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Model Predictive Control for Cascaded H-Bridge PV Inverter with Capacitor Voltage Balance

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Abstract: We designed an improved direct-current capacitor voltage balancing control model predictive control (MPC) for single-phase cascaded H-bridge multilevel photovoltaic (PV) inverters. Compared with conventional voltage balancing control methods, the method proposed could make the PV strings of each submodule operate at their maximum power point by independent capacitor voltage control. Besides, the predicted and reference value of the grid-connected current was obtained according to the maximum power output of the maximum power point tracking. A cost function was constructed to achieve the high-precision grid-connected control of the CHB inverter. Finally, the effectiveness of the proposed control method was verified through a semi-physical simulation platform with three submodules.

Keywords: Model predictive control (MPC); Photovoltaic system; Cascaded H-bridge (CHB) inverter; Capacitor voltage balance

1. Introduction

The cascaded H-bridge (CHB) inverter is an ideal topology for PV grid-connected power generation systems, which can realize independent maximum power point tracking (MPPT) [1]. The control variables of a single-phase cascaded H-bridge mainly include the power factor on the grid side, grid-connected current, and direct-current (DC)-link voltage.

The control strategies for single-phase cascaded H-bridge rectifiers can be roughly divided into two categories: current control and power control. Current control takes the grid-connected current as the control object, ensuring the actual current accurately tracks the reference value. The current commonly used control strategies include indirect current control, transient direct current control, decoupled dq-current control, predictive current control, etc.

The current flowing each H-bridge is equal (grid-connected current) and the transmitted power is different, which will make the PV modules of H-bridge with larger output power overmodulate, resulting in poor grid-connected performance and the system not being able to operate normally. Therefore, many scholars have carried out research on capacitor voltage balance control methods. Wang *et al.* [2] proposed a voltage-balancing control strategy based on reactive power compensation. The fundamental amplitude of the output voltage decreased when the reactive power compensation angle increased, which reduced the probability of over-modulation. However, the power factor of the system also decreased, and reactive power compensation devices were required, which resulted in a cost increase. Eskandari *et al.* [3] proposed an improved MPPT strategy, which solved the problem of over-modulation caused by the imbalance of CHB inverter to a certain extent, but the active power of the PV system was compromised. In order to eliminate imbalance, some PV modules with larger output power were forced to exit the maximum power point, which was contrary to the advantages of the CHB inverter. Rezaei *et al.* [4] calculated the boundary condition that all modules are not modulated and proposed a reactive power compensation strategy, which can make the PV system operate normally even under serious imbalance. However, there are still two problems that need to be addressed. Firstly, the active voltage distribution scheme lacks clarity in its physical interpretation, and the proposed distribution of reactive voltage among HBs is not well-defined. Secondly, the method involves injecting reactive power into the grid, which is prohibited.

To resolve these issues, incorporating special system requirements and compensation methods into the control strategy is essential. However, this proves challenging within classical control systems due to the need for implementing feedforward mechanisms and non-standard modulation [5]. However, model predictive control (MPC) can completely replace the traditional linear controller and can better meet the use requirements of control systems [6,7].

MPC has gained popularity due to its intuitive control approach for control targets, where a cost function assesses the loss of the PV system [8]. The control inverter selects the switching state with the lowest cost value. MPC can address multiple control objectives while considering multiple constraints, enabling simultaneous achievement of capacitor voltage balancing [9,10] and output current tracking [11].

We designed an MPC for the CHB inverter to achieve grid-connected current tracking and capacitor voltage balancing simultaneously, which can overcome the problem of overmodulation in traditional control methods. Firstly, the mathematical model of a single-phase CHB inverter was established to obtain the predicted and reference values for variables. Then, based on the constructed cost function, the control effect of the control objectives can be comprehensively reflected. Finally, the performance of the proposed MPC was verified through a semi-physical simulation platform with three H-bridges.

2. System description

The CHB inverter utilizes the H-bridge as a base unit for series connection, thereby enhancing the level of combination to achieve multi-level output. In comparison to diode-clamped and capacitor-clamped multilevel inverters, the CHB inverter requires the fewest switching devices to produce the same levels of voltage. **Figure 1** shows the topology of single-phase cascade H-bridge inverter. It can be seen that the IGBTs of the bridge leg are complementary conducting in the base unit of the inverter, the relationship of output voltage v_{abi} and the switching state can be expressed by **Table 1**. S_{i1} and S_{i2} are the switch function of the IGBTs on the left bridge leg and right bridge leg of the *i*-th H-bridge. The switch function is expressed by the binary number, “0” means the “OFF,” and “1” means the “ON.”

