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Simulation Research on Energy Storage Bidirectional DC-DC Converter in Ship Microgrids

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Abstract

As an important part of energy conversion in marine energy storage systems, bidirectional DC-DC converters play a key role in the energy storage system and it is important for the safety and stability of the power grid. In this paper, a bidirectional DC-DC converter with three-phase interleaved topology is proposed, which effectively compensates for the shortcomings of the traditional single-phase DC-DC converter, such as excessive current, low conversion efficiency, etc. Based on the analysis of the topology,we combine a shifting current sharing control strategy. Finally, the simulation results of the model are built on the Matlab/SIMLINK platform. The simulation results show that the three-phase interleaved parallel converter can be used in the PV energy storage system to obtain a stable output voltage and current waveform, which greatly reduces the inductance current and current ripple, and to some extent ensure the operating efficiency and energy conversion efficiency of the converter.

Keywords

Ship Microgrids; DC-DC converter; three-phase interleaving; shifting current sharing.

1. Introduction

The energy crisis and environmental pollution are major challenges facing the world at present, and also affect the rapid development of various transportation industries. As an important member of the transportation industry, the shipping industry has received extensive attention from its research on energy conservation and emission reduction. With the development of ship electric propulsion, the ship microgrid becomes the core of ship operation, and the research on ship microgrid can greatly promote the development of ship operation industry.

However, compared with the terrestrial power grid, the capacity of the ship power station is small, the power transmission line is short, and the working environment of the ship is relatively bad. When there is a large power load change in the ship power grid, the frequency and power of the ship power grid will be greatly fluctuated. In addition to these fluctuations, it may have a significant impact on the operation of other loads in the power grid. In order to ensure the safe and reliable power supply of the ship's power grid, energy storage devices are needed to timely control and suppress energy changes that are difficult to accurately predict.

The current microgrid energy storage DC-DC converter still uses a single-phase circuit structure, which inhibits the capacity, efficiency and output power quality of the converter to some extent, and the violent oscillation of its voltage and current ripple. The energy loss is also huge. To this end, this paper proposes a three-phase interleaved bidirectional DC-DC converter with three independent PWM control circuits. The energy storage battery connected to the DC bus uses a bidirectional DC-DC converter as the interface circuit. The DC-DC modules are operated in an interleaved parallel

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manner to obtain a stable output voltage and current waveform and improve the efficiency of the energy storage system.

2. Ship Microgrid Energy Storage System Structure

At present, microgrid technology has been widely used on land, but its application on ships is still in its infancy. Due to the complexity of the marine situation during the navigation of the ship, the application of the microgrid technology on the ship remains to be further studied[7].

Figure 1 below shows the structure diagram of a typical ship grid energy storage system. The system is mainly divided into three modules: power module, DC bus module and load module[8]. The diesel engine drives the generator to provide the main power to the system. The energy storage device is also part of the power module to provide or absorb the energy when the load fluctuates.

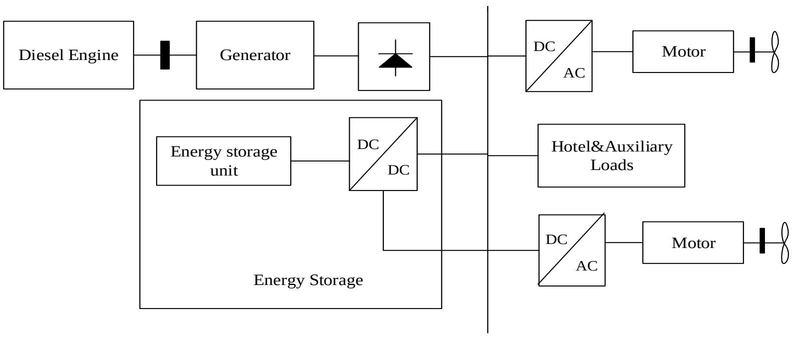

Figure 1. Ship microgrid structure diagram with energy storage module

The DC-DC converter in serves as the core for the regulation and management of the energy flow between energy storage, energy supply and load. Through the control of the energy flow direction, the storage and release of electrical energy is completed[9]. The DC-DC circuit is added between the energy storage unit and the DC bus to achieve bidirectional flow of energy between the energy storage unit and the DC bus.

3. Comparison of Three-phase and Single-phase Converter Structures

3.1 Single-phase bidirectional DC-DC converter topology

The conventional single-phase bidirectional DC-DC converter is actually formed by anti-parallel connection of two unidirectional converters. As shown in fig. 2, The switching tube Q_1 in the unidirectional converter is anti-parallel to the diode D_1, the diode D_2 is anti-parallel to the switching tube Q_2, and the two switching tubes are complementarily turned on, so that the corresponding bidirectional DC-DC converter can be obtained. The circuit has two working modes of buck and boost [10].

