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Transient Energy Adjustment of Energy Storage Systems for Stabilizing Ship Load Fluctuations

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Abstract

As ships encounter different conditions in actual navigation, the instability of operating loads will lead to fluctuations in the DC bus voltage of ships, which will cause shocks to diesel generator and affect the stability of ship power systems. In order to improve the transient characteristics of the system, an energy storage system (MESS) consisting of lithium batteries and supercapacitors is introduced. In this paper, the frequency method is used to improve the energy management system of hybrid electric boat (HEB) by distributing the load power information through two low-pass filters, so that each power source takes up the corresponding part according to its own characteristics, and the operation condition is compared with that when the energy storage system is not introduced to prove the superiority of the method. A MATLAB/Simulink simulation model is built based on the target ship model to verify the proposed method. The simulation results show that the proposed control strategy can effectively improve the transient characteristics of the system DC bus voltage and enhance the stability of the whole ship power system.

Keywords

Hybrid Electric Boat; Energy Storage System; Frequency Method; Low Pass Filter; Power Distribution.

1. Introduction

With the trend of technological development and economic integration, international trade is growing, and airplanes and ships have become the main mode of transportation, and most of the transportation is carried by ships, so the study of ship propulsion is exactly the current research hotspot [1]. For some medium and large ships, the main power source is diesel engine, so diesel generator still occupies the main position. However, diesel generator has delay, and the dynamic response is relatively slow in the face of load changes, making the output power unable to quickly track the load power, which causes the power required by the load not to be satisfied instantaneously, resulting in DC bus voltage fluctuations of the ship power system, and the overall transient characteristics of the system become poor. Moreover, the rapid load power change will also cause shock to the diesel generator and degrade the electrical performance. To avoid this problem, a hybrid energy storage system composed of lithium batteries and supercapacitors is introduced to reduce the impact of load power fluctuation on the DC bus and diesel generator during transient operation, thus improving the dynamic performance of hybrid ships. Lithium batteries and supercapacitors are used in the literature[2], but the two energy storage systems are directly coupled to the DC bus, which makes the power flow of the storage system uncontrollable, the voltage must be strictly matched to the DC bus voltage, the capacity utilization of the storage system is not high, and the service life is short.

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This paper focuses on improving the energy management system of hybrid electric ship by frequency method, and divides the load power information into three different frequency components of high, medium and low through two low-pass filters, so that each power source can take up the corresponding part according to its own characteristics, reducing the influence of load fluctuation on diesel engine and ensuring the stability of ship electric system. In this paper, we take a hybrid ship Vokoli in Paris, France as the target ship type and build the model of the whole ship power system. The whole system mainly consists of a diesel prime mover and its speed control system, a synchronous generator and its excitation system, an AC/DC converter, a group of lithium batteries, a group of super capacitors, two DC/DC converters and two propulsion asynchronous motors and other loads. Figure 1 shows the system structure of the whole hybrid electric boat.

