

Article

The DC Voltage Balance Strategy Based on Model Predictive Control with a Smooth Switching Sequence in Three-Phase 3LNPC-CR

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Abstract

The three-level neutral-point-clamped cascaded rectifier (3LNPC-CR) is a key component in power electronic transformers (PET) due to its high efficiency and modular configuration. However, voltage imbalance among submodule DC links may cause system instability and degrade power quality. To address this issue, this paper proposes a voltage balancing strategy based on Model Predictive Control with a Smooth Switching Sequence (MPC-3S). First, a negative-sequence current control strategy is introduced to equalize the voltages among phases. In addition, an improved modulation scheme is developed to predict and optimize system states in real time within the control horizon, dynamically selecting the optimal switching sequence to achieve rapid voltage equalization. Finally, simulation and experimental results on a three-phase, three-module 3LNPC-CR prototype demonstrate that the proposed MPC-3S strategy can achieve fast intra-phase voltage balancing within 0.1 s under load imbalance, while maintaining high-quality grid-side current. These results verify that the proposed method significantly enhances both the dynamic and steady-state performance of 3LNPC-CR systems, providing a practical and efficient solution to the voltage-balancing challenge in PET applications.

Keywords: three-level neutral point clamped cascade rectifier (3LNPC-CR); power electronic transformers (PET); Model Predictive Control (MPC); DC-link voltage balance

1. Introduction

In recent years, cascaded multilevel converters have been extensively studied and applied in various fields, such as power electronic transformers (PET) [1,2]. Compared with the traditional cascaded H-bridge rectifier (CHBR), the three-level neutral-point-clamped cascaded rectifier (3LNPC-CR) can achieve the same number of voltage levels with significantly fewer cascaded modules, offering advantages such as reduced system size, lower switching frequency, and improved modularity [3–6].

In the three-phase 3LNPC-CR topology shown in Figure 1, multiple rectifier modules are typically connected in series [7], making the system stability highly sensitive to DC-link voltage fluctuations across the modules [8,9]. The imbalance of DC link voltage has become one of the most critical factors limiting the reliability, service life, and safe operation of the 3LNPC-CR system. In practical applications, the imbalance of DC link voltage may lead to problems such as uneven power distribution among modules. Therefore, achieving rapid, stable, and low-loss DC link voltage balance is a prerequisite for the actual deployment and



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long-term operation of 3LNPC-CR. Voltage imbalance generally manifests in two forms: intra-phase imbalance and inter-phase imbalance, both of which can deteriorate system performance and power quality and even lead to overvoltage stress on power devices. Therefore, developing effective voltage-balancing strategies is essential for ensuring safe and reliable operation [10,11].

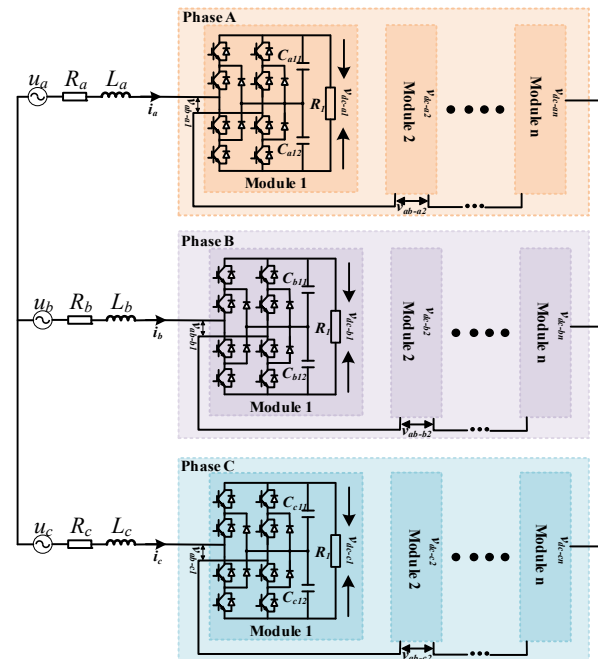


Figure 1. The topology of the three-phase 3LNPC-CR.

In response to the problem of inter-phase voltage imbalance, the negative-sequence secondary circulation injection method is proposed in [12]. By injecting a specific phase circulation to reshape the current of the bridge arm, this method realizes the alternating, charging, and discharging of the half-bridge submodule, so as to effectively maintain the voltage balance and broaden the operating range of the system without additional hardware, and thereby will not cause output waveform distortion. However, this method will introduce additional loss and increase control complexity, and it is difficult to balance efficiency and performance at the same time. Reference [9] tried to eliminate the negative-sequence current but unexpectedly aggravated the imbalance of the module voltage. Since the voltage deviation of the DC-link voltage may cause potential failures, such as overvoltage of the device, it is very important to adopt an appropriate control strategy. For example, the reference [13] proposed a fault-tolerant control strategy that combines extended modulation and reactive power injection to maintain system operation through zero-sequence voltage. However, this strategy relies on reactive power support and may affect power quality and reduce the output capacity during fault conditions. Reference [14] addressed the issues of frequent failures in cascaded Vienna front-end solid-state transformer switches, high costs of traditional fault-tolerant strategies, and excessive power loss. It proposed a fault-tolerant operation strategy with no power loss, using improved zero-sequence voltage injection to ensure the stable operation of the system after a fault, but it has limitations in applicable scenarios and insufficient coverage for extreme faults.