3.2 Three-phase interleaved parallel bidirectional DC-DC converter topology

Figure 2 shows the topology of a three-phase bidirectional DC-DC converter designed in a photovoltaic energy storage system. It consists of six IGBT switches($Q_1 \sim Q_6$)and six power diodes($D_1 \sim D_6$) to form a three-phase staggered parallel structure. The structure mainly includes a DC bus capacitor C_1, a battery side filter capacitor C_2, and $L_1 \sim L_3$ is an inductor. U_{dc} is the DC bus terminal voltage and U_{bat} is the battery terminal voltage.

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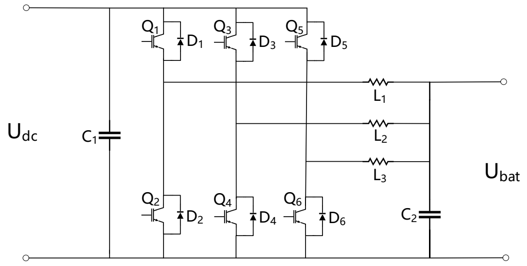
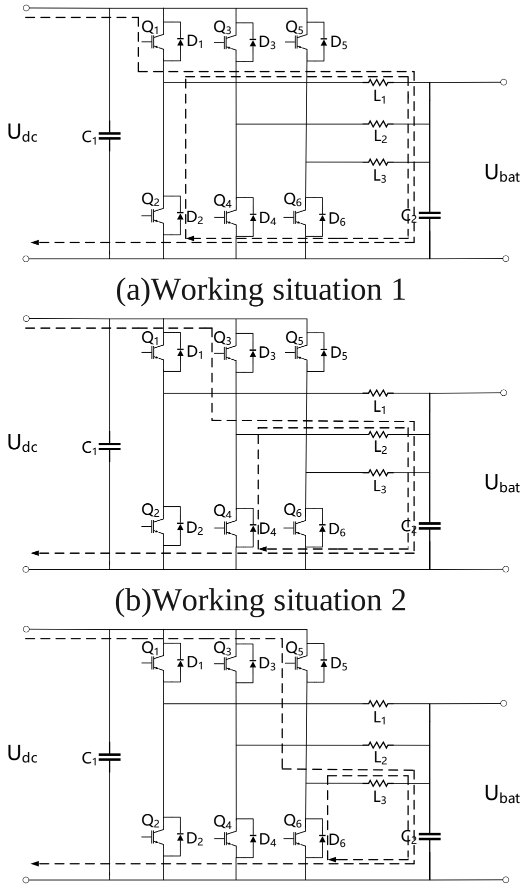


Figure 2. Three-phase bidirectional DC-DC converter circuit diagram

4. Three-phase DC-DC Converter Working Principle

When the converter is operating, it controls charging when it is in Buck mode and controls discharge when it is in Boost mode [11]. Since the working conditions of the two modes are similar to the formula derivation, this paper only analyzes the Buck mode. The triggering times of Q_1, Q_3, and Q_5 are 120° apart, and the duty cycles are d_1, d_3, d_5, respectively. Figure 3 shows the three operating conditions of the circuit in one T_s cycle.



(a)Working situation 1

(b)Working situation 2

(c)Working situation 3

Figure 3. Three kinds of working condition equivalent circuits in Buck mode

When each phase circuit works, the IGBT switch of the phase is turned on, the corresponding inductor is charged.Then the switch is turned off, relative diodes are used to continue the flow.The output current i_0 is superposed by the three inductor currents i_{L1}, i_{L2} and i_{L3},which is $i_0 = i_{L1} + i_{L2} + i_{L3}$.

Interleaved parallel power supply technology is a special parallel power supply working mode. To ensure the normal and effective operation of the whole system, the design of the control circuit is a very important part. However, due to the multi-phase structure of the three-phase interleaved parallel

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converter, a phase shift current sharing control strategy is adopted to ensure the equalization of the current energy of each phase circuit, reduce the output current ripple and reduce the buffer stress of the IGBT switch to large current. The overall control mode block diagram of the converter is shown in Figure 4.

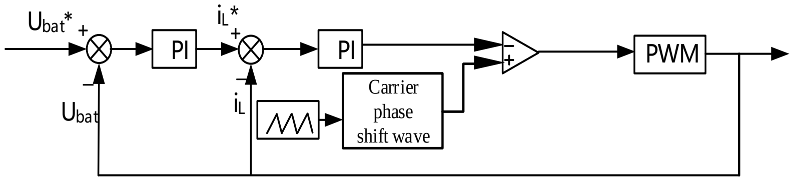


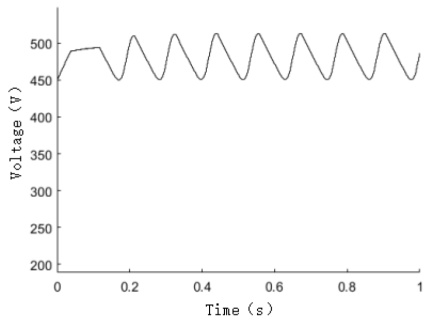
Figure 4. Buck mode converter control block diagram