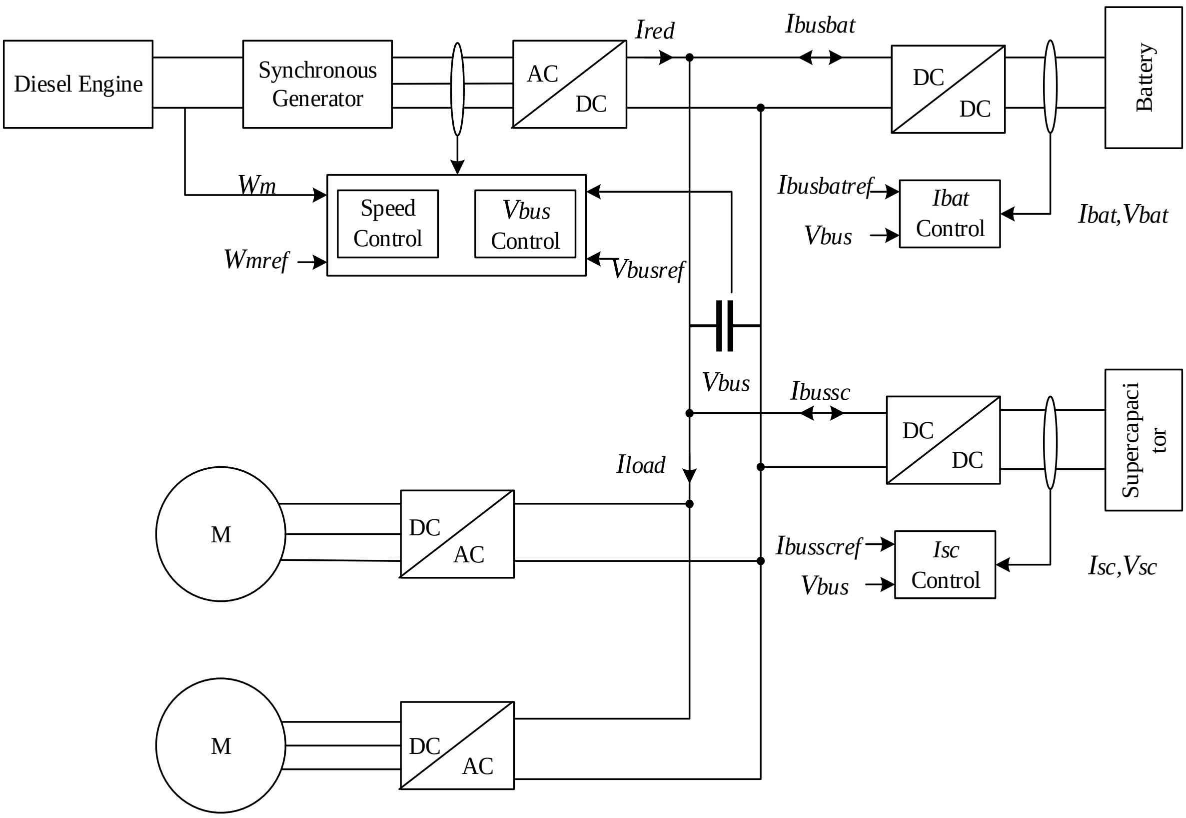

Fig. 1 Hybrid electric boat system structure

2. Generator Set Model

2.1 Diesel Engine And Speed Control System

For in the ship power system simulation, some internal behavioral characteristics of the diesel engine can be ignored for more convenience and only research torque and speed. The equations of motion of the diesel engine are shown in (1).

$$j\frac{d\omega}{dt}=T_d-T_g-T_f \tag{1}$$

where j is the rotational inertia; ω is the angular velocity; T_d is the diesel engine output torque; T_g is the resistance torque; and T_f is the frictional resistance torque.

The excitation system will control the generator speed change when the load power changes. at the same time, for diesel engines, a speed control device is needed to control the amount of diesel supply, which in turn regulates the speed of the diesel engine. The speed control system of diesel engine is mainly composed of controller, actuator, diesel engine and speed detector, and shows in Fig. 2.

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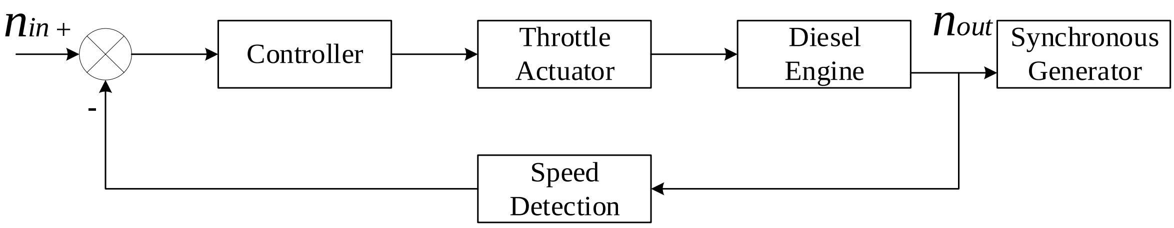

Fig. 2 Diesel engines and speed control systems

2.2 Synchronous Generators And Excitation System

The stator-rotor parameters of synchronous generators are all time-dependent parameters, they are very difficult to analysis. To solve this difficulty, the model is greatly simplified by using park transformation, which transforms the stationary ABC coordinates into dq coordinates for the solution. The equations of the magnetic chain equation of the synchronous generator in dq coordinates can be expressed as equations (2).

$$\begin{bmatrix} \psi_d \\ \psi_q \\ \psi_o \end{bmatrix} = \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \\ 0 & 0 & L_o \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} + \begin{bmatrix} M_{af} & M_{aD} & 0 \\ 0 & 0 & M_{aQ} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_f \\ i_D \\ i_Q \end{bmatrix} \tag{2}$$

And the voltage equation of the synchronous generator in dq coordinates can be expressed as equations (3).

$$\begin{bmatrix} u_d \\ u_q \\ u_o \end{bmatrix} = p \begin{bmatrix} \psi_d \\ \psi_q \\ \psi_o \end{bmatrix} + \begin{bmatrix} 0 & -\omega & 0 \\ \omega & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \psi_d \\ \psi_q \\ \psi_o \end{bmatrix} + R \begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} \tag{3}$$

During the operation of ship, the voltage from the synchronous generator will be much lower than the rated voltage due to various operating conditions. In this paper, a phase compound excitation device is used to regulate the voltage and compensate the current at the same time. The simulation model of the phase compound excitation system is shown in Fig.3.