For the problem of in-phase voltage imbalance, the imbalance mechanism of 3LNPC-CR is similar to that of CHBR. The existing research focuses on control methods based on modulation, including carrier phase shift [15], transition vector interpolation [16], hybrid modulation [17], three-dimensional spatial vector pulse width modulation (3D-SVPWM) [18], and sequential pulse modulation [19]. These modulation methods can

significantly simplify the control structure and expand the voltage balance range, but there are still certain limitations: reference [15] may cause voltage level jumps and switching frequency increases; reference [17] fails to completely solve the problem of switching state conversion; reference [18] faces scalability issues when the number of modules increases. Challenge: Reference [19] sacrifices the dynamic response ability of the system to simplify the search table.

In order to meet the above challenges, this paper proposes a 3LNPC-CR voltage balance strategy based on the MPC-3S strategy combined with double closed-loop control and negative-sequence current injection (NSCI). This strategy can dynamically adjust the switching state of the module and realize the rapid balance of the DC chain voltage and the smooth transition of current response under load imbalance conditions. The organizational structure of the rest of this article is as follows: Section 2 establishes the system topology and mathematical model, and analyses the relationship between module voltage and current; Section 3 explains the basic control strategy adopted in this article; Section 4 introduces the MSC-3S strategy, which achieves rapid equalization of module voltage through prediction and optimization; Section 5 validates the strategy via simulation and experiments, showing effective voltage equalization and smooth current under load imbalance, thereby enhancing system dynamic and steady-state performance. Section 6 presents the conclusions.

2. The Configuration and State Space Equation of 3LNPC-CR

2.1. Configuration

The three-phase 3LNPC-CR is composed of multiple three-level neutral-point clamped (3LNPC) rectifier modules connected in series in each phase. Each basic unit in the system is a 3LNPC rectifier, as shown in Figure 2. This rectifier consists of two bridge legs (denoted as (S_a) and (S_b)). Where u_s is the grid voltage, and i_s is the input current of phase s . The AC-side voltage v_s is given by Formula (1). v_{dc-sn} denotes the DC-link voltage of the n th module of phase s . Based on the principle of power conservation, Formula (2) can be obtained, where v_s and i_s denote the input voltage and current of phase S , and R is the load resistance.

$$v_s = v_{ab-s1} + \cdots + v_{ab-sn} = \sum_{i=1}^n v_{ab-si} \quad (1)$$

$$\frac{S_i \cdot v_s \cdot i_s}{2} = \frac{1}{2} C \cdot v_s \cdot \frac{dv_s}{dt} + \frac{v_s^2}{R} \quad (2)$$

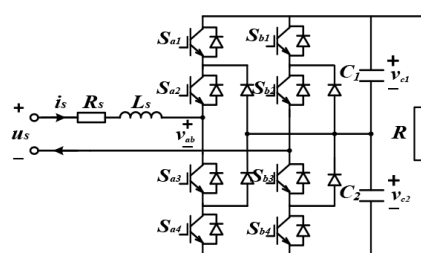


Figure 2. The topology of 3LNPC rectifier.

2.2. State Space Equation

The switching function of one module in each phase of the 3LNPC-CR can be represented by Formula (3), where x represents the phase where the module is located, i

represents the number of the cascaded module, and a and b represent bridge arm a and bridge arm b , respectively (with “1” indicating ON and “0” indicating OFF).

$$S_{xi} = S_{xia} - S_{xib} = \begin{cases} 2, (S_{xia}, S_{xib}) = (1, -1) \\ 1, (S_{xia}, S_{xib}) = (1, 0) \text{ or } (0, -1) \\ 0, (S_{xia}, S_{xib}) = (1, 1) \text{ or } (0, 0) \text{ or } (-1, -1) \\ -1, (S_{xia}, S_{xib}) = (0, 1) \text{ or } (-1, 0) \\ -2, (S_{xia}, S_{xib}) = (-1, 1) \end{cases} \quad (3)$$

Combining the switching states of both legs results in five typical operating modes for the module, as shown in Table 1, producing the input voltages v_{ab} of $+2E$, $+E$, 0 , $-E$, and $-2E$, where E represents the voltage of capacitor C_1 and C_2 . When the current reverses, the energy exchange pattern of the capacitors also reverses. Therefore, by adapting the switching states accordingly, the DC-link voltage can be effectively stabilized.

Table 1. The switch states of 3LNPC rectifier.

M	v_{ab}	S_i	$S_{a1}\text{--}S_{a4}$	$S_{b1}\text{--}S_{b4}$	C/D	V_{dc}
1	$2E$	2	1100	0011	C	$\uparrow$
2	E	1	1100	0110	C	$\uparrow$
	E	1	0110	0011	C	$\uparrow$
3	0	0	1100	1100	-	-
	0	0	0110	0110	-	-
	0	0	0011	0011	-	-
4	$-E$	-1	0110	1100	D	$\downarrow$
	$-E$	-1	0011	0110	D	$\downarrow$
5	$-2E$	-2	0011	1100	D	$\downarrow$

When the 3LNPC-CR operates normally, according to Formula (3):

If the switching state S_i is in the same direction as the current i_s , the output power is positive, indicating that active power is transferred from the grid side to the cascaded module, and the module voltage v_s increases.

If both S_i and i_s are zero, there is no power exchange between the grid and the module, and v_s remains unchanged.

If S_i and i_s are in opposite directions, the output power is negative, meaning that active power is fed back from the cascaded module to the grid, and v_s decreases.

Therefore, the output power is proportional to v_s . To achieve voltage balancing among the modules, when the current flows in the positive direction, modules with lower voltage should be set to state 1 or 2, while those with higher voltage should be set to state -1 or -2 , and vice versa.

