Stability Improvement of Electric Ship Propulsion System Using Supercapacitor

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Abstract: Owing to the serious greenhouse gas emissions and inflexible control of traditional ship propulsion system, the electric ship propulsion system has been widely introduced into the ship’s power system. However, the variations of ship propellers will lead to the instability of electric propulsion system so this paper studied the transient characteristics of electric ship propulsion system by performing a series of experiments on a real electric ship propulsion system platform. Based on the experimental results, a detailed model of supercapacitor energy storage system (SCESS) is proposed to improve the voltage and frequency response for the electric ship propulsion system. To enhance the stability and reliability, a double closed-loop control method combined with Pulse-Width Modulation algorithm (PWM) is utilized to control the energy storage system for smoothing the power fluctuations caused by the electric propulsion system. The simulation results demonstrate the high efficiency of supercapacitor to improve the transient stability of the whole power system of the ship.

1. Introduction

Compared to the ship traditional propulsion system, an electric propulsion system is more flexible to control with a lower cost and noise [1]. However, as the ship sails in the ocean, the propellers operate in various modes such as acceleration and deceleration, which cause instability of the electric ship propulsion system. Regarding the issue above, energy storage system is regarded to be one of the best solutions for maintaining the stable for the electric ship propulsion system and keeping the power balance [2-4].

Due to the high power density and fast response to the fluctuations, supercapacitor energy storage system has already been applied in many areas [5-10] such as electric vehicles [5-6], urban rail transit [7-8], renewable energy [9-10].

However, to the best of the authors’ knowledge, the application of SCESS into an electric ship propulsion system has not been extensively discussed. The coordinated control has been developed in [11] to mitigate power fluctuation caused by different ocean conditions using hybrid battery-supercapacitor hybrid energy storage in electric ship propulsion system. In [12], Tang et al. have explored the feasibility of the battery-supercapacitor energy storage systems which meet the requirements of both 100~500kW propulsion system for naval applications.

Therefore, this paper establishes a supercapacitor energy storage system to improve the dynamic performance for the whole electric ship propulsion system. Furthermore, in order to achieve a fast responding to restrain the fluctuations of electric ship propulsion system, the voltage-current dual closed-loop control approach cooperated with PWM is employed to control the SCESS charging and discharging. In addition, different operational situations are considered.
2. Problem description and experiments

2.1. Problem description
To study the transient characteristics of the electric ship propulsion system, experiments are carried on a real electric ship propulsion system platform, which is shown in Fig. 1. The experimental equipment consists of a 15 kW diesel generator, a motor for driving propellers, ship propellers with a magnetic powder brake and ship loads with the size of 6 kW. The electric ship propulsion system is tested under consideration of various working conditions of ship propellers, including accelerating, decelerating, rushing out of water, respectively.

![Figure 1. Configuration of real electric ship propulsion system platform](image1)

2.2. Experiments for electric ship propulsion system
The system runs in the stable state before conducting the experiment of acceleration and deceleration of the ship propellers. The experimental results are shown in Fig. 2.

![Figure 2. Experimental results of ship acceleration and deceleration](image2)

As is seen from Fig. 2, the deceleration of the ship propellers causes a sudden reduce of the torque and current of motor and an increase of the voltage of the DC bus. In contray, the acceleration of the ship results in a dramatic rise of the torque and current of the motor with a decrease of the voltage of the DC bus.
Similarly, the electric ship propulsion system has a large fluctuation when the ship propellers rush out of the water, which is described in Fig. 3.

It can be seen from Fig. 2-3 that the voltage of DC bus and the current of motor have a sudden change and a dramatic deviation when the ship propellers operate in the mode of accelerating, decelerating and rushing out of water, which is beyond the safe requirement of the electric ship propulsion system. Moreover, the speed and torque of the motor vary so tremendously that the diesel generator cannot compensate the power fluctuations and then the system has to face with unreliable problem.

3. Electric ship propulsion system configuration and components

3.1. Structure of electric ship propulsion system

As mentioned in Section 2, the system has a risk of instability when the propulsive load fluctuates frequently. In order to study the transient characteristics of large electric ship propulsion system and to enhance the stability of the whole system, the focus of this work is to make use of the SCESS to improve the transient stability of electric ship propulsion system in a barge ship. The detailed parameters of this barge are 146 m long by 14 m wide with the system scale of 690 V and 60 Hz consisting of one 2800 kW diesel generator and a 10 F supercapacitor. Figure 4 presents the proposed configuration of the electric ship propulsion system with SCESS.

