Research on Modular Multilevel Converter Technology Used in Ship Medium Voltage DC Power System

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Abstract

Taking the ship medium voltage DC(MVDC) power system as the research object, in order to solve the rectification problem of the generator voltage of the MVDC system, a modular multilevel converter(MMC) suitable for the medium voltage DC power system of the ship is established. Then the control strategy of MMC suitable for ship MVDC power system is proposed. Finally, a simulation model of the ship MVDC power system based on the five-level MMC rectification is built in Matlab/Simulink. The simulation results show that the proposed control strategy can meet the stability requirements of the ship MVDC power system and ensure that the ship MVDC power system can quickly restore stability after a fault occurs.

Keywords

Ship MVDC Power System; MMC; MMC Control Strategy; Matlab/Simulink.

1. Introduction

With the development of modern semiconductor and power electronics technology and the continuous improvement of modern ship energy requirements, the ship power system has transformed from an AC system to a MVAC and then to a MVDC system [1, 2]. Compared with the AC system, the DC system has lower transmission line loss, shorter cable length, higher power quality, and can suppress reactive power [3, 4]. And it can easily realize the efficient access and flexible management of renewable energy, DC and variable frequency loads. And it can provide efficient, economical and flexible power supply services according to user needs [5].

The rectifier is one of the key subsystems in the ship MVDC system. With the advancement of power electronic technology, power electronic converter devices are developing in the direction of high efficiency and high power. With the gradual increase in the capacity of the ship's integrated power system, due to the low level of traditional rectifiers, in order to improve the output characteristics of the rectifier, it is necessary to increase the switching frequency to meet the high-frequency PWM strategy, which will cause excessive switching losses, and at the same time Larger harmonics will also be generated, and a larger filter device needs to be added. These shortcomings are not good for the development of the ship MVDC power system [6]. In order to ensure the stability of the DC side voltage of the ship MVDCpower system, a rectifier with stable DC output is required. As a new type of converter, MMC is composed of multiple sub-modules cascaded. The number of sub-modules can be changed according to voltage requirements. The degree of modularity is higher and the output harmonics are less. It has received extensive attention in DC transmission systems. The main advantages of MMC applied to the ship MVDC power system are as follows [7]:

(1) The output voltage has low harmonic content and relatively good waveform, which improves the stability of the system;

(2) It can realize fault current limitation and fault ride-through under certain conditions, which can improve the reliability and recovery of the ship MVDC system.

(3) MMC is easy to modularize management, reduces the space occupied by the converter on the ship, and can adapt to the higher voltage level of the ship MVDC power system by changing the number of sub-modules, and the configuration is flexible. In this way, the higher bus voltage can be shared equally by the sub-modules of MMC, reducing the pressure on a single electronic device. At the same time, when the system DC bus fails, the impact of the fault on each sub-module of MMC has also been reasonably dispersed.

(4) The switching frequency of the power devices of the MMC main circuit is low, which reduces the switching loss. Using the MMC topology structure can control the loss of the MMC to about 1%, and improve the energy utilization rate of the ship's MVDC system.

Based on the above advantages, the application of MMC in the ship MVDC system has become a research hotspot in recent years, and it is a frontier subject with research value in the world today.

Aiming at the ship MVDC system, this paper establishes an MMC converter suitable for the ship MVDC system. In addition, the mathematical model and working principle of MMC are described in detail, and an MMC voltage equalization control strategy suitable for ship MVDC is proposed. Finally, a MMC-MVDC system was built with Matlab/Simulink, and various working conditions were simulated to verify the feasibility of the proposed topology and control method.

2. MMC topology and principle

2.1 MMC topology

The full-bridge MMC (FMMC) structure is adopted in this paper. As shown in Figure 1. FMMC adopts a three-phase six-arm structure. The bridge arm is composed of N sub-modules, current-limiting inductance L_s, and bridge arm resistance R_s. The upper and lower bridge arms form a phase unit. Its sub-module (SM) structure is shown in Figure 2.

