ISSN: 2414-1895 DOI: 10.6919/ICJE.202105_7(5).0073

# Research on Stability of Ship Power Grid based on Supercapacitor

Deyun Mao[1,a], Jianmei Xiao[1,b] and Xihuai Wang[1,c]

[1]Logistics Engineering College, Shanghai Maritime University, ShangHai 201306, China.

[a]1547720752@qq.com, [b]jmxiao@shmtu.edu.cn, [c]wxh@shmtu.edu.cn

## Abstract

**In order to solve the problem of power fluctuation at bus terminal of power grid caused by sudden change of load, a double closed-loop PI control strategy is proposed. Firstly, a hybrid ship model with super-capacitor is built in Matlab/Simulink. Then, a double closed-loop controller is designed in the DC/DC converter to control the charging and discharging of the super-capacitor, so that the supercapacitor can quickly compensate the energy of the ship grid bus and absorb the excess energy for storage. The simulation results show that the super-capacitor can effectively smooth the power fluctuation of marine power grid bus, provide energy for DC bus quickly, maintain bus voltage stability, and keep the speed and output active power of diesel generator set stable.**

## Keywords

**Diesel Generator Set; Super-capacitor; Double Closed Loop PI Control; Power Fluctuation.**

## 1. Introduction

With the continuous development of power electronic components, the load type and capacity of ship power grid are increasing [1]. The structure of ship's power system becomes complex, and the sudden change of load is easy to occur when sailing on the sea, which will cause the disconnection of ship's power grid and economic loss. Sudden load change will cause power fluctuation of DC bus in marine power grid [2], affect the stability of bus voltage, and cause marine diesel generator set and electrical equipment cannot work normally.

In order to solve the above problems effectively, energy storage system and control strategy are added to ship power grid. M. S. Khan et al. [3] According to the voltage, current and charging state of battery and super capacitor, an energy storage management system based on fuzzy logic is designed. It can change the charging and discharging rate according to the SOC state of energy storage. It doesn't need deep discharge and over discharge protection controller, but it needs fuzzy controller to provide reference power for charging and discharging of hybrid energy storage unit at all times and design power generation limit check controller. Zhou et al. [4] proposed a coordinated power management strategy based on dynamic load power distribution of diesel generator and battery. In order to suppress power fluctuation, high frequency fluctuation value was extracted from load power and distributed to battery pack. However, due to the lack of high- power density energy storage elements, the number of battery pack should be increased. Liu Zhong et al. [5] proposed load power distribution method of equivalent SOC consistency control and dynamic droop control to evaluate SOC parameters.

The energy storage system can stabilize the power fluctuation caused by load change during islanding operation of power grid, maintain the frequency stability of power grid, provide power compensation, improve power quality, and stabilize DC bus voltage [6]. In this paper, super capacitor and double closed-loop PI strategy are used to solve the imbalance between the output active power and load consumption power of diesel engine, and to stabilize and smooth the voltage fluctuation of ship power grid. The supercapacitor in microgrid can quickly provide power compensation to buffer the impact

ISSN: 2414-1895 DOI: 10.6919/ICJE.202105_7(5).0073

of load changes on the grid. The control strategy can make the supercapacitor quickly provide power through bidirectional DC/DC converter when the diesel engine output is insufficient. When the power consumption of diesel engine and load is balanced, the excess energy on DC bus can be absorbed and stored.

## 2. The establishment of the model

### 2.1 Mathematical modeling of diesel generator set

Diesel generator set includes diesel engine speed control system and synchronous generator excitation system [7], which provides main power for ships. However, the working system is nonlinear and very complex, so it is usually simplified as a first-order inertia link with delay link [8]. The overall control block diagram of diesel generator set is shown in Figure 1, and the program diagram is shown in Figure 2.

