Research on control strategy of hybrid electric ship based on minimum equivalent fuel consumption

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Abstract. In order to improve the economy of the hybrid electric-electric ship, the parallel hybrid electric ship is taken as the research object, and an energy control strategy of the electric-electric hybrid ship based on the minimum equivalent fuel consumption is proposed. The efficiency factor and its correction function are used to maintain the balance of battery power, and the target optimization function is adjusted to control the power consumption rate of the power battery, thereby realizing the optimization of the control strategy for the traveling ship. Finally, Matlab/Simulink is used for simulation. The experimental results show that when the control strategy with the minimum equivalent fuel consumption is used, the fuel consumption is 1.95L less than the CD-CS-based strategy, and the fuel saving rate is 31.2%. At the same time, the engine and motor work Efficiency is greatly improved.

Keywords: Hybrid electric power, energy control strategy, equivalent consumption minimization strategy, SOC.

1. Introduction

Traditional ships have good power and long battery life, but the exhaust emissions produced have a serious impact on the environment; while pure electric ships have the characteristics of zero emissions, but the power performance and battery life can not meet the needs of working conditions, and have diesel power generation. The hybrid ship of the unit and the energy storage system can achieve the complementarity of power and economic and environmental protection. For sustainable energy development, although the hybrid ship is not the most perfect solution, it provides the best guidance for the ship from the traditional internal combustion engine power system to the electrification process [1]. At the same time, in order to achieve the best structural advantages of the hybrid vessel, the energy control strategy plays a very important role. Energy control strategy, as one of the core technologies for the research of hybrid electric-electric ships, is of great significance for improving the fuel economy of hybrid electric-electric ships, reducing the pressure of shortage of non-renewable energy, and reducing the pollution of ships to the environment. The energy control strategy of the hybrid-electric ship can allocate and coordinate different energy sources according to the actual situation of navigation, so that it can automatically switch operations in various working modes, so as to achieve the optimal power and energy optimal distribution. Therefore, studying how to achieve the optimal control of power/energy between multiple energy sources has become a difficult point in the research field of hybrid ships [2].
After extensive research by scholars at home and abroad, the strategies can be divided into the following types: (1) Rule-based energy control strategies, by optimizing the threshold decision part of the power control components of the system, thereby changing its working state [3-6]. However, such methods cannot consider the dynamic characteristics of the system, and therefore cannot consider the optimization of the system; (2) Global optimization strategies, through the use of planning algorithms (such as DP, MPC, etc.) to optimize the global travel of the ship, gain the global optimal Solution [7-9]. This method has the advantages of a dynamic system with strong dynamics and nonlinearity that is suitable for multiple control targets, but also has the disadvantage of relying on the ship's operating experience. In actual ship applications, a combination of global optimization strategies and rule strategies is generally used for processing optimization; (3) Instantaneous optimization strategy, the electrical energy released at the current stage of the battery is equivalent to the amount of diesel consumed by the future diesel engine, and then the minimum value of the instantaneous equivalent diesel consumption (Equivalent Fuel Consumption Minimization Strategy, ECMS) is calculated to obtain the optimal energy allocation The ratio [10-12]. This method can adapt to strong dynamics without knowing the working conditions in advance, and can theoretically obtain results close to DP, so it has a wide range of application prospects. In the ECMS method, how to obtain the equivalent factor is the difficulty of research. At present, most of the ship's driving conditions are used as templates to select the optimal factor in different ways [13-14], and then select the optimal equivalent factor according to the actual situation. However, the selection of the equivalent factor is more dependent on the state of the ship, and it is necessary to have a certain understanding of the sea state in advance. This is a drawback of the selection of the equivalent factor.

At present, rule-based strategies cannot consider the dynamic characteristics, and the global optimization strategy has the characteristics of relying on the experience of the prophet. Both strategies have deficiencies. In order to balance the optimization effect and computational efficiency, this paper studies the ECMS algorithm in the optimization control method. Taking the parallel hybrid ship as the research object, introducing the ECMS control strategy, formulating a reasonable equivalent factor and its correction function according to the State of Charge (SOC) of the battery to maintain the balance of battery power, in Matlab/Simulink The control strategy based on ECMS algorithm is established in the simulation, and the fuel economy is studied in depth. The minimum fuel consumption equivalent strategy is adopted to maintain power balance, and compared with traditional CD-CS to prove that the proposed ECMS has more energy-saving effect.

