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An Optimized Capacitor Voltage Balancing Method for Modular Multilevel Converter

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Abstract. The problem of voltage balancing among the submodules (SM) in modular multilevel converter (MMC) urgently needs to be solved. This paper compares traditional voltage balancing method with the sorting method based on two maintaining factors in terms of voltage balancing effects and switching frequency. Upper limits of voltage difference are set in a gesture to combine these two methods, which can realize the balance between voltage balancing effects and switching frequency. The model of MMC with 20 submodules on each arm is realized by MATLAB/Simulink, and the improved method is verified. The simulation results demonstrate that the improved method is reasonable and effective.

1. Introduction

In view of the deficiencies of the existing conventional multilevel converters in higher application voltage levels and active power transmission, the German scholar Marquardt R. and his collaborators proposed a modular multilevel converter based on a cascade structure. The capacitors of the converter are independent and the difference in charge, discharge, loss, and capacitance of each capacitor will cause voltage to be unbalanced. The imbalance of the capacitor voltage will directly affect the output waveform quality of the device and may endanger the normal and safe operation of the device. Therefore, how to maintain the capacitor voltage balance of each SM is a key factor to ensure the reliable operation of multi-level converters. The capacitor voltage equalization strategy is also a hot issue in multilevel converters.

2. MMC topology

The structure of MMC is shown in Figure 1. The inverter consists of three phase units, each with two arms, and each arm with n SMs and a reactor. Taking into account the characteristics of the modular design, the reactors and SMs on the individual arms of the MMC are the same. The structure of MMC SMs used in most current projects is half-bridge type. Its structure is shown in Figure 2. It consists of 2 IGBTs, 2 anti-parallel diodes and 1 DC capacitor C. Under normal operating conditions, T1 and T2 are turned on respectively. When T1 turns on T2 turns off, the SM port voltage equals the capacitor voltage in SM; when T1 turns off T2 turns on, the capacitor in SM is bypassed and the SM port voltage is 0.