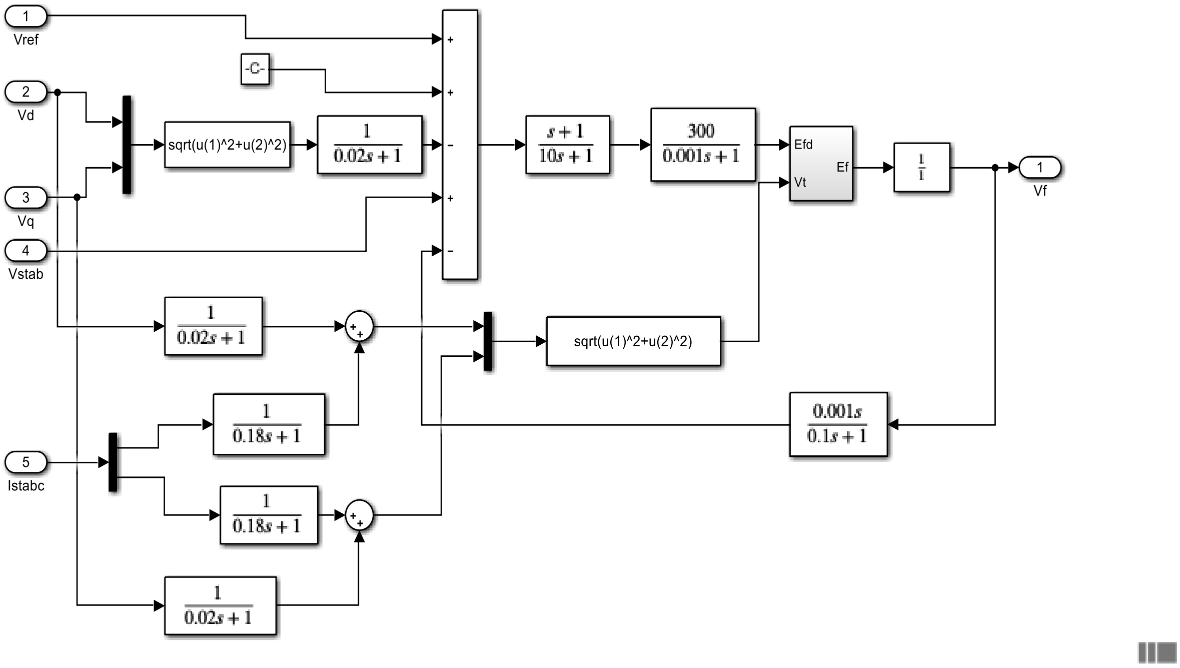

Fig. 3 Phase compound excitation system

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3. Energy Storage System Model

3.1 Lithium Battery Model

The marine energy storage system does not require an accurate mathematical model of the energy storage components, and an equivalent model is generally used for the analysis. Several electrical models that can describe the electrochemical process and dynamic behavior of the battery are proposed in the literature [3,4,5], and in this paper, the classical second-order *RC* equivalent circuit model is chosen for the operational analysis of lithium batteries, and its equivalent circuit model is shown in Fig. 4.

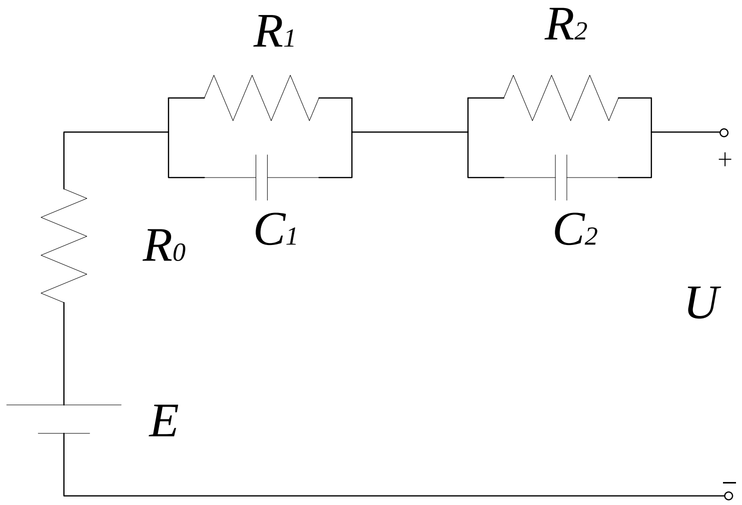

Fig. 4 Second-order RC equivalent circuit model

Where E represents the open-circuit voltage of the battery; R_0 is the internal resistance of the battery; R_1, C_1 and R_2, C_2 represent the electrochemical and concentration difference polarization resistance and polarization capacitance, respectively; U indicates the terminal voltage of the battery. The parameters related to the lithium iron phosphate battery of model SP-LFP100AHA/3.2V are verified by simulation in simulink environment, using 85 single cells in series and 8 branches in parallel.