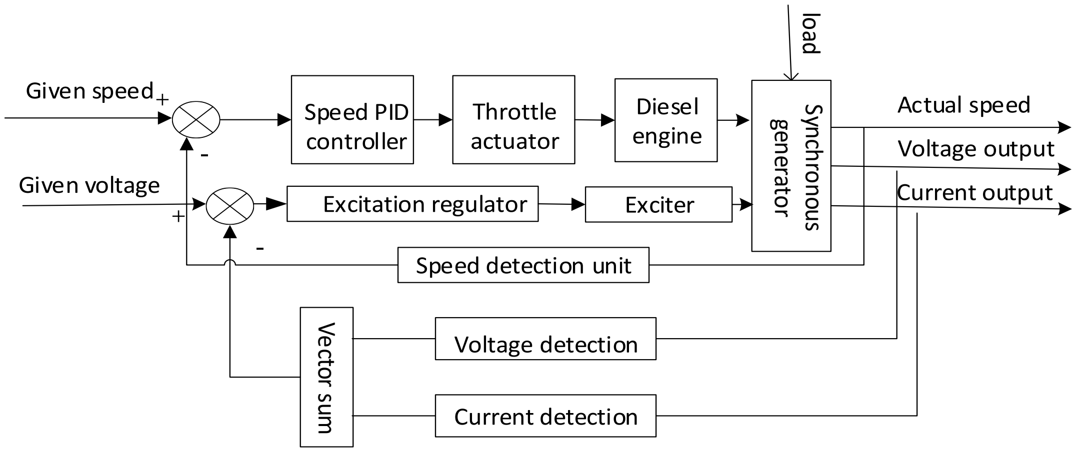


Figure 1. Control block diagram of diesel generator set

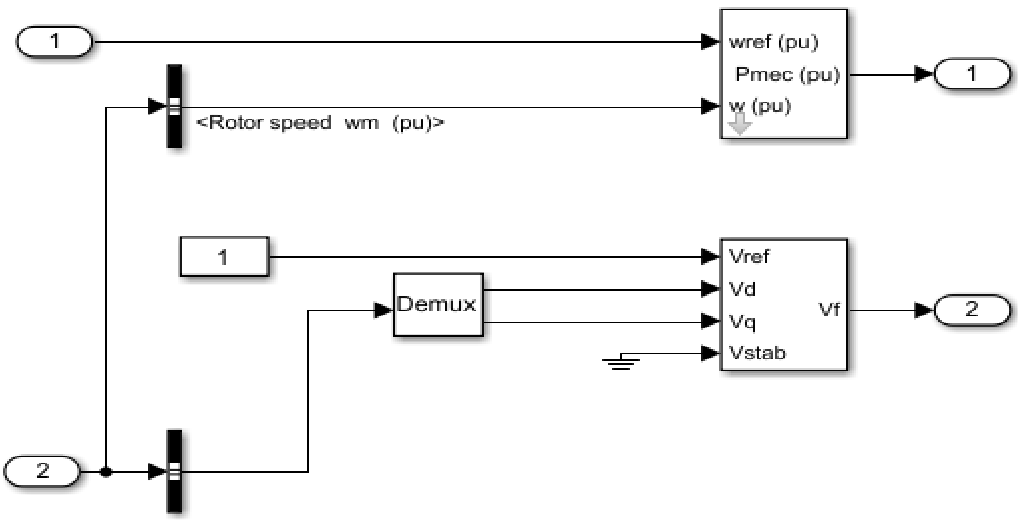


Figure 2. Control program diagram of diesel generator set

### 2.2 Mathematical modeling of bidirectional DC/DC converter

The topology of non-isolated DC/DC converter is simple, the energy conversion ratio is small, and the dynamic response is fast [9], which meets the requirements of marine power grid. Therefore, the bi-directional half bridge DC/DC converter is selected, and its topology is shown in Figure 3. In the DC/DC converter, the high voltage side is connected with the DC bus terminal, and the low voltage side is connected with the super capacitor.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202105_7(5).0073

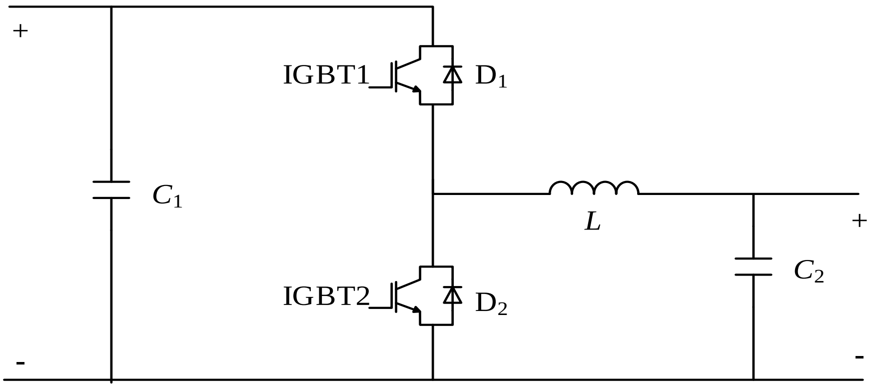


Figure 3. Topology of bidirectional half bridge DC/DC converter

According to the topology, the DC/DC converter is modeled by the state space averaging method with $C_2$ and $L$ as the state variable [10,11].

(1) In buck mode, the transfer function is:

$$\begin{cases} G_{id}(s)=\left.\dfrac{\hat{i}_L(s)}{\hat{d}(s)}\right|_{\hat{U}_{dc}(s)=0}=\dfrac{U_{dc}(sc_2+\dfrac{1}{R_{ep}})}{LC_2s^2+\dfrac{L}{R_{ep}}s+1} \\ G_{vd}(s)=\left.\dfrac{\dot{\hat{U}}_{C_2}(s)}{\hat{d}(s)}\right|_{\hat{U}_{dc}(s)=0}=\dfrac{U_{dc}}{LC_2s^2+\dfrac{L}{R_{ep}}s+1} \end{cases} \tag{1}$$

