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Application and Simulation of Three-level Active Power Filter in Pulse Load Ship

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Abstract

Different from the land-based power grid, the ship power grid is an isolated network with limited capacity. When working with pulse loads with low average power and high peak power, it will have a more serious continuous impact on the power grid. This paper designs a three-level active power filter with supercapacitor energy storage for the current impact caused by the pulse load in the ship. An ANN based method is proposed to control the active power filter, so as to maintain the stability of supply current and avoid the continuous and large impact on the power grid. Based on the method of double closed-loop PI control, the supercapacitor energy storage unit is controlled to meet the energy demand of pulse load, maintain the stability of DC voltage and ensure the APF can work properly. The simulation results show that the proposed topology and control strategy can solve the problem of current impact in the ship power grid.

Keywords

Pulse Load; Active Power Filter; Supercapacitor Energy Storage; Artificial Neural Network.

1. Introduction

In recent years, the development of ships tends to be large-scale, intelligent and multi-purpose. More and more power electronic devices and load with pulse characteristics are applied to the ship power grid, such as high-energy weapons, phased radar, electromagnetic launchers, etc. [1-6]. The peak power of these pulse loads can reach kilowatts or even megawatts, and they switch frequently. For ship power grids with limited generator capacity and small system inertia [7], it is difficult to withstand the impact of repeated loading and unloading. Therefore, the ship power grid with pulse load is always in an unstable state, and the current will change greatly with the switch of pulse load, which will cause damage to the power grid and other electrical equipment.

At present, the research on solving the impact of pulse load mainly focuses on the following three aspects. One is to increase the inertia of the system [8]. Reference [9] analyzed the mechanical characteristics of the rotor and the electrical characteristics of the stator of the synchronous generator, and adopted the method of increasing the inertia time constant of the synchronous generator to suppress the impact of pulse load on the power grid. The second is to optimize the control strategy of the energy storage system. Reference [10] adds a battery energy storage module to the ship power system, realizes the energy exchange between the battery and the ship power system through a converter, and uses a fuzzy control system to overcome the influence of impulse load in the DC ship power system. The third is to add a compensation device. Reference [11] uses a two-stage three-phase AC-DC converter as a compensator to offset the impact of pulse load on the power supply line, and proposes a low-pass filter power feedforward control method based on pulse detection, which speeds up the response speed of the compensator.

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In this paper, the method of adding a compensator is used to design a three-level active power filter with supercapacitor energy storage. The active power filter (APF) is used to generate a compensation current with the same magnitude and opposite direction to the pulse current to solve the current impact of the pulse load on ship power grid. Utilizing the characteristics of high power density and fast charging and discharging speed of supercapacitors, the problem of frequent and large changes in pulse load power is solved, and the rapid absorption and release of energy in the system is realized. In terms of control strategy, a method based on artificial neural network (ANN) is proposed to calculate the compensation current of APF, and the method of double closed-loop PI control is used to realize the rapid charging and discharging of the supercapacitor energy storage unit. The Park transform (abc-dq0) in three-phase static coordinates and low-pass filtering are eliminated, which reduces the complexity of modeling and calculation, and avoids the phase lag caused by multiple filters. Finally, the rationality and effectiveness of the method proposed in this paper are verified by MATLAB/ Simulink simulation.

2. Three-level APF with Supercapacitor Energy Storage System

The structure of the three-level APF with supercapacitor energy storage system designed for pulse load ships is shown in Figure 1. It is mainly composed of three parts: pulse load, active power filter, and super capacitor energy storage unit.

