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Comparison and Analysis of Improved NLM Strategy for Modular Multilevel Converter in Ship Medium Voltage DC Power System

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Abstract

Modular multilevel converter (MMC) is applied to medium voltage direct current (MVDC) of ships, In MVDC power system, due to the small number of sub modules, using the traditional nearest level modulation (NLM) strategy, the harmonic content of output voltage is large and the voltage distortion is high. Therefore, it is of great significance to optimize the modulation strategy to improve the harmonic content of output voltage. The working principle and characteristics of traditional NLM modulation strategy, output 2N+1 level NLM modulation strategy and hybrid NL-PWM modulation strategy are compared and analyzed. The simulation model is built on MATLAB/Simulink platform, and the differences of harmonic characteristics of output voltage among the three modulation strategies are analyzed. Finally, the characteristics of the two optimized modulation strategies are summarized.

Keywords

Modular Multilevel Converter(MMC); Medium Voltage DC(MVDC) Power System; Nearest Level Modulation(NLM); Hybrid Nearest Level Pulse Width Modulation; Output Harmonic Characteristics.

1. Introduction

The voltage level of marine mvdc power system is much lower than that of land-based HVDC power system, and the number of MMC sub modules is small. If the modulation method of step wave approaching sine wave in land-based HVDC power system is still used, it will cause problems such as larger equivalent error, obvious low order harmonic and serious current distortion [1]. However, when the traditional carrier phase shifting pulse width modulation (CPS-PWM) strategy is adopted, the complex carrier generation leads to the difficulty of hardware implementation, and multiple groups of PI controllers are needed to realize the capacitor voltage balance control, which will increase the cost of the controller [2]. Therefore, when designing the MMC modulation strategy, it is necessary to comprehensively consider the voltage withstand and harmonic requirements of the ship power grid, the cost and loss of the equipment, and whether it can be well matched with the capacitor voltage sharing control algorithm, so as to ensure the efficient and stable operation of the system [3].

In view of the limitation of output performance and control structure of traditional NLM modulation method in the scenario of small number of sub modules, scholars have proposed a series of improved modulation strategies. Reference [4] improves the integer function of the traditional NLM strategy, which can output 2N+1 levels without changing the number of sub modules, making the output voltage more close to the modulation strategy of sinusoidal modulation wave. By introducing the deviation between modulation wave and step wave in reference [5], the problems of capacitor voltage fluctuation and circulating current in the case of low level number are effectively avoided. In reference [6], the influence of DC voltage level and the number of bridge arm sub modules on the

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harmonic characteristics of MMC inverter output voltage is studied, and the harmonic performance of MMC inverter is optimized. In reference [7], the output characteristics, advantages and disadvantages of five improved modulation strategies are compared, and the applications of different modulation strategies are summarized.

Therefore, this paper will analyze the improved NLM strategy when the DC bus voltage of ship mvdc power system is 5kV. Comparing the output harmonic performance changes before and after using the improved modulation strategy and the advantages and disadvantages between the improved strategies, and building a simulation model on MATLAB/Simulink, through the comparative analysis of the simulation results, on the premise of meeting the requirements of total harmonic distortion rate of ship power grid, the MMC with fewer sub modules is selected to reduce the control complexity and cost budget of MMC, which is of great significance to the actual project Application research has important guiding significance.

2. MVDC-MMC topology and mathematical model

2.1 MVDC-MMC topology of ship

In view of the high reliability of ring grid structure and its suitability for marine medium voltage DC power system, the research on MMC improved NLM strategy in this paper is based on ring grid structure. In this model, two main generators with rated power of 1MW and two auxiliary generators with rated power of 0.5MW are used to supply power to 5kV medium voltage DC bus after rectification. The power distribution mode is adopted to supply power to four regional load centers from bow to stern. All rectifiers and inverters adopt MMC topology.

2.2 MMC topology

Fig.1 shows the topology of MMC three-phase system, which is composed of six bridge arms. The upper and lower bridge arms of each phase are respectively composed of N sub modules (SM1,SM2,…SMN). It is a typical three-phase system structure with N+1level output. In this paper, the MMC sub module adopts the asymmetric sub module (ASM) structure, which is composed of a full bridge sub module and a power transistor. Compared with half bridge sub module (HBSM) and full bridge sub module (FBSM), ASM not only has the ability to block DC fault, but also reduces the complexity of device input and control. The topology has three working states: blocking and switching. When the system gives T1 always "1" conduction signal, ASM works in the same way as HBSM, and there is no need to redesign the driving control strategy. The topological structure is shown on the right side of Fig.1.