2. System model
Hybrid ships usually have three power assembly methods, namely series, parallel and hybrid [3]. The object of this paper is the parallel hybrid ship. Its transmission system structure is shown in Figure 1. The characteristic of the structure is that it is driven by a diesel engine all the way, and the other route sends out electrical energy from the battery pack and then drives the operation of the transmission device through the power converter to the propulsion motor. They can provide energy at the same time, or they can work alone. Compared with the series hybrid power system, the parallel type engine does not have multiple energy conversions, and can directly drive the ship through the transmission device, which improves the energy utilization rate.

![System structure diagram](image-url)
2.1. Ship power requirements.
The dynamics of the ship includes the response of the ship's speed to different forcing effects, including the effects of the power system, wave excitation, wind and hydrodynamic drag from water and the environment. According to Newton's second theorem, ship motion can be expressed as:

\[ T(1-t_d) + R_{\text{ship}} + F = (m + m_x) \times \frac{dU}{dt} \] (1)

Where \( m \) is the mass of the ship, \( m_x \) is the additional mass of the ship, \( U \) is the speed of the ship, \( T \) is the thrust of the ship, \( t_d \) is the thrust deduction coefficient, and represents the thrust loss caused by the hull resistance; \( F \) is the wave disturbance, \( R_{\text{ship}} \) includes the frictional resistance \( R_F \), wave resistance \( R_R \), wind resistance \( R_{\text{wind}} \) [15-16]:

\[ R_{\text{ship}} = R_F + R_R + R_{\text{wind}} \] (2)

Among them:

\[ R_F = \frac{1}{2} C_F \rho U^2 S \]
\[ R_R = \frac{1}{2} C_R \rho U^2 S \]
\[ R_{\text{wind}} = \frac{1}{2} C_{\text{air}} \rho U^2 A_T \] (3)

In equation (3), \( S \) is the wetted area of the ship, \( A_T \) is the advancing area in the atmosphere, \( C_F \), \( C_R \) and \( C_{\text{air}} \) are the friction coefficients of water wheel friction, wave making and wind, respectively, and these parameters are assumed to be constant.

In equation (1), the average ship speed is determined by the total resistance \( R_{\text{ship}} \) and the ship thrust \( T(1-t_d) \). The oscillation of the ship speed is mainly caused by the wave excitation term \( F \) [16-17]. In this paper, only the first-order wave excitation is considered, and the second-order drift force due to the wave is ignored. The first-order wave excitation has little effect on the average speed of ship motion, but it will cause the fluctuation component of ship motion, which is essential for model research.

2.2. Key component model

2.2.1. Numerical modeling of diesel engines. This paper uses the experimental data modeling method to establish the diesel engine fuel consumption model and torque model. According to the numerical interpolation method, the relationship between the speed, torque and specific fuel consumption of the diesel fuel consumption numerical model is shown in equation (4) [17]

\[ Q = \frac{1}{3.6 \times 10^6 \rho} \int_0^t b_1 P_c dt \] (4)
\( Q \) is the fuel consumption; \( h_c \) is the fuel consumption rate; \( P_e \) is the engine output power; \( \rho_f \) is the fuel density. The working condition simulation in this paper is low sea state [23], the power used is small, and the model established is modeled by means of table look-up. The efficiency of the diesel engine is shown in Figure 2. Figure 2 is a contour map. The maximum torque curve of a diesel engine is the maximum torque the engine can reach at different speeds. If the torque is exceeded, the engine will not run. The optimal working curve of the diesel engine is the optimal efficiency curve that the engine can achieve at different speeds and torques. The circle with an efficiency of 0.4 is a high efficiency of more than 40%. The diesel engine should be kept in the circle as much as possible. The speed and torque should be controlled within this range.

![Figure 2. Diesel engine efficiency distribution](image)

2.2.2. Numerical modeling of propulsion motor and battery. One end of the ship's system model is driven by a diesel engine, and the other end is powered by a battery pack and then driven by a power converter to a propulsion motor to drive the transmission. Therefore, the modeling of the propulsion motor is also essential. This modeling considers the characteristics of the fast response of the propulsion motor, and uses the first-order transfer function to obtain the output torque of the propulsion motor, as shown in equation (5)

\[
T_m = \frac{1}{\tau_m \times s + 1} T_{m\text{--req}} \tag{5}
\]

In the formula, \( T_m \) is the motor torque; \( \tau_m \) is the time constant; \( T_{m\text{--req}} \) is the motor torque demand.