Assuming that all the devices of the three-phase cascaded rectifier are ideal devices, the state Formula (4) can be listed according to the KVL theorem. Here, Δv_n represents the voltage difference between the midpoint voltage on the grid side and the midpoint voltage on the load side. Assuming that the rectifier is operating normally and the three-phase voltages remain balanced at this time, the midpoint voltage Δv_n will be 0, and the vector sum of the three-phase voltages on the grid side will also be 0. Thus, Formula (5) can be derived. The simplified state Equation (6) of the three-phase rectifier can be obtained from Formula (5).

$$\begin{cases} u_a - L_a \frac{di_a}{dt} - v_a - \Delta v_n = 0 \\ u_b - L_b \frac{di_b}{dt} - v_b - \Delta v_n = 0 \\ u_c - L_c \frac{di_c}{dt} - v_c - \Delta v_n = 0 \end{cases} \quad (4)$$

$$u_a + u_b + u_c = 0 \quad (5)$$

$$\begin{cases} u_a - L_a \frac{di_a}{dt} - v_a = 0 \\ u_b - L_b \frac{di_b}{dt} - v_b = 0 \\ u_c - L_c \frac{di_c}{dt} - v_c = 0 \end{cases} \quad (6)$$

Formula (7) can be derived from the KCL theorem. Finally, the mathematical model of the 3LNPC-CR can be obtained as shown in Figure 3.

$$C_s \frac{dv_{dc-sn}}{dt} = S_{xi} i_s - \frac{v_{dc-sn}}{R_s} \quad (7)$$

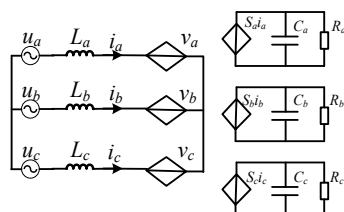


Figure 3. Simplified model of 3LNPC-CR.

3. The Basic Control Strategy

Figure 4 illustrates the overall control strategy proposed in this paper, which consists of three main parts. Part A presents the double closed-loop control structure, composed of an outer voltage loop and an inner current loop. The outer voltage loop regulates the total DC-link voltage by comparing the reference voltage u_{dc}^* with the measured total DC-link voltage $\sum u_{dcn}$. A proportional–integral (PI) controller is employed to eliminate the steady-state error caused by load variations and to generate the reference current i_d^* for the inner loop. By setting the reactive current reference $i_q^* = 0$, a unity power factor can be achieved. The internal current loop uses PI controllers to precisely adjust the d-q axis current, and combines the feedforward item ωL and the set voltage component ($u_d = 0.866$, $u_q = 0$) to obtain the positive-sequence voltage signals v_{a+} , v_{b+} , and v_{c+} after dq-abc transformation.

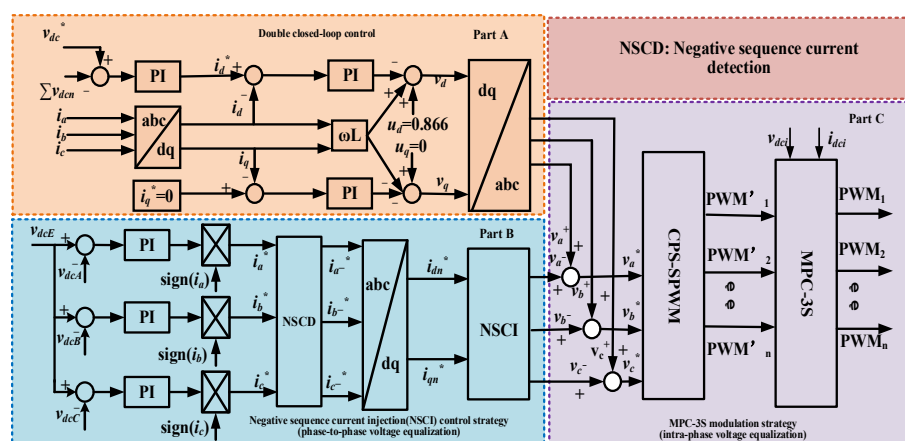


Figure 4. The overall control strategy.

Part B explains the control strategy of negative current injection (NSCI). In this section, the three-phase DC-link voltage is processed by the PI controllers, respectively, to generate current reference values i_a^* , i_b^* , and i_c^* . Subsequently, these current reference values generate negative-sequence current components i_{a-}^* , i_{b-}^* , and i_{c-}^* through the negative sequence current detection (NSCD) module, and then obtain the negative-sequence d-q axis

current reference values i_{dn}^* and i_{qn}^* through abc-dq transformation. Based on i_{dn}^* and i_{qn}^* , the NSCI module finally outputs the negative sequence voltage signals v_{a-} , v_{b-} , and v_{c-} .

Part C implements the MPC-3S modulation strategy. The voltage signals generated from Parts A and B are summed to form the reference voltages v_a^* , v_b^* and v_c^* , which are then processed through carrier phase-shifted sinusoidal PWM (CPS-SPWM) to generate intermediate PWM signals (PWM'1 to PWM'n). The fundamental idea of the CPS-SPWM strategy is that each power module adopts the same sinusoidal reference modulation wave, but the corresponding carrier triangular waves are phase-shifted by a certain angle from each other. The multi-level output and the equivalent switching frequency are achieved through the phase shift between the carriers. Taking a cascaded converter with n power modules as an example, each module is configured with a set of carrier signals with the same amplitude and frequency but phase-shifted from each other. The phase shift angle between adjacent carriers is $2\pi/n$.

