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Application of Flywheel Energy Storage in Ship Medium Voltage DC Power System

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Abstract

Due to the limited capacity of the generator, it is unable to quickly respond to the power demand of the pulse type load when the pulse type load is suddenly added in the medium voltage direct current (MVDC) power system of the ship, which leads to the large fluctuation of the DC bus voltage, and even the collapse of the power system. In order to make the high-power load smoothly connected to the system, a short-time high-power flywheel energy storage system is used to connect to the DC bus for power regulation and voltage compensation to enhance its stability. In this paper, based on MATLAB/Simulink platform, the simulation model of ship medium voltage DC power system and flywheel energy storage is built, and the restraining effect of flywheel energy storage device on bus voltage fluctuation caused by pulse load access is explored. Simulation results show that flywheel energy storage can improve the stability of bus voltage and restrain voltage sag.

Keywords

Medium Voltage DC Power System; Flywheel Energy Storage System; Pulse Load; Bus Voltage.

1. Introduction

The switching of instantaneous high-power load on the ship is inevitable in the ship power system. If the generation module is configured according to the full power, its volume and weight will far exceed the allowable range of ship loading. The imbalance of system power is the main cause of voltage fluctuation in the power system. Therefore, an energy storage system can be added to the power system to dynamically compensate the ship voltage and power, so as to reduce the fluctuation of bus voltage and maintain the system stability [1]. Flywheel energy storage system has the advantages of high energy storage density, high output power, short charging time, compact structure, low working temperature requirement, long service life and no pollution. Compared with other energy storage technologies, it has great advantages and is one of the most promising energy storage technologies[2].

In reference[3], it is compared whether the flywheel energy storage system can restrain the fluctuation of bus voltage caused by the switching of pulse load because the generator can not respond to its high power demand in time. In reference[4], a control strategy of flywheel energy storage system based on bidirectional DC/DC is proposed, It includes constant current, constant voltage, speed closed-loop compound control strategy in charging and two degree of freedom PI control strategy in discharging. Finally, it verifies that the proposed control strategy solves the limitations of traditional control strategy in charging and has flexible control; it has better anti load interference and target value following ability in discharging. The influence of pulse load operation on the stability of ship power system is studied in reference [5]. This paper analyzes the fluctuation of bus voltage with or without flywheel energy storage, and verifies that flywheel energy storage system is of great significance in

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maintaining the stability of ship power system. In reference [6], the operation characteristics of the flywheel energy storage device in ship power system are analyzed in detail. The flywheel energy storage device is divided into three working modes: charging, holding and regulating. A comprehensive control strategy based on vector control is designed. The simulation results show that the working mode of the flywheel energy storage device can switch smoothly and quickly, the power control response speed is fast, and the DC bus voltage transient process is stable The fluctuation decreases significantly. In reference [7], permanent magnet brushless DC motor and independent charge discharge current converter are used to build the charge discharge circuit of flywheel energy storage system. The charging adopts double closed-loop control strategy of speed and current, the inner current loop adopts hysteresis control mode, and the discharging adopts voltage closed-loop control mode. The final simulation results verify the feasibility of the circuit topology and control method.

In this paper, aiming at the safe access of high-power pulse load in ship medium voltage DC power system, the flywheel energy storage system is established, and the power control strategy to stabilize the fluctuation is designed to realize the charging and discharging of flywheel. The simulation results show that the access of flywheel energy storage system can suppress the fluctuation of bus voltage.

2. A new model of medium voltage DC power system for ring warship

In order to optimize the configuration of ship power system, save energy, further reduce the size of ship, improve efficiency, and overcome the technical challenges related to large-scale power generation, distribution and optimization, a conceptual structure model of ring ship medium voltage DC power system (MVDC) was proposed in reference[8]. The system model is divided into port side and starboard side. Each side is equipped with a rated power main generator and a rated power auxiliary generator. The generator voltage regulator and diode rectifier cooperate with each other to provide energy for the medium voltage DC bus and ensure that the DC bus can realize 5kV voltage stabilization. The circuit breaker is located at the bow and stern of the ship, connecting the port and starboard DC buses. When at least one circuit breaker is closed, the port bus and starboard bus run together, and the MVDC is in a ring shape; when both circuit breakers are disconnected, the MVDC is separated into two DC buses, and the port bus and starboard bus work independently. The ship load includes four regional load centers and one high-power radar load regional center, which are respectively connected with the port bus and starboard bus through independent DC-DC converters to realize voltage level conversion. In addition, the energy storage device and pulse load are respectively configured in MVDC Therefore, the new ring ship medium voltage DC power system can keep the best working condition even in the extremely harsh working environment.

