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Study on Dual Closed-Loop Control Strategy for Energy Storage System of Pulse Loaded Ship

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Abstract

Pulse load running, will lead to the pulse load a dramatic fluctuations of ship power system, its essence is the pulse load large instantaneous power needed for the runtime, in addition to the let pulse load of ship stability of DC bus voltage fluctuation in the range of the reliable and energy storage device is not in overcharge or over-discharge state for a long time, it will be to study the contents of this paper. In view of the above problems, this paper designs a bidirectional DC/DC converter under the voltage and current dual closed-loop control strategy to conduct research and analysis on the energy storage system of pulse-loaded ships, and builds a simulation model of the power system based on MATLAB/ Simulink platform. Finally, it is concluded that the dual closed-loop control strategy designed in this paper can effectively solve the problem according to the state of the supercapacitor itself.The energy transmission between the DC bus and the supercapacitor can guarantee the stable and efficient operation of the power system of the whole pulse-loaded ship.

Keywords

Pulsed Load; Dual Closed-loop Control; Bidirectional DC/DC; Supercapacitor; Energy Storage System.

1. Introduction

With the development of Marine power system, all-electric ship provides a new application platform for various high-energy pulse loads.At the same time, the huge instantaneous power required by the operation of the pulse load will bring drastic fluctuations to the ship's power system, thus bringing potential dangers to the ship's power system [1-2].

Secondly, the independent power system is the direction of the future development of the ship power system, which will shoulder the energy supply of most of the ship system.An advanced independent power system should be able to operate normally and continuously in a relatively complex operating environment and carry out reasonable automatic control [3].For pulse load, due to its special energy demand and operation characteristics, it brings severe challenges to the safe and stable operation of ship power system [3-4]. At present, the research on pulse load mainly includes the simulation of energy demand, operation characteristics and the influence on power system, the coordinated control strategy between pulse load and other loads, the energy storage medium and storage control of pulse load, etc.

In this paper, the dual closed-loop control strategy is used to control the voltage and current of the two-way controllable DC/DC converter, and then the energy transmission between the DC bus and the super capacitor in the pulse load ship energy storage system under the dual closed-loop control strategy whether it is more reasonable and effective, and whether it provides a guarantee for the stable and efficient operation of the entire pulse load ship's power system is studied.

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2. Pulse Load Characteristic Analysis

Pulse load refers to radar, laser weapons, electromagnetic guns, electromagnetic transmitters, etc. need to release a high power load in a short period of time[5-6]. The energy density and power density of pulsed loads are extremely large, and ordinary power systems are difficult to withstand such shocks, requiring energy storage for this type of load.

The periodic charging and discharge process of pulsed load makes the integrated power system no longer have a steady-state balance point, but is represented by a series of periodic alternating processes of running points, and the change of state variables inevitably affects the generator and other loads, which brings great impact to the system.

Figure 1 is the load characteristics of a new type of pulse load, the cycle of power pulse and duty cycle changes randomly, the task system load of a sequence consists of random several different cycles, different duty cycle ratio and different peak power pulse composition, sequence time T1 is 0.1s to 1.5s, cycle range T2 is 0.5ms to 33.0ms, duty cycle range D is 5% to 100%.

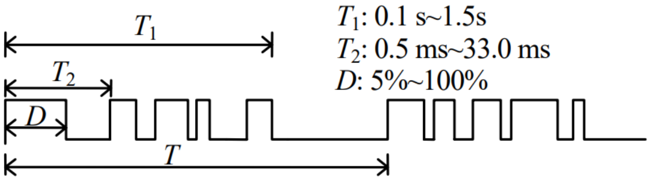

Figure 1. Load characteristics of a new pulse load

3. Dual Closed-Loop Control Strategy Research And Analysis

3.1 Bidirectional DC/DC Converter Operating Mode Analysis

The bidirectional DC/DC converter has two modes of operation: Buck mode and Boost mode [7-8].

