An Optimal Model Predictive Control Method for Five-Level Active NPC Inverter

ZHAN LIU, (Member, IEEE), ZHENG LONG XIA, (Member, IEEE), DAN LI, YU WANG, AND FEI LI, (Member, IEEE)

1 School of Electrical Engineering and Automation, Jiangsu Normal University, Xuzhou 221116, China
2 Xinyi Power Supply Branch, State Grid Jiangsu Electric Power Company Ltd., Xuzhou 210024, China

Corresponding author: Zhan Liu (liuzhan_cumt@163.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 51907083, and in part by the Natural Science Foundation of the Jiangsu Higher Education Institutions of China under Grant 19KJB470003.

ABSTRACT Finite Control Set Model Predictive Control (FCS-MPC) can improve the control performance of Five-level Active NPC (5L-ANPC) inverter effectively. However, with the increasing of the levels of inverter, the traditional FCS-MPC method has many problems, such as large amount of rolling optimization calculation and difficulty in weight coefficient design. In order to solve those problems, an Optimal Model Predictive Control (O-MPC) method is proposed. First, an optimal control method based on level jump limitation is proposed to reduce the number of switch states. Second, in order to solve the conflict problem of multiple control objectives and reduce the design difficulty of weight factors, a satisfactory optimal control method based on hierarchy is proposed. After the optimization, the calculation time of the controller is greatly reduced and the control performance of the multi-objective control system will be significantly improved. At last, the effectiveness and feasibility of the proposed O-MPC are validated by the experimental results.

INDEX TERMS Five-level active NPC (5L-ANPC) inverter, an optimal model predictive control (O-MPC) method, switching states, satisfactory optimal control.

I. INTRODUCTION

Traditional NPC three-level inverter cannot be applied to 6kV and above high-voltage system because of the limitation of power devices. Therefore, multilevel converters have attracted a great deal of interest in high-power medium-voltage applications due to the low voltage stresses, low dv/dt and high-power quality [1], [2]. Diode clamped, flying capacitor and cascaded H-bridge multilevel converters are the three classic multilevel topologies. However, with the increasing demands of higher voltage level and higher performance, all of them have encountered some problems, such as the mass number of diodes, flying capacitors, isolated DC sources and the resulting complex control problems. Compared with classic multilevel topologies, five-level ANPC converter has the advantages of fewer switches, fewer capacitors and simpler voltage balance method [3], [4].

FCS-MPC technology, with the outstanding advantages in reducing system loss, improving system efficiency and realizing optimal control of system, is widely studied in two-level and three-level conversion. Compared with traditional control, it has outstanding advantages in reducing system loss, improving system efficiency and realizing optimal control of system [5], [6]. The realization of predictive controller needs to consider the influence of all switch states on system control variables [7]–[9]. In order to select the optimal switching state, the control system needs to calculate and compare all possible switching states, so the calculations of the whole system are directly proportional to the amount of switching states existing in the converter. For multi-level and multi-phase converter systems, it is necessary to consider an appropriate optimization method to reduce the computational complexity of the predictive control. In [10], an improved five-level bidirectional converter based on FCS-MPC was presented, which consisted in using the discrete time nature of the improved five-level bidirectional converter to define its state in each sampling interval. In response to the problem of the conventional five-phase FCS-MPC suffers from heavy computational burden, a novel FCS Model Predictive Current Control (MPCC) with continued modulation was proposed in [11]. In [12], a simple Model Predictive Direct Power Control (MP-DPC) of single-phase pulse width-modulated...
rectifiers with constant switching frequency using modulation function optimization was proposed.