The MPC-3S module predicts and evaluates all possible voltage vectors using a cost function to determine the optimal switching state that facilitates voltage balancing. The selected switching state is directly applied to control the IGBT devices, achieving rapid balancing of the module DC-link voltages. A detailed explanation of Part C is provided in Section 4.

4. Modulation Strategy

The MPC-3S Strategy

Model Predictive Control (MPC) is a control approach based on the principle of rolling optimization. Compared with the traditional finite control set model predictive control (FCS-MPC), the MPC-3S voltage-balancing strategy has obvious advantages in terms of computational complexity. The traditional FCS-MPC needs to predict and evaluate the cost function of all feasible switching states in each sampling cycle. With the increase in the number of cascaded modules, the number of candidate states increases exponentially, and the computational burden is significantly increased. MPC-3S makes full use of the modular structure and voltage-vector layering characteristics of the cascade NPC rectifier to greatly reduce the number of switching vectors involved in the prediction calculation by sorting and screening the input voltage vectors, thus effectively reducing the online calculation volume. Table 2 presents the comparison between the proposed MPC-3S and the classic FCS-MPC.

Table 2. Comparison between the proposed MPC-3S and classical FCS-MPC.

Item	Classical FCS-MPC	Proposed MPC-3S
Candidate switching states	All possible switching states	Reduced voltage vector
Computational burden	High	Significantly reduced
Voltage level transitions	Possible abrupt transitions	Smooth transitions

MPC is established based on the system state-space equation. Since MPC is designed for discrete-time systems, the continuous-time state equation must first be discretized to obtain the discrete mathematical model. The continuous-time state-space model is expressed in Formula (8), where $x(t)$ represents the state variable, $u(t)$ denotes the control variable, A is the state matrix, and B is the control matrix. After discrete treatment, the discrete system model is shown in Formula (9). In order to achieve optimal control, the realization of optimal control can be transformed into a secondary planning optimization problem, and its performance index definition is shown in Formula (10). Among them, J represents the cost function. When J reaches the minimum value, the corresponding optimal control sequence can be obtained. $x_{[k+Np|k]}$ represents the terminal state within

the prediction horizon, while S , q , and R are the weighting matrices corresponding to the terminal cost, the running cost, and the control effort, respectively. In practical applications, these weighting coefficients can be adjusted to balance the overall system performance.

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (8)$$

$$x(k+1) = Ax(k) + Bu(k) \quad (9)$$

$$J = \frac{1}{2}x_{[k+N_p|k]}^T S x_{[k+N_p|k]} + \frac{1}{2} \sum_{i=0}^{N_p-1} \left[x_{[k+i|k]}^T q x_{[k+i|k]} + u_{[k+i|k]}^T R u_{[k+i|k]} \right] \quad (10)$$

The mathematical models of active power and reactive power of the NPC cascade rectifier system in the d-q coordinate system are shown in Formula (11), where ω represents the angular frequency of the voltage on the grid side, T_s is the switching period, and $P(k)$ and $Q(k)$ respectively represent the active power and reactive power at time k . While $P(k+1)$ and $Q(k+1)$ correspond respectively to the active power and reactive power at time $k+1$. $u_{abd}(k)$ and $u_{abq}(k)$ are the D-axis and Q-axis components of the input voltage u_{ab} respectively, and $u_{sd}(k)$ represents the amplitude of the grid voltage. Among them, $u_{ab\alpha}(k)$ and $u_{ab\beta}(k)$ can be expressed as Formula (12).

$$\begin{cases} P(k+1) = P(k) + \frac{T_s}{2L_s} u_{sd}(k)^2 - \frac{T_s}{2L_s} u_{abd}(k) u_{sd}(k) - \omega T_s Q(k) \\ Q(k+1) = Q(k) + \frac{T_s}{2L_s} u_{abq}(k) u_{sd}(k) + \omega T_s P(k) \end{cases} \quad (11)$$

$$\begin{bmatrix} u_{abd}(k) \\ u_{abq}(k) \end{bmatrix} = \begin{bmatrix} \cos \omega(kT_s) & \sin \omega(kT_s) \\ -\sin \omega(kT_s) & \cos \omega(kT_s) \end{bmatrix} \begin{bmatrix} u_{ab\alpha}(k) \\ u_{ab\beta}(k) \end{bmatrix} \quad (12)$$

$u_{ab\alpha}(k)$ and $u_{ab\beta}(k)$ represent the α -axis component and the β -axis component of the input voltage of u_{ab} at the k -th moment on the α - β axis. $u_{ab\alpha}(k)$ is the value of the input voltage $u_{ab}(k)$ at the k -th moment of the rectifier, and $u_{ab\beta}(k)$ is the 90° lagging virtual axis component, which is usually 0. Therefore, the Formulas (13) and (14) are obtained through simplification.

$$\begin{cases} P(k+1) = P(k) + \frac{T_s}{2L_s} u_{sd}(k)^2 - \frac{T_s}{2L_s} u_{ab}(k) \cos \omega(kT_s) u_{sd}(k) - \omega T_s Q(k) \\ Q(k+1) = Q(k) + \frac{T_s}{2L_s} u_{ab}(k) \sin \omega(kT_s) u_{sd}(k) + \omega T_s P(k) \end{cases} \quad (13)$$

$$\begin{cases} u_{s\alpha}(k) = u_{sd}(k) \cos \omega(kT_s) \\ u_{s\beta}(k) = u_{sd}(k) \sin \omega(kT_s) \end{cases} \quad (14)$$

Based on Formulas (13) and (14) and according to the mathematical model of 3LNPC-CR, Formula (15) is ultimately obtained. According to Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL), the system's differential equations can be derived as Formula (16). Performing forward Euler discretization on Formula (16) yields Formula (17).