Table 1. The relationship of output voltage v_{abi} and switching state

S_{i1}		S_{i2}		v_{abi}
1	0	0	1	$+v_{ci}$
1	1	1	0	0
0	1	0	1	0
0	1	1	0	$-v_{ci}$

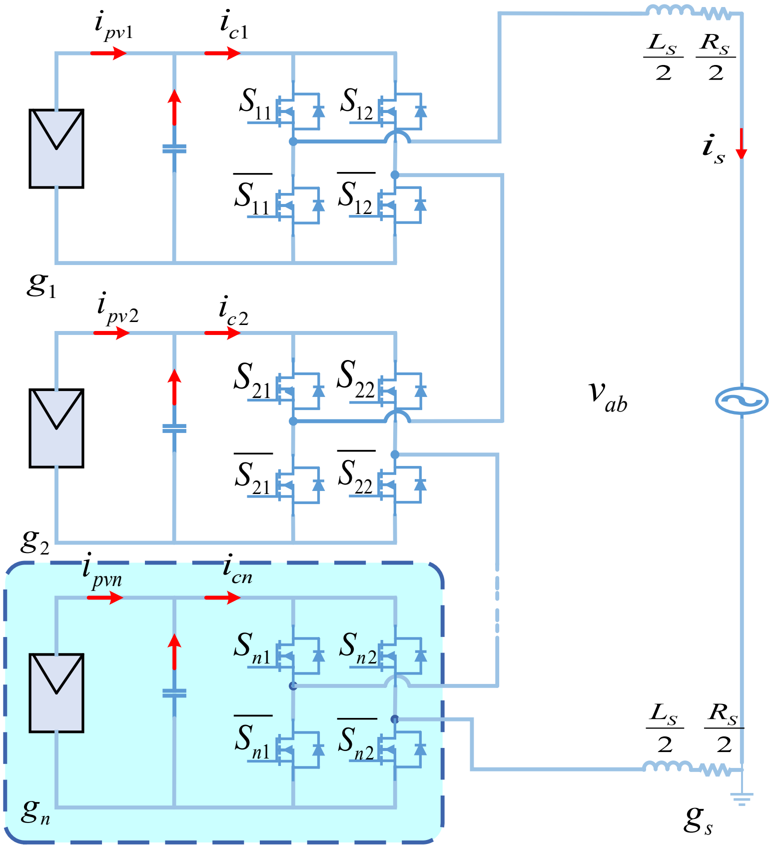


Figure 1. Topology of single-phase cascade H-bridge inverter

3. Model predictive control strategy

3.1. Cost function design

The flowchart for the proposed method is shown in **Figure 2**. The cost function g should include quadratic error between the predicted value and reference value, which is expressed as Equation (1).

$$g(k+1) = \lambda_i \left[i_{sref}(k+1) - i_s(k+1) \right]^2 + \lambda_v \sum_{i=1}^{n} \left[\left(v_{ciref}(k+1) - v_{ci}(k+1) \right)^2 \right] \qquad (1)$$

λ_i is the weighting factor of current tracking and λ_v is the weighting factor of capacitor voltage balance; i_s and v_{pvi} are the predicted values of the grid-connected current and capacitance voltage of the i-th h-bridge module; i_{sref} and v_{pviref} are the reference values of them, k is the current sampling period, and k+1 is the next sampling period.