![Figure 4. Structure of electric ship propulsion system](image-url)
In this paper, various actual situations are taken into account to improve the accuracy of the simulation models. The voltage source rectifier (VSR) and trilevel inverter are selected as the frequency converter [13-14]. An asynchronous motor is chosen as the propulsive motor [15].

3.2. Mathematical model of SCESS

The aim of this work is to use supercapacitor to improve the transient stability of the system. Therefore, it’s necessary to utilize the bidirectional DC / DC converter to achieve the energy absorption and release.

When SCESS charges, the bidirectional DC / DC converter is working at buck mode. VT1 periodically turn on or off and the VT2 is blocked all the time [16]. Conversely, when SCESS discharges, the converter is working at boost mode. VT2 periodically turn on or off and the VT1 is blocked. Figure 6 depicts energy flow between the energy storage device and the system side.

In (1)-(2), \( i_L \) denotes inductance current, \( U_{sc} \) represents supercapacitor voltage, \( L \) is inductance value, \( C_{sc} \) is equivalent capacitance of the supercapacitor, \( r \) is equivalent series resistance of the supercapacitor, \( U_{dc} \) is the DC bus voltage of the system.

4. Control method for SCESS

4.1. Design for SCESS parameters

Due to the significant role of SCESS, its capacity has a large effect on the cost and voltage stability of the electric ship propulsion system. Therefore, a method to design the parameters for SCESS is proposed in this paper, which is described as follows.
\[ W = \frac{1}{2} C_{sc} (U_{\text{max}}^2 - U_{\text{min}}^2) \]  

(3)

Where, \( W \) and \( C_{sc} \) respectively denote the sum of the absorbed or released energy and the equivalent capacitance value of the supercapacitor. \( U_{\text{max}} \) and \( U_{\text{min}} \) represent the maximum and minimum operating voltage of the supercapacitor which must satisfy the following equations.

\[ U_{\text{min}} \geq 0.3U_{dc}, \quad U_{\text{max}} \leq 0.6U_{dc} \]  

(4)

Noticed that the energy stored in the SCESS must be higher than the energy demand of the system and should be designed by the maximum power compensation \( P_{\text{max}} \) of the system DC bus, as follows.

\[ W \geq \int_{t_0}^{t} P_{\text{max}} dt \]  

(5)

Among them, \( t \) is the last time of the system transient process. According to equation (3)-(5), the minimum capacity \( C_{sc} \) of the supercapacitor can be determined.

In addition, as is shown in Fig. 6, the inductance \( L \) must be able to large enough to ensure the continuity of the current. And the value of inductance \( L \) is given by the following equations [17]:

\[ L_{\text{Buck}} = \frac{U_{dc} \times D_{\text{Buck}}(1 - D_{\text{Buck}})}{\Delta I_{\text{Buck}} \times f_{\text{Buck}}} \]  

(6)

\[ L_{\text{Boost}} = \frac{U_{dc} \times D_{\text{Boost}}(1 - D_{\text{Boost}})}{\Delta I_{\text{Boost}} \times f_{\text{Boost}}} \]  

(7)

\[ L_{\text{max}} = \max(L_{\text{Buck}}, L_{\text{Boost}}) \]  

(8)

Where \( D_{\text{Buck}}, \Delta I_{\text{Buck}}, f_{\text{Buck}} \) and \( D_{\text{Boost}}, \Delta I_{\text{Boost}}, f_{\text{Boost}} \) denote the duty cycle, inductance ripple current and switching frequency of the converter at Buck mode or Boost mode.

4.2. SCESS control strategy

In order to ensure the stability of the system and to smooth the transient process, the voltage-current double closed-loop control approach is proposed to control the charging and discharging of the SCESS. Specifically, based on the energy requirement of the system, the charging and discharging reference current of inner loop can be obtained by different voltage comparators and it’s necessary to set a reasonable limit for the current to avoid exceeding. Then the current deviation of charging and discharging are transformed into modulation wave signal and integrated with PWM modulation to control the SCESS operating in different modes.
Additionally, the critical reference voltage of charging mode $U_{refc}$ and discharging mode $U_{refc}$ are respectively determined according to the DC bus voltage’s stable working scope which is within the stable voltage plus or minus 10% in ship power system. Then combined with the real time voltage of the supercapacitor, it is able to divide the SCESS into different status. The control scheme and the flow chart of working status changing of the SCESS is shown in Figure 6.

