Energy management strategy of marine lithium batteries based on cyclic life

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Abstract. In recent years, pure electric ship research has become a hot spot in the field of ship research, and lithium battery packs are a major difficulty in the research of pure power ships. Especially the life and safety problems of lithium battery packs seriously affect the future practical application of ships. Therefore, the energy storage system is designed as two sets of lithium battery packs. While increasing the energy of the energy storage system, the power supply of the battery pack is ensured, which not only ensures the safety of the pure electric ship, but also reduces the aging reaction rate of the lithium battery pack. Through the multi-energy ship modeling, specifically related to the control and safe operation of lithium battery packs, a lithium battery pack energy management strategy is provided. The specific scheme is: the model of ship sailing mileage and SOC is established by the theory of energy conservation, the lithium battery aging model is obtained by the lithium battery data of the actual pure electric ship navigation, and the lithium battery pack energy switching based on the mileage aging battery model is proposed. The strategy uses a logic threshold optimization algorithm to reduce the aging rate of the lithium battery pack. Finally, the experimental results show that the lithium battery pack with energy management strategy can perform 400 more navigations when the capacity loss reaches 15% in the same environment. It shows that this strategy is beneficial to improve the cycle life of lithium battery packs.

1. Introduction

With the increasingly severe energy and environmental problems, China has enacted a series of regulations to limit the emissions of ships [1-2] Therefore, pure electric ships are regarded as an important direction for the development of ships in the future because of their advantages of zero emissions and zero pollution. The prospects are widely optimistic. Pure electric ships and pure cars have great differences in battery life and battery life. Ships are generally long-distance sailing. There is no charging station at sea. When the ship is sailing, the mileage range anxiety is more significant than that of the car, and there will be multiple groups. Battery backup, the ship’s navigation conditions in the water is more variable than the car, high temperature, high humidity, wave impact and other issues not only increase the safety risk of lithium batteries, but also greatly reduce the life of lithium batteries. Because ships require large capacity for lithium-ion power batteries, the risk increases exponentially with capacity. Therefore, the method of using lithium battery packs separately not only increases the capacity of lithium batteries, but also increases the safety of maritime navigation. [3]

The development of pure electric ships needs to focus on safety issues and cycle life issues. [4] Many scholars consider the two issues of power lithium batteries from optimizing battery safety structure design and developing full life cycle battery monitoring. A life cycle method is proposed in
reference [5] for evaluating the feasibility of using a small LTO battery. Reference [6] proposes to develop a lithium battery specification based on an electrochemical thermal model generated by a lithium battery. Reference [7] proposes a uniform optimal configuration and power scheduling scheme for different batteries. The paper is based on the actual navigation conditions (temperature, ship speed, remaining lithium battery capacity, etc.) to establish an energy management system with lithium battery pack energy switching strategy. Switching control is performed according to the battery aging rate. Optimize the unreasonable use of the lithium battery pack during the navigation of the ship, reduce the capacity loss rate of the lithium battery pack, and improve the service life of the lithium battery pack. The development cycle in practical applications is short, and it is not necessary to separately develop different lithium batteries, which is more suitable for practical applications.

2. Model of lithium battery
State of charge required for ship sailing mileage
In the course of sailing, the output energy of lithium battery is converted into the energy of sailing [8]. According to the conservation of energy, the other losses of the ship in the course of sailing are neglected. It is assumed that the output energy of lithium battery is equal to the energy consumed by the ship in the course of sailing. Establishment of mathematical model flow chart of endurance mileage 1. As shown in Figure 1, the specific steps are as follows:

2.1. Model of propeller's thrust and torque
During the voyage of the ship, the propeller generates thrust and propels the ship forward. According to the formula (8) and the ship speed, [9] acquired by the ship per second, the propeller speed ratio J is obtained, and then $K_c$ and $K_M$ are obtained according to the propeller water digging characteristic curve. Finally, the relationship between propeller thrust and torque is obtained [10]

\[ J = \frac{V_s (1 - \omega)}{nD} \]  

\[ M = \frac{K_c}{K_M} DT \]  