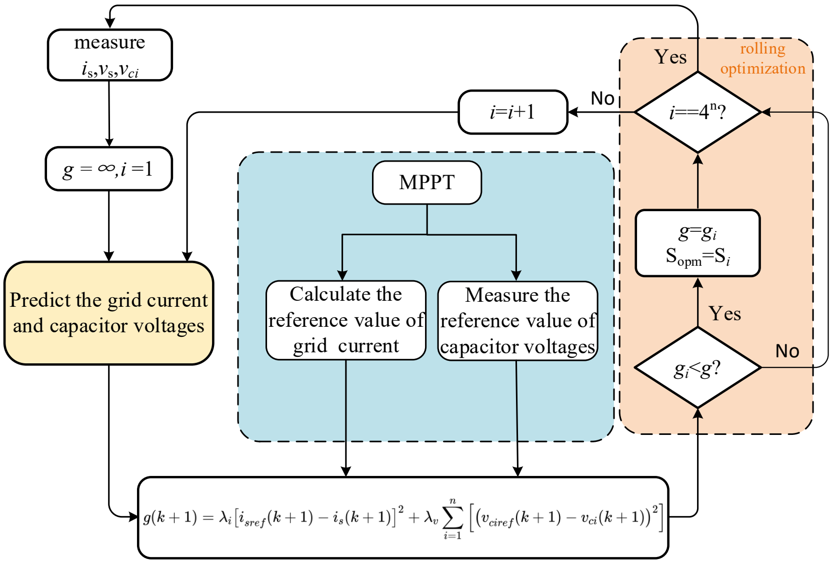


Figure 2. Flowchart for the proposed method

3.2. Calculation of predicted value

$i_s(k+1)$ is predicted through AC output voltage $v_{ab}(k)$, grid voltage $v_s(k)$, grid-connected current $i_s(k)$, and inductor L_S, resistor R_S in the CHB inverter, which can be expressed as Equation (2).

$$i_s(k+1) = i_s(k) + \frac{T_S}{L_S}\left[v_{ab}(k) - v_s(k) - R_s i_s(k)\right] \tag{2}$$

T_S is the sampling period, $v_{ab}(k)$ can be expressed as Equation (3).

$$\begin{aligned} v_{ab}(k) &= v_{ab1}(k) + v_{ab2}(k) + \cdots + v_{abn}(k) \\ &= \sum_{i=1}^{n}\left[S_{i1}(k) - S_{i2}(k)\right] v_{ci}(k) \end{aligned} \tag{3}$$

The capacitor voltage can be calculated according to the voltage equation of the capacitor and then compute $v_{ci}(k+1)$ by Euler discretization, which can be expressed through Equation (4).

$$v_{ci}(k+1) = v_{ci}(k) + T_s\left[\frac{i_{pvi}(k) - i_{ci}(k)}{C}\right] \tag{4}$$

$i_{pvi}(k)$ is the output current of the PV series of the i-th H-bridge, $i_{ci}(k)$ represents the current of the i-th submodule flowing into the H-bridge, which can be presented by:

$$i_{ci}(k) = (S_{i1}(k) - S_{i2}(k)) i_s(k); \quad i = 1, \cdots, n \tag{5}$$

3.3. Calculation of reference value

The reference value of grid-connected current $i_{sref}(k+1)$ is obtained according to the maximum power point of the PV modules detected by the MPPT of each H-bridge, which can be calculated using Equation (6).

$$i_{sref}(k+1) = \frac{P_{pv1ref}(k+1) + \cdots + P_{pvnref}(k+1)}{\left[v_{srms}(k)\right]^2} v_s(k) \tag{6}$$

In Equation (6), v_{srms} is the effective value of the grid voltage and $P_{pviref}(k+1)$ is the maximum power point of the i-th H-bridge on the DC side.

The reference value of capacitor voltage $v_{pviref}(k+1)$ is the total operating voltage at the maximum power point of the PV modules according to MPPT algorithm.

4. Experiments

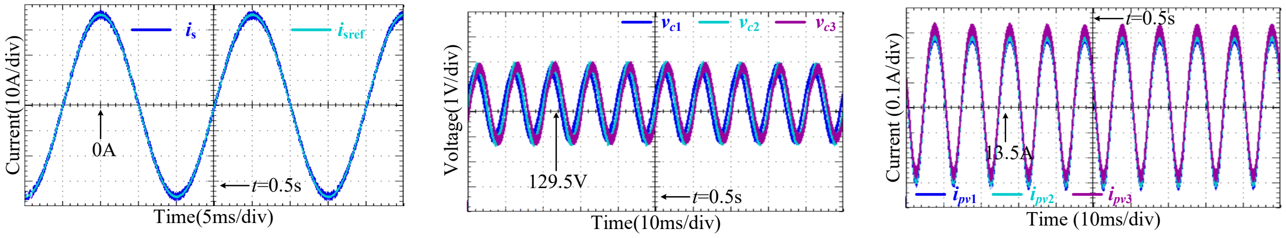
Two sets of experiments were performed to verify the feasibility of the proposed method in balanced and imbalanced conditions on a semi-physical simulation platform with three H-bridges shown in **Figure 3**. The parameters of the platform are shown in **Table 2**.