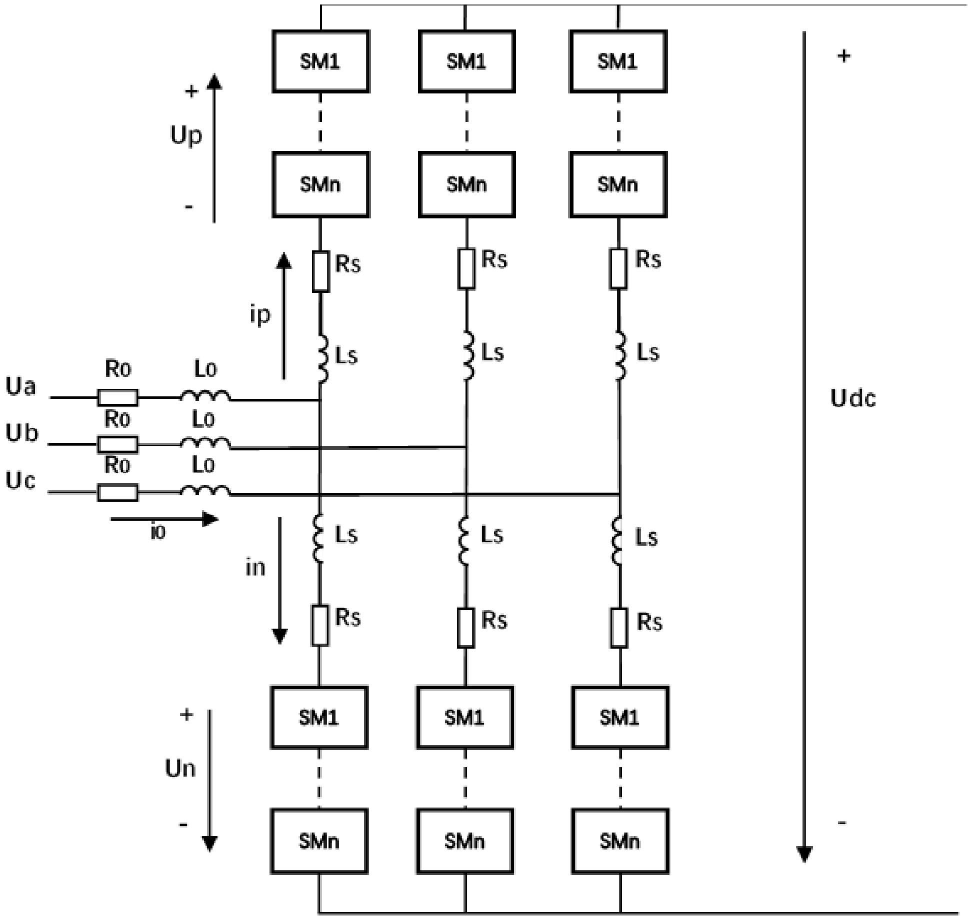

Figure 1. FMMC structure

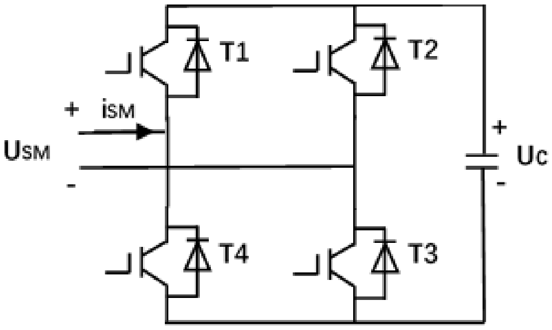

Figure 2. SM structure

Table 1 shows the working conditions of the FMMC sub-modules, including three types: input, cut and lock (1 represents on, 0 represents off).

Table 1. Working status of sub-modules

Mode	T1	T2	T3	T4
Input	1	0	0	1
	0	1	1	0
Cut	1	1	0	0
	0	0	1	1
Lock	1	1	0	0
	1	1	0	0

2.2 MMC mathematical model and working principle

2.2.1 MMC mathematical model

As shown in Figure 1. The mathematical model of MMC in the three-phase coordinate system is [8]:

$$\begin{cases} u_a(t) - v_a(t) = L\frac{di_a(t)}{dt} + Ri_a(t) \\ u_b(t) - v_b(t) = L\frac{di_b(t)}{dt} + Ri_b(t) \\ u_b(t) - v_b(t) = L\frac{di_b(t)}{dt} + Ri_b(t) \end{cases} \tag{1}$$

Among them,

$$i_a = i_{ap} + i_{an} \tag{2}$$

$$L = L_0 + L_s \tag{3}$$

$$R = R_0 + R_s \tag{4}$$

$$v_a = \frac{U_{an} - U_{ap}}{2} \tag{5}$$

The mathematical model of MMC in the two-phase coordinate system is:

$$\begin{cases} u_d(t) - v_d(t) = L\frac{di_d(t)}{dt} + Ri_d(t) + \omega Li_q(t) \\ u_q(t) - v_q(t) = L\frac{di_q(t)}{dt} + Ri_q(t) - \omega Li_q(t) \end{cases} \tag{6}$$