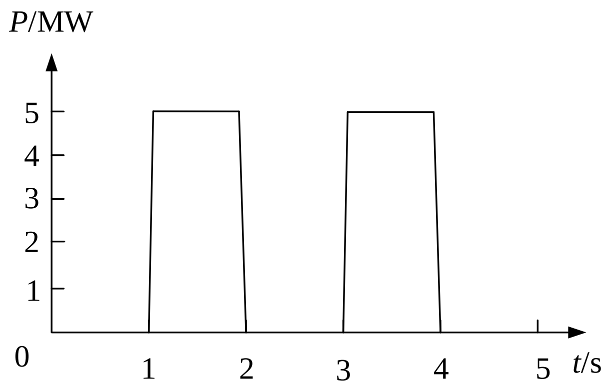

Fig. 1 Pulse load simulation waveform

Pulse load in ship power system mainly includes electromagnetic ejection device, railgun, pulse radar and other periodic instantaneous high power loads. It can be seen from Fig.1 that the power of high-

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power load of a ship can rise from 0 MW to about 5 MW in 0.01 s, and its power change rate can reach 500 MW /s. Compared with other energy storage methods, flywheel energy storage has its unique advantages: high energy storage density, high discharge power, fast charging and discharging speed, long service life and environmental friendly. Therefore, it can be used as one of the energy storage methods of high power pulse load.

3. Flywheel energy storage system

3.1 Basic structure of flywheel

The flywheel energy storage device is mainly composed of rotor system, bearing system and motor system. The motor is the main component of the flywheel energy storage device. Because the motor speed is very fast, the speed range is large, and it is required to work in a vacuum environment with poor heat dissipation, it has very high performance requirements for the motor. Compared with traditional motor, permanent magnet synchronous motor has the advantages of simple structure, low loss and high efficiency. And it has wide speed range, reliable operation, high power density, high efficiency in electric and power generation state, and can design high speed, store more energy, especially suitable for application in flywheel energy storage system. Therefore, in this paper, permanent magnet synchronous motor is selected as the simulation model of flywheel [9].

3.2 Working principle of flywheel energy storage system

Generally, the flywheel energy storage system can be divided into three states: charging state, holding state and discharging state. When the system is in the charging state, the flywheel motor operates as a motor, and the electric energy input from the DC bus accelerates the rotation of the flywheel through the DC/DC converter, which converts the electric energy into kinetic energy and stores it in the flywheel; when the flywheel reaches the set maximum speed, the system will absorb little energy from the DC bus to keep the flywheel speed constant and the stored energy unchanged. When the system is in the discharge state, the speed of the flywheel decreases, the motor will be used as a generator to convert the mechanical energy into electrical energy, and the AC will be rectified into DC through the DC/DC converter and sent to both ends of the DC bus to meet the demand of high-power load. Thus, the storage, maintenance and release of electric energy in the whole system are realized. The schematic diagram of flywheel energy storage system is shown in Fig.2.

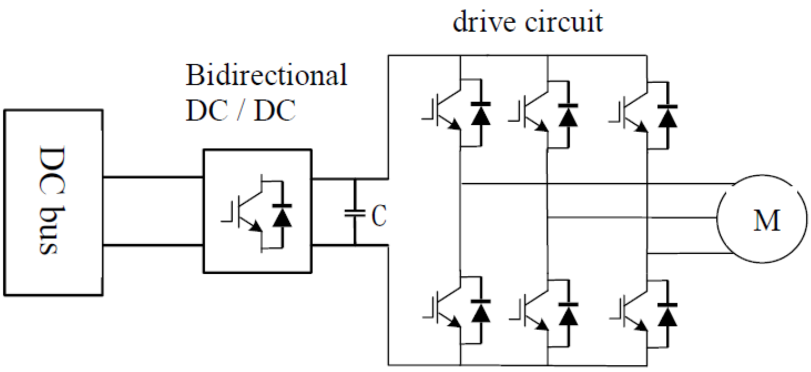

Fig. 2 Schematic diagram of flywheel energy storage system

The mathematical model of PMSM Based on the coordinate system [10] is as follows:

$$\begin{cases} u_{fd} = R_{fs} i_{fd} + p\psi_{fd} - \psi_{fd}\omega_f \\ u_{fq} = R_{fs} i_{fq} + p\psi_{fq} + \psi_{fq}\omega_f \end{cases} \tag{1}$$

$$\begin{cases} \psi_{fd} = L_{fd} i_{fd} + \psi_f \\ \psi_{fq} = L_{fq} i_{fq} \end{cases} \tag{2}$$

$$T_{em} = \frac{3}{2} P_n [\psi_f i_{fq} + (L_{fd} - L_{fq}) i_{fd} i_{fq}] \tag{3}$$

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Ignoring the loss, there are

$$P_e = \frac{dW}{dt} = J\omega_f \frac{d\omega_f}{dt} = T_{em}\omega_f \quad (4)$$

Where, u_{fd}, u_{fq} is the motor side voltage axis component; $i_{fd,}\ i_{fq}$ is the stator current component; $\psi_{fd,}\ \psi_{fq}$ is the stator flux axis component; $L_{fd},\ L_{fq}$ is the stator inductance axis component; R_{fs} ω_f is the stator inductance; ψ_f is the motor synchronous angular velocity; T_{em} is the air gap flux; P_n is the electromagnetic torque; is the pole number, J is the motor moment of inertia; P_e is the flywheel power.

It can be seen from Fig.4 that the core component of the flywheel energy storage system is the rotating flywheel, which determines the energy E stored and released by the flywheel ,it can be expressed by formula (5).

$$E = \frac{1}{2}J\omega^2 \quad (5)$$

Where J is the moment of inertia, the moment of inertia of the flywheel, which is related to the shape, size and material of the flywheel; ω is the angular velocity of the flywheel.

In order to improve the life of the flywheel, the flywheel speed is usually controlled between the minimum speed ω_{min} and the maximum speed ω_{max} , What is the energy stored or released by the flywheel

$$\Delta E = \frac{1}{2}J(\omega_{max}^2 - \omega_{min}^2) \quad (6)$$

The definition of discharge depth is introduced:

$$\alpha = 1 - \frac{\omega_{max}^2}{\omega_{min}^2} \quad (7)$$

Among them, $\omega_{max,}\ \omega_{min}$ is the maximum and minimum angular velocity of the energy storage system. The energy storage capacity of the flywheel energy storage system is proportional to the square of the maximum speed, and the discharge capacity is proportional to the square difference between the maximum speed and the minimum speed. Therefore, high speed and wide speed range operation is very important to improve the energy storage capacity and discharge depth of the flywheel energy storage system. When the minimum speed is set to half of the maximum speed, the discharge depth can reach 75%.

3.3 Control strategy of flywheel

The control strategy of flywheel energy storage system can be divided into three modes according to the operation status of external system connected by DC port: (1) speed control; (2) power control; (3) bus voltage control. When it is used in the system with strong dc voltage source, the controller of flywheel energy storage system mostly adopts power control mode, and the control system structure at this time is shown in Fig.3. The power command generates the reference value of shaft current through the power controller and then inputs it into the current controller. The shaft reference voltage generated by the current controller is sent to the SVPWM unit, and the pulse signal generated by the SVPWM module is sent to the converter. When the flywheel energy storage system is in charging state, $P_e^*>0$, $i_q^*>0$; In discharge state, $P_e^*<0$, $i_q^*<0$.

When the flywheel energy storage system is in the discharge state, the external load and bus voltage jointly determine the power output from the bus capacitor, while the electromagnetic power of the permanent magnet synchronous motor determines the power injected from the flywheel to the bus capacitor. The power difference between the two affects the change direction and speed of the bus voltage, and the charging state is similar to it, so the power output of the flywheel energy storage system is stable The control mode in which the input/output power follows the external power command is essentially to keep the bus voltage matching the external power command by adjusting the input/ output electromagnetic power of the motor.