Figure 3. The experimental platform

Table 2. System parameters

Parameters	Numerical value
Number of H-bridges	3
Filter inductance/mH	5
Grid voltage amplitude/V	200*1.414
Sampling period/us	50
Temperature/°C	8
Capacitance/uF	25
Light intensity in a balanced condition	1000W/m^2
Light intensity in an imbalanced condition	500W/m^2, 1000W/m^2, 1500W/m^2

The experimental results of balance power are shown in **Figure 4**. The grid-connected current tracking was well achieved. However, there was a lack of divergence in the three DC capacities or voltages, meaning that the DC-link voltages were effectively balanced at the maximum power points as expected.



(a) **(b)** **(c)**

Figure 4. The experimental results in balance condition. (a) Waveforms of i_s and i_{sref}. (b) Waveforms of v_{c1}, v_{c2}, v_{c3}. (c) Waveforms of i_{pv1}, i_{pv2}, i_{pv3}.

The second set of experiments was validated under the condition of imbalanced power, as shown in **Figure 5**. It can be seen that the grid current still achieved good tracking. The DC-link voltage and current of three submodules were different, indicating that the PV strings of each submodule had achieved their respective maximum power tracking, thereby improving the power generation of the PV system.

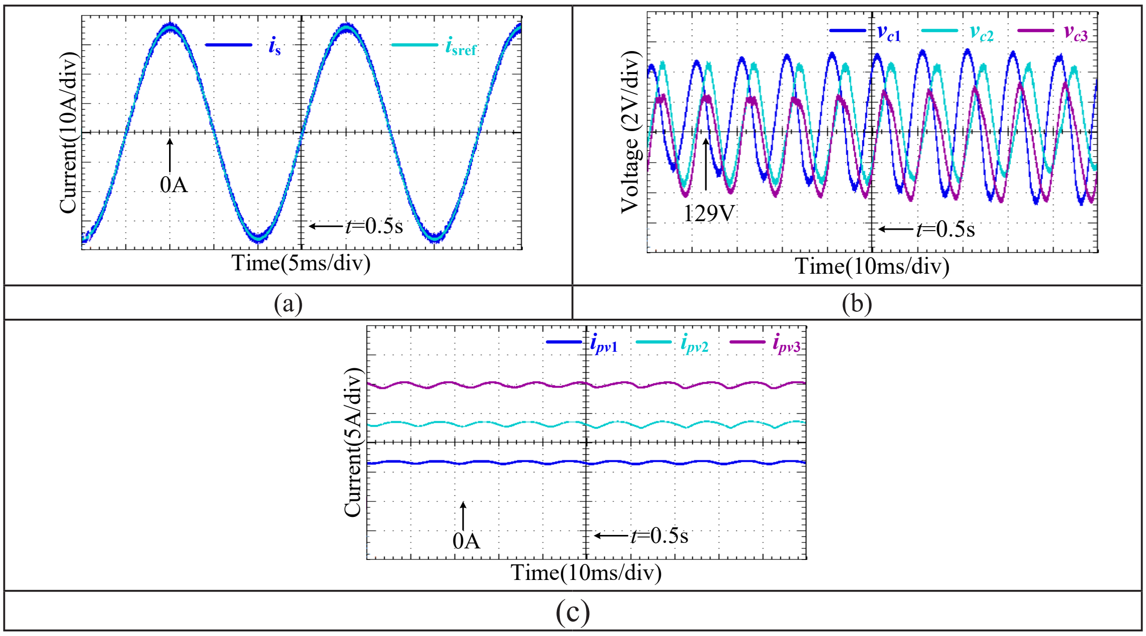


Figure 5. The experimental results in imbalance condition: (a) Waveforms of i_s and i_{sref}, (b) Waveforms of v_{c1}, v_{c2}, v_{c3}, (c) waveforms of i_{pv1}, i_{pv2}, i_{pv3}.

5. Conclusion

The article focuses on the single-phase CHB inverter, aiming to enhance steady-state performance, achieve voltage balance control, and reduce output voltage harmonics. A model predictive control strategy with dc-link voltage balance was proposed, and its performance was verified through a semi physical simulation platform with three H-bridges. Experiments were performed under balanced and imbalanced conditions. The results showed that the method proposed can effectively track the grid current and achieve voltage balance of the submodules.

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Disclosure statement

The authors declare no conflict of interest.

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