictive control (MPC) algorithm and time-sequence control algorithm is adopted. The simulation model is built on the MATLAB/Simulink platform, and the different value combinations of two equalization parameters (i.e., equalization period $T$ and number of batteries connected to the battery pack $q$) were simulated and analyzed. The results show that the designed equalization control strategy can quickly and accurately achieve SOC equalization, by optimizing two key parameters, the equalization accuracy and equalization speed of the marine lithium battery pack can be improved, also the energy loss in the equalization process can be reduced.

1. Introduction
Countries around the world are vigorously developing clean energy, and the shipping industry is also making continuous efforts in the direction of energy saving and environmental protection, and putting clean energy into ships for use [1]. Lithium batteries have become more and more popular with ship electric power systems because of their high energy density, low self-discharge rate, and environmental friendliness [2]. At present, some ships have adopted all-electric power. As shown in Figure 1, a green ship containing a marine lithium battery pack is shown.

Figure 1. Green ships containing marine lithium battery packs.
Due to the low working voltage and small capacity of lithium batteries, in order to meet the high voltage and large capacity requirements of the ship's power system, multiple single lithium batteries are usually combined into lithium battery packs in series and parallel, and large-scale arrays design is carried out to provide enough energy for the ship [3]. However, after group use, lithium batteries will aggravate the problem of voltage and capacity inconsistency between individual batteries, which will eventually shorten the service life of the battery, reduce the overall performance of the battery pack, and even cause safe accidents [4]. In the current research, most researchers solve the inconsistency of lithium battery packs by equalization topology structure and equalization strategies [5].

Aiming at the problems of slow equalization rate, low efficiency, and high system loss in current equalization methods, this paper designs a equalization topology that switches batteries based on the SOC of single cells, and the corresponding equalization control strategy based on algorithm fusion.

2. Lithium battery pack equalization system structure

This paper designs a equalization topology that switches on and off according to the SOC of a single battery, as shown in Figure 2. The battery $C_i$ ($i=1,2,...,n$) is connected in series to form a battery pack through the switches $(S_i', S_i)$ that reverse the control signals by $i$, and is connected in parallel with the bidirectional DC-DC converter, its output voltage $V_{DC}$.

The above structure can control the charge and discharge capacity of each single battery by controlling the on-off state of the switch, and finally make the SOC of each single battery tend to be consistent.

3. Equalization control strategy

Due to the similarities between the two charging and discharging modes of lithium battery packs, this article mainly introduces the equalization control strategy designed in the discharge mode.

3.1. Model predictive control algorithm

To allocate the connection time of each single battery in the equalization period, this paper adopts the Model Predictive Control (MPC) algorithm[6]. Under the condition of non-linear constraints, the optimal ratio $\omega_1, \omega_2,...,\omega_n$ is calculated, the introduction of the MPC algorithm is as follows. Assuming that the equalization period is $T$ and the prediction step size is 1, the prediction model is shown:

$$
\begin{bmatrix}
    SOC_i(s+1) \\
    SOC_i(s+1) \\
    \vdots \\
    SOC_i(s+1)
\end{bmatrix} = 
\begin{bmatrix}
    SOC_i(s) \\
    SOC_i(s) \\
    \vdots \\
    SOC_i(s)
\end{bmatrix} + 
\begin{bmatrix}
    \omega_1(s) \\
    \omega_2(s) \\
    \vdots \\
    \omega_n(s)
\end{bmatrix} \times \frac{nTAI_p}{C_s}
$$

Among them, $I_{p,n}$ is the current when the battery is fully connected to the current loop, $C_s$ is the battery capacity, $\lambda$ is the coulombic efficiency of the battery, $SOC_i(s)$ is the actual value of the SOC of the $s$-th
step and the i-th battery, \( SOC_i(s+1) \) is the SOC prediction value; \( \omega_i(s) \) is the s-th step, the i-th battery is the proportion of discharge in the equalization period \( T \).

The establishment of the cost function is shown in formula (2):

\[
J_{\text{in}}(s+1) = \sum_{i=1}^{n} \left| SOC_i(s+1) - \overline{SOC}_i(s) \right|^2
\]  

(2)

Standard Deviation (SD) can describe the degree of dispersion corresponding to the data and reflect the accuracy of the data [7]. The standard deviation calculation formula is shown in (3):

\[
\varepsilon = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( SOC_i(s+1) - \overline{SOC}_i(s) \right)^2}
\]  

(3)

Where \( \overline{SOC}_i(s) \) is the predicted average SOC value of the battery pack, as shown in formula (4):

\[
\overline{SOC}_i(s) = \frac{\sum_{i=1}^{n} SOC_i(s) - nT\lambda I_{p+}}{nC_u}
\]  

(4)

The constraint equation is shown in formula (5):

\[
\begin{align*}
0 & \leq \omega_i \leq \frac{1}{q}, i = 1, 2, \cdots, n \\
\omega_1 + \omega_2 + \cdots + \omega_n & = 1
\end{align*}
\]  

(5)

Convert the above-mentioned optimization problem of nonlinear constraints into a quadratic programming problem for solution, while

\[
r = \frac{nT\lambda I_{p+}}{C_u}
\]  

(6)

Then formula (4) can be simplified into the form of formula (7):

\[
\overline{SOC}_i(s) = \frac{\sum_{i=1}^{n} SOC_i(s) - r}{n}
\]  

(7)

In summary, the smaller the value of the cost function, the better equalization of the lithium battery pack. In practical, when the SOC standard deviation of single cell reaches the set threshold, the above algorithm optimization process, that is, the battery pack balancing process will stop.