(2) In boost mode, the transfer function is:

$$\begin{cases} G_{id}(s)=\left.\dfrac{\hat{i}_L(s)}{\hat{d}(s)}\right|_{\hat{U}_{dc}(s)=0}=\dfrac{U_{dc}(sc_2+\dfrac{2}{R_{ep}})}{LC_{dc}s^2+\dfrac{L}{R_{dc}}s+(1-D')^2} \\ G_{vd}(s)=\left.\dfrac{\dot{\hat{U}}_{dc}(s)}{\hat{d}(s)}\right|_{\hat{U}_{dc}(s)=0}=\dfrac{D'U_{dc}(1-\dfrac{sL}{D'^2R_{dc}})}{LC_2s^2+\dfrac{L}{R_{dc}}s+(1-D')^2} \end{cases} \tag{2}$$

## 2.3 Mathematical modeling of supercapacitor.

The super capacitor adopts the classical RC equivalent model, and the circuit is shown in Figure 4, which is composed of ideal capacitor C and equivalent series resistance R [12].

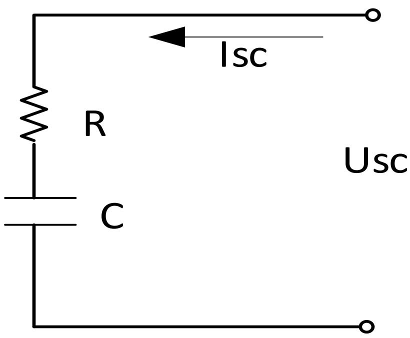


Figure 4. RC equivalent model of supercapacitor

ISSN: 2414-1895 DOI: 10.6919/ICJE.202105_7(5).0073

The circuit equation can be obtained from Figure 3:

$$U_{sc} = I_{sc} * R - \frac{1}{C}\int I_{sc} d_t \tag{3}$$

The supercapacitor SOC is [13]:

$$SOC = \frac{Q_t}{Q_N} = \frac{C(U_{sc} - U_{\min})}{C(U_{\max} - U_{\min})} = \frac{U_{\text{int}} + \frac{1}{C}\int_0^t I_{sc} d_t - U_{\min}}{U_{\max} - U_{\min}} \tag{4}$$

The super capacitor energy storage is:

$$J_{sc} = \frac{1}{2} C(U_{max}^2 - U_{min}^2) \tag{5}$$

To sum up, the program of supercapacitor is shown in Figure 5:

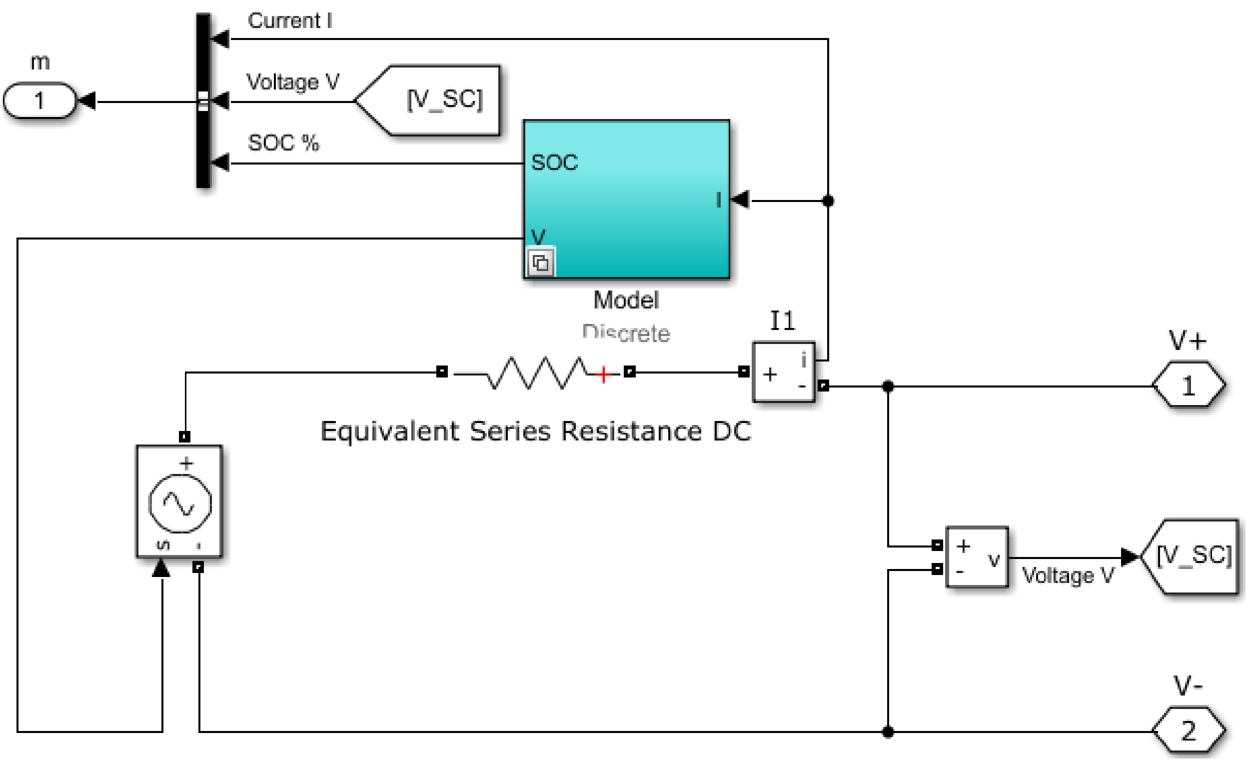


Figure 5. Super capacitor program diagram

# 3. Controller design

## 3.1 Control chart design of DC/DC converter.

In order to quickly eliminate the influence of power fluctuation caused by load change, double closed-loop PI control of current inner loop and voltage outer loop is adopted for super capacitor [14], which is mainly to improve the response speed of providing instantaneous power in case of power mutation, compensate energy for DC bus, and balance the mismatch between active power output of diesel engine and power consumed by load, The fluctuation of DC bus voltage is smoothed and stabilized to keep the speed and output power of diesel generator set constant. The super capacitor control diagram is shown in Figure 6.

$U_{bus-ref}$ is the reference voltage of DC bus; $U_{out}$ is the actual voltage of DC bus. The difference between $U_{bus-ref}$ and $U_{out}$ generates the current reference value $I_{SC-ref}$ under the action of voltage regulator and limiting link, and then compares with the super capacitor current $I_{SC}$ in DC/DC converter. The PWM modulation wave is generated by the action of current regulator, which becomes the gate trigger signal of IGBT and drives DC/DC converter to work in Buck mode or boost mode.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202105_7(5).0073

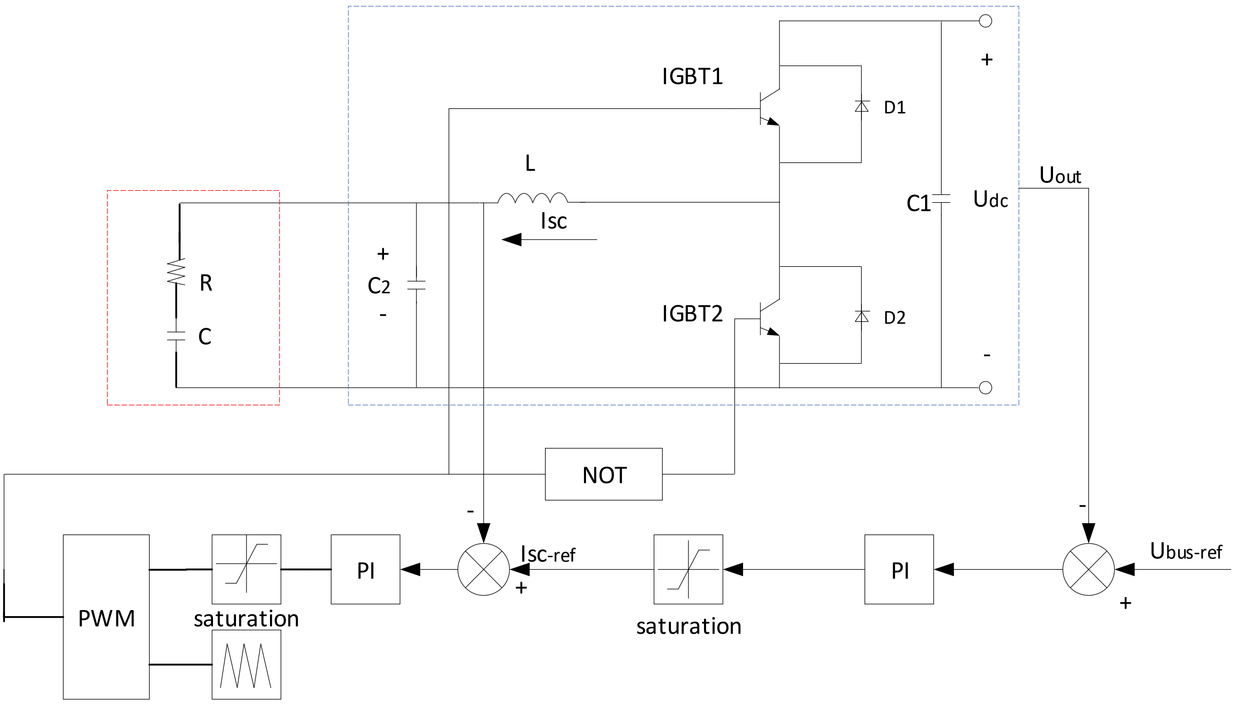


Figure 6. Control diagram of DC/DC converter

### 3.2 Parameter design of DC/DC converter controller.

The principle of double closed loop PI control for DC/DC converter is shown in Figure 7:

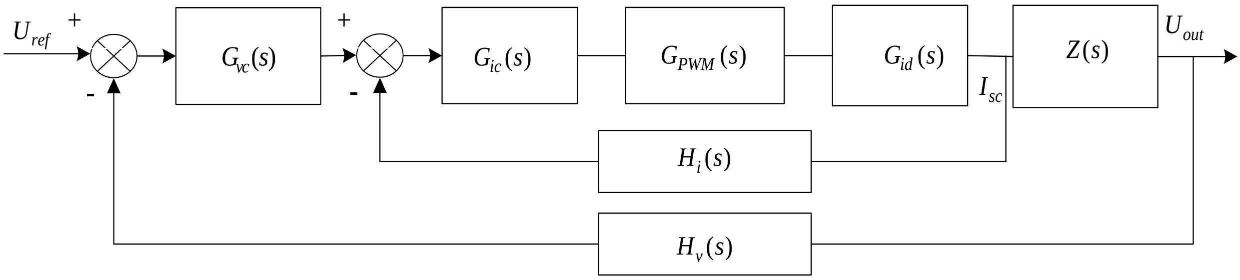


Figure 7. Schematic diagram of double closed loop PI control of DC / DC converter

According to figure 7, the open-loop and closed-loop transfer functions of the current inner loop are equation (6) and equation (7) respectively:

$$G_1(s) = G_{PWM}(s)G_{id}(s)H_i(s) \tag{6}$$

$$G_2(s) = \frac{G_{ic}(s)G_{PWM}(s)G_{id}(s)H_i(s)}{1+G_{ic}(s)G_{PWM}(s)G_{id}(s)H_i(s)} \tag{7}$$

The inner current loop adopts PI controller, and its transfer function can be set as follows:

$$G_3(s) = K_{ci} + \frac{K_{cp}}{s} \tag{8}$$

The controller parameters meet the following requirements:

$$\begin{cases} \dfrac{k_{cp}}{2\pi k_{ci}} = f_{nid} \\ \left|G_1(s)G_3(s)\right\|_{s=2\pi jfcid} = 1 \end{cases} \tag{9}$$

ISSN: 2414-1895
DOI: 10.6919/ICJE.202105_7(5).0073

Where: $f_{nid} = 100HZ$, $f_{cid} = 1000HZ$ [15], it can get $k_{ci} = 0.3$, $k_{cp} = 40$.

The open-loop transfer function of the outer voltage loop is as follows:

$$G_4(s) = G_2(s)Z(s)H_v(s) = G_2(s)\frac{R}{RCs+1}H_v(s) \tag{10}$$

The outer voltage loop adopts PI controller, and the transfer function can be set as:

$$G_5(s) = K_{vi} + \frac{K_{vp}}{s} \tag{11}$$

Where: $f_{nvd} = 500HZ$, $f_{cvd} = 100HZ$ [15], it can get $k_{vi} = 8$, $k_{vp} = 400$.

## 4. Simulation examples and analysis

In this paper, a ship power grid model with super capacitor is built in Matlab/Simulink environment to simulate the operation of DC bus voltage, diesel generator speed and output active power in case of load mutation. The main parameters of the model are shown in Table 1.

Table 1. Main parameters of ship power system model

| Parameter name | numerical value | Parameter name | numerical value |
|---|---|---|---|
| Output power of diesel engine | $50kw$ | Rated voltage of super capacitor | $480V$ |
| Set voltage of DC bus | $750V$ | Super capacitor rated capacitance | $10F$ |
| Inductance of DC/DC converter $L$ | $5e^{-3}H$ | DC/DC converter capacitor $C_2$ | $2e^{-3}F$ |

### 4.1 Simulation results

Within 0~2 seconds, the ship is connected to 50kw load to start operation; in the second second, the ship is loaded with 50kw power to run; in the third second, the ship is unloaded to reduce 50kw load. The loading and unloading of ship power system is shown in Figure 8.