The Buck circuit is a DC/DC buck circuit, and the converter has two switching states in one switching cycle, and the operation of each switch mode is described below:

(1) When the drive switch tube Q_1 is on and the synchronous switch tube Q_2 is open, the equivalent circuit of the Buck circuit is shown in Figure 2. The input current flows through the inducor, at which point the current at both ends of the inducor increases linearly, $L$and the capacitor enters the C charging state. When the switch tube Q_1 is on, the current on the inducor is:

$$\Delta i_L = \frac{V_{dc}-V_{sc}}{L} DT \tag{1}$$

In the formula: T - The switching cycle of the entire switch tube;

D - Duty ratio of switch Q_1 drive waveform.

(2) When the drive switch tube Q_1 in the circuit is disconnected and the synchronous switch tube Q_2 is on, the equivalent circuit of the Buck circuit is shown in Figure 2. The voltage direction at both ends of the inductive L changes, but because the inductive L current at both ends cannot produce mutations, it flows through the Q_2 discharge circuit, at which point the capacitor enters the discharge state, the inductive L, output voltage V_{sc} and switch tube Q_2 form a discharge circuit, and the output voltage remains unchanged. During the drive switch tube Q_1 disconnect, the current in the inducor drops linearly, and the current at both ends of the inducor is :

$$\Delta i_{L-} = -\frac{V_{sc}}{L}(1-D)T \tag{2}$$

When the Buck circuit is in a stable operating state, the current stored in the inductor is equal to the inductor discharge flow, i.e. the inductor current is equivalent to :

$$\Delta i_{L+} = |\Delta i_{L-}| \quad \rightarrow \quad \frac{V_{dc}-V_{sc}}{L} DT = \frac{V_{sc}}{L}(1-D)T \tag{3}$$

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Finally simplified to:

$$V_{sc} = DV_{dc} \quad (4)$$

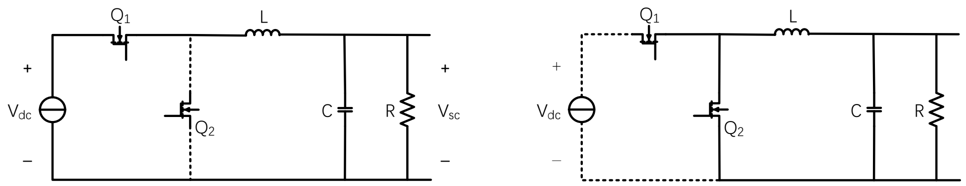

Figure 2. Buck circuit equivalent circuit

It can be concludedfrom formula (4) that the output voltage V_{sc} of the Buck circuit is much smaller than the power supply voltage V_{dc}, which also indicates that the input DC high voltage is changed from a DC high voltage to a DC low voltage by the converter, so the Buck converter is called a buck converter.

The Boost circuit is a DC/DC boost circuit[10], and the converter has two switching states during a switching cycle of the Boost circuit, and the following describes the operation of each switch mode:

(1) When the drive switch tube Q_2 is on and the synchronous switch tube Q_1 is switched off, the equivalent circuit of the Boost circuit is shown in Figure 3. V_{sc} supplies current to the inductor L, energy stored on the inductor, inductor current will be linearly increased, because the synchronous switch tube Q_1 is switched off, the current can not be transmitted to the output, so the circuit can not be directed. At this point, the energy storage inductor continues to rise, and the inductor storage current is:

$$\Delta i_{L+} = \frac{V_{sc}}{L} DT \quad (5)$$

(2) When the drive switch tube Q_2 is disconnected and the synchronous switch tube Q_1 is on, the equivalent circuit of the Boost circuit is shown in Figure 3. At this point, the supply voltage and inductive voltage at both ends of the voltage discharge to the output through the synchronous switch tube Q_1 while charging the capacitor C, at which point the inductive release of the current is:

$$\Delta i_{L-} = \frac{V_{sc} - V_{dc}}{L} (1 - D)T \quad (6)$$

When the Boost circuit is stable, the inductive storage current is equal to the discharge current and is available:

$$\Delta i_{L+} = |\Delta i_{L-}| \quad \rightarrow \quad \frac{V_{sc}}{L} DT = \frac{V_{sc} - V_{dc}}{L} (1 - D)T \quad (7)$$

