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A novel model predictive control strategy of modular multilevel converters using voltage prediction

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ABSTRACT

The model predictive control (MPC) is promising for control of the modular multilevel converter (MMC) owing to its advantages in inclusion of nonlinearities and constraints for complex systems. Existing MPC methods need to define cost functions, and the calculation burden will increase as the level of the MMC rises. This paper proposes a novel voltage predictive based MPC strategy, which combines the ac-side current and circulating current control by using forward differential voltage prediction and nearest level approximation. The chosen of switching states is intuitive according to the voltage predictive results, and there is no need to define cost functions. A pre-scaled voltage sorting method is used to balance the capacitor voltages and reduce the switching frequency. In addition, circulating current hysteresis control is introduced to further reduce the switching frequency. The performance of the proposed method is evaluated based on the simulation results of an MMC with 20 submodules per arm.

1. Introduction

The modular multilevel converter (MMC) has become a particularly promising converter topology for high voltage and high power applications, especially for the high voltage direct current (HVDC) transmission and grid-connection of renewable energy power generation applications [1–3]. Compared with traditional voltage source converter (VSC), the MMC has favorable characteristics in power quality, power regulation ability, power semiconductor device losses, expanding flexibility and structural simplicity [4–7]. Due to the special modular topology, the circulating current control and submodule (SM) capacitor voltage balancing should be taken into account in addition to the power and ac-side current control for the MMC, making it a highly concerned technical challenge to achieve control and modulation strategies that meet the demand of high computational efficiency and good operating performance [8–11].

The model predictive control (MPC) has been applied to a variety of power converters, owing to its flexible inclusion of nonlinearities and constraints, no demand for additional modulation procedures and simplicity in digital implementation [12–15]. In the existing literatures, the MPC strategies for the MMC are mostly based on current predictive method for ac-side current and circulating current control [16–21], in which the values of a cost function are calculated for all possible switching states according to the predicted results, and the switching state with the minimum value will be selected. One of the earliest attempts to apply MPC for the MMC is proposed in Ref. [16]. However, the number of considered switching states in Ref. [16] is C_{2N}^{N} when N represents the number of SMs in each arm, and as N grows up the computational cost will increase exponentially. In Refs. [17,18], the calculation burden is reduced by combining the capacitor voltage sorting method with the MPC and narrowing the searching space of the considered switching states. A model predictive direct control strategy with long prediction horizons is proposed in Ref. [19] to improve the output performance. In Ref. [20], a MPC method based on hierarchical structure is proposed, and the algorithm is modified to simplify the calculation by defining three independent cost functions to control the ac-side current, circulating current and SM voltage separately.

The utilization of the MPC can avoid the drawbacks of complex parameter tuning and additional requirements for pulse width modulation (PMW) strategy [22–26], e.g. multi-carrier PWM and space vector PWM, which exist in traditional double closed-loop proportional integral (PI) control strategies. However, there are still some defects in existing MPC methods for the MMC. The optimal switching states are decided by a single coupled cost function with multiple weighting factors in Refs. [16–18] while the principle to determine these factors is not clearly described, making overall optimization of multiple control objectives hard attainable at the same time. Besides, no steady-state error caused by dis-

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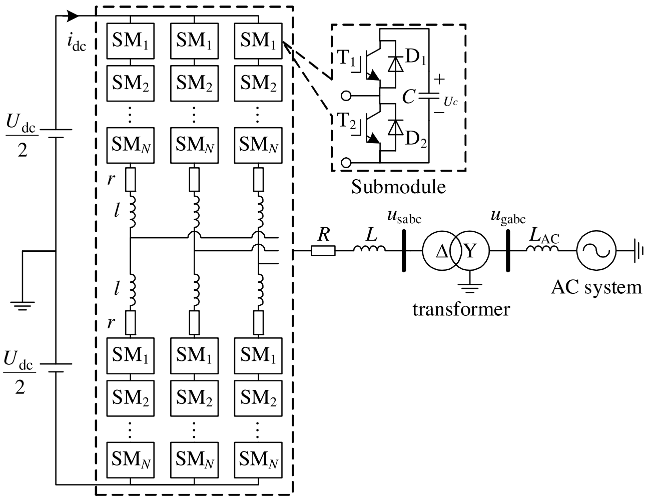

Fig. 1. Block diagram of a three-phase MMC system.

crete sampling is considered in the aforementioned MPC strategies. Moreover, despite of the simplifying effort, the calculation burden of existing MPC methods will rise as the arm SM number N increases.

In this paper, a novel voltage predictive based model predictive control (VP-MPC) method for the MMC is proposed. The control method is based on forward differential voltage prediction and nearest level approximation, which combines the ac-side current control and circulating current control and determines the optimal switching states directly, according to the current references and average values of arm SM capacitor voltages. Meanwhile, the hysteresis control is introduced to the circulating current control to reduce the switching frequency and switching losses, cooperating with a pre- scaled SM voltage sorting method. The feasibility and effectiveness of the proposed method is validated by the simulation results of an MMC with 20 SMs per arm.