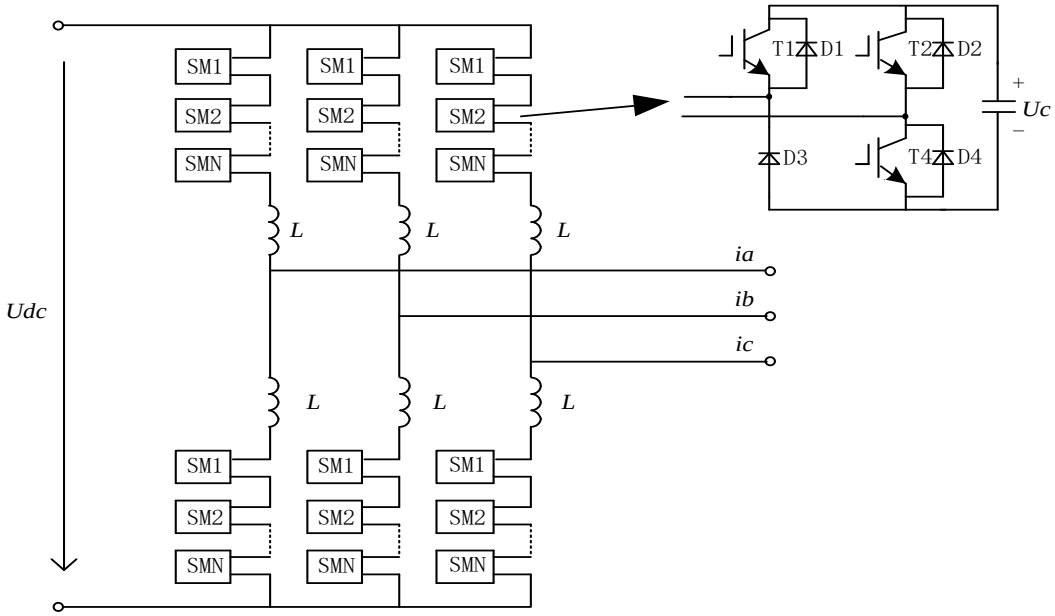

Fig. 1 MMC topology and asymmetric sub module topology

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2.3 MMC mathematical model

Due to the symmetry of MMC system, A-phase equivalent circuit diagram is taken as an example for further analysis, as shown in Fig.2. Among them, U_{dc} represents the DC bus voltage, ipa, inarepresent the current of the upper and lower arm of 2.3a respectively, R and L represent the resistance and inductance of the arm respectively, u_{ao} represents the voltage of phase a, ia represents the current of phase a, R1, L1 represent the equivalent load resistance and inductance of phase a.

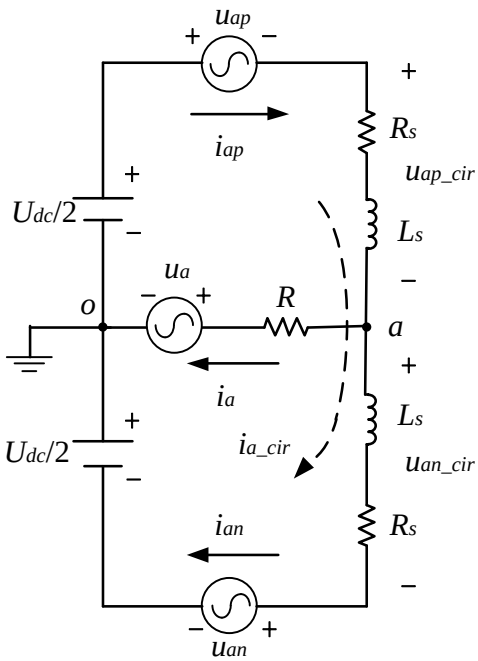

Fig. 2 MMC single phase equivalent circuit diagram

According to Kirchhoff's voltage law:

$$\begin{cases} u_{ao} = \frac{U_{\mathrm{dc}}}{2} - u_{\mathrm{ap}} - R_s i_{\mathrm{ap}} - L_s \frac{di_{\mathrm{ap}}}{dt} \\ u_{ao} = -\frac{U_{\mathrm{dc}}}{2} + u_{\mathrm{an}} + R_s i_{\mathrm{an}} + L_s \frac{di_{\mathrm{an}}}{dt} \end{cases} \tag{1}$$