Based on the above formula, the final prediction model is obtained, as shown in Formula (18).

$$\begin{cases} P(k+1) = P(k) + \frac{T_s}{2L_s} u_{sd}(k)^2 - \frac{T_s}{2L_s} u_{s\alpha}(k) \sum_{i=1}^n S_i(k) v_{dci}(k) - \omega T_s Q(k) \\ Q(k+1) = Q(k) + \frac{T_s}{2L_s} u_{s\beta}(k) \sum_{i=1}^n S_i(k) v_{dci}(k) + \omega T_s P(k) \end{cases} \quad (15)$$

$$\begin{cases} L_s \frac{di_s}{dt} = u_s - u_{ab} \\ C_i \frac{dv_{dci}}{dt} = S_i i_s \end{cases} \quad (16)$$

$$v_{dci}(k+1) = v_{dci}(k) + \frac{T_s}{C_i} [S_i(k) i_s(k) - i_{dci}(k)] \quad (17)$$

$$\begin{cases} P(k+1) = P(k) + \frac{T_s}{2L_s} u_{sd}(k)^2 - \frac{T_s}{2L_s} u_{sa}(k) \sum_{i=1}^n S_i(k) v_{dci}(k) - \omega T_s Q(k) \\ Q(k+1) = Q(k) + \frac{T_s}{2L_s} u_{s\beta}(k) \sum_{i=1}^n S_i(k) v_{dci}(k) + \omega T_s P(k) \\ v_{dci}(k+1) = v_{dci}(k) + \frac{T_s}{C_i} [S_i(k) i_s(k) - i_{dci}(k)] \end{cases} \quad (18)$$

To ensure optimal system performance, a cost function is further established. Since this method aims to achieve simultaneous control of active power, reactive power, and voltage balance, all weighting factors are set to 1, and these variables are normalized. Consequently, the final cost function is expressed as Formula (19).

$$J = \frac{|P^* - P(k+1)|}{p} + \frac{|Q^* - Q(k+1)|}{q} + \frac{\sum_{i=1}^n |v_{dc_avg} - v_{dci}(k+1)|}{u} \quad (19)$$

Taking the three-module three-phase 3LNPC-CR as an example, the proposed MPC-3S voltage-balancing strategy can be further illustrated. For the three-module three-phase 3LNPC-CR, the cost function can be expressed as Formula (20), where i_s^* represents the reference value of the grid-side current generated by the control strategy, $i_s(k+1)$ is the predicted grid-side current at the $(k+1)$ th instant, v_{dci} denotes the DC-link voltage of the i th module, ΔS represents the switching action number, and λ_1, λ_2 are the weighting coefficients. When the performance index J reaches its minimum value, the corresponding control sequence is taken as the optimal solution and directly applied as the control switching signal, thereby realizing the optimal control.

$$J = |i_s^* - i_s(k+1)|^2 + \lambda_1 \sum_{i=1}^N (v_{dci}(k+1) - v_{dc}^*)^2 + \lambda_2 \cdot \Delta S \quad (20)$$

Within each switching cycle, a three-module three-phase 3LNPC-CR system can theoretically generate up to 125 distinct voltage vector combinations. The fundamental idea of the proposed MPC-3S voltage-balancing strategy is to identify, from this large set of candidate voltage vectors, those that are most favorable for DC-link voltage balancing, and then convert the selected optimal voltage vector into specific IGBT switching commands assigned to each submodule, thereby enabling rapid voltage equalization among modules.

Figure 5 presents the voltage adjustment rules for each module under the MPC-3S strategy in the three-module three-phase 3LNPC-CR. Here, PWM_{min} denotes the PWM state of the module with the lowest voltage, PWM_{min+1} corresponds to the module with the second-lowest voltage, PWM_{max} to the highest voltage, and PWM_{max-1} to the second-highest. The variable i represents the current direction, where $i = 0$ indicates a positive current, and $i = 1$ indicates a negative current. D is used to determine whether the voltage level is increasing or decreasing: $D = 0$ if the voltage level increases, and $D = 1$ if it decreases.

An example of the MPC-3S prediction process is presented in Table 3. At each sampling instant, the MPC algorithm predicts the voltage vector evolution over the next five steps but applies only the first selected voltage vector to the system. For a three-module cascaded rectifier with a voltage vector state of $[1, 0, -1]$, the voltage magnitudes are ordered as $v_{dc1} < v_{dc2} < v_{dc3}$, the current direction is positive, and the voltage level needs to

be increased by 1. Therefore, the voltage level of the module with the lowest voltage (and not already at level 2) is increased by 1, resulting in the new voltage vector $[2,0,-1]$, which is then converted into switching signals and directly applied to the IGBTs for on/off control. Figure 6 shows the vector transformation diagram predicted by MPC.

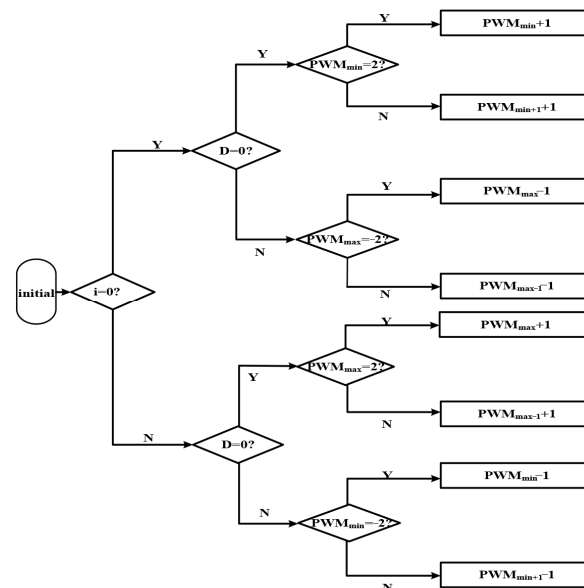


Figure 5. Three module 3LNPC-CR module voltage adjustment rule under MPC-3S strategy.