2.2.2 MMC working principle

When the system is running normally, the DC voltage needs to be kept stable, so the number of sub-modules in the three units of MMC should be equal and remain unchanged, which means [9, 10]

$$U_{dc} = U_p + U_n \tag{7}$$

Assuming that the number of sub-modules connected to the upper bridge arm is N_p, and the number of sub-modules connected to the lower bridge wall is N_n, the sum of the number of sub-modules input to the upper and lower bridge arms is N. Explain that half of the sub-modules of each phase unit are put into operation at any time, and the sub-modules are controlled to be put in or removed through the trigger signal. A reasonable allocation of the number of sub-modules in the upper and lower arms of each phase unit can be used to achieve multi-level voltage waveform output on the AC side of the converter.

According to the above principle, FMMC can output N+1 levels at most. The more sub-modules in series with the bridge arm and the higher the number of levels, the closer the AC side output voltage waveform is to a sine wave.

3. Control strategy

3.1 MMC modulation method

Aiming at the characteristics of MMC requiring a large number of levels, the easy-to-implement carrier phase shift modulation is adopted. Carrier phase-shift modulation is the product of the combination of natural sampling SPWM technology and multiple technology. It has the characteristics of high equivalent switching frequency and good output harmonic characteristics. For the N sub-modules in each bridge arm, SPWM with a lower switching frequency is used, so that their corresponding triangular carrier is sequentially shifted by 1/N triangular carrier period, that is, $2\pi/N$ phase angle. Then it compares with the same sine modulated wave to generate N groups of PWM modulated wave signals, respectively drive N sub-module units, and decide whether they are put in or removed. The output voltage U_{SM} of each sub-module put in is superimposed, and the output voltage waveform of the bridge arm of the MMC is obtained.

3.2 MMC control strategy

3.2.1 Capacitor voltage balance control

In order to avoid non-negligible circulating currents in the circuit, it is very important to keep the voltage levels of the sub-modules in the MMC topology consistent. In order to ensure the stable operation of MMC in the ship MVDC system, it is necessary to adopt corresponding control strategies to control the sub-module capacitor voltage balance.

The capacitor voltage balance control strategy can be divided into two parts:

The first part is energy sharing control. The function of this part is to ensure that the average value of the capacitor voltage of several sub-modules in each phase unit tracks its reference value, so that the energy is evenly distributed to these sub-modules. Double closed-loop control of voltage and current is adopted. The outer voltage loop uses a PI controller. The average capacitor voltage value in the control phase unit tracks the capacitor voltage reference value. The output of the PI controller is used as the current setting. The current inner loop also uses a PI controller to control the circulating current to track the change of a given circulating current reference value, and its output is used as the capacitance voltage balance control adjustment.

The simulation block diagram of energy sharing control is shown in Figure 3. Among them, U_{cref} is the capacitor voltage reference value, U_{ac}, U_{bc}, U_{cc} are the capacitor voltages of the three-phase unit, I_{aarm}, I_{barm}, and I_{carm} are the currents flowing through the three-phase unit.

The second part is voltage balance control. The function of this part is to make the capacitor voltage of several sub-modules on the bridge arm track its reference value.

The voltage loop uses a proportional regulator to control the sub-module capacitor voltage to track the capacitor voltage reference value, and its output is the capacitor voltage balance control adjustment value. Take the A-phase upper arm as an example, since the capacitive voltage balance control is adjusted according to the direction of the upper and lower arm currents, the polarity of

U_{capref} is also determined by the arm current I_{arm}. When $U_{cref} \geq U_{cap}$, the converter should obtain energy from the DC side to charge the capacitor on the bridge arm. If the upper bridge arm current $I_{ap}>0$, U_{capref} is a positive value, so that a positive power flow with I_{ap} is combined to the converter ; If $I_{ap}<0$, U_{capref} is a negative value, which is combined with I_{ap} into the power flowing to the converter. The control block diagram is shown in Figure 4.