According to Kirchhoff's current law:

$$i_a = i_{\mathrm{ap}} - i_{\mathrm{an}} \tag{2}$$

Consider the loop current in the circui of $i_{\mathrm{a\_cir}}$ on the bridge arm current can be expressed as follows:

$$i_{\mathrm{a\_cir}} R_s + L_s \frac{di_{\mathrm{a\_cir}}}{dt} = \frac{U_{\mathrm{dc}}}{2} - \frac{u_{\mathrm{ap}} + u_{\mathrm{an}}}{2} \tag{3}$$

From equations (1) and (3), it can be concluded that:

$$i_{\mathrm{a\_cir}} = \frac{i_{\mathrm{ap}} + i_{\mathrm{an}}}{2} \tag{4}$$

Combining with equations (2) and (4), it is concluded that:

$$\begin{cases} i_{\mathrm{ap}} = i_{\mathrm{a\_cir}} + \frac{1}{2} i_a \\ i_{\mathrm{an}} = i_{\mathrm{a\_cir}} - \frac{1}{2} i_a \end{cases} \tag{5}$$

According to equations (1) and (2), A-phase voltage and DC bus can be further expressed as equations (6) and (7)

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$$u_{\mathrm{ao}} = \frac{u_{\mathrm{na}} - u_{\mathrm{pa}}}{2} - \frac{R_s}{2} i_a - \frac{L_s}{2} \frac{di_a}{dt} \tag{6}$$

$$U_{\mathrm{dc}} = u_{\mathrm{ap}} + u_{\mathrm{an}} + L_s\left(\frac{di_{\mathrm{ap}}}{dt} + \frac{di_{\mathrm{an}}}{dt}\right) + R_s(i_{\mathrm{ap}} + i_{\mathrm{an}}) \tag{7}$$

Since the equivalent inductance voltage drop in the circuit is related to the AC and DC circulating current components in the bridge arm current, and has nothing to do with the phase current components in the bridge arm current, and its value is not large in the normal operation of the system, its influence can be ignored in the study of the interaction between MMC and external AC system, and the equivalent resistance voltage drop can be ignored in order to simplify the analysis.

$$U_{\mathrm{dc}} = u_{\mathrm{ap}} + u_{\mathrm{an}} = NU_c \tag{8}$$

Let $u_a = \frac{u_{\mathrm{na}} - u_{\mathrm{pa}}}{2}$, then the reference voltage is:

$$u_{\mathrm{a\_ref}} = \frac{m}{2} U_{dc} \cos(wt) \tag{9}$$

m is the modulation ratio of inverter output voltage, *w* is the angular velocity of output voltage.

The reference voltage expression of the upper and lower bridge arms can be obtained from the above formula.

$$\begin{cases} u_{ap\_ref} = \frac{U_{\mathrm{dc}}}{2}(1 - m\cos(wt)) \\ u_{an\_ref} = \frac{U_{\mathrm{dc}}}{2}(1 + m\cos(wt)) \end{cases} \tag{10}$$

3. MMC modulation strategy

3.1 Traditional NLM modulation strategy

Traditional NLM modulation is one of the most commonly used methods in MMC. This modulation method has the advantages of low switching loss, high efficiency and simple voltage and current sharing. It is suitable for high voltage and high power applications with large number of sub modules. When it is applied to the medium and low voltage MMC with few modules, the low order harmonics of the step wave are obvious, the current distortion is high, and the harmonic characteristics of the output voltage are poor.