Finally simplified to:

$$V_{dc} = \frac{V_{sc}}{1 - D} \quad (8)$$

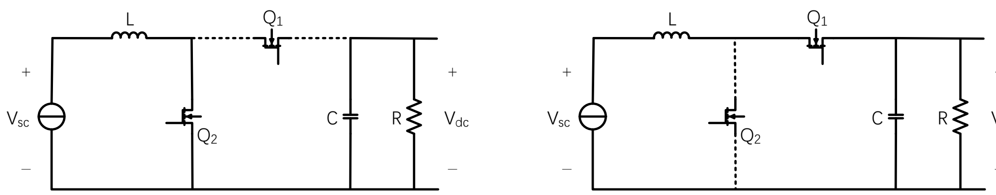

Figure 3. Boost circuit equivalent circuit

The formula (8) concludes that the output voltage V_{dc} value of the converter will always be greater than the supply voltage V_{sc}, which means that the DC low voltage at the output is changed from the converter to DC high voltage, so the Boost converter is called the boost converter.

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3.2 Bidirectional DC/DC converter control method

The energy storage equipment system designed in this paper uses the supercapacitor group as the energy storage and energy storage element, and installs the two-way controllable DC/DC converter module at the super capacitor group end, so as to realize the charge and discharge control of the supercapacitor. The bidirectional DC/DC converter requires the supercapacitor to provide power compensation to the DC master during the two-way transmission process, while during charging, the DC master is required to have a constant charging current for the supercapacitor[11]. Therefore, this paper uses the current control mode, that is, the voltage current dual closed-loop control structure[12], as shown in Figure 4, to achieve optimal control of the supercapacitor charge and discharge process.

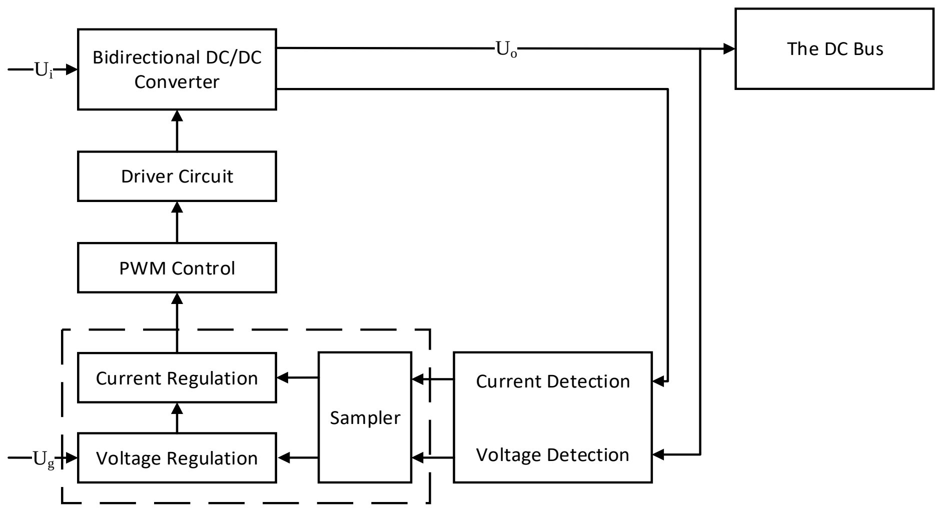

Figure 4. Bidirectional DC/DC energy storage control principle

3.3 Control policy

The energy management strategy designed in this paper is divided into three main working conditions: (1) Condition I: DC bus voltage fluctuations within the critical voltage reference value range, the bidirectional DC/DC does not work; (2) Condition II: DC bus voltage below the lower critical voltage reference value, bidirectional DC/DC trigger Boost mode; (3) Condition III: DC bus voltage is higher than the upper limit critical voltage reference value, bidirectional DC/DC trigger Buck mode. As shown in Figure 5, the energy management strategies under these three working conditions will be introduced and analyzed respectively.