The motor drive power is the output power of the battery, as shown in equation (6)

\[
P_m = \frac{T_m \times n_m}{\eta_m(T_m, n_m)} \tag{6}
\]

In the formula, \( P_m \) is the motor drive power; \( n_m \) is the motor speed; \( \eta_m(T_m, n_m) \) is the motor efficiency, as shown in Figure 3.
Figure 3. Motor efficiency model

It can be seen from Figure 3 that the established propulsion motor model has higher efficiency in the area with larger speed and torque, and the maximum efficiency can reach about 90%. In the low speed or low torque area, the motor’s effective output power is less, resulting in lower motor system efficiency. In the high speed and high torque motor overload area, due to the field weakening control of the motor, the system efficiency is also reduced.

The estimation of battery SOC can be calculated by formula (7), (8):

\[
V_t = \sqrt{P_m(t) g R_d}
\]

\[
I_d(t) = \frac{V_0 - V_t}{R_d}
\]

\[
SOC(t) = SOC_0 - \int_0^t \frac{I_d(i)}{Q_c} \, di
\]

In the formula, \( V_t \) is the battery output voltage; \( R_d \) is the internal resistance; \( I_d \) is the battery operating current; \( SOC_0 \) is the initial state of charge of the battery; \( Q_c \) is the battery capacity.

3. Equivalent fuel consumption minimum strategy

3.1. Analysis of the minimum strategy of equivalent fuel consumption

When the external energy input is not considered (such as braking energy recovery), fuel is the key to ultimately provide energy consumption for the hybrid power system. From the perspective of energy conservation, the equivalent fuel consumption minimization strategy equates electrical energy to the fuel quality of the diesel engine, providing theoretical support for the instantaneous optimal control of the hybrid power system. The calculation model of ECMS is [17]:

\[
m(t,u) = m_c(t,u) + s(t) \frac{P_{ba}(t,u)}{H_L}
\]
In the formula, $\dot{m}_g$ is the instantaneous equivalent fuel consumption of the system at time $t$, $s$ is the conversion factor of electric energy and fuel consumption, that is, the equivalent factor, $P_{bat}$ is the output power of the battery, and $H_L$ is the low heating value of the fuel.

When the control variable $u$ takes different values, the ECMS strategy controls the system, and finally the minimum equivalent fuel consumption value is obtained. If the penalty factor [18-19] added due to power maintenance is not considered, the equivalent factor $s$ in formula (9) is the core parameter. The essence of equivalent fuel consumption is to convert the power consumption into a fuel consumption value by changing The size of the equivalent factor controls the consumption of electrical energy and fuel. In order to make the battery consistent with the initial state of power, the supplement of electrical energy can be regarded as the future engine fuel consumption for energy filling, but due to the unknown operating conditions, the selection of the equivalent factor cannot be determined, so for any equivalent factor How to find the optimal solution is very important for ECMS. In order to make the current energy have the best conversion efficiency when it is compensated in the future, it is only under this premise that the energy distribution at the current moment has the optimal conditions.

Studies have shown [20-21] that for a given driving cycle, the equivalent factor in equation (9) can be replaced by a constant value (optimal equivalent factor) to optimize energy distribution. At present, the method of obtaining the optimal equivalent factor is generally an exhaustive method, and this method is only selected according to the advantages and disadvantages of the optimization result. This method is simple and easy to implement, but it is impossible to explain clearly which factors are affected by the optimal equivalent factor and the internal laws, and it is greatly affected by the overall driving cycle, and the adaptability of the working conditions is poor. In this paper, the optimal equivalent factor is first obtained by exhaustive method, and then by analyzing the simulation results, the variation rule of the optimal equivalent factor with respect to the SOC maintenance value is obtained, and the minimum equivalent fuel consumption strategy is designed based on this.

3.2. ECMS strategy design

The ECMS algorithm minimizes the sum of the actual fuel consumption rate $\dot{m}_g$ of the engine (calculated from the engine steady-state model interpolation) and the equivalent fuel consumption rate $\dot{m}_{eq}$ of the electric motor consumption at each time $t$ [22].

This paper establishes the equivalent factor $s(t)$ to calculate $s$:

$$\dot{m}_m = s(t)[\lambda \frac{P(t)}{\eta_{dis}H_i} + (1 - \lambda) \frac{\eta_{char}P(t)}{H_i}]$$

$$s(t) = s_0 + k_p \Delta SOC + k_i \int \Delta SOC dt$$

$$\lambda = \frac{1 + \text{sgn}[P(t)]}{2}$$

$$\Delta SOC = SOC_{ref} (t) - SOC(t)$$

In the formula, $H_i$ is the gasoline mass calorific value constant; $\eta_{dis}$ and $\eta_{char}$ are the battery charge and discharge efficiency; $s_0$ is the equivalent factor constant part; $k_p$ is the proportional coefficient; $k_i$ is the integral coefficient; $SOC_{ref} (t)$ is the current SOC target value; $SOC(t)$ is Current SOC.