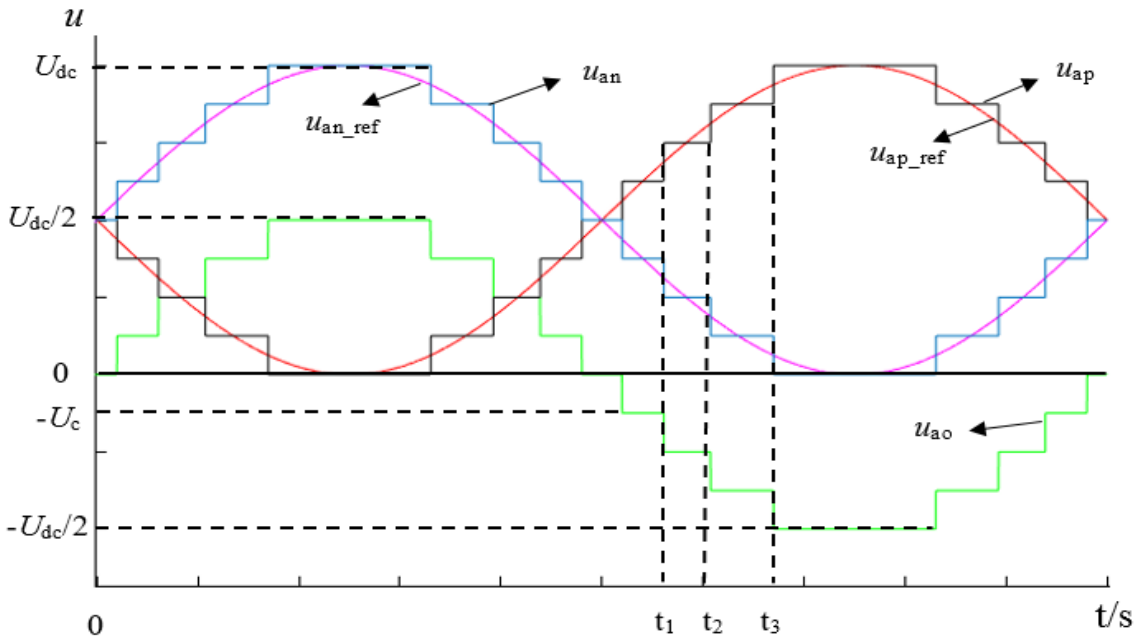

Fig. 3 Schematic diagram of traditional NLM strategy

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In Fig.3, the phase voltage at the AC side is 0 at 0, and the voltages of the upper and lower arms are equal. With the rise of voltage modulation wave, the number of sub modules in the lower arm of phase A is gradually increasing, while the number of sub modules in the upper arm is gradually decreasing. The number of sub modules input at each time of the upper and lower bridge arms can be summarized into a mathematical relationship as shown in equation (11). N_{up}, N_{down} respectively represent the number of sub modules of the upper and lower bridge arms in the input state round $_{0.5}()$ represents the rounding function, and subscript 0.5 means that the rounding function is calculated by the rounding rule.

$$\begin{cases} N_{\text{up}} = \text{round}_{0.5}\left\{\frac{U_{dc}}{2U_c}(1 - m\cos(wt))\right\} \\ N_{\text{down}} = \text{round}_{0.5}\left\{\frac{U_{dc}}{2U_c}(1 + m\cos(wt))\right\} \end{cases} \tag{11}$$

3.2 Output 2N+1 level NLM modulation strategy

In view of the serious distortion of traditional NLM modulation waveform when the number of sub modules is small, the output 2N+1level NLM modulation strategy can double the number of output levels without changing the number of sub modules, which can significantly improve the harmonic characteristics of the output voltage. In reference[8], the specific implementation measures of the modulation strategy are proposed. The difference between the improved method and the traditional method lies in the change of integer function, as shown in equation (12). In the formula, the subscript comparison formula (11) of rounding function changes from 0.5 to 0.25, which means that the accuracy of rounding is twice as high as before.

$$\begin{cases} N_{\text{up}} = \text{round}_{0.25}\left\{\frac{U_{dc}}{2U_c}(1 - m\cos(wt))\right\} \\ N_{\text{down}} = \text{round}_{0.25}\left\{\frac{U_{dc}}{2U_c}(1 + m\cos(wt))\right\} \end{cases} \tag{12}$$