3.2 Supercapacitor Model

For the energy storage of ship power system, supercapacitor also does not need too precise mathematical model, and the classical model of supercapacitor is also generally used for analysis[6], and its circuit equivalent model is shown in Fig. 5.

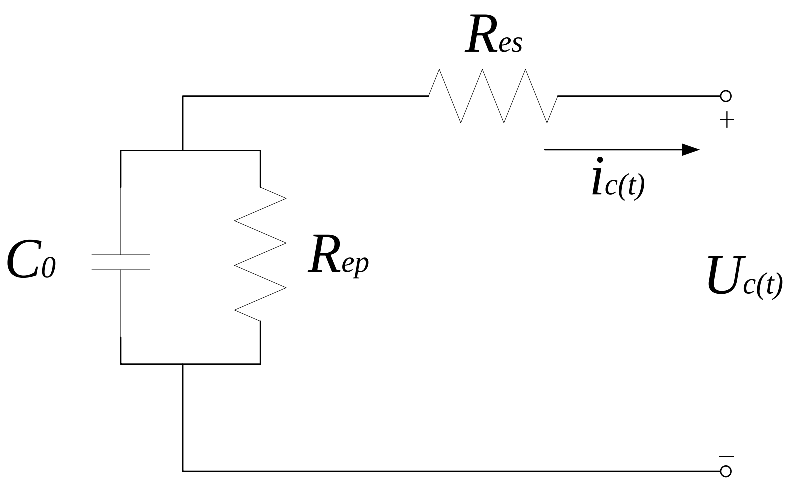

Fig. 5 Supercapacitor Equivalent Model

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where C_0, R_{ep}, and R_{es} denote the capacitance of the ideal capacitor, the equivalent parallel resistance when leakage current is generated, and the equivalent series resistance when losses are generated, respectively. $i_{c(t)}$ is the supercapacitor charging and discharging current, and $U_{c(t)}$ is the capacitor terminal voltage. Since R_{ep} is much larger than R_{es}, which is equivalent to an open circuit, it can be ignored to an RC series model, which is beneficial to system analysis. Simulation is performed in simulink environment with reference to BCAP3000F (2.7V/3000F) model supercapacitor, using 120 single cells in series and 34 branches in parallel.

4. AC/DC And DC/DC Converter Models

4.1 AC/DC Converter Model And Control Strategy

In this paper, a three phase voltage source rectifier is used to convert the alternating current from the synchronous generator into a controllable dc[7]. The mathematical model of the machine side converter with filter inductor in the dq coordinate system can be represented by equation (5).

$$\begin{cases} e_d = L\dfrac{di_d}{dt} + Ri_d - \omega Li_q + v_d \\ e_q = L\dfrac{di_q}{dt} + Ri_q - \omega Li_d + v_q \end{cases} \tag{5}$$

Where e_d, e_q and i_d, i_q are the AC side supply voltage and current in the dq coordinate system; v_d, v_q are the rectifier bridge side voltage in the dq coordinate system; ω is the grid fundamental angular frequency, R and L are the AC side filtering resistor and inductor, respectively. From equation (5), it can be seen that there is cross-coupling of the current in the dq coordinate system, which can be eliminated by using the feedforward decoupling method[8], and the double closed-loop decoupling control block diagram is shown in Fig. 6.