It can be seen from equations (11) and (13): when $SOC(t) > SOC_{ref} (t)$, the equivalent factor decreases, and the power consumption is increased under the condition of satisfying the required power;
when \( SOC(t) < SOC_{ref}(t) \), the equivalent factor increases, when the demand power is met under the conditions of engine power generation, it is guaranteed to work in the high-efficiency interval; when \( SOC(t) = SOC_{ref}(t) \), that is, \( \Delta SOC = 0 \), the equivalent factor remains unchanged, and the control strategy at the previous moment is maintained.

The system constraints are:

\[
\begin{align*}
P_{\text{min}}(t) & \leq P_e(t) \leq P_{\text{max}}(t) \\
P_{\text{min}}(t) & \leq P_{\text{m}}(t) \leq P_{\text{max}}(t) \\
SOC_{\text{min}} & \leq SOC(t) \leq SOC_{\text{max}}
\end{align*}
\]

Among them, \( P_{\text{min}}(t) \) and \( P_{\text{max}}(t) \) are the minimum and maximum power of the engine at time \( t \); \( P_{\text{min}}(t) \) and \( P_{\text{max}}(t) \) are the minimum and maximum power of the motor at time \( t \); \( SOC_{\text{min}} \) and \( SOC_{\text{max}} \) are the minimum and maximum SOC constraints of the battery.

### 4. Simulation analysis

In order to verify the effectiveness of the developed full-mileage ECM control strategy, the simulation model applied to the ship's energy control strategy was first established through Matlab/Simulink for experimentation, and then conducted through hardware-in-the-loop test with the CD-CS-based ECMS strategy Comparative Test. Test using test conditions.

The initial battery SOC for this test was 0.9, and the SOC entering the power maintenance stage was set to 0.3. The total capacity of the battery pack is 100Ah; the diesel generator has a rated power of 60kW; the rated output power of the propulsion motor is 65kW. The specific parameters are shown in Table 1 below:

| Name                       | Parameter        |                         |
|-----------------------------|------------------|--------------------------|
| Power battery pack          | Total rated capacity | 100Ah                   |
|                             | Rated voltage    | 500V                     |
|                             | Internal resistance | 26mΩ                    |
| Diesel generator sets       | Rated power      | 60kW                     |
|                             | Rated power      | 65kW                     |
|                             | Rated speed      | 2500r/min                |

#### 4.1. Test conditions

In the simulation experiment, the sailing conditions of the hybrid ship simulated in this paper include its start-up phase, acceleration process, full-speed forward stage, deceleration process and final stop operation. During the experiment, you can clearly feel the different operations at different stages The changes in ship's sailing demand power under operating conditions, the simulated mileage and ship speed are shown in Figure 4.
4.2. Simulation and result analysis

Figure 5 a) and b) show the fuel consumption and battery SOC of the CD-CS strategy and the ECMS algorithm, respectively, with the mileage change curve. The traditional CD-CS strategy first enters the power consumption mode, when the SOC decreases to a critical value, and then starts the engine to enter the power maintenance mode, resulting in poor fuel economy of the ship. ECMS can perform global power distribution in advance according to the ship status information to ensure that there is sufficient power for pure electric driving in the low-speed stage. In the high-speed stage, the distributed power is less. Fuel economy. The specific value changes are shown in Table 2.

Figure 4. Relationship between ship speed and mileage

Figure 5. Fuel consumption and battery SOC change curve with mileage
Table 2. Comparison of CD-CS and A-ECMS different mileage results

| Mileage  | Control Strategy | Remaining SOC | Fuel consumption (L) |
|----------|------------------|---------------|----------------------|
| 15.6 km  | CD-CS            | 0.3           | 0                    |
|          | ECMS             | 0.6           | 1.8                  |
| 34.8 km  | CD-CS            | 0.3           | 6.25                 |
|          | ECMS             | 0.3           | 4.3                  |

It can be seen from Table 2 that the CD-CS has all used up the battery at 15.6km, and all fuel consumption for the next trip. A-ECMS uses only 0.3 battery at 15.6km. Fuel and battery are consumed simultaneously. When the battery is used up, it saves 1.95L of fuel compared with CD-CS, and the fuel saving rate is 31.2%, which achieves fuel saving purpose. Figure 6 shows the MAP of the engine operating point distribution. Compared with the CD-CS strategy, the ECMS strategy has more operating points distributed within the optimal efficiency curve.

![Engine operating point distribution](image-url)

Figure 6. Engine operating point distribution

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