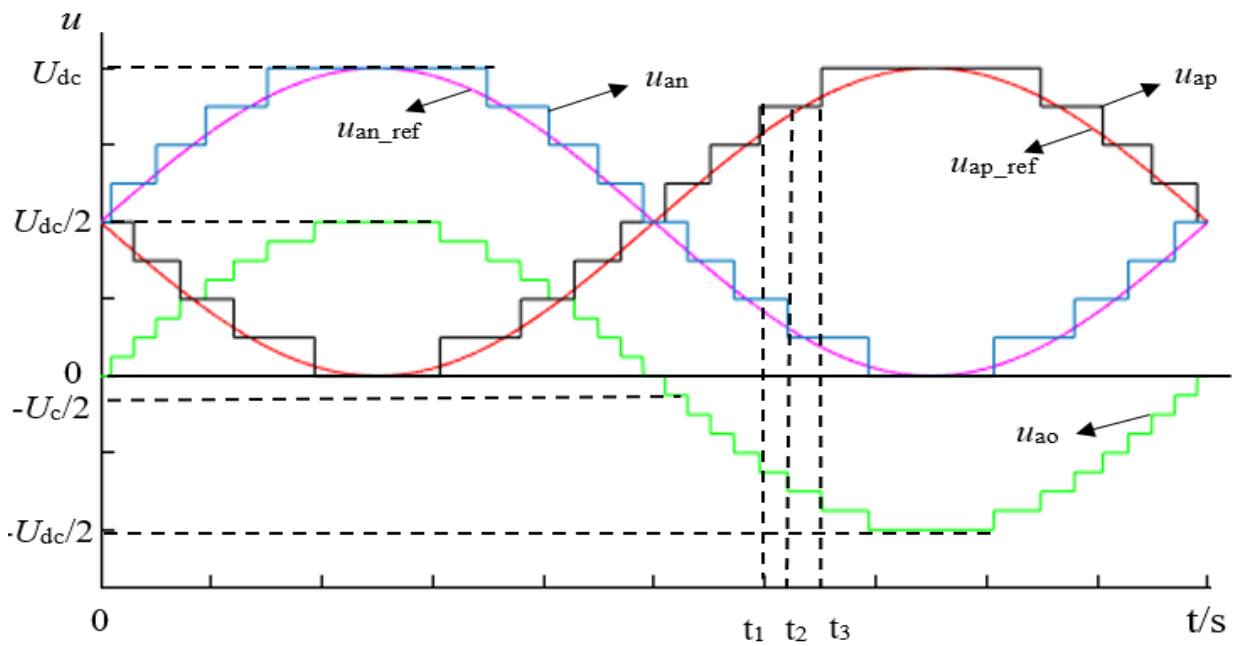

Fig. 4 Schematic diagram of NLM strategy for output 2N+1 level

Comparing Fig. 3 and Fig. 4, we can see that the output phase voltage in Fig. 3 has a total of 9 levels. From equations (11) and (12), we can see that the size of each step wave is U_c, and the number of common input levels of upper and lower bridge arms in a cycle is always n. in Fig. 4, there are 17 output phase voltage levels, we can know that the size of each step wave is $U_c/2$, which can play a significant role in the output waveform compared with the traditional modulation strategy The optimization effect of the system is analyzed. However, when t_1-t_2, the total number of sub modules

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is N+1, and when t_2-t_3, the number of sub modules is N. compared with the traditional modulation strategy, because the change of the total number of sub modules in the phase unit will lead to the asymmetry of phase to phase voltage, it will increase the phase to phase circulating current and have a greater impact on the harmonic characteristics of the output voltage.

3.3 Hybrid NL-PWMmodulation strategy

In order to solve the problems of large harmonics in traditional NLM modulation, complex voltage balance control in traditional CPS-PWMmodulation and unstable input sub modulus of output 2N+1 level NLM modulation method, a hybrid NL-PWM modulation strategy suitable for MVDC-MMC is proposed in reference[9]. The working principle of the modulation strategy is to add a PWM pulse generator to each bridge arm, so that each bridge arm has a sub module working in PWM mode, and the rest of the sub modules still work in NLM mode. The working state of the sub modules is shown in table 1. This strategy inherits the advantages of traditional NLM control, and does not need additional control in each SM. Therefore, the voltage balance control of hybrid NL-PWM modulation is simple and easy to implement.