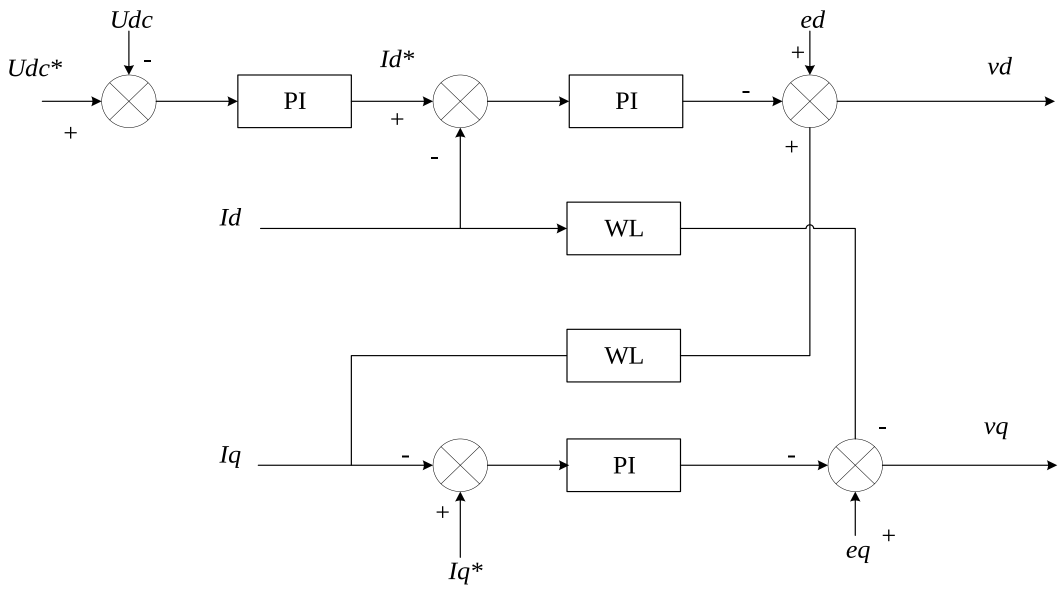

Fig. 6 Double closed-loop decoupling control

4.2 Bidirectional Buck-boost Model And Control Strategy

Through theoretical analysis and comparison, it is concluded that the bidirectional buck-boost converter topology requires fewer devices and transfers energy through the inductor, which is easy to design [9]. Considering the above characteristics, the bidirectional buck-boost converter is chosen in this paper to realize the charge and discharge control of the energy storage device. The model of bidirectional buck-boost can be represented by equation (6).

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$$\begin{cases} V_{L_{sc}} = L_{sc} \times \dfrac{d}{dt}(I_{sc}) = k_{sc} \times (V_{sc} - \alpha_{sc} \times V_{bus}) \\ V_{Lbat} = L_{bat} \times \dfrac{d}{dt}(I_{bat}) = k_b \times (V_{bat} - \alpha_{bat} \times V_{bus}) \end{cases} \tag{6}$$

Where k_{sc} and k_b is the current direction of supercapacitor and battery respectively, α_{sc} and α_{bat} is the duty cycle of each of the two converters respectively. The control of the bidirectional buck-boost converter is mainly to realize the function of charging and discharging the energy storage device according to the specified power, and the power can be controlled by the control of its current, which is realized by the single current loop of direct power control in this paper, and Fig. 7 shows its control block diagram.

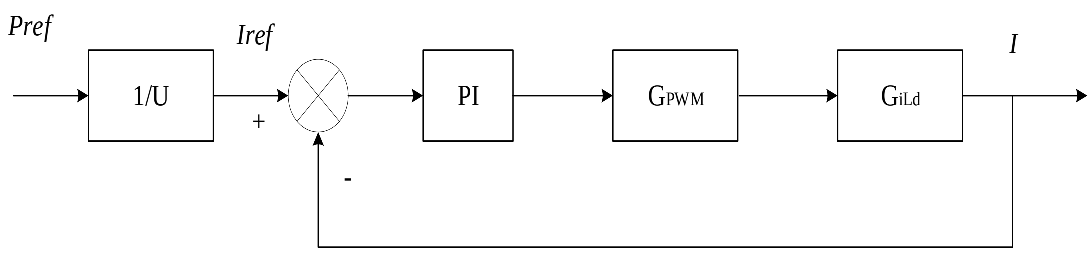

Fig. 7 Bidirectional buck-boost converter control block

5. Energy Management Strategy Based On Frequency Method

The main purpose of introducing energy storage device in this paper is to reduce the influence of load fluctuation on the bus voltage and diesel generator, so as to improve the system transient characteristics and make the whole ship power system more stable. In this paper, two low-pass filters are used to divide the load power curve, as shown in Fig. 8, so that each power source takes up the corresponding part according to its own characteristics, with supercapacitor taking up the high frequency component HC, battery taking up the medium frequency component MC, and diesel generator taking up the low frequency component LC.

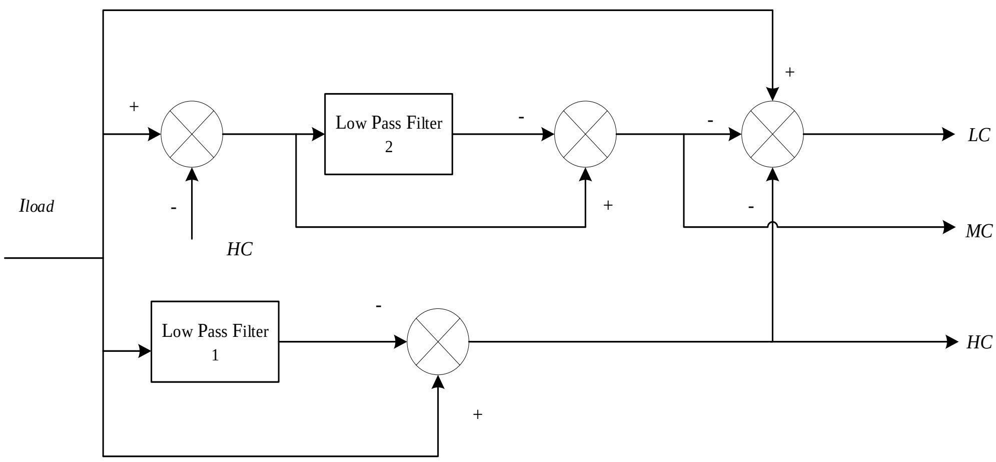

Fig. 8 Power distribution based on frequency method

The energy management strategy based on the frequency method, the reference currents of the supercapacitor and the lithium battery can be given by Fig. 8, and the remaining low frequency components are borne by the diesel generator, where the time constants of the respective low-pass