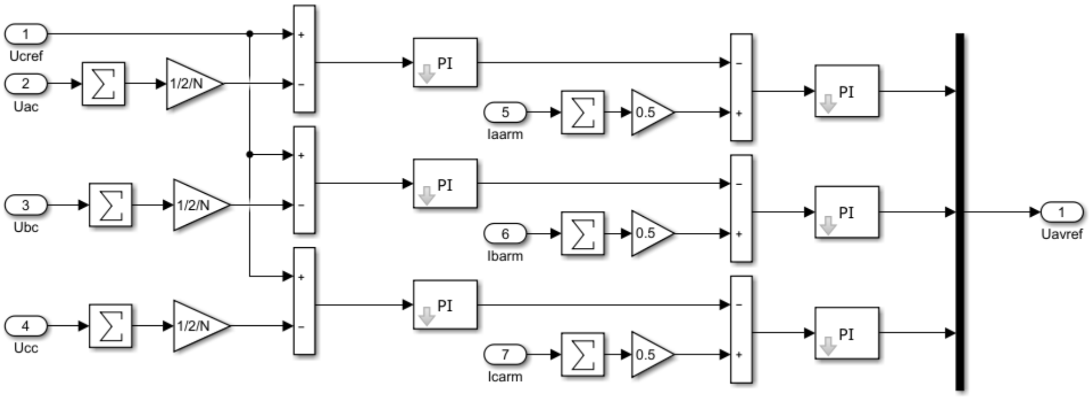

Figure 3. Energy sharing control

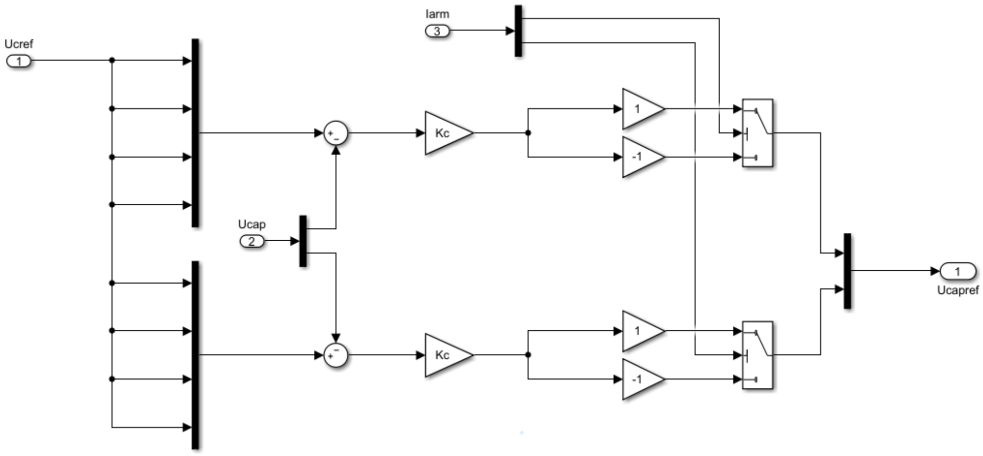

Figure 4. Voltage balance control

3.2.2 DC bus voltage control strategy

For MMC, the current direct current control strategy is mainly used, based on the synchronous rotating coordinate system (dq coordinate system) vector control technology, and the coordinate change is used to convert three-phase alternating current into two-phase direct current, thereby simplifying the mathematical model and suitable for MMC control. Taking i_d and i_q as state variables, u_d and u_q as disturbance components, v_d and v_q as input variables, introducing voltage coupling compensation terms $\omega L i_q$ and ωLid, when PI control is used, the inner loop current control expression can be obtained:

$$\begin{cases} v_d = u_d + \omega L i_q - k_{p1}\left(i_{dref} - i_d\right) - k_{i1}\int\left(i_{dref} - i_d\right)dt \\ v_q = u_q - \omega L i_d - k_{p1}\left(i_{qref} - i_q\right) - k_{i2}\int\left(i_{qref} - i_q\right)dt \end{cases} \tag{8}$$

Among them, i_{dref} and i_{qref} are current reference values, k_{p1} and k_{p2} are the proportional coefficients of the PI controller, and k_{i1} and k_{i2} are the integral coefficients of the PI controller. The inner loop controller adjusts the converter output voltage so that the d and q axis currents quickly track the reference value of the device. The inner loop control block diagram is shown as in Figure 5.