Table 1. Working state of sub module of hybrid NL-PWM modulation strategy

pattern	T1	T2	T4	state
1	1	0	1	on
2	1	1	0	off
3	1	1 ⟷ 0	0 ⟷ 1	PWM wave

Each sub module in the bridge arm has three working states, as shown in table 1. When the sub module works in the input state, the number of sub modules of the upper and lower bridge arms can be calculated by expression (13).

$$\begin{cases} N_{\mathrm{ap}} = floor(\frac{0.5U_{dc}-u_{a\_ref}}{U_c}) \\ N_{\mathrm{an}} = floor(\frac{0.5U_{dc}+u_{a\_ref}}{U_c}) \end{cases} \tag{13}$$

Where *floor*() is a downward rounding function, that is, the integer value not greater than the function is obtained, $u_{\mathrm{a\_ref}}$ is the reference voltage. Thus, the number of sub modules in the bridge arm working in PWM mode can be obtained from expression (14).

$$\begin{cases} N_{\mathrm{ap\_pwm}} = \frac{u_{ap\_ref}-N_{\mathrm{ap}}U_c}{U_c} \\ N_{\mathrm{an\_pwm}} = \frac{u_{an\_ref}-N_{\mathrm{an}}U_c}{U_c} \end{cases} \tag{14}$$

According to formulas (13) and (14), the schematic diagram of hybrid NL-PWM modulation strategy waveform generation can be drawn, as shown in Fig.5.

Through the introduction of the principles and characteristics of the above three modulation strategies, it can be seen that the NLM and hybrid NL-PWM modulation methods with 2N+1output level not only solve the problem of large harmonics under the traditional NLM modulation, but also simplify the complex voltage balance control under the traditional CPS-PWM modulation; while the NLM modulation method with 2N+1output level has small switching loss and simple control, but there will be phase unit switching The total number of sub modules is not always N, which increases the phase to phase voltage asymmetry and intensifies the circuit circulating current. Therefore, combined with the above factors, the hybrid NL-PWM modulation method is more suitable for marine MMC modulation strategy. In order to fully demonstrate this point of view, the following will carry on the simulation verification.

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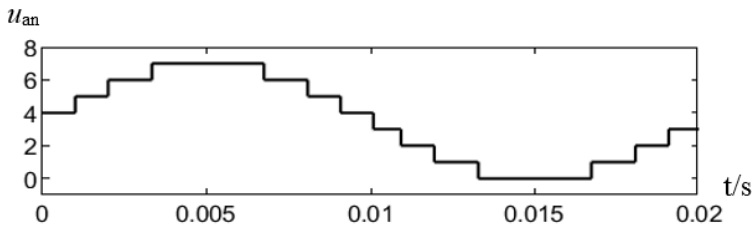
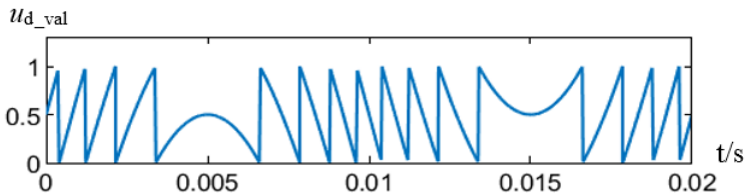
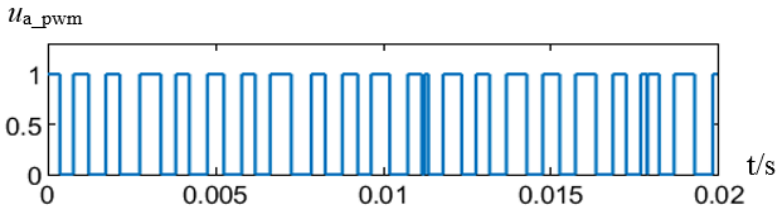


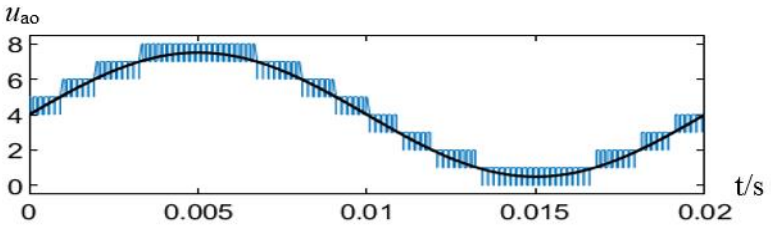
(a) N-level step wave generated by modulation



(b) Difference between modulated wave and stepped wave



(c) Compare the generated PWM waveform



(d) Output waveform after superposition of step wave and PWM wave

Fig. 5 Schematic diagram of hybrid NL-PWM modulation strategy

4. Simulation analysis

In order to verify that the MMC modulation strategy based on hybrid NL-PWM has good output voltage characteristics, the simulation model of MMC inverter side is built on MATLAB/Simulink for simulation verification. According to reference[6], the number of MMC single arm sub modules is 14, and the relevant simulation parameters are shown in table 2.