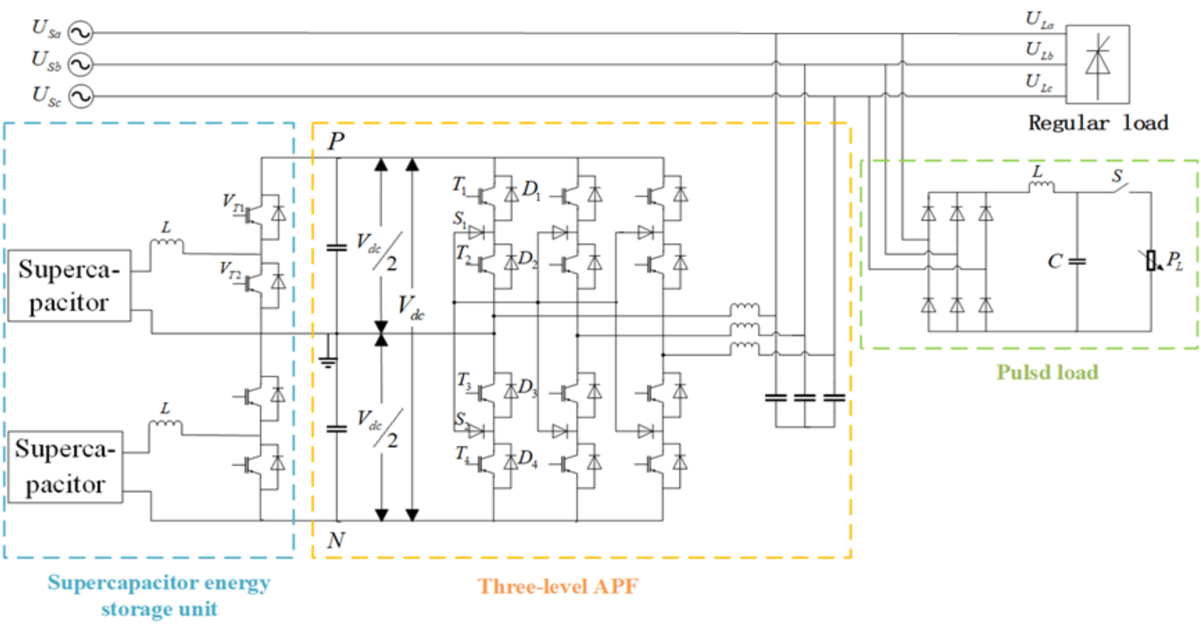

Figure 1. The structure of three-level APF with supercapacitor energy storage system

2.1 Pules Load

Unlike regular load, pulse load has short working cycle and large peak power. Its working characteristics can be simulated by pulse cycle, peak power and duty cycle. The pulse load test model used in this paper is partially adjusted on the basis of the model proposed in [12], as shown in Figure 1. The model of the diesel generator set with pulse load is equivalent to three-phase AC power, three-phase rectifier, LC filter, DC switch and load.

For the peak power of the pulse load, different resistance values are selected to simulate. The cycle and duty cycle ratio are controlled by the gating pulse of the IGBT. As shown in Figure 2, the cycle of the pulse load is T_S, the turn-on time is T_{on}, the turn-off time is T_{off}, the duty cycle $D=\frac{T_{on}}{T_S}$, the peak power is P_L. By changing the cycle T_S, duty cycle D, and peak power P_L, different pulse loads and different working modes of pulse loads can be simulated.

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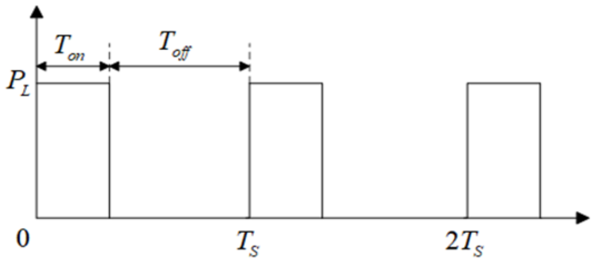

Figure 2. The ideal working model for pulse load

2.2 Three-level APF

This paper designs a three-level APF for pulse load ships, as shown in Figure 1. The APF is connected in parallel on the transmission line in front of the load to compensate the impact current caused by the pulse load. Each phase bridge arm of the APF consists of four IGBTs and two clamp diodes. Two energy storage capacitors on the DC side provide three levels of output for the APF. Assuming that the voltage on the DC side is V_{dc}, then the average voltage per of each IGBT is $\frac{1}{2}V_{dc}$. Compared with two-level APF, the maximum voltage and switching frequency that each IGBT needs to bear are reduced, and the ability of resisting pulse load impact is stronger. At the same time, the level of the output terminal increases the zero potential, that is, the single-phase output voltage on the AC side has 3 cases, and the three-phase output voltage has 9 cases, which can be selected more accurately according to the operation of the load in the power grid. Taking phase A as an example, the relationship between IGBT working state and output voltage of three-level APF is shown in Table 1.

Table 1. Relationship between IGBT working state and output voltage

Output Voltage	T_1	T_2	T_3	T_4
$\frac{1}{2}V_{dc}$	ON	ON	OFF	OFF
0	OFF	ON	ON	OFF
$-\frac{1}{2}V_{dc}$	OFF	OFF	ON	ON

2.3 Supercapacitor Energy Storage Unit

Considering that the peak power of pulse load can reach kilowatts or even megawatts, it may be difficult to satisfy the energy change requirements of the pulse load ship by relying on capacitor energy storage. Supercapacitors are needed to maintain the voltage stability on the DC side. Different from the electrochemical reactions of batteries, supercapacitors are charged through a physical process in which energy is stored by electrostatic charges. Therefore, it has stable performance, long cycle life, and can charge and discharge quickly. For high current and frequent charge and discharge in a short time, supercapacitor is an ideal energy storage material [13]. Thus, supercapacitor energy storage unit can better meet the energy requirements of pulse load ships with frequent changes and ensure that the system always works in a stable state.