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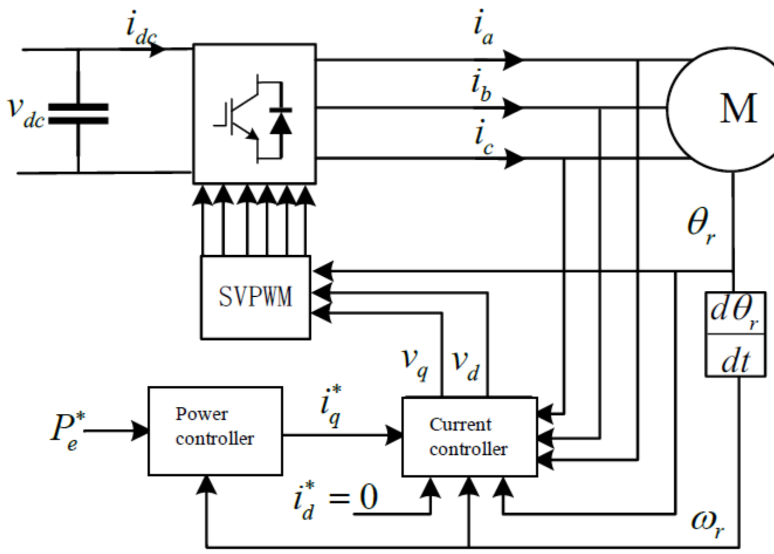

Fig. 3 Schematic diagram of control system for power control mode of flywheel energy storage system

4. Simulation analysis of flywheel energy storage system

Based on the external flywheel energy storage control system in the ship MVDC power system, this paper builds the ship two terminal MMC-MVDC system simulation model with DC bus voltage of 5kV in MATLAB/Simulink, as shown in Fig.4. The power generation system consists of synchronous generator model with rated power of 20MW, conventional load with AC load of 15MW and pulse load with maximum power of 5MW. The parameters of permanent magnet synchronous motor for flywheel are: stator phase winding resistance is $R = 0.15\Omega$, stator phase and phase winding inductance is $L_d = L_q = 0.001H$, moment of inertia is $J = 400kg \bullet m^2$, permanent magnet flux linkage is $\psi = 0.8\, V \bullet s$, pole pair P=2, rated speed is $n = 5732rpm$. The damping coefficient is $1e^{-4}\ N \bullet m \bullet s$.

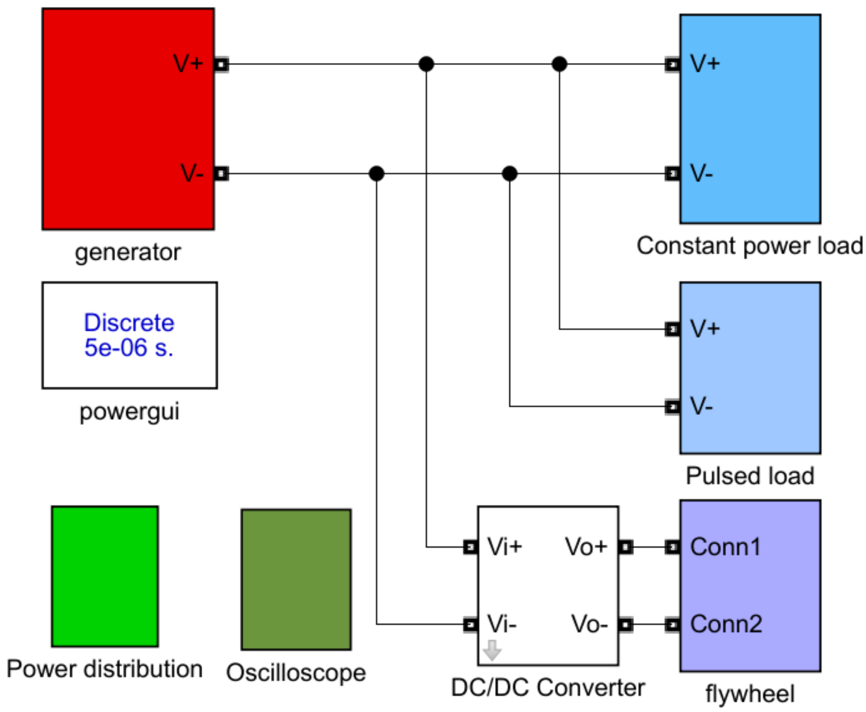

Fig. 4 Simulation model of ship double ended MVDC system with flywheel energy storage