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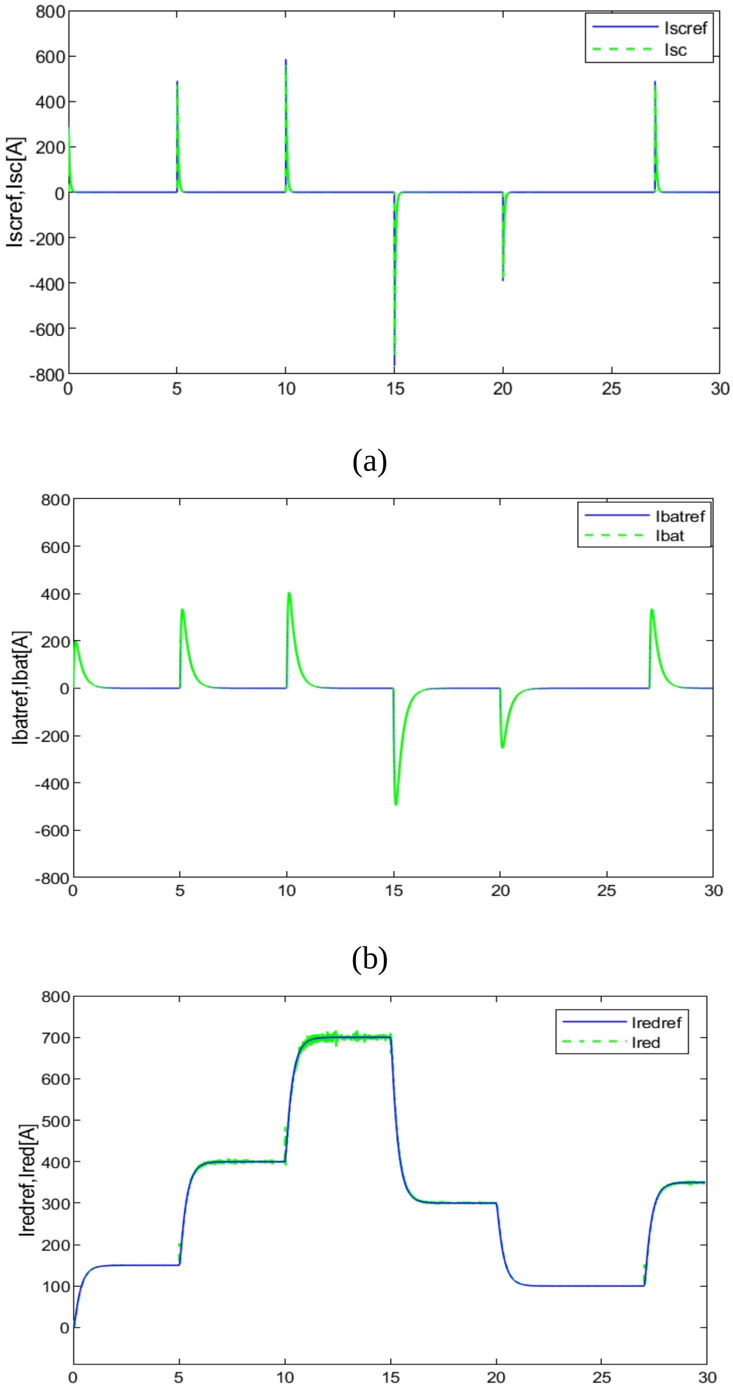
filters are set to 0.05s and 0.3s. By changing the time constants of the two low-pass filters, the magnitude of the load power assigned to the supercapacitor and the lithium battery can be adjusted, and thus the energy management system can be controlled.

6. Hybrid Electric Boat Behavior Simulation

6.1 Simulation Conditions

The simulation system of the hybrid ship mainly consists of diesel generators (rated at 500KVA/380V/50Hz), a lithium battery pack (rated at 300V/100Ah), a supercapacitor pack (rated at 350V/100F), an AC/DC rectifier, two DC/DC converters, and loads. The main parameters are as follows: $C_{bat}=C_{sc}=2mF$, $C=50mF$, $L_{bat}=L_{sc}=0.18mH$, $L=0.5mH$, $R=0.02\Omega$.