The topographic structure of the supercapacitor energy storage unit designed in this paper is shown in Figure 1. The energy flow between the supercapacitor group and the DC side is realized by a DC/DC bidirectional converter. When the DC side voltage is higher than the set value, the switch V_{T1} is turned on. The converter works in Buck mode, and the super capacitor group absorbs energy on the DC side; When the DC side voltage is lower than the set value, the switch V_{T2} is turned on. The converter works in Boost mode, and the super capacitor group releases energy to the DC side. According to the designed three-level APF structure, it can be known that two supercapacitor energy storage units are required to be connected in parallel with the two energy storage capacitors. Since the working voltage of a single supercapacitor is $2.7V$, multiple single supercapacitors are connected in series as a supercapacitor group.

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3. System Control Strategy

The overall control strategy of three-level APF with supercapacitor energy storage is shown in Figure 3. The three level APF is controlled by ANN, and the current compensation is calculated by using neural network to ensure the stability of the power supply current. The supercapacitor energy storage unit adopts double closed-loop PI control to adjust the charging and discharging state of the supercapacitor module, so as to maintain the stability of DC side voltage and ensure the normal operation of APF.

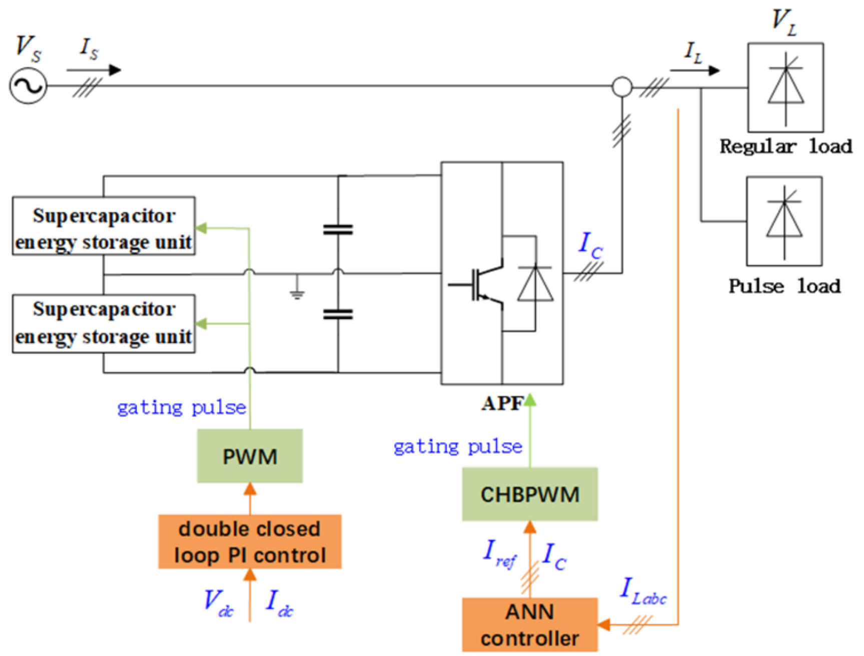

Figure 3. The overall control strategy of system

3.1 APF Control Strategy

Due to the frequent loading and unloading of pulse load, the load current will also fluctuate significantly, presenting the pulse characteristics. The function of the APF is to quickly calculate the current compensation amount according to the load current, and generate a compensation current with the same amplitude and the opposite direction as the current distortion part. Ensure that the power supply current is stable and has good sinusoidal characteristics, so as to avoid frequent impacts to the power grid.

Therefore, the neural network takes the three-phase load current (I_{La},I_{Lb},I_{Lc}) as input, and three-phase compensation current (I_{refa},I_{refb},I_{refc}) as output, and uses one hidden layer. After comparing the training results several times, the number of neurons in the hidden layer is 200. The network structure is shown in Figure 4 and Figure 5, and the Levenberg-Marquardt (LM) algorithm is used to train the network. Take the load current and the corresponding current compensation at the same time as a set of data, a total of 60000 sets of data, 70% as the training set, 15% as the validation set, 15% as the test set. The training results are shown in Figure 6.

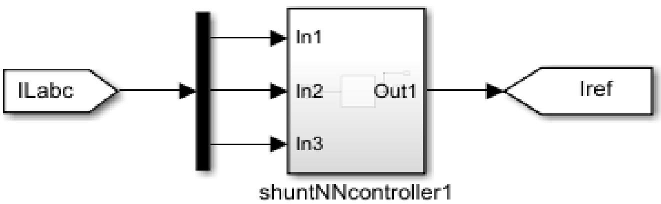

Figure 4. The input/output of ANN

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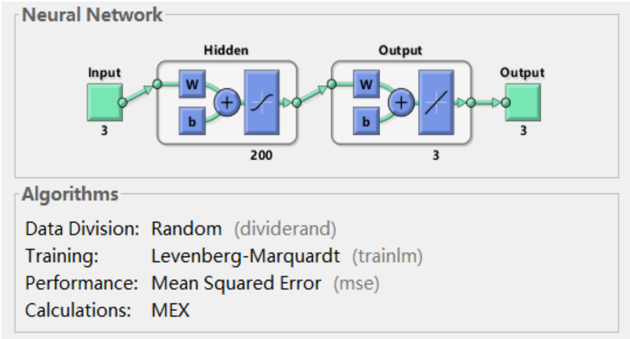