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The specific model of flywheel energy storage system is shown in Fig.5 ~ Fig.6. Fig.5 shows a DC/DC converter model for controlling the DC voltage of the flywheel, where P_{sc} is the power allocated to the flywheel by the power distribution V_1 to control the power switch on and off. Figure 6 is the equivalent model of the flywheel. The control part of the model controls the flywheel based on the principle described in Fig.3. The pulse signal generated by SVPWM triggers the power switch in the three-phase bridge converter to realize the charging and discharging function of the flywheel according to the power distribution.

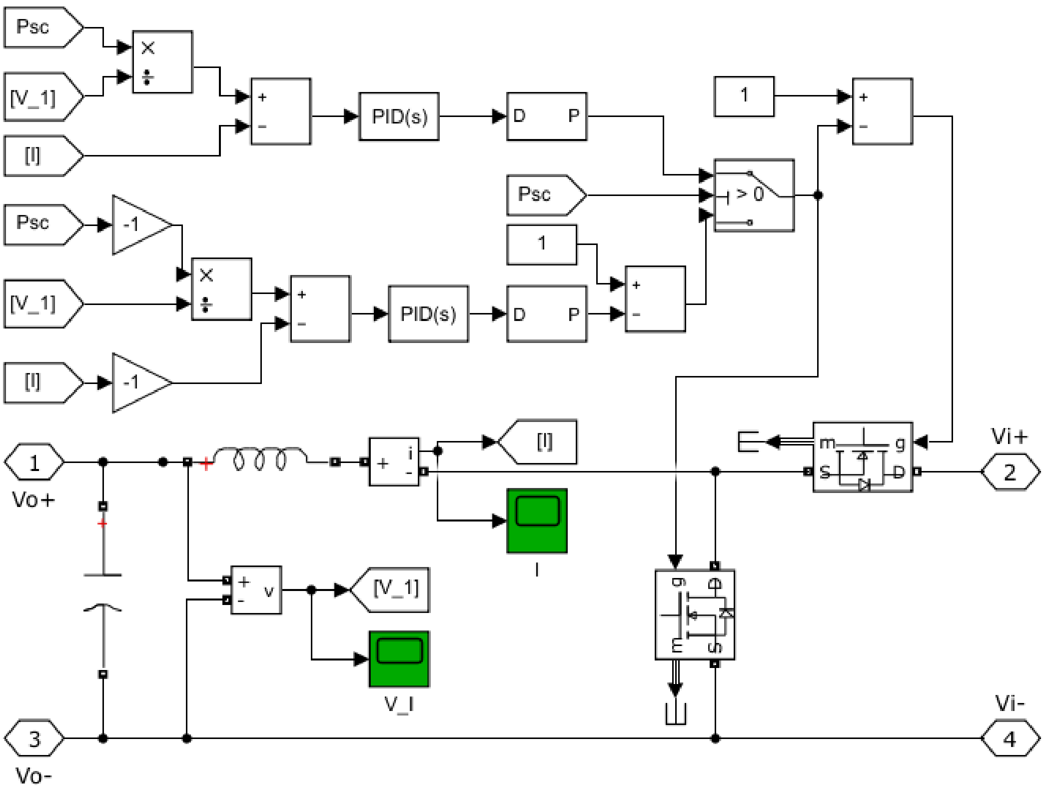

Fig. 5 Flywheel DC side DC/DC converter

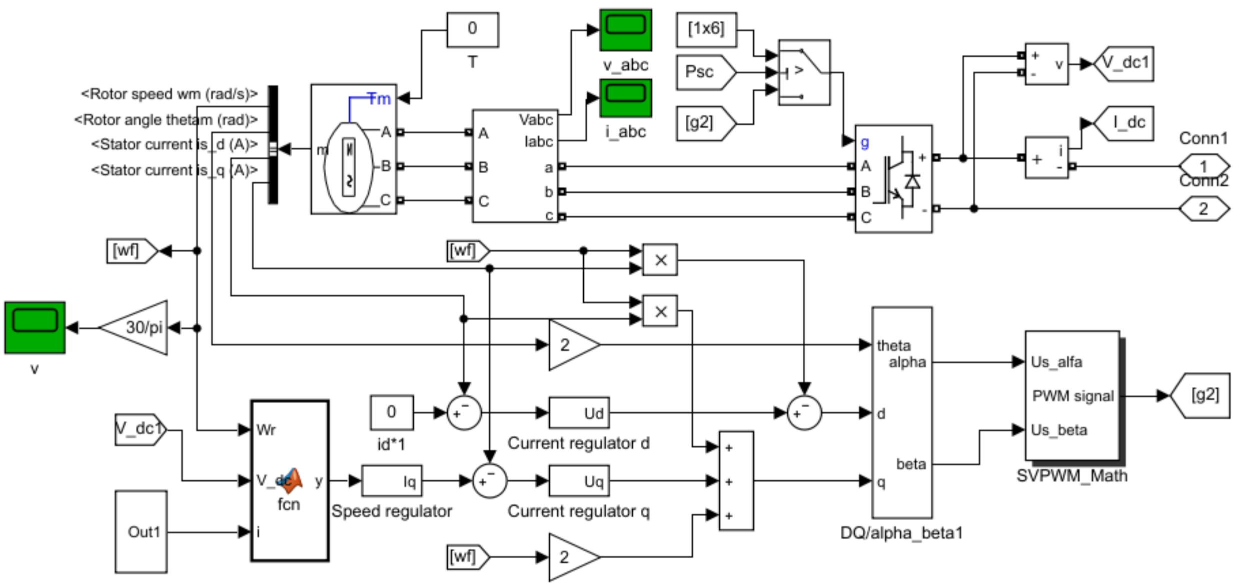

Fig. 6 Flywheel equivalent model

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When flywheel energy storage system is not included in ship mvdc power system, 5MW pulse load is connected to the system in 1s-1.01s and 3s-3.01s respectively (as shown in Fig.2), so that the power generated by generator can not be corresponding in time, resulting in large fluctuation of bus voltage, as shown in Fig.7. This will have a greater impact on the ship's power system and a greater harm to the stability of the system. Because flywheel energy storage has the advantages of fast response and high power release in a short time, the stability of the system will be improved obviously if flywheel energy storage is connected to the ship power system. When the flywheel energy storage system is connected, the waveform of DC bus voltage is shown in Fig.8. It can be seen from Fig.8 that the fluctuation of bus voltage is obviously suppressed after the flywheel energy storage system is connected.