Table 3. The prediction results of the MPC-3S strategy.

(X_{i1}, X_{i2}, X_{i3})	DC-Link Voltage	i	D	$(X_{i+11}, X_{i+12}, X_{i+13})$
$[1,0,-1]$	$v_{dc3} > v_{dc2} > v_{dc1}$	0	0	$[2,0,-1]$

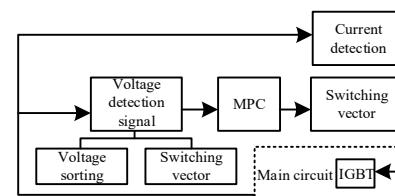


Figure 6. The vector transformation diagram predicted by MPC.

5. Simulation and Experiments

5.1. Simulation

A three-phase 3LNPC-CR prototype with three cascaded modules is simulated by Matlab/Simulink R2021b to verify the correctness and efficiency of the MPC-3S strategy.

Figure 7 illustrates the dynamic variation in three-phase voltages and currents when the load on the first module in phase A is removed under the combined control of the MPC-3S and NSCI strategies. When the MPC-3S strategy is introduced at 0.4 s, the DC-link voltages of the three modules in phases B and C gradually decrease to approximately 48 V, while those of phase A increase to about 55 V. The intra-phase voltage balancing is completed within 0.4–0.6 s. Meanwhile, the input currents of all three phases decrease, with the current of phase A dropping more significantly, approximately to three-fourths of its initial value.

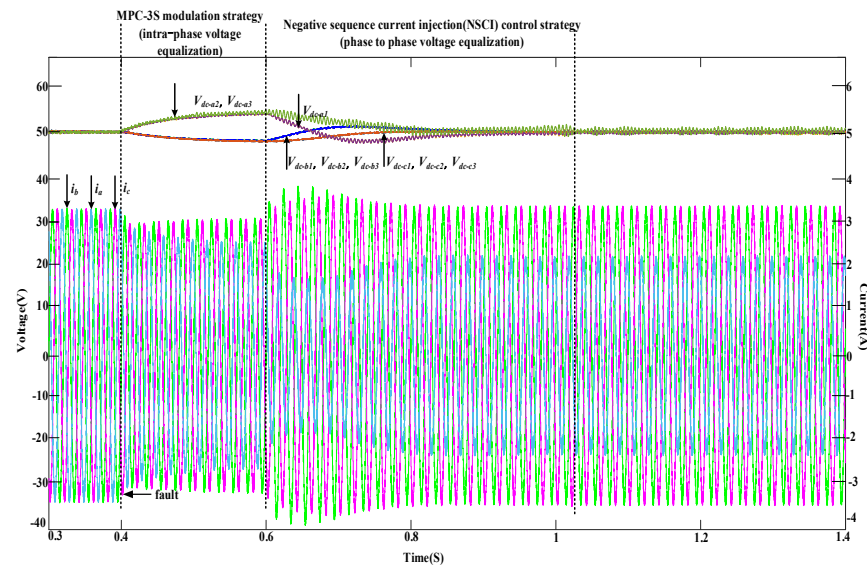


Figure 7. DC-link voltages and input currents in the three-phase 3LNPC-CR with three modules.

At 0.6 s, the NSCI strategy is activated. Subsequently, the DC-link voltages of the three modules in phase A gradually decrease, while those of phases B and C increase. The DC-link voltages of all three phases are stable at about 50 V in 1 s, achieving inter-phase voltage balance. In this process, the input current of phase A decreased by about one-third of the initial value, and the current of phases B and C basically returned to the original level.

The simulation results verify that the MPC-3S strategy can quickly achieve three-phase voltage equalisation, reflecting its good dynamic response performance, but there is still a slight imbalance in the three-phase current.

5.2. Experiments

As shown in Figure 8, an experimental platform was established to validate the effectiveness of the proposed MPC-3S strategy. The corresponding system parameters are summarized in Table 4.

Table 4. Parameters of the experimental platform.

Parameter Name	Value
Number of modules per phase	3
DC-link voltage of the submodule	50 V
Load resistance	40 Ω
Filter capacitor	3 mF
Filter inductor	0.84 mH
DC support capacitor	470 μ F
AC inductance	5 mH
Carrier frequency	1 kHz
Sampling frequency	200 kHz
AC input voltage	75 V
Voltage sensors	LV25 (LEM, Geneva, Switzerland)
Current sensors	LA20 (LEM, Geneva, Switzerland)
FPGA chip	EP3C55F484C8 (Altera (Intel PSG), San Jose, CA, USA)

Figure 9 shows the waveform of the port voltages of each module in phase A under the MPC-3S modulation strategy when the load of the first submodule is disconnected. As illustrated in the figure, when the voltage of module 1 becomes unbalanced, and the current is greater than zero, its input port voltage is noticeably reduced by adjusting

the switching states, thereby charging the internal capacitor to maintain voltage balance. However, to ensure the overall terminal voltage level, a portion of the high-level output is still maintained. Meanwhile, the port voltage waveforms of modules 2 and 3 also vary correspondingly under the modulation strategy, with their switching states dynamically adjusted. By observing the total terminal voltage U_{ab-a} , it can be seen that although the individual module port voltages are slightly compromised under load imbalance conditions, the voltage-balancing strategy ensures the continuity of the total terminal voltage. The staircase waveform maintains 11 levels and strictly follows a sinusoidal pattern. This demonstrates that the proposed voltage-balancing strategy effectively preserves overall system performance under load imbalance conditions while accommodating the dynamic adjustment requirements of individual modules.