Figure 5. Network structure of ANN

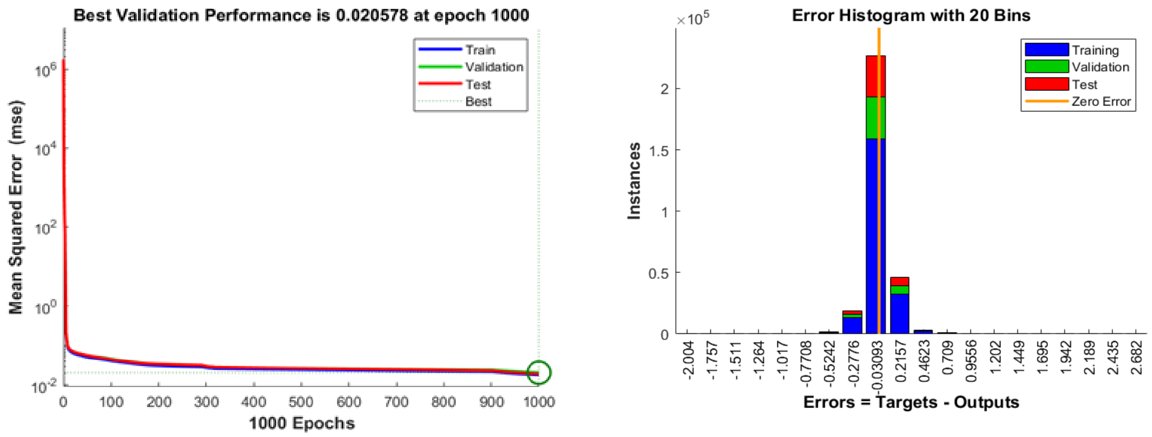

Figure 6. ANN training results

After calculating the reference value of the three-phase compensation voltage, the current hysteresis PWM is used to generate the gating pulse of each IGBT in the APF, as shown in Figure 7. The hysteresis band width is $2h$. Compare the compensation current I_{ref} calculated by ANN with the actual compensation current I_C output by APF:

a) If $I_C > I_{ref} + h$, then T_3 and T_4 are on, the output voltage is $-V_{dc}$;

b) If $I_{ref} - h \le I_C \le I_{ref} + h$, then T_2 and T_3 are on, the output voltage is 0;

c) If $I_C < I_{ref} - h$, then T_1 and T_2 are on, the output voltage is $+V_{dc}$;

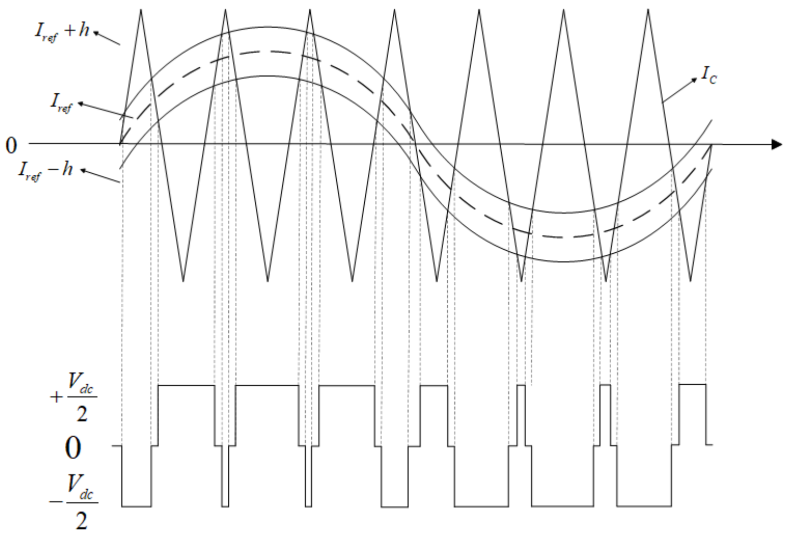

Figure 7. Current hysteresis PWM modulation schematic

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3.2 Supercapacitor Energy Storage Unit Control Strategy

The function of the supercapacitor energy storage unit is to maintain the stability of the DC voltage. The energy exchange between the supercapacitor group and the DC side is achieved by switch V_{T1} and V_{T2} in the DC/DC converter. The duty cycle of V_{T1} determines the time that the DC side charges to the supercapacitor group. The duty cycle of V_{T2} determines the time that the supercapacitor group discharges to the DC side. The double closed-loop PI control with voltage outer loop and current inner loop has faster response than single voltage loop control and can realize fast energy adjustment.