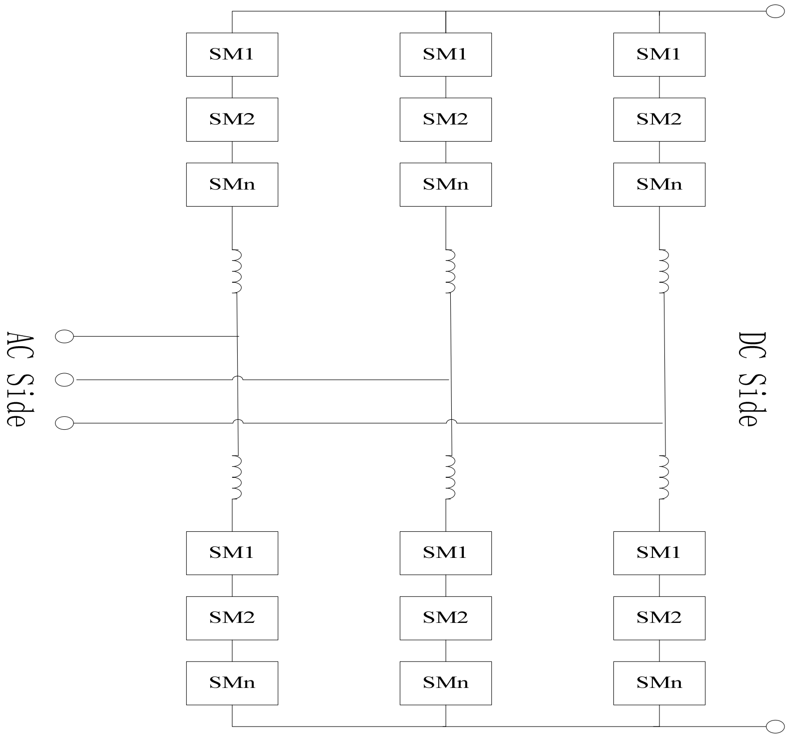

Figure 1. Topology of MMC

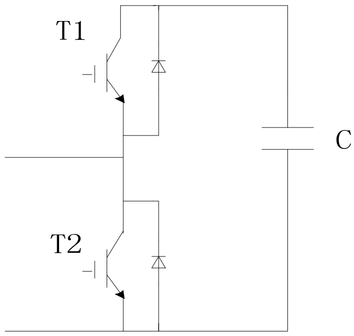

Figure 2. Structure of half-bridge SM

3. MMC modulation strategy

The NLM strategy is the modulation strategy with the most easy implementation and strong universality. Therefore, this paper adopts the NLM strategy. According to [1], the number of sub-modules put into the upper and lower arms at each time is

$$\begin{aligned} n_{up} &= \frac{n}{2} - round(\frac{u_s}{U_C}) \\ n_{down} &= n - n_{up} = \frac{n}{2} + round(\frac{u_s}{U_C}) \end{aligned} \tag{1}$$

Among them, u_s is the instantaneous value of the modulating wave, U_c is the average value of the submodule capacitance voltage.

4. Optimized Capacitor Voltage Balancing Method

The capacitor voltage balancing method can determine the input and removal status of each SM on the arm. Considering the problem of switching frequency in traditional method and the problem of the poor balancing effect caused by the optimization strategy, the threshold of the capacitor voltage difference of the sub-module is set to determine which strategy should be used in each control cycle to achieve the balance of switching frequency and voltage balancing effect.

4.1. Traditional voltage balancing strategy and voltage balancing strategy with double maintaining factors

The goal of the traditional SM voltage balancing strategy is to ensure that the voltage difference between the SMs is as small as possible. According to the voltage of each capacitor and the direction of the arm current, the corresponding SM is input or removed. Assume that the number of submodules to be put into the bridge arm is n_{on}. If the arm current is in the charging direction, the n_{on} SMs with a lower voltage on the arm are put in. This method can quickly reduce the voltage gap between SMs, but does not take into account the original conduction state of SMs. The double maintaining-factor method proposed in [2] is easier to implement in terms of reducing the switching frequency. In order to ensure the symmetry of the capacitor voltage, the introduced maintaining factors H1 and H2 satisfy the relationship.

$$H_2 = 1 / H_1 \tag{2}$$

The purpose of introducing the factors is to reduce the switching frequency. The idea of balancing strategy with double maintaining factors is as follows. If the arm current direction is in the charge direction, the voltage of SMs in the input state is multiplied by a factor H1 whose value is less than 1; if the arm current direction is the discharge direction, then multiply the voltage of SMs in the input state by a factor H2, which is greater than 1. Sorting the processed capacitor voltages of SMs can increase the probability that the SMs that were originally in the input state still remain in the original state to reduce the frequency.

4.2. Introduction of threshold and optimized capacitor voltage balancing method

Considering that the goal of the voltage balancing strategy is not to pursue the exact same value of the capacitance voltage, but to suppress the SM capacitance voltage fluctuation amplitude, by introducing a threshold to determine whether the voltage difference exceeds a limit, which strategy should be used in each cycle is decided. The literature [3] considers the deviation of the actual voltage of the submodule from the rated voltage, and [4] considers the voltage deviation between the submodules. This article considers from the latter point of view. Combining the mathematical models established in [5] and [6], the lower limit Δu_1 and upper limit Δu_2 of the threshold can be derived.

$$\begin{gathered} \Delta u_1 = \frac{1}{2C} i_{a\max} (1 + \frac{m}{4} \cos\varphi) T_S \\ \Delta u_2 = \frac{i_{a\max} T_s}{\omega C} \left\{ \sqrt{1 - \frac{m^2 \cos\varphi^2}{4}} + \frac{m}{4} \cos\varphi \left[2\pi - 2\arccos\left(\frac{m}{2}\cos\varphi \right) \right] \right\} \end{gathered} \tag{3}$$

$i_{a\max}$ Is the amplitude of the output current; φ is the power factor angle; m is the modulation ratio; T_S is the control period.