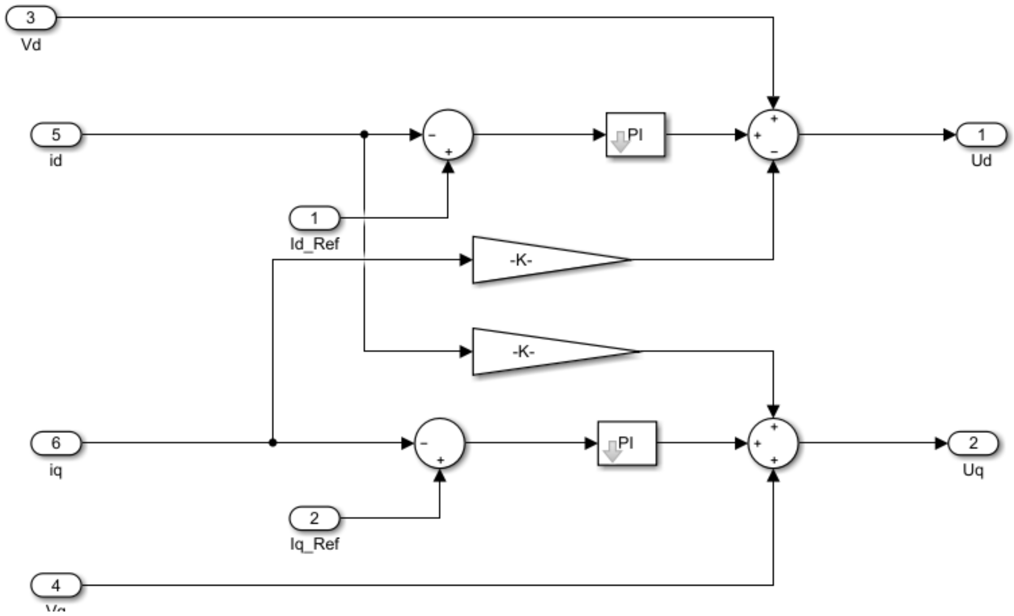

Figure 5. Inner loop control

The voltage outer loop adopts PI control, and the control block diagram is shown in Figure 6.

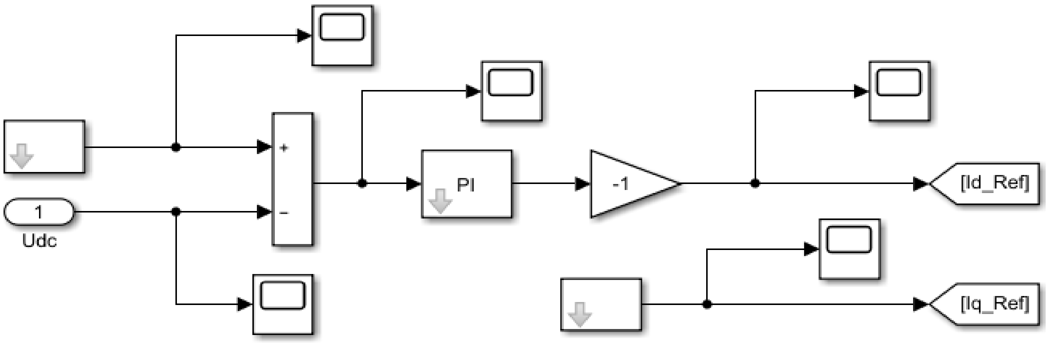

Figure 6. Outer loop control

4. System simulation and analysis

In order to verify the function of the proposed control strategy in the ship medium voltage DC power system, a simulation model of the ship medium voltage DC power system based on a modular multilevel converter (MMC-MVDC)was established in Matlab/Simulink. Select various parameters as shown in Table 2.

Table 2. Three Scheme comparing

	Parameter
Generator capacity(Sn)	10MVA
AC side line voltage(Ur)	2400V
Frequency(fn)	60Hz
DC bus voltage(Udc)	3000V
Number of bridge arm sub-modules(N)	4
Sub-module capacitance(C)	0.02F
Capacitor voltage(Uc)	750V
Bridge arm inductance(Larm)	0.01H
Bridge arm resistance(Rarm)	0.1Ω

4.1 Steady state simulations

First, run under normal operating conditions, and the bus voltage simulation results are shown in Figure 7.