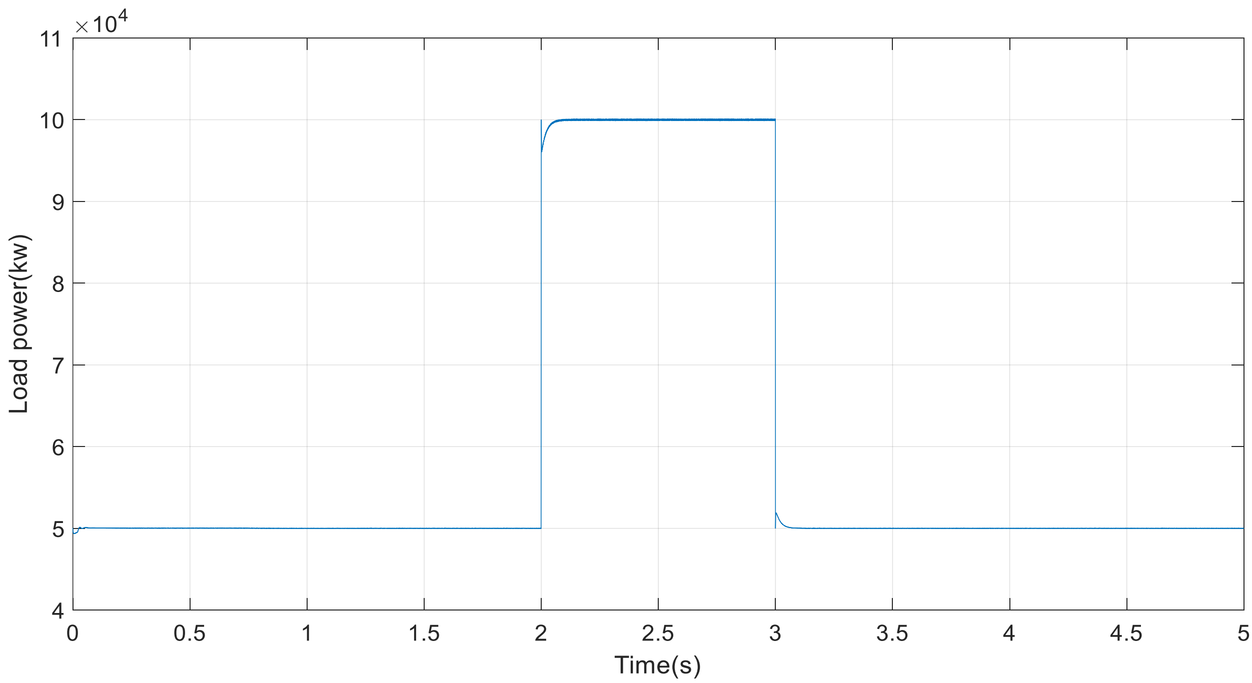


Figure 8. Loading and unloading of ship power system

ISSN: 2414-1895
DOI: 10.6919/ICJE.202105_7(5).0073

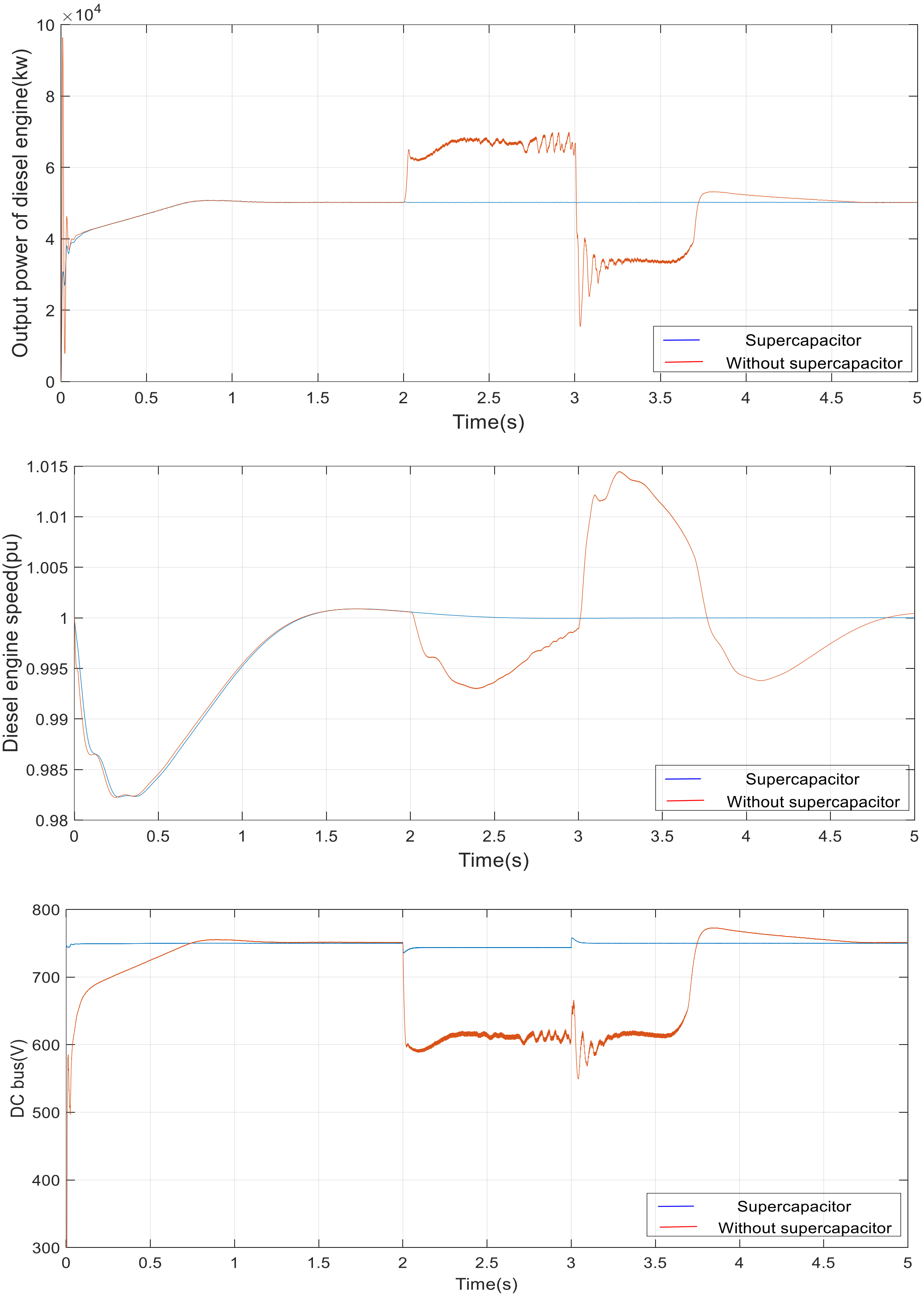


Figure 9. Comparison of operation of ship power grid under loading and unloading

It can be seen from figure 9 that in 0~2 seconds, the output active power and speed of the diesel engine are almost the same when the ship contains super capacitor and does not contain super capacitor. However, in the second second, when the ship suddenly loads, the diesel engine starts to run overload, and the speed begins to deviate from the set nominal value, and the fluctuation range is too large. In the third second, the ship suddenly unloaded, the diesel engine appeared low load operation, and the speed was still in a state of fluctuation. At the same time, the DC bus will also be greatly reduced, and the maximum voltage drop is nearly 200V. In case of sudden loading and

ISSN: 2414-1895
DOI: 10.6919/ICJE.202105_7(5).0073

unloading, it is difficult for DC bus voltage to quickly return to the set value, which is not conducive to the stable operation of ship power system and electrical equipment. After adding the super capacitor, the diesel engine has good dynamic characteristics and maintains the previous running state in case of sudden loading and unloading, which can ensure the normal operation of the ship. When the DC bus voltage is loaded in the second second and unloaded in the third second, the voltage changes, and decreases by 12.5V and 13.2V respectively. The fluctuation range is within $\pm 1.76\%$, and the voltage can quickly return and stabilize after about 0.047 seconds of load fluctuation.

### 4.2 Result analysis

The compensation power, SOC and terminal voltage of the supercapacitor are shown in Figure 10.