The rest of this paper is organized as follows: in Section 2 the mathematical model of the MMC is derived and formulated. In Section 3 the proposed voltage predictive based MPC method is elaborated. Section 4 provides the simulation results and Section 5 comes to the conclusion of this paper.

2. Mathematical model of the MMC

Fig. 1 illustrates the block diagram of a three-phase MMC system. The MMC is composed of two arms per phase, and each phase consists of an upper arm (represented by subscript up) and a lower arm (represented by subscript low). Each arm has an equivalent resistor r, an arm inductance l and N series connected half-bridge submodules (SMs). The SM has two switching states. When switch T1 is turned on and switch T2 is turned off, the SM is inserted and the output voltage of the SM equals to its capacitor voltage U_C. When T1 is turned off and T2 is turned on, the SM is bypassed and the output voltage equals to zero.

The cascaded SMs as a whole in one arm can be seen as a controlled voltage source, and a single-phase equivalent circuit shown in Fig. 2 can be used for mathematical model analysis due to the three-phase symmetry. The upper and lower arm currents can be described by

$$i_{\mathrm{up}j} = \frac{1}{2}i_j + i_{\mathrm{diff}j} \tag{1}$$

$$i_{\mathrm{low}j} = -\frac{1}{2}i_j + i_{\mathrm{diff}j} \tag{2}$$

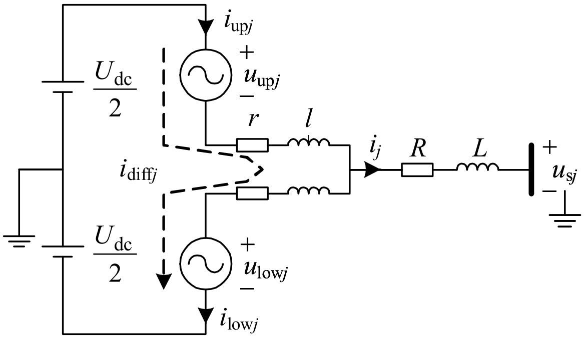

Fig. 2. Single-phase equivalent circuit of the MMC.

$$i_{\mathrm{diff}j} = \frac{i_{\mathrm{up}j} + i_{\mathrm{low}j}}{2} = \frac{1}{3}i_{\mathrm{dc}} + i_{zj} \tag{3}$$

where $j = a, b, c$, i_{dc} is the dc-link current, i_{zj} is the circulating current, and $i_{\mathrm{diff}j}$ is the inner differential current.

According to the Kirchhoff's voltage law, the dynamic behavior of the MMC in phase-j can be expressed as follows:

$$\frac{U_{\mathrm{dc}}}{2} - u_{\mathrm{up}j} - r i_{\mathrm{up}j} - l\frac{di_{\mathrm{up}j}}{dt} = R i_j + L\frac{di_j}{dt} + u_{sj} \tag{4}$$

$$-\frac{U_{\mathrm{dc}}}{2} + u_{\mathrm{low}j} + r i_{\mathrm{low}j} + l\frac{di_{\mathrm{low}j}}{dt} = R i_j + L\frac{di_j}{dt} + u_{sj} \tag{5}$$

where $u_{\mathrm{up}j}$ and $u_{\mathrm{low}j}$ are the total output voltages of the inserted SMs in upper and lower arms respectively, u_{sj} is the grid voltage, and i_j is the ac-side phase current.

Adding (4) and (5), and substituting $i_{\mathrm{up}j}$ and $i_{\mathrm{low}j}$ from (1) and (2), the external dynamic equation of the MMC can be derived as

$$e_j = \frac{u_{\mathrm{low}j} - u_{\mathrm{up}j}}{2} = R' i_j + L'\frac{di_j}{dt} + u_{sj} \tag{6}$$

where e_j represents the output voltage of phase-j, $R' = R + r/2$, and $L' = L + l/2$.

Subtracting (5) from (4), and substituting $i_{\mathrm{up}j}$ and $i_{\mathrm{low}j}$ from (3), the internal dynamic equation of the MMC can be deduced as

$$\frac{U_{\mathrm{dc}}}{2} - \frac{u_{\mathrm{up}j} + u_{\mathrm{low}j}}{2} = r i_{\mathrm{diff}j} + l\frac{di_{\mathrm{diff}j}}{dt}. \tag{7}$$

3. Design of the proposed MPC strategy

3.1. Combined AC-side current and circulating current control

Existing MPC methods need to establish cost functions and compare the function values, according to the current predictive results, to select the optimal switching states. This paper proposes a voltage predictive based MPC method, which has no demand to define cost functions and can further simplify the calculation process. From Fig. 3 we can see the difference between classical current prediction and proposed voltage prediction. In current prediction of the MMC, the prediction step has to be taken for all alternative output levels, and the predictive results should be compared with each other to determine the best choice. There is no doubt the computational burden will be huge, especially when the level N grows to a considerable number. On the contrary, using voltage prediction we need only single-time prediction to get the desired voltage, and then the optimal output level can be directly chosen by a round approximation.

If the SM voltages are well balanced, the output voltages of upper and lower arms can be expressed as

$$u_{mj} = \frac{n_{mj}\sum U_{Cmji}}{N} = n_{mj}\bar{U}_{Cmj} \tag{8}$$

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