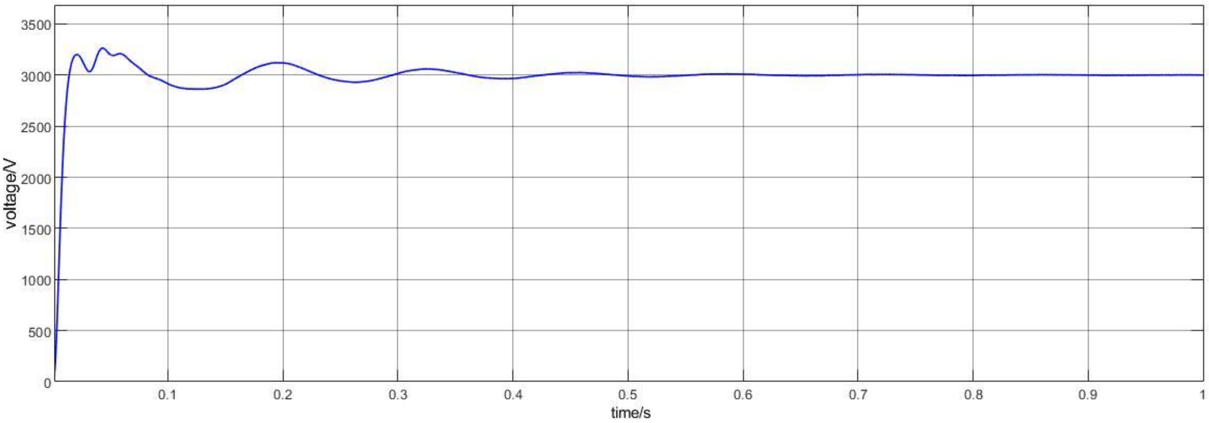

Figure 7. DC bus voltage waveform

It can be seen from Figure 7 that the DC bus voltage tends to stabilize after 0.4s, and the maximum voltage amplitude fluctuation in the early stage is 250V, which is in line with the DC bus voltage fluctuation stability range (within 10%), indicating that MMC can quickly stabilize the voltage at the specified value.

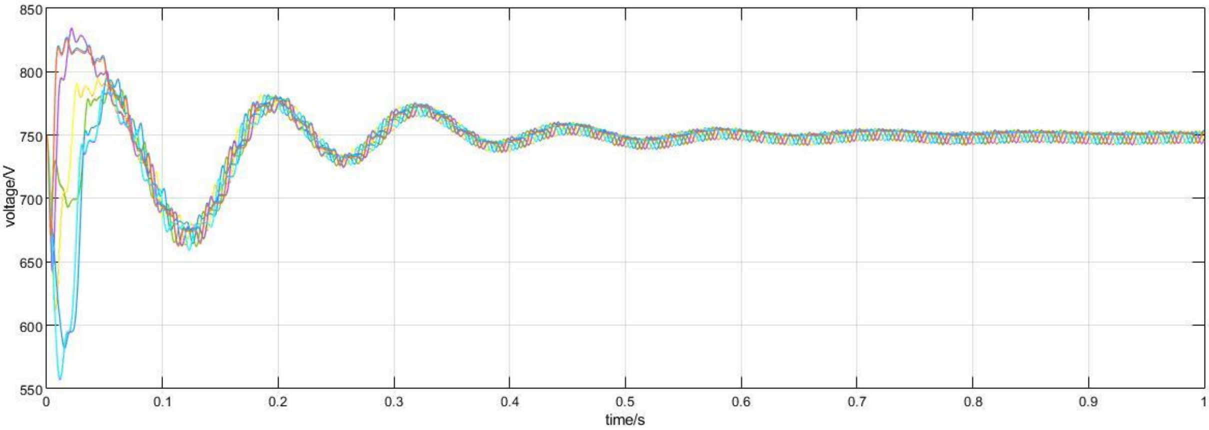

Figure 8. Capacitor voltage

Figure 8 shows the capacitor voltages of all sub-modules in MMC. It can be seen from the figure that after 0.4s, the capacitor voltage stabilizes at 750V. According to the principle of MMC, the sum of the capacitor voltages of the upper and lower arms is the DC side voltage. It meets the requirement of 3000V DC bus voltage, and verifies the correctness and effectiveness of the proposed capacitor voltage balance control strategy.

4.2 Sudden load simulation

When the system is running, add a 1MW load suddenly in 0.6s and observe the change of the DC bus voltage.

It can be seen from Figure 9 that when a load of 1MW is suddenly added at 0.6s, the voltage fluctuates, but it still meets the 10% stability requirement. After another 0.6s, the bus voltage tends to stabilize at about 1.2s, indicating that the bus voltage tends to stabilize when facing the load suddenly In the case of increasing, MMC can still effectively maintain the stability of the bus voltage.