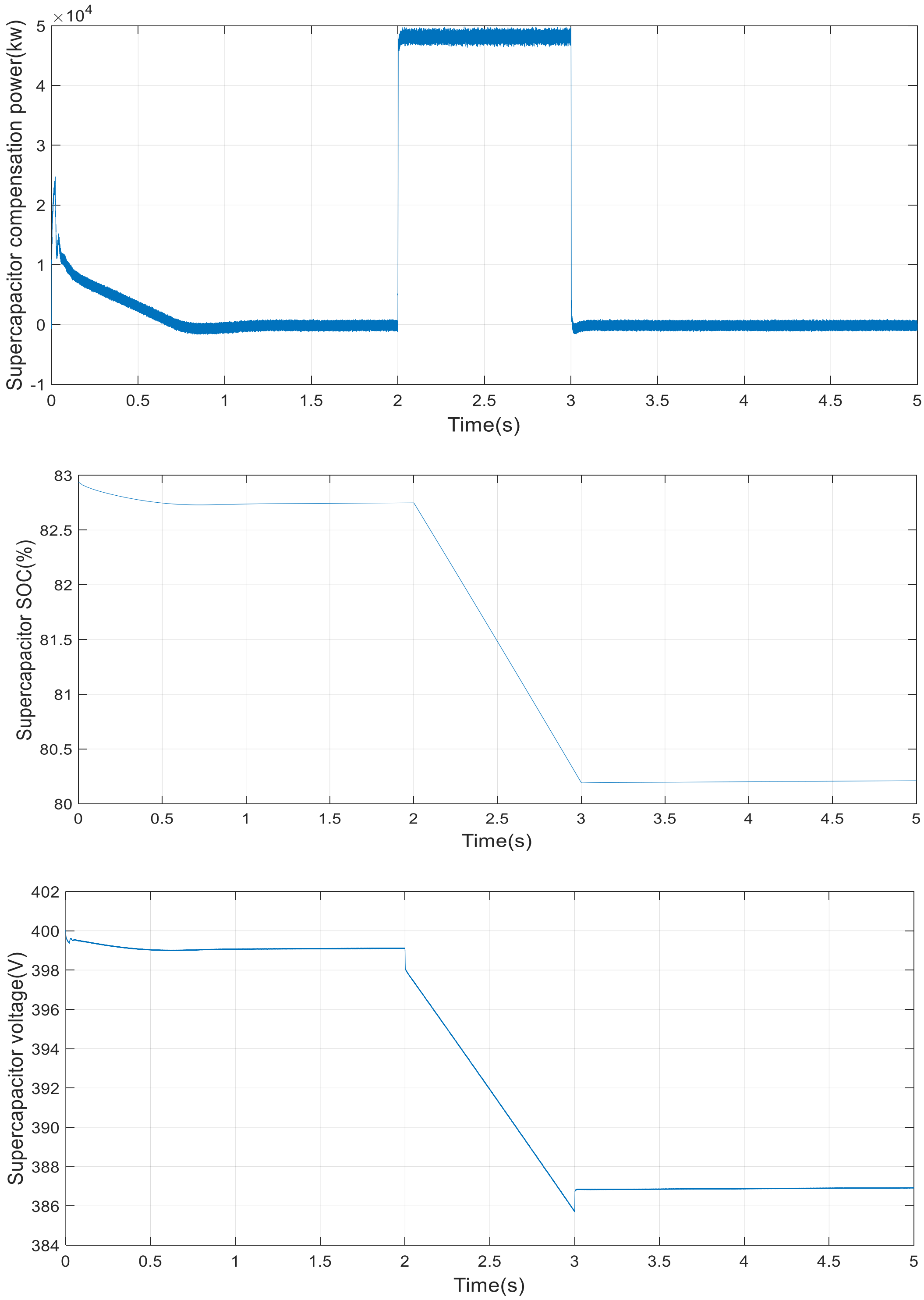


Figure 10. Compensation power, SOC and terminal voltage of super capacitor

ISSN: 2414-1895 DOI: 10.6919/ICJE.202105_7(5).0073

According to figure 10, in the second second, the sudden loading of ship power grid leads to insufficient output of diesel engine. Under the action of double closed-loop PI control strategy, super capacitor can quickly respond and provide stored energy to maintain DC bus voltage and stable operation of diesel engine. The SOC curve of super capacitor decreases continuously in 2 ~ 3 seconds, which indicates that the power supply is in the process of power supply.

## 5. Conclusion

In conclusion, the supercapacitor can meet the transient power demand, suppress the power fluctuation caused by load changes, and keep the DC bus voltage stable within the expected amplitude margin. When the total power demand of the load exceeds the total power output of the diesel generator set, the double closed-loop PI control can make the super capacitor provide energy to support the generator through the DC/DC converter, which can keep the power balance between the diesel generator set and the load; when the output power of the diesel generator set can maintain the total power demand of the load, it can absorb the excess energy on the DC bus through the DC/DC converter Quantity. The control strategy improves the response speed of super capacitor and greatly reduces the impact of load mutation on the stability of marine power system.

## References

[1] Hamoud Alafnan, Min Zhang, Weijia Yuan, et al. Stability Improvement of DC Power Systems in an All-Electric Ship Using Hybrid SMES/Battery. IEEE Trans- actions on Applied Superconductivity, vol. 28, no. 3, April 2018.

[2] M.Yue,X.H.Wang,J.M.Xiao.A ship energy management control strategy based on improved PSO[J]. Industrial Control Computer,2020,5. (in Chinese).

[3] M. M.S.Khan,M.O.Faruque,A.Newaz.Fuzzy logical based energy storage management system for MVDC power system of all electric ship[C].IEEE Trans Energy Convers,vol.32,no.2,pp.798–809,Jun.2017.