5. Simulation result and discussion

The impacts of SCESS on the electric ship propulsion system in three cases are studied and compared to demonstrate the effectiveness of the proposed control method. The optimal parameters of SCESS determined by (3)-(8) are given in Table 1.

| Table 1 Supercapacitor energy storage system parameters |
|---------------------------------------------------------|
| parameters                                              |
| SC Capacity/F                                           |
| Storage inductor /mH                                    |
| Stable voltage of DC bus /V                             |
| SC initial voltage/V                                    |
| SC maximum working voltage /V                           |
| SC minimum working voltage /V                           |
| SC equivalent series resistance /Ω                       |
| SC equivalent parallel resistance /Ω                     |

The established model of electric ship propulsion system shown in Fig. 4 is selected to analyze the transient stability with and without SCESS when the ship propellers vary with different operational situations. It can be specifically divided into two cases as follows.

Case 1: Simulation for acceleration and deceleration of the ship propellers;
Case 2: Simulation for propeller rushing out of water working condition;

In this case, the transient stability of the entire system is analyzed under consideration of the deceleration and acceleration of the propellers. Specifically, the diesel generator starts at $t=0s$; after 1.5s, the propulsive load is added to the system; the propellers decelerate at 4s and accelerate at 6s.

The results of case 1 with and without SCESS are shown in Fig.7. Especially, the charging current of the supercapacitor is positive and the discharging current is negative. The blue/green curve represents the simulation results with/without SCESS.

It can be seen from the Fig. 7 that the voltage and power have a sudden and large fluctuation, which lead to instability of the system without SCESS. However, with the help of SCESS, when the propellers decelerate, the generator power falls gently and the voltage of DC bus is dropped from 1467V to 1348V, which is in the stable working scope of the DC bus voltage. The supercapacitor charges and its voltage rises from 604V to 621V. When the propellers accelerate, the responses of speed and torque of the propulsive motor are better than without SCESS and the supercapacitor discharges and its voltage declines. The generator power rises gently and the voltage of DC bus is 6.9% higher than without SCESS.
Case 2:
Similar to Case 1, especially, the propeller working condition changes from normal to the other fault working conditions at t=4s. The simulation results of case 2 with/without SCESS are shown in Fig. 8.

Seen from Fig. 8, the voltage of DC bus without SCESS has a 237V hoist when the propellers are out of water at 4s and a 124V reduction when the propellers are back into water at 5s. Additionally, the generator power without SCESS has a sharp decrease about 0.4 pu. With the help of SCESS, the generator power falls 0.35 pu gently and the voltage of DC bus is 8% lower than without SCESS at t=4s. Comparing with the results without SCESS at t=5s, the speed and torque of the propulsive motor are higher. Furthermore, the generator power rises from 0.15 pu to 0.4 pu gently and the voltage of DC bus drops from 1247V to 1164V instead of 1130V.
The maximum fluctuation scope of DC bus voltage on each case is taken as an example for sensitivity analysis and the result is shown in Fig. 9. The sensitivity of the DC bus voltage is evaluated through the deviation between the maximum voltage and the minimum voltage in the process of each case.

As a consequence, it can be found that (a) the fluctuation of the DC bus voltage is obviously been restrained by the SCESS (b) and the improvement of voltage stability for decelerating is the best in different operational situations (c) and the voltage stability during accelerating is the worst.

6. Conclusion
In this paper, a series of experiments are conducted to research the transient characteristics of electric ship propulsion system during the change of operating conditions of the ship propellers. The experimental results show that the fluctuations on propulsive load have a negative effect on the transient stability of the ship system.

An electric ship propulsion system using SCESS is modeled to improve transient stability of the system. More specifically, in order to achieve a fast response to the fluctuations, the SCESS is divided into five different working status according to the stable working scope of DC bus voltage and the voltage-current dual closed-loop control approach integrated with PWM is employed to control the SCESS charging and discharging to achieve energy absorption and release. Additionally, two cases are studied and compared to demonstrate the effectiveness of the proposed method and the correctness of the simulation models. Some findings can be obtained as follow: (1) the improvement of voltage stability using SCESS for decelerating is the best among the different working conditions; (2) the voltage stability during accelerating is the worst of all; (3) the responses of the speed and torque of propulsive motor are better than without SCESS; (4) the power sag is mitigated and the transient stability of the entire system is evidently improved; At the same time, the feasibility of SCESS applied in electric ship propulsion system is also verified.

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