2.2. Lithium battery pack output energy and ship energy consumption

\[ M_e = K_c M = \frac{9549 P}{n_e} \]  

\[ \Delta E_2 = P \cdot t = \frac{n_e K_c M}{9549} \cdot t \]  

The equation of motion for a twin-screw ship is obtained:
\[(m + \Delta m) \frac{dv}{dt} = 2T(1 - K_i) - K_iv_i^2\]  

5. Estimation of Lithium Battery Energy Consumption:
\[\Delta E_i = U \cdot I \cdot t = U \cdot Q_{bat} \cdot (1 - SOC_i)\]  

6. 2.3. Model of lithium battery State of charge required for ship sailing mileage

It is assumed that during the course of a ship's voyage, all the energy output from the battery is converted into the energy of the ship's hull, and there is no other energy consumption, \(\Delta E_i = \Delta E_2\).

The relationship between the \(SOC_i\) and the mileage of the lithium battery is
\[SOC_i = 1 - \frac{k_v k_d Dn_i t}{9549 k_m U Q_{bat} (1 - K_i)} \left( \frac{m + \Delta m}{t^2} (s - v_o t) + \frac{1}{2} k_v v_i^2 \right)\]  

7. 3. Calculation of aging severity factor for lithium batteries

In the process of charging and discharging lithium batteries, there will be irreversible aging side effects of lithium batteries. The positive electrode of lithium batteries has a SEI film, which will become thicker as the electrolyte liquid decomposes during charging and discharging, resulting in the aging of active Li loss batteries in lithium batteries. A surface film is also formed on the surface of active particles in the negative electrode of lithium battery. During the aging process, the porosity, conductivity and diffusivity of the membranes will decrease due to the deposition of by-products. The ultimate porosity, conductivity and diffusion coefficient decrease, resulting in the reduction of battery capacity. Aging is an irreversible reaction of lithium batteries, which can only reduce the aging reaction rate and improve the service life of lithium batteries. The aging rate of the lithium iron phosphate battery pack at the current time is mainly determined by temperature, soc and discharge rate, and the growth rate of each influence factor on \(\sigma_{map}\) is different. Finding the partial derivative for each factor gives the effect on the degree of aging for each individual factor. Targeted reduction in aging caused by different factors.

8. Figure 2. Battery aging reaction process.

9. 3.1. Lithium battery semi-life model

In this paper, the semi-life model [13] is used to add the actual lithium battery data measured by the ship, and the parameter model of the lithium battery pack is obtained by MATLAB parameter identification. The semi-empirical aging model is the data obtained in a large-scale test of different situations in the laboratory, based on a phenomenological model established from a large amount of data. Based on the physics model, the actual phenomenon of internal diffusion of the battery and the
mathematical model of lithium ion charge transport are different. While the semi-life aging models are less predictable than their electrochemical aging models, they are suitable for estimating control applications because they require less computation time to predict degradation and are easier to integrate into the BMS.

\[
I_c = \frac{I}{Q_{\text{batt}}}
\]

\[
\sigma_{\text{funct}}(p) = (\alpha \cdot SOC + \beta) \cdot \exp\left(\frac{-E_a + \eta \cdot I_c}{R_g \cdot (273.15 + \theta)}\right)
\]

\[
Q_{\text{batt}} = (\alpha SOC + \beta) \cdot \exp\left(\frac{-E_a + \eta \cdot I_c}{R_g \cdot (273.15 + \theta)}\right) \cdot Ah^z
\]

The parameters \(E_a = 31500\), \(R_g = 8.314\) and \(\eta = 370.3\) were obtained according to the reference [13]. Where \(SOC\) is based on EKF estimation [15]. The average data of the lithium battery pack when the ship is sailing is \(SOC = 69.2\), \(I_c = 6\), \(\theta = 45\). It is identified in two steps. The first step identifies the values of \(f\) and \(z\). The second step substitutes \(f\) into the original expression to obtain the values of \(\alpha\) and \(\beta\). Identify \(\alpha = 3081.6\), \(\beta = 7421.8\), \(z = 0.6\);

3.2. \(\sigma_{\text{map}}\) solution

SS1: When the capacity lost by the battery is set to 20% of the initial capacity, the battery cycle life ends. [16]

\[
20 = \sigma_{\text{funct}}(I_{c,\text{nom}}, \theta_{\text{nom}}, SOC_{\text{nom}}) \cdot \Gamma^\gamma
\]