(c)

Fig. 9 (a) Capacitor current, (b) battery current, (c) diesel current

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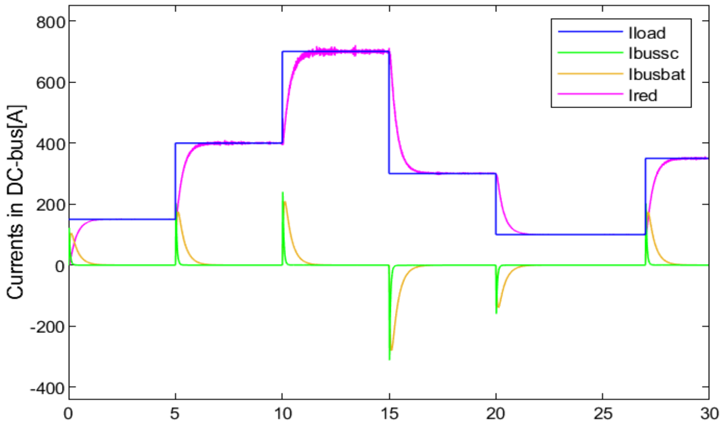
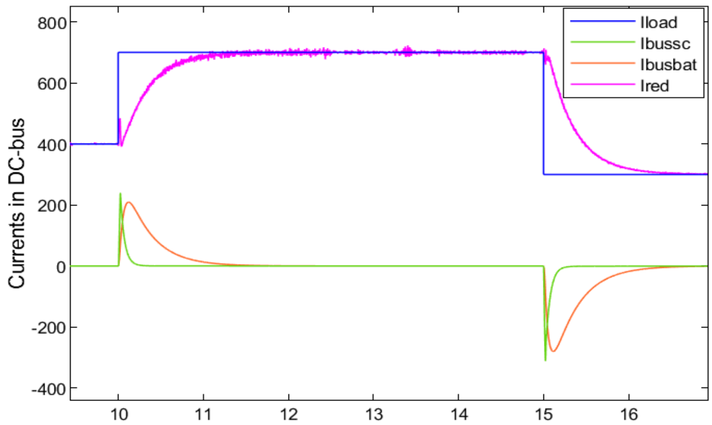
6.2 Simulation Results

For a ship power system with a constant DC bus, the load power can be expressed in terms of the load current [10]. The static data measured by the power consumption of the vessel Vokoli during a voyage allows to plot the load curve with different operating conditions between the interval [100 700], which is decomposed into three components: low, medium and high frequency components. The supercapacitor takes up the high frequency components, the lithium battery takes up the medium frequency components, and the diesel engine takes up the low frequency components. Fig. 9 illustrates that the actual current value of each power supply remains almost the same as the reference current value, which reduces the impact of load fluctuations on the diesel generator.

Fig.9 shows that due to the sudden increase of load in the transient process, the supercapacitor quickly tracks the high-frequency component of the load, which leads to the sharp discharge of the model, and the more the load increases, the larger the capacitor discharge current; When load suddenly decreases in the transient process, the supercapacitor quickly absorbs the high-frequency component of the load and is in the charging state. The charging and discharging current of lithium battery in the transient process is similar to supercapacitor, the main difference is that lithium battery assumes the medium-frequency components of the load. This makes the diesel engine bear the lowest frequency components of the load. When the load suddenly increases in the transient process, the dynamic response of supercapacitor and lithium battery is faster, and they bear most of the power of the load, so that the diesel generator current can slowly increase and reduce the impact of load fluctuation on the generator; when the load suddenly decreases in the transient process, the diesel engine current will not drop sharply due to the presence of capacitor and battery.



(a)



(b)

Fig. 10 (a) Contribution of the sources in dc-bus. (b) Zoomed in view of the contribution of the sources in dc-bus

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The purpose of using frequency method energy management strategy is to take the maximum power as possible when the load changes in the transient process, the power given value of the diesel generator set in steady state is all the load, and the power given value of the energy storage system in steady state is 0. Since the voltage on both sides of the bidirectional DC/DC converter connecting the energy storage unit and the DC bus is different, according to the law of power conservation, it is known that the given current on both sides of the converter is also different. For the convenience of analysis, the given current of the energy storage side is transformed to the DC bus side, and the contributions of the sources in dc-bus are shown in Fig.10(a).

The partial enlargement of Fig. 10(b) shows that the system is in a steady state for a period of time before 10s, and the diesel engine takes up all the load power, about 240KW (DC bus voltage level is 600V), and the supercapacitor and lithium battery take up 0. At 10s, a load of 180KW is suddenly added for 5s. At the moment of loading, due to the fast dynamic characteristics of the supercapacitor, the supercapacitor bears most of the load at the first time, which is about 145KW, while the diesel generator falls back quickly after a short tiny shock and bears a small part of the load power. Since the supercapacitor has the characteristics of high power density and low energy density, it should be matched with low power density and high energy density lithium battery. Immediately after the lithium battery is discharged according to the instantaneous given power to bear a considerable part of the load power, and the diesel generator can slowly increase to the steady state given value after about 1.5s, thus improving the system stability. Similarly, when the 240KW load is suddenly discharged at 15s, the super capacitor quickly absorbs most of the load power for charging, followed by the lithium battery which also absorbs a considerable part of the load current for charging, so that the diesel engine slowly decreases to the steady-state, effectively reducing the impact of load fluctuation on the diesel generator, and also effectively reducing the DC bus voltage fluctuation. The comparison of the DC bus voltage with and without the energy storage system can be well illustrated.