3.3.1 Condition I

In this working condition, the DC bus voltage reasonable fluctuation range is $510\,V \leq U_{dc} \leq 530\,V$, in this range voltage fluctuations are considered to be within the acceptable range of the ship's power grid, at this time the two-way DC/DC does not work.

3.3.2 Condition II

In this working condition, the lower critical voltage reference value is $U_{refmin} = 510\,V$, when $U_{dc} < U_{refmin}$ the pulse load impact on the power grid is large, the need for supercapacitor timely response, power compensation, at this time two-way DC/DC will trigger Boost mode.

3.3.3 Condition III

Under this condition, the upper limit critical voltage reference value is $U_{refmax} = 530\,V$, when $U_{dc} > U_{refmax}$ the excess energy in the ship's power grid is indicated, at which point the bidirectional DC/DC will trigger the Buck mode and transfer the excess energy in the power grid in the form of supercapacitor charging to the supercapacitor end in order to stabilize the ship's power grid[13].

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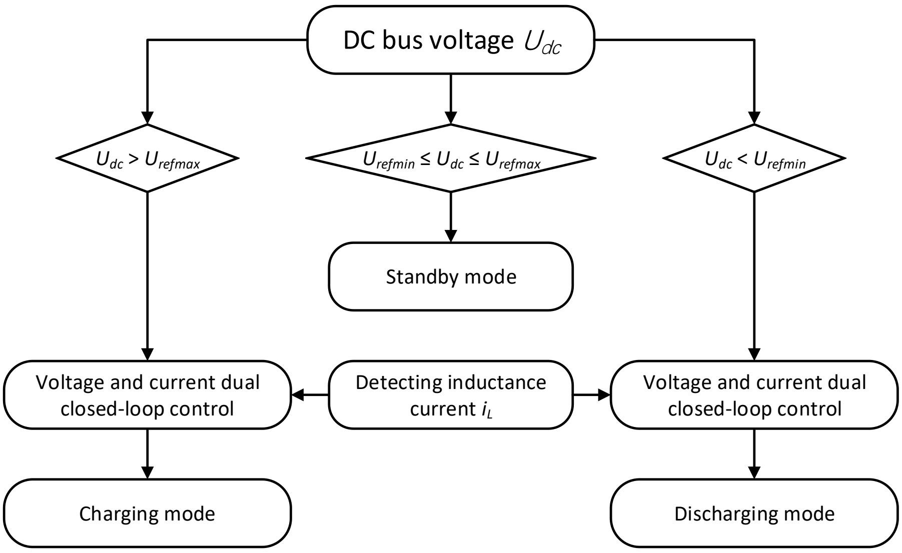