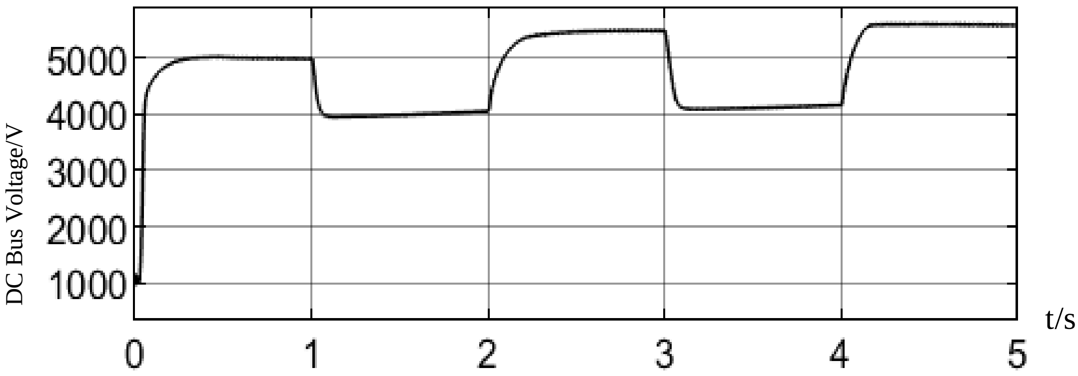

Fig. 7 Bus voltage without flywheel energy storage system

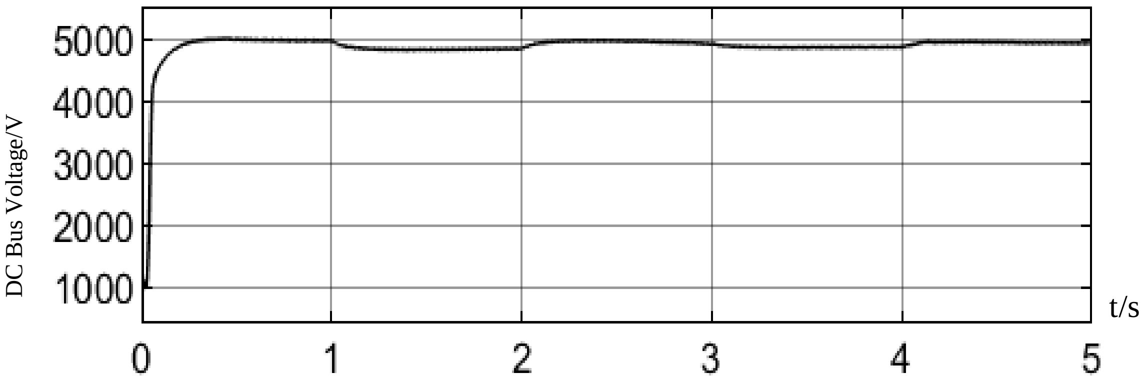

Fig. 8 Bus voltage when connected to flywheel energy storage system

Fig.9 shows the power distribution diagram of pulse load. After the instantaneous pulse power is processed by the power distribution module, the generator and flywheel share the corresponding power respectively, so as to meet the timely response of short-term high-power load. Fig.10 shows the change curve of flywheel speed in the whole simulation process. The change of flywheel speed can be roughly divided into three sections. The first section: in 0-1s, there is no additional load except the loss of flywheel itself, so the speed is almost constant. The second stage: in the 1s-1.01s and 3s-3.01s time period, due to the access of pulse load, the flywheel speed began to decline. The third stage: in the period of 2s-3s and 4s-5s, combined with figure 9, it can be seen that the power distribution of the flywheel is negative, so at this time, both ends of the flywheel absorb electric energy from the DC grid, and the flywheel speed begins to rise slowly. From the slope of the curve in Fig.10, it can be concluded that the charging speed is relatively slow compared with the flywheel discharge process, and the stable operation of the energy storage system can be achieved by adjusting the frequency of the pulse load in practical application.

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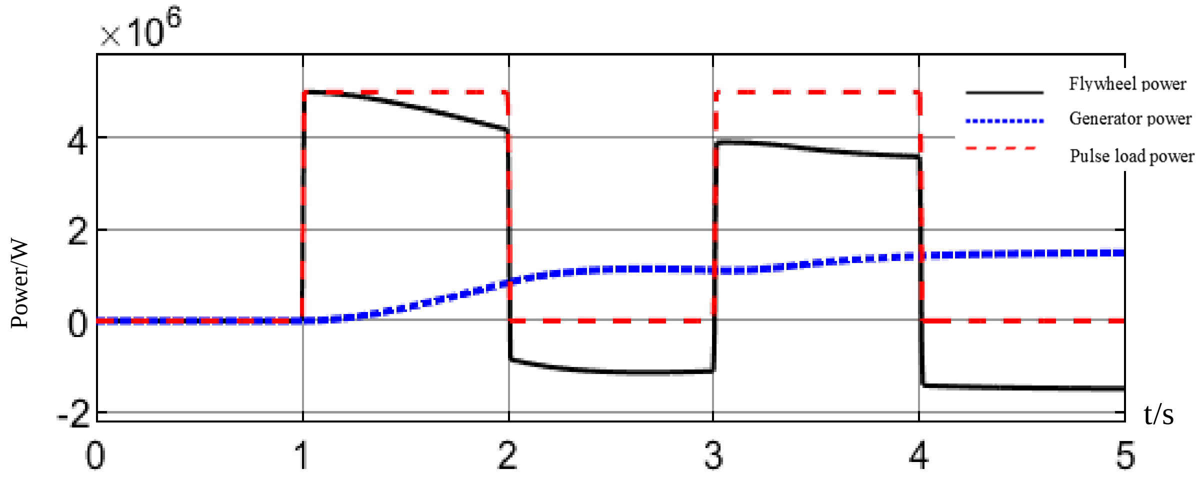