The control process is shown in Figure 8. The reference voltage V_{dc} on the DC side and the actual voltage V_{dcref} constitute a negative feedback of the voltage outer loop. The error is calculated by PI and used as the reference value of the output current of the supercapacitor group I_{dcref}. The negative feedback of the current inner loop is consisted of I_{dcref} and the actual output current of the supercapacitor group I_{dc}. The error is superimposed with the feedforward signal V_{dcref} after PI, and the output of the double closed-loop control is modulated into the gating pulse of the switch V_{T1}, V_{T2} by using the PWM to realize the control of the DC voltage.

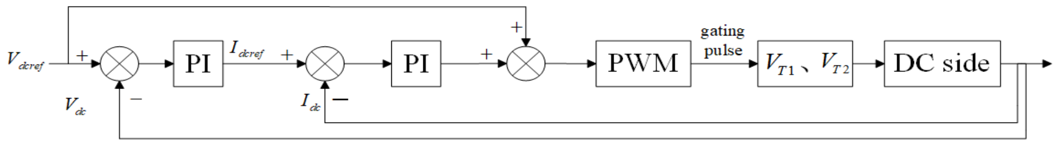

Figure 8. Double Closed-Loop PI Control Diagram

4. Simulation and experimental results analysis

In order to verify the feasibility of the topology and control strategy proposed in this paper, a three-level APF system model with supercapacitor energy storage was built in MATLAB/Simulink for simulation testing, as shown in Figure 9. The relevant parameters are set as follows. The supply voltage and frequency of the ship are $311V$ and $50Hz$. A voltage sag occurs in 0.15 s ~ 0.3 s, and a voltage swell occurs in 0.3 s ~ 0.45 s, and then returns to normal. The active and reactive power of the regular load are $3000W$ and $1860\,var$. The DC voltage is $800V$. The filter inductor and capacitor of the APF are $7.5mH$ and $3.3\mu F$. The energy storage inductor of the supercapacitor energy storage unit is $0.9mH$.

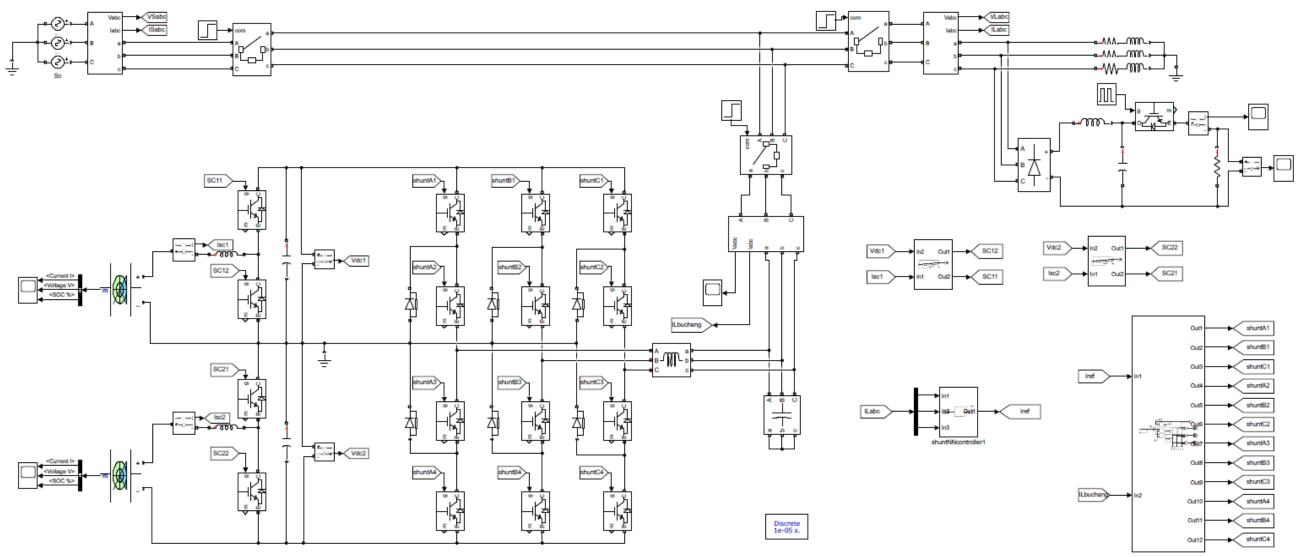

Figure 9. System simulation diagram in MATLAB/Simulink

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As for the pulse load, its peak power is $12kW$, and it is simulated in the following three working modes:

a) Cycle $T = 60ms$, duty cycle $D = 0.4$;

b) Cycle $T = 80ms$, duty cycle $D = 0.4$;

c) Cycle $T = 60ms$, duty cycle $D = 0.6$.