The three-phase interleaved bidirectional DC-DC converter adopts a double closed loop control mode. The feedback outer loop is the energy storage battery voltage, and the inductor current is used as the inner loop. After the sampled energy storage battery voltage is superimposed on the feedback energy storage battery voltage and passed through the PI device, the sampling inductor current and the feedback inductor current are superimposed again, and then compared with the triangular wave after the carrier phase shift control to form a pulse width modulation PWM signal, thereby driving the IGBT. Break. The phase shift of the carrier in the control realizes the phase shift control of each bridge arm in phase by 120°, achieves the effect of current sharing, and greatly reduces the total current ripple amount. And through verification, it is found that when the PWM duty ratio is $1/3$ and $2/3$, the total output current ripple value of the system is 0, so the circuit duty ratios of the above Buck and Boost modes are $1/3$ and $2/3$, respectively.

5. Simulation Test Verification

In order to verify the superiority of the three-phase interleaved bidirectional DC-DC converter in the ship energy storage system, the model was built in MATLAB/Simulink according to the above control method, and the single-term circuit and the three-phase interleaved parallel circuit were compared and analyzed by experimental results. Since the operation of the Boost mode circuit and the simulation result are similar to those of the Buck mode circuit, only the Buck charging mode of the DC-DC converter is analyzed here.The rated voltage of the energy storage battery pack $U_{dc} = 1000V$ and five energy blocks are connected in series; inductance $L_1 = L_2 = L_3 = 0.05H$; DC terminal capacitance $C_1 = 1mF$; load terminal capacitance $C_2 = 0.5mF$; switching frequency $f_s = 3.2kHz$.

Figure 5 shows the output voltage simulation waveform of the converter operating in Buck mode, and Figure 6 shows the simulation waveform of the charging inductor current.



(a) Single-phase Buck voltage waveform

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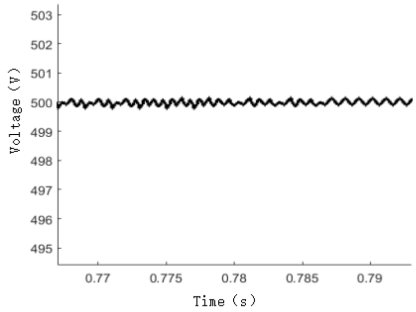
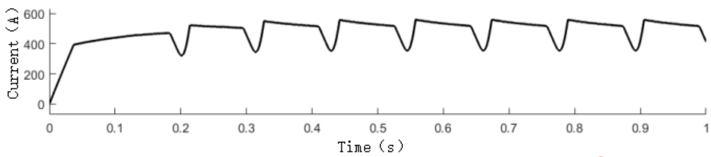
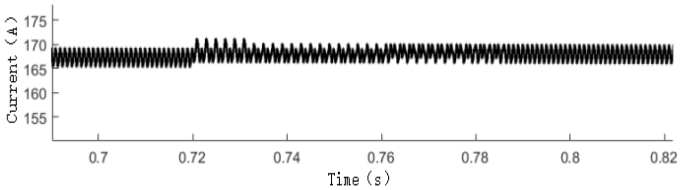


(b) Three-phase interleaved parallel Buck voltage waveform

Figure 5. Simulation waveform of output voltage in Buck circuit



(a) Single-phase Buck inductor current waveform



(b)Three-phase interleaved parallel Buck inductor current waveform

Figure 6. Inductor current simulation waveform in Buck circuit

By comparing and analyzing (a) and (b) in Fig. 5, it is found that the output voltage ripple of the three-phase circuit is significantly smaller than that of the single-phase circuit. By comparing and analyzing (a) and (b) in Fig. 6, it is found that the ripple current of the three-phase circuit energy storage battery charging inductor current is smaller than that of the single-phase circuit, and the current average value is about one third of the single-phase circuit.

The ship simulation equipment is used to build a platform to realize the practical application of this type of energy storage converter. During the test, we chose an AGM lead-acid battery as the energy storage system for the ship's microgrid. Among them, the bus voltage reference value is set to 330V, the IGBT switching frequency is 5kHz, the grid side reactance value $L = 6mH$, and the battery internal resistance $R_s = 20\Omega$. According to the data obtained from the platform, we draw a table to compare and analyze the current average and ripple coefficient of the three-phase interleaved circuit and the single-phase circuit, as well as the influence of the voltage average and ripple coefficient on the energy storage module of the ship system. It is verified by Table 1 that the output voltage and the inductor current of the three-phase interleaved parallel are greatly reduced compared to the single-phase ripple coefficient.

Table 1. Comparison of single-phase and three-phase interleaved simulation results

	single-phase	three-phase
Average of i_L	453.2	151.4
Peak-to-peak value of i_L	197.1	1.7
The ripple factor of i_L	43.5	0.37

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Average of U_0	479.5	483.2
Peak-to-peak value of U_0	201.6	3.4
The ripple factor of U_0	42.4	0.23

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