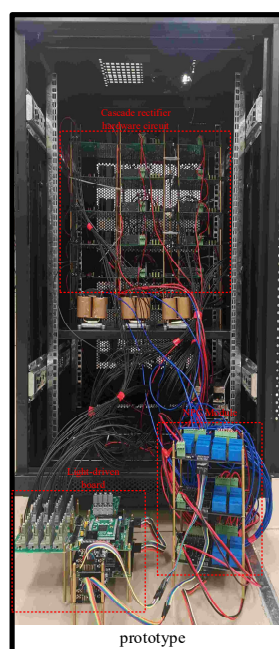


Figure 8. Experimental platform of three-phase 3LNPC-CR.

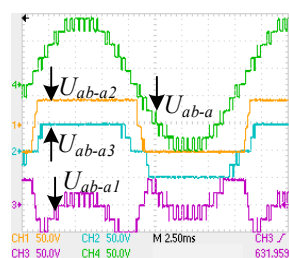


Figure 9. Port voltage waveforms under MPC-3S after removing the first submodule load in phase A.

Figure 10 illustrates the three-phase currents of phases A, B, and C, as well as the DC-link voltages of each phase module under the proposed overall control strategy during steady-state operation. It can be observed that the DC-link voltages of all modules in the three phases remain stable around 50 V with minimal fluctuation. Meanwhile, the phase currents of A, B, and C are smooth and free of noticeable ripple, indicating that the overall system operates stably. These results confirm that the proposed overall control strategy can effectively maintain voltage balance among the modules.

Figure 11 presents the grid-side voltage of phase A and the voltage waveforms of its two supporting capacitors within the first module, along with the grid currents of phases A, B, and C under the same control condition. As shown in Figure 11a, the grid-side voltage

of phase A remains stable at approximately 100 V, and the three-phase currents are smooth and well phase-aligned. Figure 11b shows that both supporting capacitor voltages in the first module of phase A are stably maintained around 50 V with small fluctuations, and the A-phase current remains steady. These results demonstrate that the proposed control strategy achieves effective capacitor voltage balancing and smooth current regulation within each module.

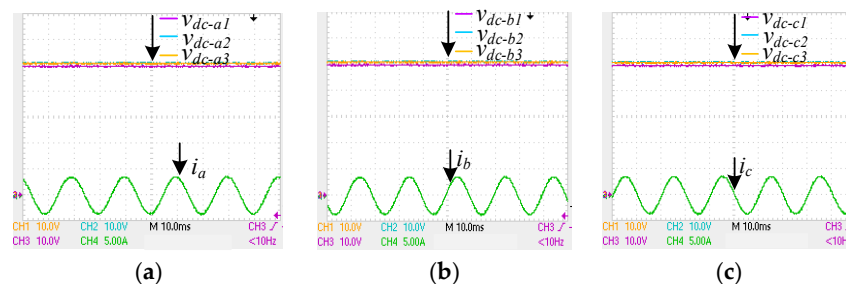


Figure 10. Phase currents and DC-side voltages of each module under the proposed overall control strategy during steady-state operation: (a) Input current and DC-side voltages of each module in phase A; (b) Input current and DC-side voltages of each module in phase B; (c) Input current and DC-side voltages of each module in phase C.

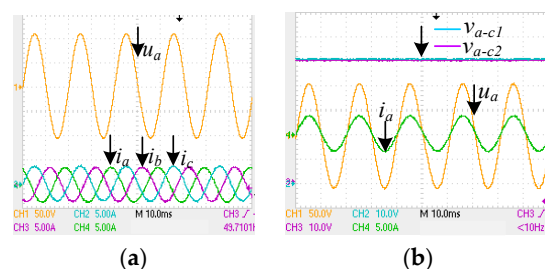


Figure 11. Waveforms of grid-side voltage and capacitor voltages of the first module in phase A, and grid-side current variations of phases A, B, and C under the proposed overall control strategy during steady-state operation: (a) Grid-side voltage of phase A and input currents of phases A, B, and C; (b) Grid-side voltage of phase A, capacitor voltages of the first module, and input current of phase A.

Figure 12 shows the DC-link voltages of the three submodules in phase A and their input current when the MPC-3S strategy is integrated into the overall control framework. The results indicate that all three submodules maintain stable voltages around 50 V with high waveform coincidence. By comparing Figures 10a and 12, it can be observed that, compared with the system using only the overall control strategy, the addition of the MPC-3S strategy significantly enhances voltage consistency among submodules. This confirms that the MPC-3S strategy achieves precise submodule voltage balancing, effectively suppresses voltage deviation, and demonstrates its superiority in voltage equalization control.