In order to make the FCS-MPC can be better used in other converter topologies, various optimization methods for MPC have been widely studied [13], [14]. In [15], a fast finite-level-state model predictive control (FFLS-MPC) strategy was proposed in predictive control regulated modular multilevel converter (MMC), which aims to overcome the high computational complexity. However, this method has certain limitations and is only suitable for multilevel converters with multiple sub-modules in a similar MMC structure. In [16] a new algorithm, based on the control of the switching period within the cost function was proposed, which was easy to design and implement, demanding very low computation power, and enabled a combination of the advantages of FCS-MPC with the benefits of a PWM-like power quality. An improved FCS-MPC algorithm with fast computation and fixed switching frequency is proposed for two-level three-phase inverters in [17]. Compared with the conventional fixed switching frequency FCS-MPC method, the number of sectors involved in the FCS-MPC calculation can be reduced from 6 to 1, which greatly improves the computation efficiency. In [18], A fixed switching frequency scheme for finite-control-set model predictive control was presented to achieve an output waveform quality that compares well to that of a pulse-width-modulator-based linear controller, while retaining the benefits of model predictive control. The above schemes are all aimed at the optimization of two-level or three-level converter. When the number of levels in the converter increases, these methods cannot fully adapt to the new structure.

Compared with MPC of two-and-three level converter, the MPC of 5L-ANPC converter has the following characteristics:

1) 5L-ANPC converter has more switching states, which means that the number of rolling optimizations of prediction model increases and the amount of calculation rises, which poses a challenge to the hardware design of control system [18].

2) The stable operation of the 5L-ANPC converter needs to meet two basic control objectives when predictive control is carried out. The two control objectives are the control of neutral point potential and the control of floating capacitor voltage in each leg of 5L-ANPC converter. The difficulty of control is that the establishment of predictive model is more complicated because of the cross coupling between the two control objectives [19].

3) 5L-ANPC converter has 512 switching states, where the switching must follow certain rules, which will greatly increase the complexity of predictive control algorithm [20].

Considering the above factors, the traditional MPC applied in 5L-ANPC converter has some disadvantages, such as complex prediction model, many rolling optimization times and complex control algorithm.

Therefore, an Optimal Model Predictive Control (O-MPC) method is presented to solve the above problems. This proposed method can effectively reduce the number of switching states involved in the rolling optimization, so the efficiency of the processor will be improved. In addition, because of the difficulty at selecting weight factors in predictive control, the design method of weight factor in the O-MPC controller will be also described in detail.

This paper is organized as follows. the 5L-ANPC topology and the control principle of floating-capacitor voltage are summarized in Section II. In Section III, mathematical models of each control objective are presented. In Section IV, the optimization method of 5L-ANPC inverter switching state is introduced in detail. Section V shows the design of O-MPC controller for 5L-ANPC Inverter. The experimental results are presented in Section VI. Finally, in Section VII, the conclusion is drawn.

II. ANALYSIS ON THE STRUCTURE OF 5L-ANPC INVERTER AND THE CONTROL PRINCIPLE OF FLOATING-CAPACITOR VOLTAGE

A. THE STRUCTURE OF 5L-ANPC INVERTER

The topological structure of five-level ANPC inverter is displayed in Figure 1, where $C_{up}$ and $C_{dn}$ are the capacitance of upper bus and lower bus respectively, while $U_{up}$ and $U_{dn}$ are the voltages on the two capacitors respectively; $C_i$ is the Floating-Capacitance (FC) of the inverter; $U_{fx}$ is the voltage of the $C_{fx}$, where $x$ represents phase a, b, or c.

Tab. 1 lists the switching states of five-level ANPC inverter. The switches $Sx1$–$Sx4$ and $Sx1’$–$Sx4’$ are operated complementarily. It can be seen that each phase of the inverter can output five levels, a total of eight switching states, as shown in Table 1, where $i_{fx}$ and $i_{fxx}$ are the corresponding FC current and neutral-point current, $i_{fx}$ is the phase current.

The voltage of FC in each phase should be stable at 1/4 of DC bus voltage, which is the premise for 5L-ANPC inverter to operate normally. Therefore, it is necessary to study the voltage balance of FC.

B. THE VOLTAGE CONTROL OF FC

FIGURE 1. The topological structure of five-level ANPC inverter.