Figure 5. Control mode flowchart

4. Simulation analysis

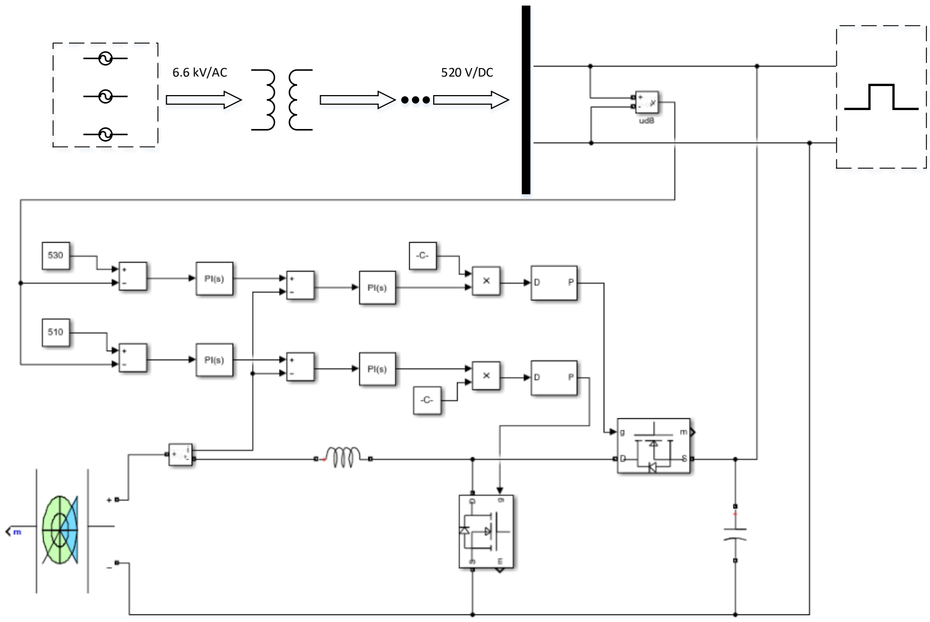

Figure 6. Dual closed-loop control energy storage system

Table 1. Supercapacitor Parameters

Parameter Name	Parameter Value
Rated capacitance	250 F
Rated voltage	552.1 V
Initial voltage	300 V

Table 2. Bidirectional DC/DC Parameters

Parameter Name	Parameter Value
Energy-storage inductance	4.42 μH
Filtering capacitance	2.17 mF
Switching frequency	13 kHz

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Table 3. Voltage Outer Ring Proportional Integration Parameters