SS2: The maximum battery life, that is, the battery manufacturer's laboratory test cycle life total charge throughput is the maximum life of the lithium battery. Current battery life, which is the total charge throughput of the battery during the ship's navigation.

\[
\Gamma = \left[\frac{\sigma_{\text{funct}}(I_{c,\text{nom}}, \theta_{\text{nom}}, SOC_{\text{nom}})}{20}\right]^{\frac{1}{\gamma}}
\]

SS3: The aging severity factor is the ratio of current battery life to maximum battery life.

\[
\sigma_{\text{map}}(I_c, \theta, SOC) = \frac{\Gamma(I_{c,\text{nom}}, \theta_{\text{nom}}, SOC_{\text{nom}})}{\gamma(I_c, \theta, SOC)}
\]

3.3. The discharge rate, SOC and temperature have an effect on the aging severity factor \(\sigma_{\text{map}}\).

Effect of discharge rate \(I_c\) on aging severity factor \(\sigma_{\text{map}}\) [17]:

\[
\frac{\partial \sigma_{\text{map}}}{\partial I_c} = \frac{1}{z} \left(\frac{\eta}{R_g}\right) \Gamma \cdot \frac{1}{\gamma} \cdot \frac{1}{273.15 + \theta}
\]

Effect of residual capacity \(SOC\) of lithium battery pack on aging severity factor \(\sigma_{\text{map}}\):

\[
\frac{\partial \sigma_{\text{map}}}{\partial SOC} = \frac{\alpha}{z} \cdot \frac{\Gamma}{\gamma} \cdot \left[\frac{1}{\alpha \cdot SOC + \beta}\right]
\]
Effect of temperature $\theta$ on aging severity factor $\sigma_{map}$:

$$
\frac{\partial \sigma_{map}}{\partial \theta} = \frac{1}{\Gamma} \left[ \frac{E_a - \eta \cdot I_c}{R_g} \right] \frac{1}{(273.15 + \theta)^\gamma}
$$

(17)

Therefore, the aging rate of the lithium battery pack is judged according to the four parameters $\sigma_{map}, \frac{\partial \sigma_{map}}{\partial I_c}, \frac{\partial \sigma_{map}}{\partial SOC}$ and $\frac{\partial \sigma_{map}}{\partial \theta}$.

4. Lithium battery pack energy management strategy

According to the logic threshold algorithm, the lithium battery pack switching strategy control is performed with $\sigma_{map}$, $n$, $SOC_d$, $\frac{\partial \sigma_{map}}{\partial I_c}$, $\frac{\partial \sigma_{map}}{\partial SOC}$, and threshold values. As shown in Figure 3.

![Figure 3. Flow chart of the lithium battery pack switching strategy.](image)

SS1: Judging a size; the size of the aging severity factor can directly reflect the health of the current lithium battery. When the temperature, soc and discharge rate of the lithium battery gradually become unfavorable for the life of the lithium battery, choose to switch the lithium battery pack, let The aging rate of lithium batteries is relatively low. Ultimately extend the overall life of the lithium battery. When it is 0-20, a grows slowly, and when it is greater than 20 , a grows faster. when $\sigma_{map} < 20$, Do not switch battery packs and continue sailing directly; when $\sigma_{map} >= 20$, Perform SS2 judgment;

SS2: Judging the size of n; dividing the mileage of the voyage into two parts for control, when the mileage is less than 100 meters and different control strategies will be carried out during the voyage. when $n < 100$, Perform SS3 judgment; when $n >= 100$, Perform SS5 judgment;

SS3: The size of a and b is judged; when the remaining mileage is within 100, the ship starts to stop. Determine if the soc reaches the lower limit of the remaining battery capacity specified by the lithium
battery pack. When $SOC_i < SOC_{d}$, perform SS4 judgment; when $SOC_i \geq SOC_{d}$, reduce the discharge rate, and continue sailing directly;