Figure 13 depicts the DC-link voltages and input currents of each module in phase A, as well as those of the first modules in phases B and C, when the load of the first module in phase A is removed, and only the intra-phase voltage balancing strategy (MPC-3S) is applied. As shown in Figure 13a, after the load of the first module in phase A is removed, its DC-link voltage gradually rises to approximately 56 V and stabilizes, while the voltages of the first modules in phases B and C slowly drop to about 48 V. Figure 13b shows that the voltages of all A-phase modules synchronously rise to around 56 V, while Figure 13c indicates that the input current of phase A decreases by about one-fourth compared with those of phases B and C. Overall, the results demonstrate that the MPC-3S strategy can effectively maintain intra-phase voltage balance under load-removal conditions.

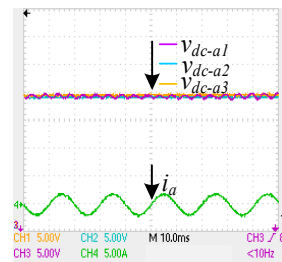


Figure 12. DC-link voltages of the three submodules in phase A and their input current when the MPC-3S strategy is integrated into the overall control framework.

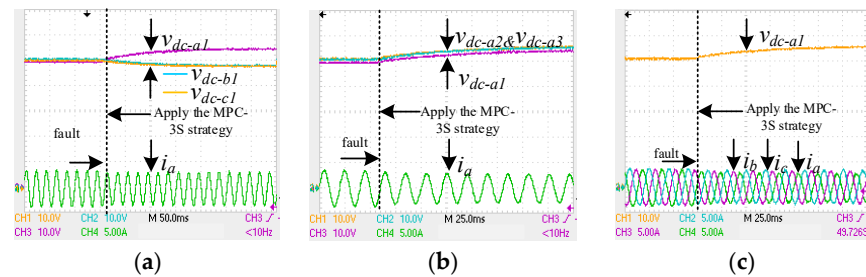


Figure 13. Variations of DC-side voltages and input currents of each module in phase A and the first modules in phases B and C after removing the load of the first module in phase A: (a) DC-side voltages of the first modules in phases A, B, and C, and input current of phase A; (b) DC-side voltages and input current of each module in phase A; (c) Input currents of phases A, B, and C, and DC-side voltage of the first module in phase A.

Figure 14 illustrates the DC-link voltages and input currents of the three submodules in phase A, as well as those of the first submodules in phases B and C, when both the MPC-3S and NSCI strategies are applied after removing the load of the first submodule in phase A. As shown in Figure 14a, when the load of the first submodule in phase A is disconnected at 0.35 s and the MPC-3S strategy is immediately introduced, the DC-link voltage of the first submodule gradually increases to 53 V, while the voltages of the first submodules in phases B and C slightly drop to about 49 V. After incorporating the NSCI strategy, all three-phase voltages stabilize at 50 V within 0.1 s, achieving inter-phase voltage balance. Figure 14b shows that the input current of phase A decreases by approximately one-fourth after applying the MPC-3S strategy, and further decreases to about two-thirds of the input currents of phases B and C after the NSCI strategy is introduced. Figure 14c further presents the variation of the DC-link voltages of the three submodules and the input current of phase A, verifying that the proposed voltage-balancing strategy can rapidly achieve both intra-phase and inter-phase voltage equalization.

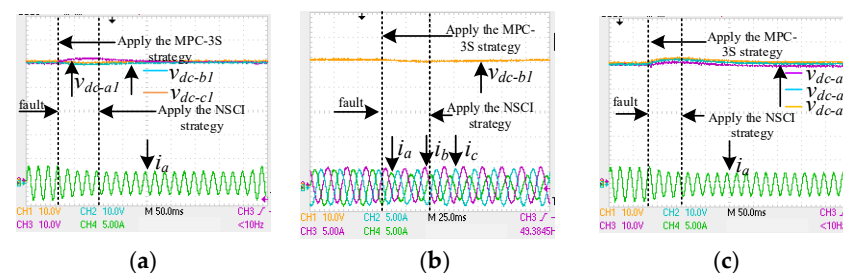


Figure 14. Variations of DC-side voltages and input currents of three submodules in phase A and the first submodules in phases B and C after removing the load of the first module in phase A: (a) DC-side voltages of the first modules in phases A, B, and C, and input current of phase A; (b) Input currents of phases A, B, and C, and DC-side voltage of the first module in phase A; (c) DC-side voltages of each module in phase A and input current of phase A.

6. Conclusions

This paper addresses the voltage-balancing issue of the three-phase three-level neutral-point clamped cascaded rectifier (3LNPC-CR) by establishing a mathematical model and control framework, and proposes an MPC-3S voltage-balancing strategy. Through theoretical analysis, simulation, and experimental testing, the effectiveness and feasibility of the MPC-3S strategy have been verified.

Judging from the system structure, 3LNPC-CR adopts a multi-module cascading topology, and each sub-module can independently realize two-way energy flow, with good voltage regulation ability.

On the basis of this structure, the control system is composed of an external voltage loop, an internal current loop, and a negative sequence current injection (NSCI), which realizes DC-link voltage regulation and input current control, and ensures the unified operation of the power factor. By introducing the MPC-3S method on top of the basic control strategy, by optimizing the prediction model and cost function, the computational burden of traditional exhaustive search is reduced, and the voltage balance speed under dynamic conditions is improved.

Simulation and experimental results show that when the submodule has a load mutation or voltage imbalance, this method can complete the voltage adjustment in-phase and inter-phase, improve voltage consistency, and improve the stability of system operation. When used with the NSCI strategy, the inter-phase voltage deviation is further reduced, and the input current waveform is improved, indicating that the control method has good coordination and dynamic response ability.

The proposed MPC-3S voltage balance control method demonstrates good performance in terms of regulation accuracy and dynamic performance, which can provide a reference for the voltage balance control of multi-module cascading systems.

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