### 3.2. Time-sequence control algorithm

Figure 3 is a time-sequence diagram. The fusion time-sequence algorithm can ensure that the number of single cells is constant, thereby eliminating the impact of terminal voltage jumps.

![Figure 3. Schematic diagram of time-sequence algorithm.](image)

The MPC algorithm calculates the optimal discharge ratio \( \omega_1, \omega_2, \ldots, \omega_n \), and according to formula (8), we can figure out the duration \( t_1, t_2, \ldots, t_n \) of each single cell connected to the battery pack.
The discharge current of the DC-DC output terminal is $I_{bus}$, the output voltage is $V_{DC}$, and the average voltage of single battery is $V_{n-avg}$. According to the law of conservation of power, when all single cells are connected to the battery pack, the current through the battery pack is $I_{p,n}$, as shown in formula (9):

$$I_{p,n} = I_{bus} \frac{V_{DC}}{V_{n-avg}} \quad (9)$$

When the number of cells connected to the current loop in the group is $q$, the current through the group of batteries is $I_{p,q}$, as shown in formula (10):

$$I_{p,q} = q \frac{n}{n} I_{p,n} \quad (10)$$

It can be seen from formulas (9) and (10), The fewer the number of single cells, the greater the current through the battery pack. So it should be limited to a certain safety threshold. The range of $q$ is shown:

$$n \frac{I_{n,n}}{I_{m}} \leq q \leq n \quad (11)$$

Define $y$ to be the number of unconnected batteries, so you can get:

$$\begin{cases} y = n - q \\ 0 \leq y < q \leq n \end{cases} \quad (12)$$

Then $\omega$ has the constraints as:

$$\frac{1}{q} (\omega_{1} + \omega_{2} + \ldots + \omega_{y}) \leq \omega_{y+1} \leq \frac{y+1}{q} \quad (13)$$

It should be noted that the change of $I_{p,n}$ during the equalization period $T$ may cause the current $I_{p,q}$ to exceed the safe range, so the given maximum discharge current $I_{m}$ of the lithium battery should be reduced and limit the number of connected single cells $q$ to prevent it from being too small.

### 4. Parameter optimization and simulation analysis

To verify the feasibility of the proposed strategy, this article chooses in MATLAB/Simulink platform to affect the equilibrium system in the performance of the two main parameters (balanced period $T$, access to the battery cell number $q$) analyzes the different value combinations of contrast and parameter optimization. Model parameters are shown in Table 1.

#### Table 1. Simulation model parameters.

| Model parameters                          | Value   |
|------------------------------------------|---------|
| Total number of batteries                | 7       |
| Nominal voltage of single battery        | 3.6V    |
| Single battery charge and discharge capacity | 3.4Ah  |
| Maximum sustainable discharge current    | 5A      |
| Discharge rate                           | 1C      |
| SOC SD threshold                         | 0.002   |

#### 4.1. Optimization and simulation analysis of equalization period $T$

Equilibrium period $T$ the switching loss of the balancing precision and system has an important impact. This paper set the battery number $q$ is 5, discharge rate is 1C, respectively in the 5s, 10s and 20s under three different equilibrium cycle simulation. The simulation waveforms are shown in Figure 4-6.
The results show that, lithium battery pack can achieve SOC equalization. The smaller the standard deviation, the higher equalization precision. Finally, the equalization period $T=10s$ is set.

4.2. Optimization and simulation analysis of the number of connected batteries $q$

The simulation was carried out when the number of single batteries $q$ was 4, 5 and 6 in Figure 7.
According to the simulation results, it shows that the number of batteries $q$ connected to the battery pack is smaller, the required equalization time is shorter, that is, the battery pack equalization speed is faster, which is consistent with the analysis above. Considering the battery string balancing speed and battery life, the number of connected batteries $q$ can be set to five after optimization.

5. Conclusion
This paper designs a monomer battery SOC to proceed with the balance of batteries for topology, using both model predictive control and sequential control algorithm combines the equilibrium control strategy, by studying the equilibrium period $T$ and access of battery cell number $q$ the effects of the two important parameters on the equilibrium and different combination of the two parameters optimization. Simulation results show that the proposed scheme improved the precision of Marine lithium battery pack equilibrium rate and equilibrium, the monomer battery SOC, realize the balance control of Marine lithium battery, at the same time, the balance of the designed topology structure to reduce the energy loss in the process of equilibrium, proved the feasibility of the proposed balancing system structure and control strategy. It provides a reference for further exploring a more flexible and fast equalization control system of Marine lithium battery pack.

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