SS4: Determine the size of $n$; when the soc reaches the lower limit, if the ship has started to dock, then the lithium battery pack will not be switched. Switching the battery pack also has certain damage to the ship equipment and the lithium battery pack itself. If it has already started to dock, then the soc The consumption is not much, so it is more reasonable to switch to the second battery. When $n < 10$, do not switch battery packs and continue sailing; when $n \geq 10$, switch to the second lithium battery pack;

SS5: Judging the size of $\frac{\partial \sigma_{map}}{\partial \theta}$ when $\frac{\partial \sigma_{map}}{\partial \theta} < 1$, perform SS6 judgment; when $\frac{\partial \sigma_{map}}{\partial \theta} \geq 1$, switch to the second lithium battery pack;

SS6: Judging the size of $\frac{\partial \sigma_{map}}{\partial I_c}$ when $\frac{\partial \sigma_{map}}{\partial I_c} < 1$, perform SS8 judgment; when $\frac{\partial \sigma_{map}}{\partial I_c} \geq 1$, perform SS12 judgment;

SS7: Judging the size of $t$ and $t_{max}$; Used to determine if the current speed can reach the destination on time. When $t < t_{max}$, reduce the output current of the lithium battery pack and continue sailing; when $t \geq t_{max}$, switch to the second lithium battery pack;

SS8: Judging the size of $\frac{\partial \sigma_{map}}{\partial SOC}$ when $\frac{\partial \sigma_{map}}{\partial SOC} \geq 1$, perform SS9 judgment; when $\frac{\partial \sigma_{map}}{\partial SOC} < 1$, perform SS10 judgment;

SS9: Judging the size of $SOC_i$ and $0.8 \times SOC_{d}$, if $SOC_i < 0.8 \times SOC_{d}$, it indicates that the soc2 of the second group of lithium batteries meets the soc required for the remaining mileage, and can directly switch to the second group of lithium batteries. If $SOC_i \geq 0.8 \times SOC_{d}$, it indicates that the soc2 of the second lithium battery is insufficient to complete the remaining voyage. When $SOC_i < 0.8 \times SOC_{d}$, switch to the second lithium battery pack; when $SOC_i \geq 0.8 \times SOC_{d}$, perform SS10 judgment;

SS10: Judging the size of $j$; when the aging rate of the first group of lithium batteries increases, the second group of lithium batteries cannot complete the remaining voyage. When $j = 0$, it indicates that the first occurrence of this situation can reduce the aging rate of the first group of lithium batteries by reducing the output current of the lithium battery pack. When $j = 1$, it indicates that this happens more than once. When $j < 1$, $j = j + 1$, and reduce the output current of the lithium battery pack and continue sailing; when $j \geq 1$, perform SS11 judgment;

SS11: Judging the size of $SOC_i$ and $0.5 \times (SOC_i + SOC_{d} - SOC_{d})$; when the aging rate of the first group of lithium batteries increases more than once, and the second group of lithium batteries cannot complete the remaining voyages, the soc required to estimate the remaining distance is equally distributed to SOC1 soc1 and SOC2 soc2. When $SOC_i < 0.5 \times (SOC_i + SOC_{d} - SOC_{d})$, switch to the second lithium battery pack; when $SOC_i \geq 0.5 \times (SOC_i + SOC_{d} - SOC_{d})$, continue sailing;

SS12: Judging the size of $i$; when the effects of temperature, discharge rate and soc have not seriously affected the normal use of the lithium battery pack, there may be two possibilities, the first one is that the three are within the range of values, leading to serious The factor $\sigma_{map}$ is improved overall, and the second is that the energy management system may be in error during the navigation. In both cases, the judgment is made uniformly, and when the energy management occurs three times, the lithium battery pack is changed. When $i < 3$, $i = i + 1$, continue sailing; when $i \geq 3$, switch to the second lithium battery pack, recording; [19]
5. Control the ship according to the control strategy

In the power ship energy management optimization framework based on the lithium battery energy switching strategy, the ship navigation structure flow is shown in Figure 4. [20]