Table 2. Simulation parameters

parameters	value
DC voltage U_{dc}/kV	5
Number of bridge arm SM	14
Bridge arm reactance L/Mh	9
SM capacitance C/mF	15.4
carrier frequency f/Hz	2000
Modulation ratio M	1
Simulation step size /μs	60
Load active power /MW	2
Load reactive power /MVar	0.1

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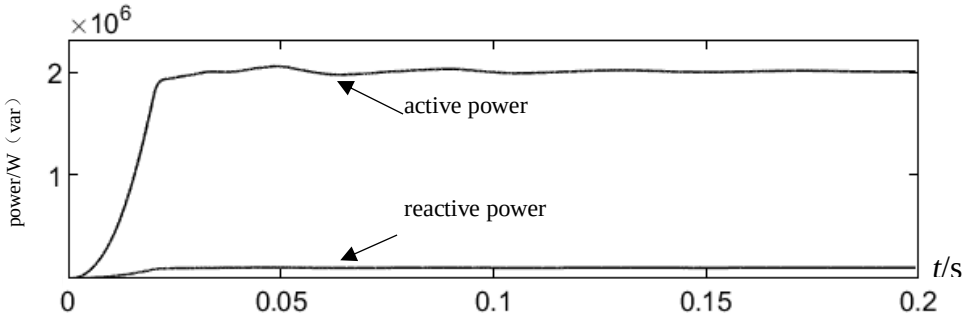
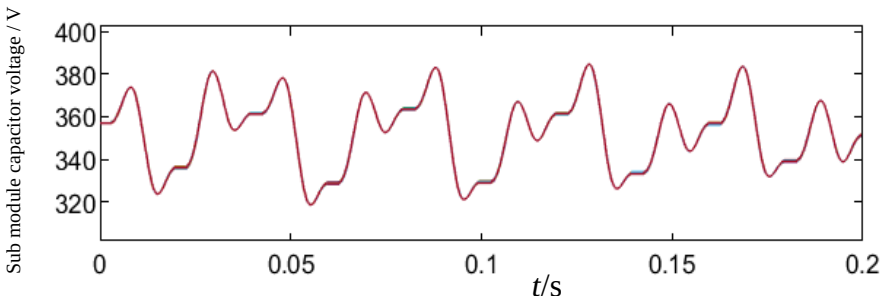
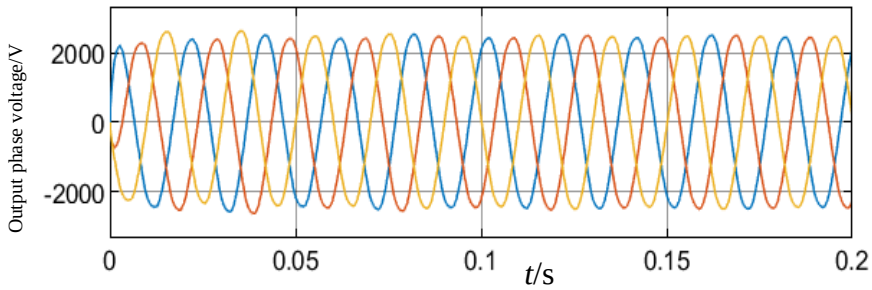
The above parameters are applied to the simulation model of the hybrid NL-PWM modulation strategy to verify the effectiveness of the hybrid NL-PWM modulation strategy. In Fig.6, it can be observed from (a) that after 0.02s, the active power is basically maintained at about 2MW, and the reactive power is approximately stable within the preset rated value range; (b) the figure shows the change of voltage at both ends of the capacitor of the bridge arm sub module with time charge and discharge. It can be seen from the figure that the voltage fluctuation starts to maintain within ± 20V within 0.18s, and the calculated voltage fluctuation rate is 0.056, which is similar to the preset voltage fluctuation rate of 0.05 Same; (c) the figure shows the waveform of three-phase voltage output by the inverter, and the output phase voltage waveform is similar to sine wave from 0.02s, and the amplitude reaches the rated output value.