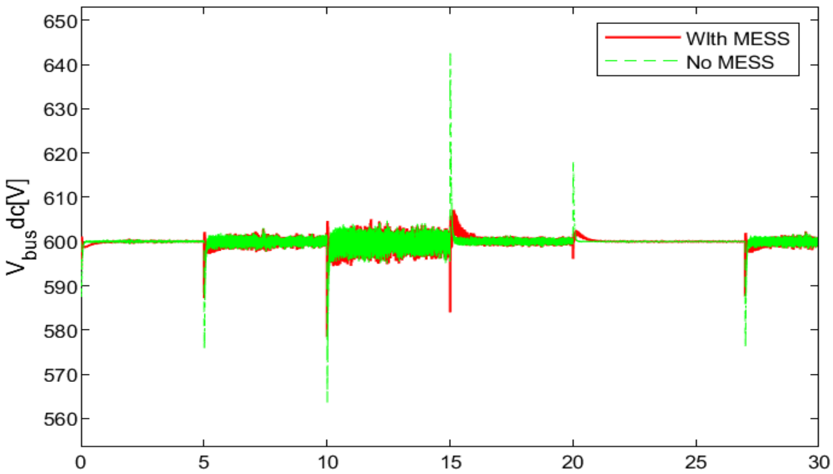

Fig. 11 Dc-bus voltage

The red and green curves in Fig. 11 indicate the DC bus voltage variation have and without energy storage system respectively, which shows that the DC bus voltage fluctuation of the hybrid electric ship with energy storage system is smaller in the transient moment of load change, and the maximum deviation from the given value of 600V is 22V, which is about 3.7% of the given value voltage and stays within the specified range (5%) of the ship voltage fluctuation. In contrast, the maximum offset of the voltage fluctuation of the system without energy storage system reaches 43V, which is about 7.2% of the given value voltage and exceeds the specified range.

Figure 12 also gives the output torque variation of the diesel engine have and without the addition of energy storage system. The red curve represents the addition of energy storage, and it can be seen

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that the torque curve of the diesel engine with the introduction of energy storage changes more gently, and the torque at the transient moment is smaller, and the shock is also smaller. While the green curve indicates that no energy storage system is introduced, it can be seen that the diesel engine torque curve at this time has a certain degree of repeated fluctuations before stabilization, which may exceed the maximum torque that the diesel engine can withstand, which is very unfavorable to the diesel engine. In summary, the energy management strategy proposed in this paper can not only effectively reduce the DC bus voltage fluctuation of the ship, but also reduce the impact of load fluctuation on the diesel engine and improve the transient stability of the hybrid electric ship.

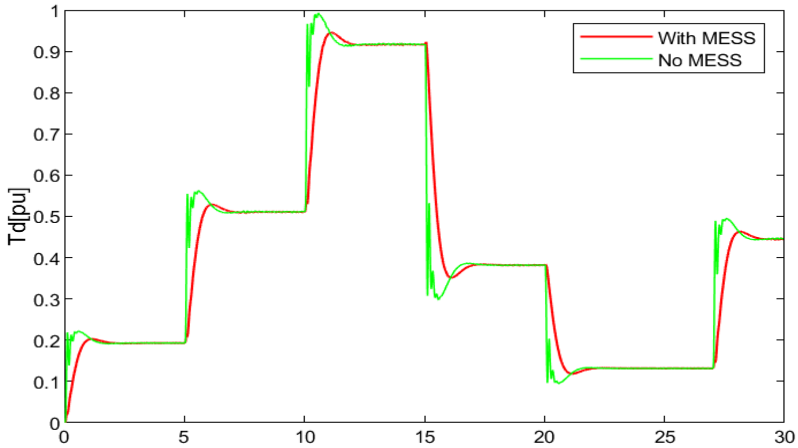

Fig. 12 Diesel engine output torque

7. Conclusion

This paper discusses the energy deployment problem of adding an energy storage system composed of supercapacitors and lithium batteries to the ship DC power network to smooth out the load power fluctuations, and proposes an energy management strategy based on the frequency method, so that each power supply can take up the load power at different frequencies according to its own dynamic characteristics. The simulation results show that the ideal dynamic characteristics can be obtained by this method, and each power source can effectively improve the stability of the ship's power system by cooperating with each other according to their given power. The proposed energy management strategy can not only reduce the impact of load fluctuation on the diesel generator, but also reduce the DC bus voltage fluctuation.

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