Fig. 9 Power distribution

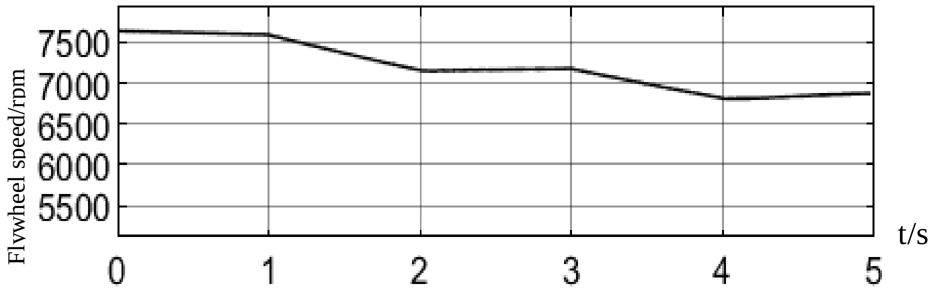

Fig. 10 Flywheel speed curve

5. Conclusion

In view of the fact that when the ship mvdc power system is connected to the high-power pulse load, it can not quickly respond to the fluctuation of the grid voltage. In this paper, the flywheel energy storage system is connected to the power mutation of the flat complex pulse load in the grid, and a simulation model is built on MATLAB/Simulink to verify the effectiveness of the proposed scheme. Firstly, the basic structure and working principle of flywheel energy storage are introduced; then the control strategy of flywheel is introduced; finally, the simulation model is built to verify that the flywheel energy storage system can suppress the grid voltage fluctuation. The disadvantage of this paper is that the energy storage method is only a single flywheel energy storage scheme, which can be combined with battery energy storage to realize the hybrid energy storage of ship, which is more conducive to the stability of power grid system.

References

[1] Fu Lijun, Liu Lufeng, Wang Gang, et al. Research progress of medium voltage DC integrated power system for ships in China [J]. China Ship Research, 2016,11 (1): 72-79 DOI:10.3969/ j.issn.1673-3185. 2016.01.009.

[2] Ma Weiming. Electromechanical energy conversion technology in shipboard integrated power system [J]. Journal of electrical engineering, 2015, 10 (4): 3-10

[3] S.Kulkarni and S.Santoso,"Impact of pulse loads on electric ship power system: With and without flywheel energy storage systems," 2009 IEEE Electric Ship Technologies Symposium, Baltimore, MD, 2009, pp. 568-573, doi: 10. 1109 /ESTS.2009.4906568.

[4] PI Zhenhong, Dai Jianjian, Wei Dianju, et al. Capacity analysis and design of flywheel energy storage system [J]. Energy storage science and technology, 2019, 8 (4): 778-783 DOI:10.12028/ j.issn.2095-4239. 2019.0047.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0037

[5] Ji Feng, Fu Lijun, Wang Gongbao, et al. Design of flywheel energy storage contro-ller for shipboard integrated power system [J]. Chinese Journal of electrical engin-eering, 2015, (12): 2952-2959 DOI:10. 13334/j.0258-8013.pcsee.2015.12.005.

[6] Yao yuan. Modeling and Simulation of flywheel energy storage system for wind turbine [D]. North China Electric Power University; North China Electric Power University (Baoding), 2017

[7] Zhao Sifeng, Tang Yingwei, Wang Sai, et al. Research on control strategy of urban rail transit renewable energy recovery based on flywheel energy storage technology [J]. Energy storage science and technology, 2018,7 (3): 524-529 DOI:10.12028/j.issn.2095-4239.2018. fifty-three

[8] Ou yuexiong, fan Shaosheng, Tang xunlu. Research on control strategy of flywheel energy storage system based on bidirectional DC/DC [J]. Electrical engineering, 2016, (4): 12-16 DOI:10.3969/j.issn.1007-3175. 2016.04.004.

[9] Wang Ruitian, Fu Lijun, Ji Feng, et al. Study on suppressing DC bus voltage fluctuation of shipboard integrated power system with flywheel energy storage [J]. Shipboard power technology, 2010,30 (12): 5-8,16 DOI:10.3969/j.issn.1003-4862.2010.12.002.

[10] Li Baojun, Wang Zhixin, Wu Dingguo. Modeling and Simulation of charging and discharging process of flywheel energy storage system [J]. Industrial control computer, 2011,24 (12): 107-109111 DOI:10.3969/ j.issn.1001-182X.2011.12.051.