In order to ensure the coordination between the two sides, the following pressure-sharing idea was designed. If the maximum voltage difference between the SMs does not exceed the allowable range, use the double maintaining-factor method to reduce the switching frequency; if the maximum voltage difference between SMs has exceeded the allowable range, then use the traditional voltage balancing strategy to quickly adjust the voltage to prevent over-limits. In this way, the balancing effect and the switching frequency can be balanced.

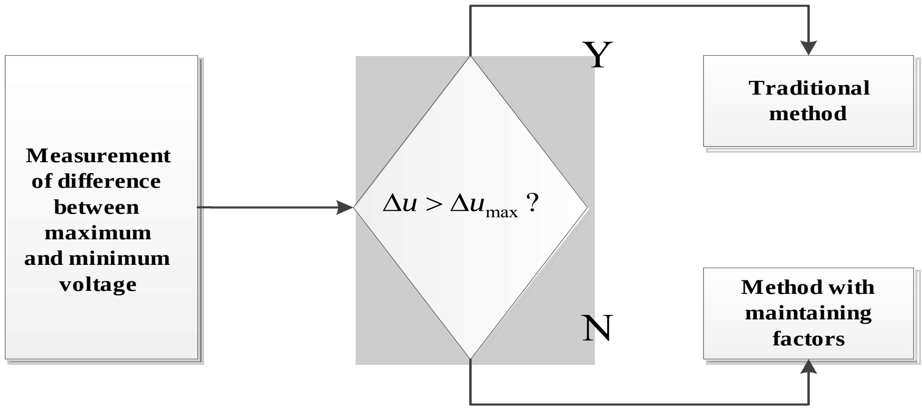

Figure 3. Schematic diagram of the optimized voltage balancing method

5. Simulation

In order to verify the correctness and effectiveness of the proposed optimization method, the MMC model shown in Figure 1 was built in Simulink. Each arm of the model is connected by 20 SMs. The SM has a capacitance of 5000 μF, an arm inductance of 76 mH, a rated DC voltage of 400 KV, and a modulation ratio of 1. Switching frequency can be calculated according to [7].