It consists of the following subsystems: 1) Lithium battery module: The real-time information of the lithium battery pack, State of charge, current, temperature, etc., is sent to the energy management system. 2) Energy Management System: It is a supervisory controller that determines the switching of lithium battery packs and motor torque. The input to the controller is the feedback signal, such as motor torque, lithium battery pack State of charge, temperature, current, current ship speed, from the ship power system and Lithium battery module. The output is the motor torque. 3) Ship power system: The actual ship speed feedback and motor torque are fed back to the energy management system. According to the energy management system, the lithium battery pack is switched and the speed of the ship is changed. [22]

![Figure 4. Structure state diagram.](image_url)

Before the ship starts, first input the destination and the time required to reach the energy management system, and predict the use of the lithium battery SOC. [23] During the navigation of the ship, the energy management system judges the aging severity factor of the lithium battery pack and the SOC required for the remaining miles and the time required for navigation in each minute. [24] According to the feedback information, the lithium battery pack and the change ship will be switched. The speed control information is sent to the power system. As shown in Figure 5. [25]

![Figure 5. Flow chart of implementation of ship navigation control strategy.](image_url)

6. Conclusions

Applying the control strategy to the ship, compared with the lithium battery capacity attenuation of the previous ship, as shown in Figure 6, the two sets of lithium battery packs of the same model are in the
same initial capacity of 175, and the first group of lithium battery packs without the control strategy are added. When the capacity loss is 15%, the navigation is about 800 times, and the second lithium battery is about 1000 sailing. When the capacity loss of the first group of lithium batteries added to the control strategy was 15%, about 1000 times were sailed, and the second group sailed about 1200. It can be concluded that the lithium battery pack energy switching strategy based on the mileage aging battery model improves the cycle life of the lithium battery.

![Battery pack capacity attenuation comparison](image)

**Figure 6.** Comparison of capacity attenuation of different control strategies for lithium battery packs.

### Symbols and descriptions

- $U$: Rated voltage for lithium batteries, (V);
- $K_r$: Resistance Coefficient of Ship Hull Navigation;
- $K_t$: Thrust reduction factor
- $K_p$: Propeller thrust coefficient;
- $V_s$: Velocity of the hull,(m/h);
- $D$: Propeller diameter, (m);
- $t$: Time of arrival at destination,( h);
- $Q_{loss}$: Normalized capacity loss, (A*h);
- $SOC_d$: Lower limit of Residual Electricity for Lithium Batteries;
- $K_M$: Torque coefficient of propeller;
- $SOC_i$: Model of lithium battery State of charge required for ship sailing mileage
- $S$: Ship mileage,(m);
- $K_c$: Transmission Ratio of Propulsion Motor and Propeller Torque;
- $n_r$: Motor's speed, (r/s);
- $Q_{batt}$: Battery capacity, (A*h );
- $V_0$: Initial Velocity of Navigation,( m/h);
- $SOC_1, SOC_2$: Lithium battery pack 1/ Lithium battery pack 2 State of charge
- $\omega$: Flow coefficient;
- $\gamma$: The total charging throughput of the battery during actual ship navigation;
\[ \frac{\partial \sigma_{map}}{\partial \text{SOC}} \]  
Effect of residual capacity of lithium battery pack on aging severity factor;

\[ \frac{\partial \sigma_{map}}{\partial \theta} \]  
Effect of temperature on aging severity factor;

\[ \sigma_{func} \]  
Severity factor function

\[ \theta \]  
Battery internal temperature, (K);

\[ z \]  
Average power law exponent;

\[ R_g \]  
Universal gas constant

\[ \theta_{\text{nom}} \]  
Nominal battery temperature, ( );

\[ I_{c,\text{nom}} \]  
Nominal current rate

\[ SOC_{\text{nom}} \]  
Nominal state of charge

\[ \Gamma \]  
Manufacturer cycle life test battery total charge throughput;

\[ \frac{\partial \sigma_{map}}{\partial I_c} \]  
Effect of discharge rate on aging severity factor;

\[ \sigma_{map} \]  
Characterize battery aging severity;

\[ \text{SOC}_t \]  
Lithium battery t remaining power;

\[ \alpha, \beta, \eta \]  
Model parameter;

\[ E_a \]  
Activation energy;

\[ Ah \]  
Accumulated charge throughput

\[ \theta \]  
Internal temperature,( );

\[ I_c \]  
Current rate normalized to battery charge capacity,(A);

\[ SOC \]  
State of charge

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