(a) AC measured active power and reactive power



(b) Capacitor voltage of bridge arm sub module



(c) Three phase voltage at AC side

Fig. 6 Simulation waveform of traditional NLM modulation strategy

The simulation results show that the parameter design is reasonable and the hybrid NL-PWM modulation strategy is effective. On this basis, the MMC output voltage based on traditional NLM and output 2N+1level modulation strategy is simulated and analyzed, and the simulation results are shown in Figure 7. According to the thd value in the figure, under the condition of keeping the same parameters, the order of the harmonic characteristics of the output voltage is: NL-PWM hybrid modulation strategy is better than the output level number of 2N+1method, and better than the traditional NLM method.

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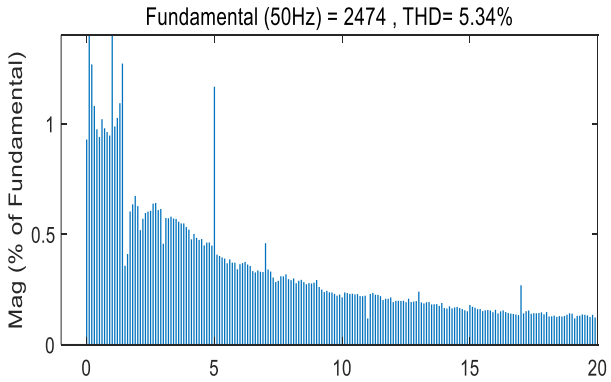
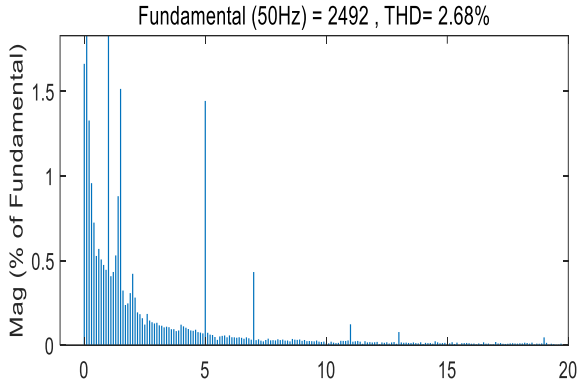
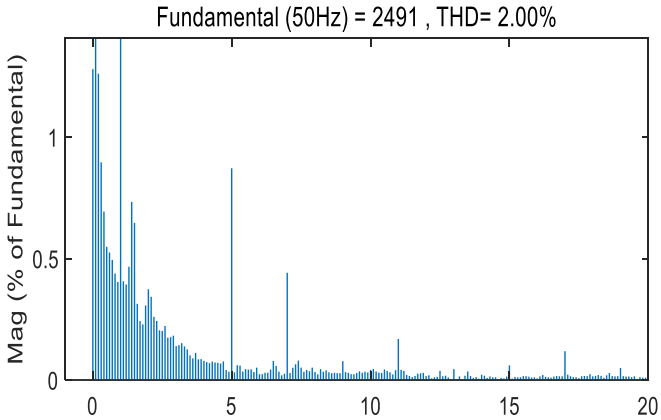


(a) Traditional NLM modulation strategy



(b) 2N+1level modulation strategy



(c) NLM-PWM modulation strategy

Fig. 7 Simulation spectrum of AC side phase voltage

5. Conclusion

In order to solve the problem that the number of MMC modules in ship medium voltage DC power system is small and the output voltage waveform quality is poor when using traditional NLM modulation strategy, this paper compares two improved modulation strategies with traditional modulation strategy. By using the fast Fourier decomposition in Simulink/Powergui, the harmonic analysis of MMC output voltage of three modulation strategies is carried out. The output harmonic performance of NL-PWMmodulation strategy is the best without considering the additional energy consumption and switching loss of carrier PWM. The NLM modulation strategy with 2N+1 output level has simple control and better output voltage harmonic performance than the traditional method. However, the total number of input sub modules of phase cells fluctuates, which aggravates the circulating current in the circuit. When the number of bridge arm sub modules reaches a certain value, increasing the number of sub modules has little effect on reducing the output voltage harmonics.

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