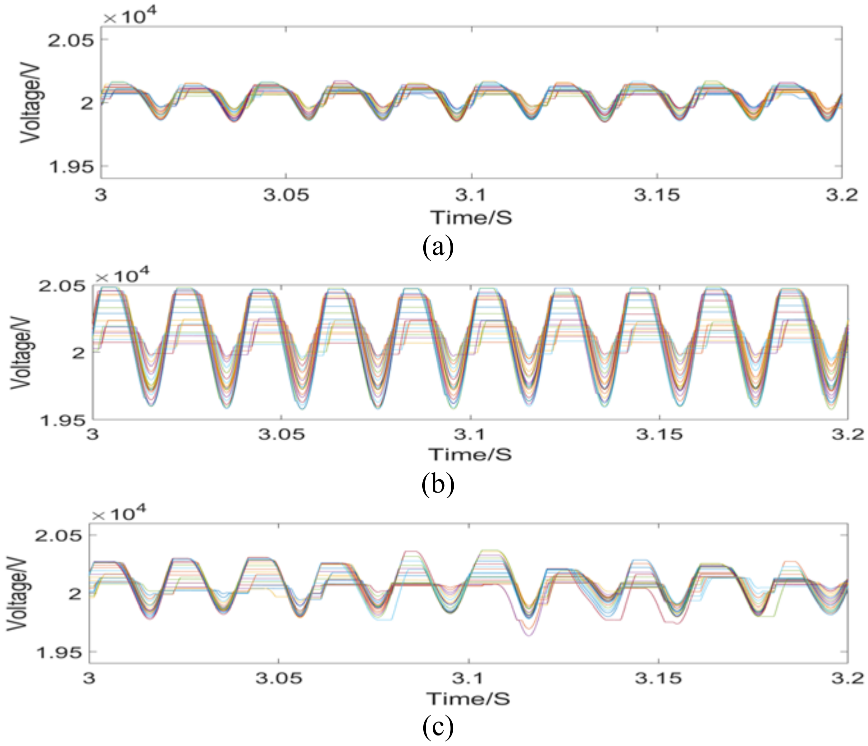

Figure 4. Capacitor voltage waveforms of different strategies

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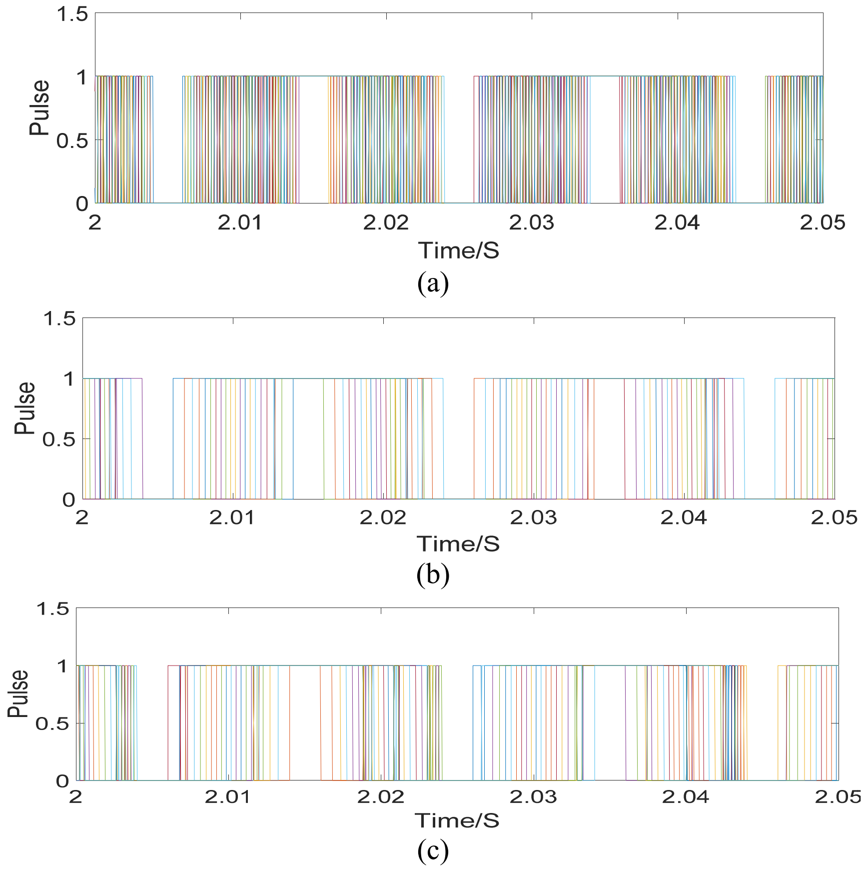

Figure 5. Switching frequencies of different strategies

(a) represents the situation under the traditional voltage balancing strategy.(b) represents the case where the factors 0.98 and 1.02 are introduced and the upper limit of the voltage difference is not set.(c)represents the case where the factors 0.98 and 1.02 are introduced and the upper limit of the voltage difference is set to 300V. The voltage difference in Fig.4 is 150V in (a) and 400V in (b), and the switching frequency in Fig.5 is 250HZ in (a) and 65HZ in (b), which means the double maintaining factor method causes the balancing effect to deteriorate, but reduce switching frequencies at the same time. By setting the upper limit of the voltage difference, the switching frequency increases to 82HZ in (c) in Fig.5, which is bigger than 65HZ, but the balancing effect is better. Voltage difference is limited to 300V. Therefore, the voltage balancing effect can be improved by sacrificing the switching frequency. And by introducing upper limit of the voltage difference and maintaining factors at the same time, the balancing effect and the switching frequency can be adjusted.

6. Conclusion

The article proposes an optimized voltage balancing strategy which combines traditional method with the double maintaining-factor method by introducing upper limits of voltage difference. The simulation shows that the proposed method is correct and effective.

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