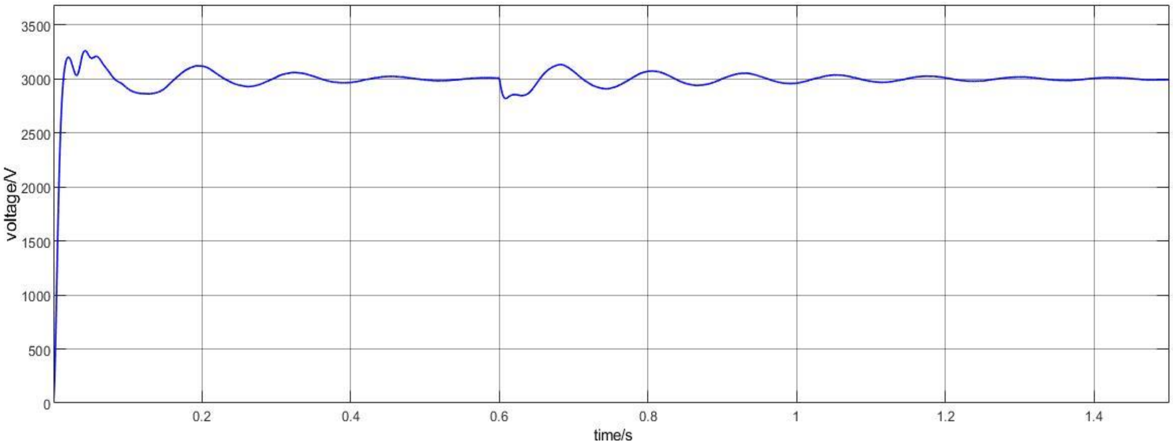

Figure 9. DC bus voltage

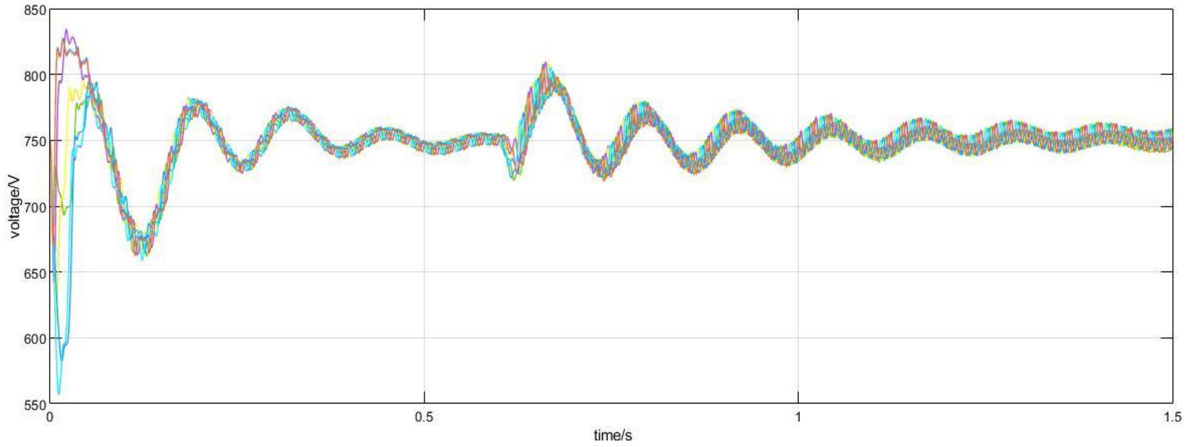

Figure 10. DC bus voltage

Figure 10 shows the capacitor voltage waveform diagram of the MMC sub-module. After a 1MW load is suddenly added in 0.6s, it can be quickly adjusted and stabilized, which verifies the correctness of the proposed MMC control strategy.

4.3 Simulation under fault conditions

The fault type used in this paper is a short circuit between the DC side poles. The short circuit is set at 0.6s and the 0.7 short circuit fault is removed. The simulation results are as follows.