[4] zhibin Zhou,Mamadou bailo camara,Brayima dakyo.Coordinated power control of variable-speed diesel generators and lithium-battery on a hybrid electric boat[C]. IEEE Transactions on Vehicular Technology, vol. 66, no.7 July 2017.

[5] Z.Liu,C.Yang,W.Jiang, et al. Consensus algorithm based power distribution technology for energy storage system in DC Microgrid[J]. Automation of Electric Power Systems, 2020,44(07):61-75. (in Chinese).

[6] J.Wu,Y.C.Ding,G.X.Ding. Research on sliding mode control strategy for micro network super capacitor energy storage system[J]. Transducer and Microsystem Technologies,2017,36(07):26-28. (in Chinese).

[7] L.Sun,S.L.Xue,Y.M.Zhang, et al. Modeling and simulation of ship DC power supply[J]. Journal of Shanghai Institute of Electrical Engineering, 2017,20(03):132-138+167. (in Chinese).

[8] Y.Z.Mao.Research on power management system of 1500 m depth of drilling ship vehicles[D]. Jiangsu University of Science and Technology,2018.6.(in Chinese).

[9] Q.Huang,J.Tang,W.Z.Li.Design of bidirectional DC-DC converter for photovoltaic system[J]. Transducer and Microsystem Technologies, 2020,39(01):85-87. (in Chinese).

[10] CUI B Z, PWM DC-DC power conversion circuit、dynamic characteristics and control design[M].LEI J M,WANG S Q,et al. Bei Jing: China Machine Press,2018.8:162-193. (in Chinese).

[11] Y.Q.Hou, D.Wu. Small Signal Modeling and Stability Analysis for DC/DC[J]. Journal of Jiangsu Ocean University (Natural Science Edition), 2018,27(01):21-25. (in Chinese).

[12] C. Liu. The Configuration Optimization and Energy Management for Li-ion BatterylUltracapacitor Hybrid Energy Storage System[D]. University of science and technology of China,2020.6.

[13] J.C.Shan,W.Y.Chen. Super capacitor and communication standby power supply[A]. Communication power supply Committee of China communication society.2008:6.

[14] X.H.Cao, Y.L.Liu,S.H.Miao, et al. Research on virtual inertial control strategy of DC/DC converter in DC microgrid considering self-adaptive parameters[J]. High Voltage Engineering, 2020,46(04):1281-1290.(in Chinese).

[15] G.L.Zhen. Design of Bidirectional DC-DC converter for marine microgrid energy storage system[D]. Dalian Maritime University,2015.6. (in Chinese).