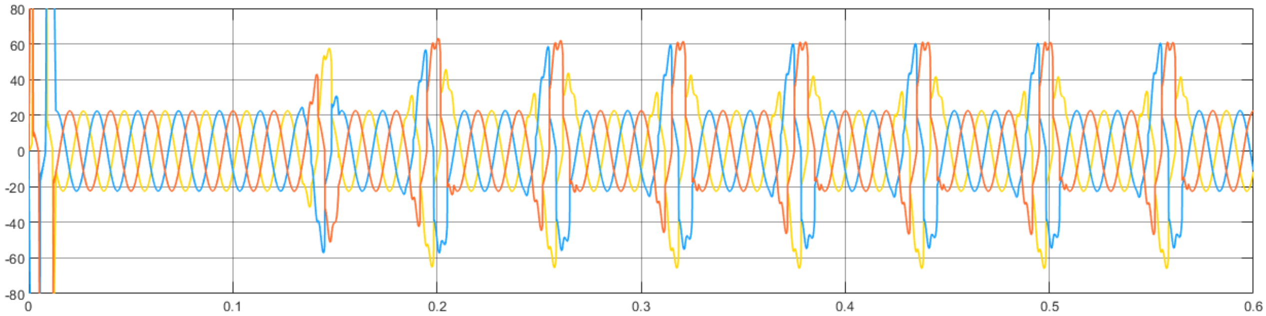

Figure 10. The load current in working mode a)

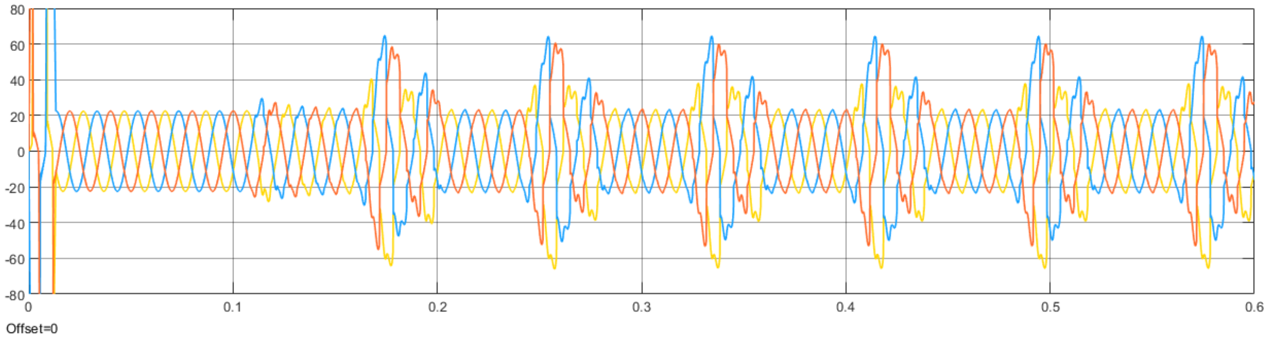

Figure 11. The load current in working mode b)

Figure 10, Figure 11, Figure 12 and Figure 13, Figure 14, Figure 15 are the load current and supply current waveforms of the pulse load in the working mode a), b), c), respectively. It can be seen that the load current will follow the working mode of the pulse load presents obvious pulse changes, but the amplitude of the supply current is stable and the sinusoidal characteristics are good. It shows that the APF can accurately calculate and modulate the compensation current based on the load current, cancel the impact current on the load side, and will not cause periodic and large impacts on the power grid. This verifies the rationality of the APF topology and the feasibility of the control strategy proposed in this paper.

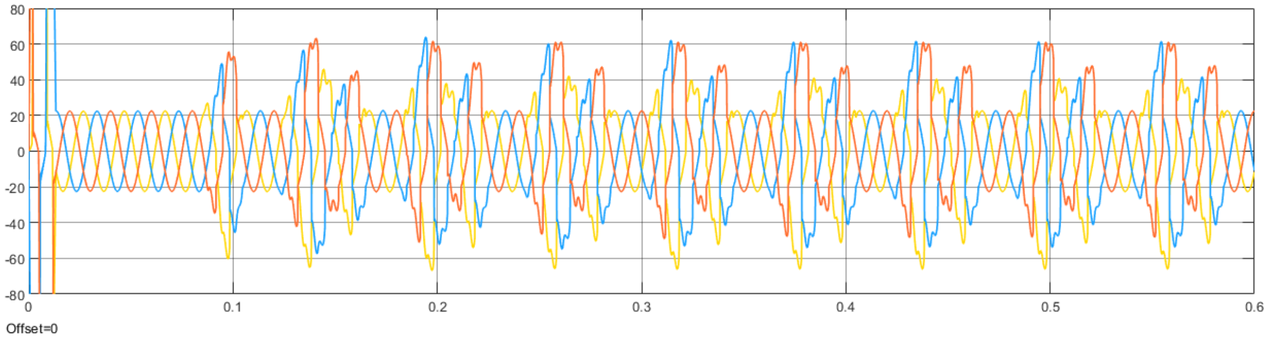

Figure 12. The load current in working mode c)