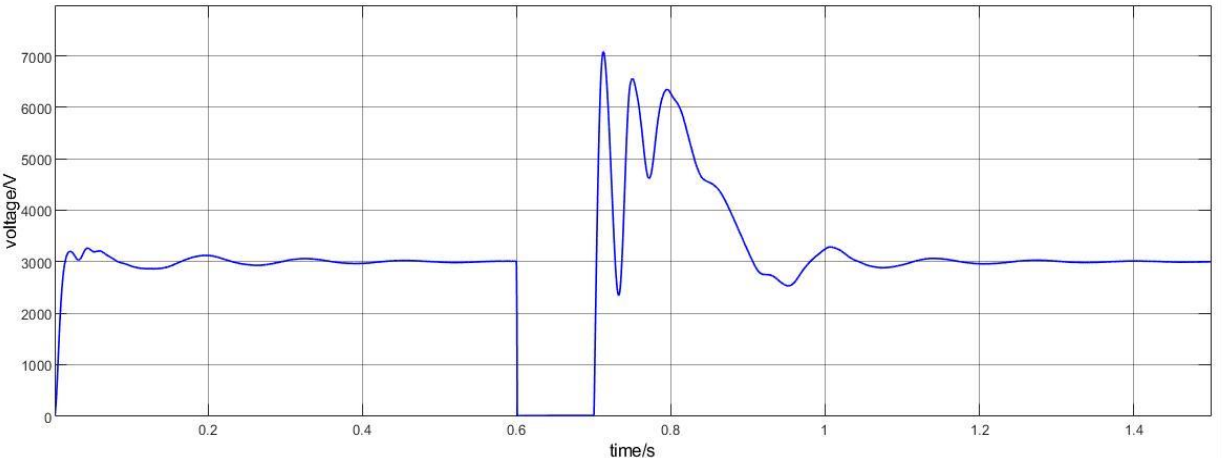

Figure 11. Bus voltage waveform during short circuit

As shown in Figure 11, the system is stable after 0.4s, an inter-electrode short circuit fault occurs in 0.6s, the voltage drops to 0V instantly, and the fault is eliminated in 0.7s, the DC bus voltage returns to 3000V after about 0.5s and remains stable. It shows that the ship MVDC system based on MMC has the ability to recover quickly after failure.

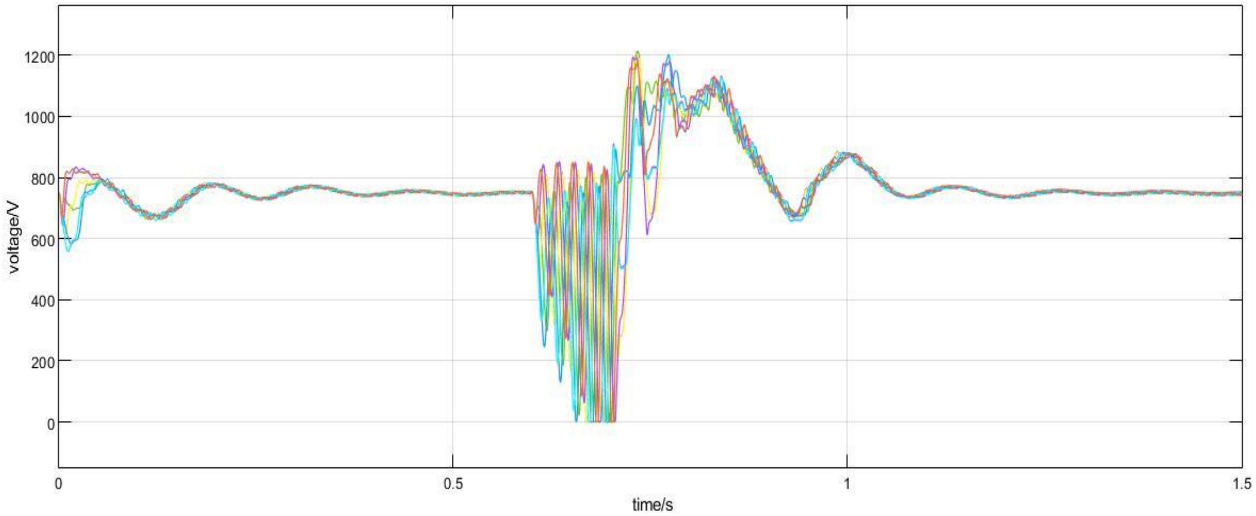

Figure 12. Bus voltage waveform during short circuit

Figure 12 shows the capacitor voltage waveform diagram of the MMC sub-module. It can be seen that the capacitor voltage drops rapidly and fluctuates sharply during the 0.6s to 0.7s failure period of the system. After the failure is eliminated, it will be stable after about 0.5s. This result also proves the validity and correctness of the proposed MMC voltage control strategy.

5. Conclusion

The use of modular multilevel converters in ship medium voltage DC power systems has many advantages such as high output voltage quality, high efficiency, and superior fault response. According to the topological structure and working principle of MMC, this paper proposes the MMC topology and modulation strategy suitable for ship MVDC system. On this basis, a capacitor voltage balance control strategy and an energy balance control strategy are proposed, so that the capacitor voltage of each sub-module of MMC can be kept consistent, thereby ensuring the stability of the DC bus voltage. Finally, a 5-level MMC-MVDC system model is built on the Matlab/Simulink simulation platform. The simulation results show that the proposed MMC modulation strategy and voltage control strategy have good performance and can achieve dynamic adjustment.

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