Parameter Name	Parameter Value
P	5
I	25

Table 4. Current Inner Ring Proportional Integration Parameters

Parameter Name	Parameter Value
P	100
I	100

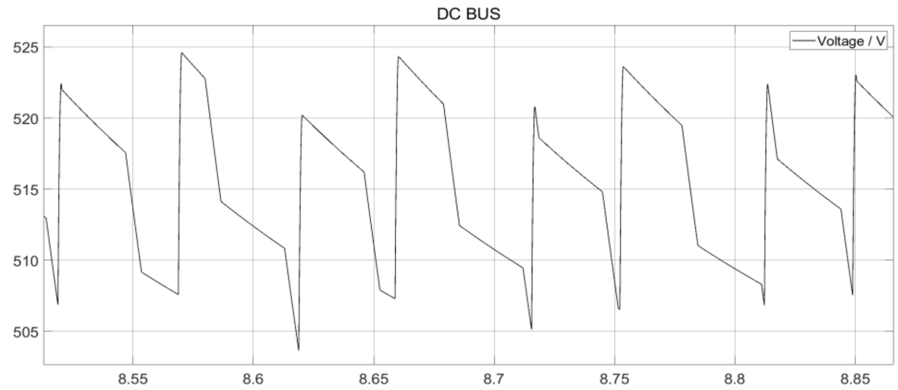

Figure 7. DC bus voltage

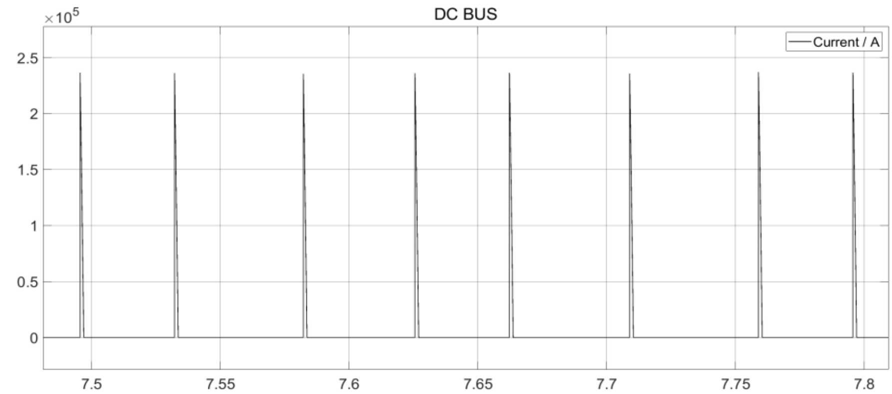

Figure 8. DC bus current

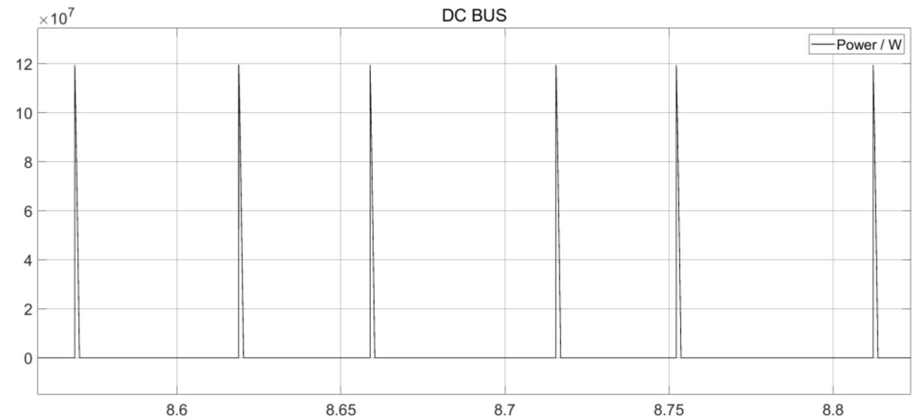

Figure 9. DC bus power

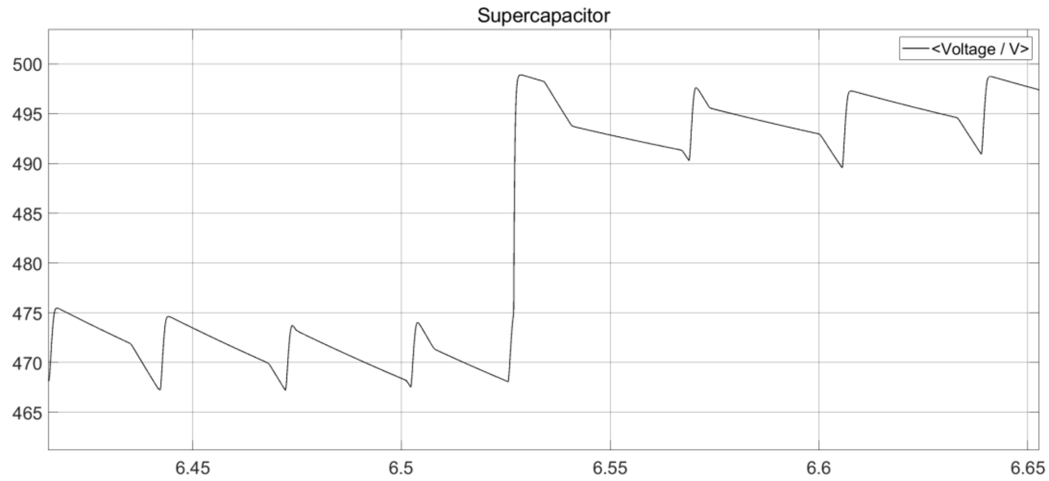

Figure 10. Supercapacitor voltage

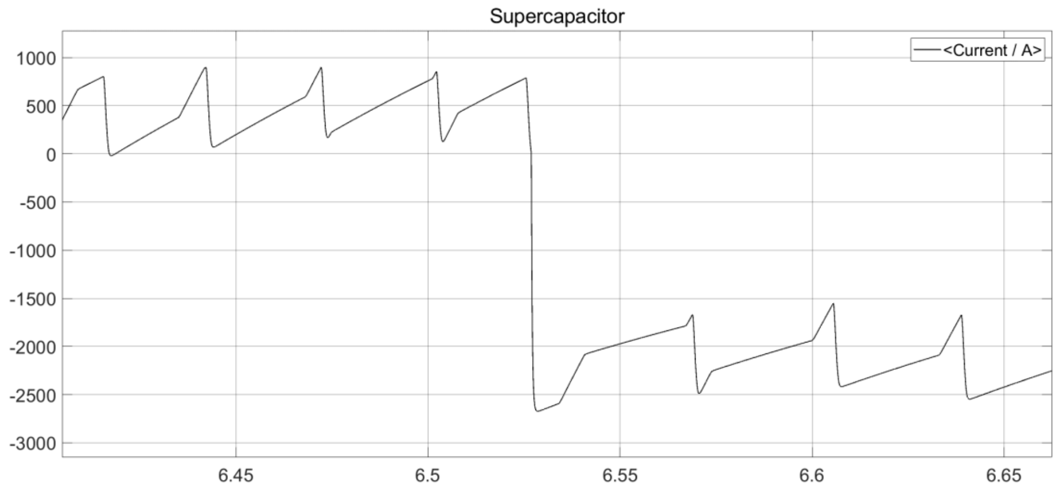

Figure 11. Supercapacitor current

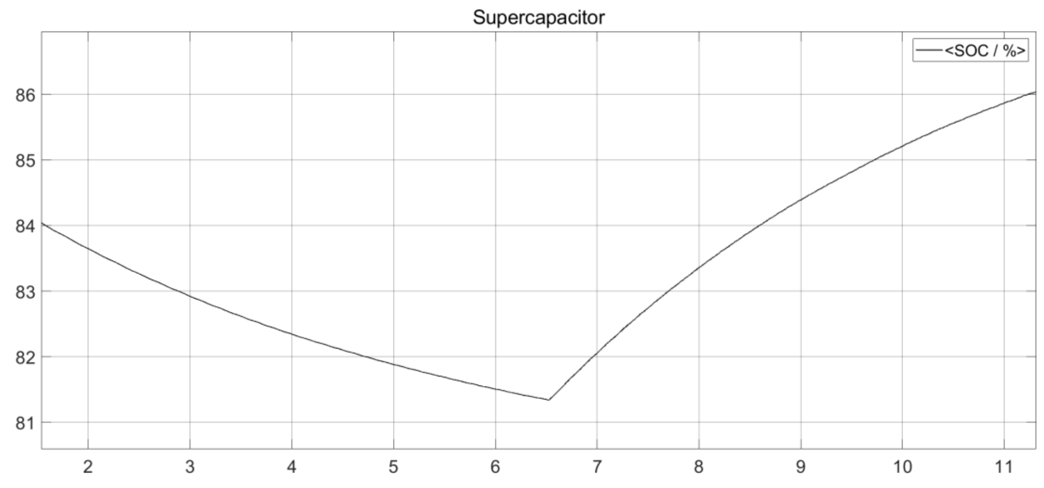

Figure 12. Supercapacitor state of charge

As can be seen from the simulation results: The maximum value of the DC bus voltage is 524.6V, the minimum value is 503.7V, and the peak-to-peak value is 20.9V. Designed with a rated voltage of

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520V, the DC bus voltage fluctuation range is -3.13%~+0.88%, DC bus voltage ripple rate $\frac{\Delta U_{dc}}{U_{dc}} = \frac{20.9}{520} = 4.02\,\%$. The bidirectional DC/DC can effectively transmit reasonable energy between the supercapacitor and the DC bus when it reaches the pre-designed charge and discharge trigger reference value.

5. Conclusion

As can be obtained from the simulation experiment in Section 4, the pulse load ship power system can be in a stable working state under the pulse load operation.

Using the two-way controllable DC/DC converter under the voltage current dual closed-loop control strategy, it can effectively monitor the DC bus-side grid voltage and feed back to the dual closed-loop control system in time for real-time comparison and analysis with the upper and lower limit critical voltage reference values set by the system. On the one hand, Buck charging mode and Boost power compensation mode can be triggered to solve the energy transmission problem between the supercapacitor and the DC bus, and on the other hand, it also ensures that the supercapacitor will not be overcharged or over-discharged for a long time, thus providing security for the entire power system.

As far as the overall effect of the system is concerned, the energy storage system of pulse load ships using the dual closed-loop control strategy can effectively control the DC bus grid fluctuation range between -3.13% and +0.88%, and reduce the DC bus voltage ripple rate to 4.02%. Thus, the energy transmission between the DC bus and supercapacitor in the pulsed load ship energy storage system under the dual closed-loop control strategy is reasonable and effective, and the stable and efficient operation of the whole pulse load ship power system is guaranteed.

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