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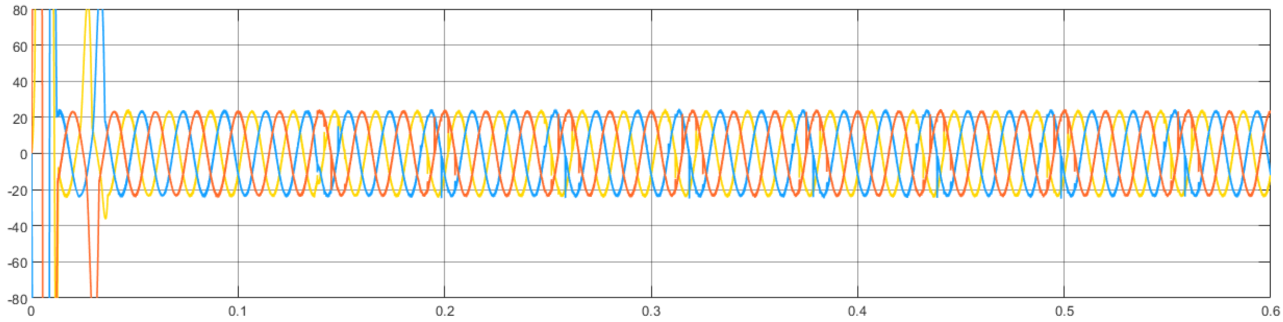

Figure 13. The supply current in working mode a)

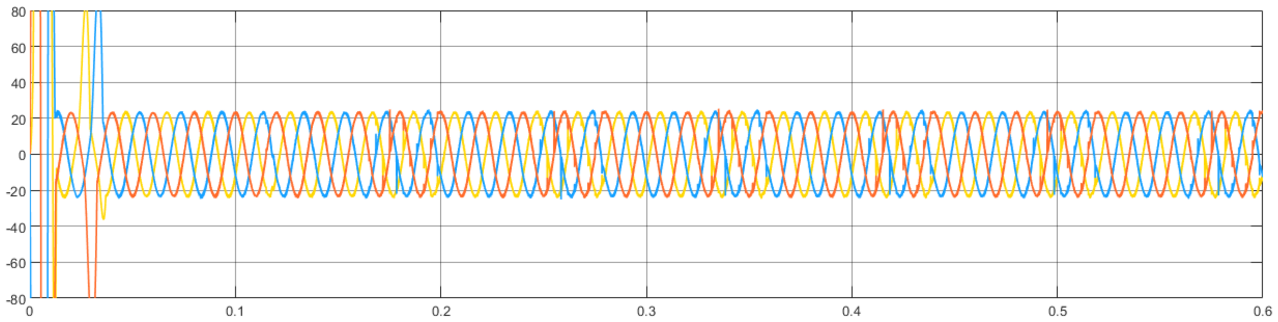

Figure 14. The supply current in working mode b)

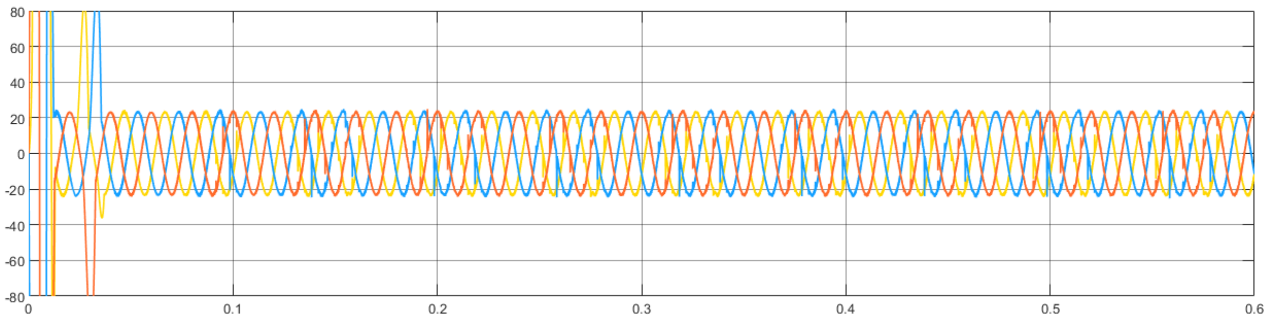

Figure 15. The supply current in working mode c)

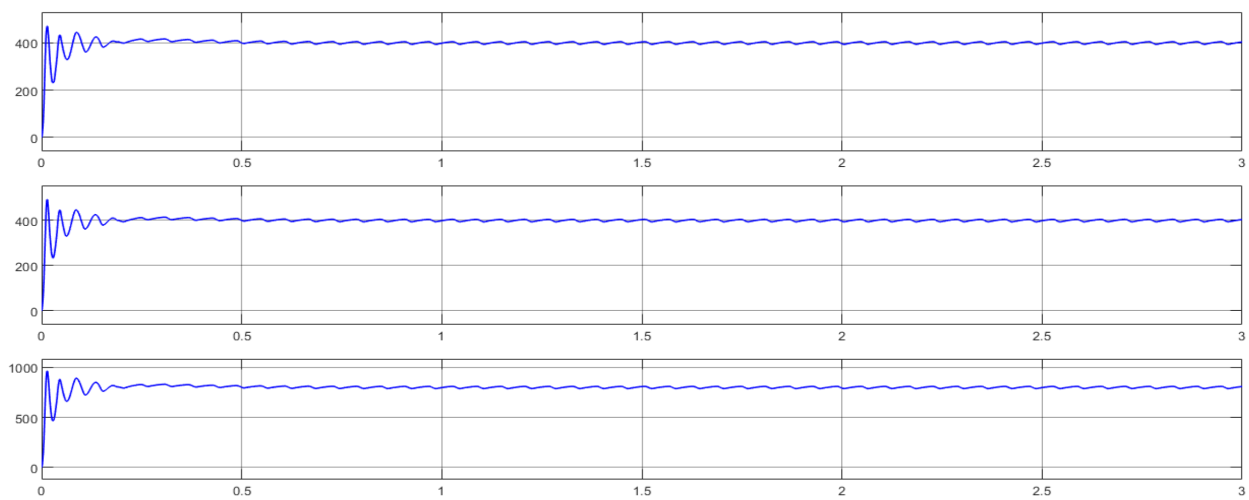

Figure 16. The DC voltage

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Figure 16 shows the terminal voltage of the two capacitors on the DC side and the total DC voltage, which are not affected by the working mode of the pulse load. The DC voltage enters a stable state after 0.15 s, fluctuates slightly between $788V$~$810V$, and the error is far less than $\pm 10\%$. It can provide a stable DC voltage for the output of the APF, which verifies the rationality of the supercapacitor energy storage unit topology and the feasibility of the control strategy proposed in this paper.

Figure 17 shows the peak power of the pulse load. When the DC voltage is stable, the peak power of the pulse load is stable at $12kW$. This indicates that the designed three-level APF with supercapacitor energy storage can ensure the normal operation of the pulse load while playing the role of current compensation.

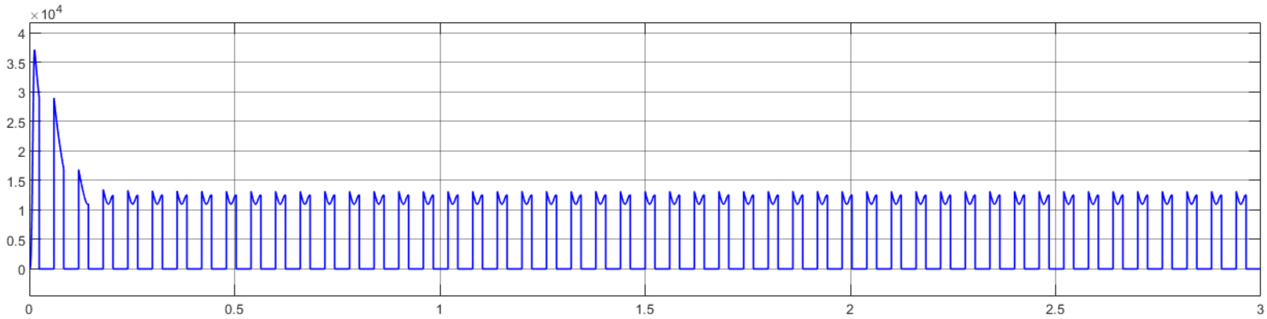

Figure 17. The peak power of the pulse load

5. Conclusion

In this paper, aiming at the current impact problem of ship power grid with pulse load, a three-level APF with supercapacitor energy storage is designed. An ANN-based method is proposed to control APF, and a double closed-loop PI control method is used to control the supercapacitor energy storage unit, which ensures that the supply current is always in a normal and stable state after compensation, and solves the problem of continuous large current impact caused by the pulse load. The experimental results of MATLAB/Simulink show that the proposed three-level APF with supercapacitor energy storage has reasonable topology and effective control strategy, which has reference value for solving the pulse load problem.

Acknowledgments

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