Figure 2 shows the flow chart of voltage control of FC. From Table 1 and Figure 2, it can be seen that the balance of the voltages across the FC can be achieved by a simple closed-loop
TABLE 1. Switching states of the five-level ANPC inverter.

| $S_{s1}$ | $S_{s2}$ | $S_{s3}$ | $S_{s4}$ | $i_k$ | $i_{nr}$ | Level | State |
|----------|----------|----------|----------|------|---------|-------|-------|
| 1        | 1        | 1        | 1        | /    | /       | 2E    | V7    |
| 1        | 1        | 1        | 0        | $i_k$ | /       | E     | V6    |
| 1        | 1        | 0        | 1        | $i_k$ | $i_{nr}$| E     | V5    |
| 1        | 1        | 0        | 0        | /    | $i_{nr}$| 0     | V4    |
| 0        | 0        | 1        | 1        | /    | $i_{nr}$| 0     | V3    |
| 0        | 0        | 1        | 0        | $i_k$ | $i_{nr}$| -E    | V2    |
| 0        | 0        | 0        | 1        | $i_k$ | /       | -E    | V1    |
| 0        | 0        | 0        | 0        | /    | /       | -2E   | V0    |

control. It can be seen from Table 1 that the FC voltage is affected by the switching states (V1, V2) and (V5, V6), when the current flow paths are coincident, the switching states V1 and V2 have opposite effects on FC and the switching states V5 and V6 have opposite effects on FC too. Therefore, when each phase output voltage has two levels $E$ and $-E$, the switching states which guarantee the stability of the FC voltage can be easily chosen by detecting the direction of the phase current $i_o$ and the voltage of FC.

It should be pointed out that there is coupling between the control of FC voltage and the control of neutral-point voltage in some states. When the redundant switch state is selected to control the voltage of FC, the influence of the two optional switch states on the neutral-point voltage is different. The traditional control methods put the control of the FC voltage in the first place, which will inevitably affect the control of the neutral-point voltage and lead to the increase of the fluctuation of the neutral-point voltage.

III. MODEL OF 5L-ANPC INVERTER SYSTEM

A. SPACE VECTOR MODEL OF 5L-ANPC INVERTER

If the output state of each bridge arm is represented by the switching variables $S_a$, $S_b$ and $S_c$, then the three-phase output voltage is:

$$
\begin{align*}
V_a &= S_a \cdot E \\
V_b &= S_b \cdot E \\
V_c &= S_c \cdot E
\end{align*}
$$

(1)

where $V_a$, $V_b$ and $V_c$ are the output voltage of phase a, b and c respectively; $E$ is 1/4 of the DC bus voltage, the switching state corresponding to $S_x = -2$ is V0, the switching state corresponding to $S_x = -1$ is V1 and V2, the switching state corresponding to $S_x = 0$ is V3 and V4, the switching state corresponding to $S_x = 1$ is V5 and V6, the switching state corresponding to $S_x = 2$ is V7, where $x$ represents phase a, b, or c.

According to the analysis, there are $5^3 = 125$ voltage states that can be combined in three-phase five-level converter, which correspond to 125 different switching states. In the three-phase static coordinate system, the voltage space vector of the five-level converter can be expressed as:

$$
V = \frac{2}{3} E \cdot (S_a + \alpha \cdot S_b + \alpha^2 \cdot S_c)
$$

(2)

where $\alpha = e^{j\frac{2\pi}{3}}$. The voltage space vector diagram corresponding to 125 switching states of five level inverter is given in Figure 3.

The digital combination (such as 414) in the circle shown in Figure 3 represents the level state of phase a, b and c respectively from left to right. In 5L-ANPC converter, digit 4 represents level state +2, digit 3 represents level state +1, digit 2 represents level state 0, digit 1 represents level state -1, and digit 0 represents level state -2.

B. MODELING OF 5L-ANPC INVERTER LOAD SYSTEM

Referring to Figure 1, the load dynamic current equation for each phase of 5L-ANPC inverter is obtained:

$$
\begin{align*}
u_{a_0} &= L \frac{d}{dt} i_a + R i_a + e_a + u_{n_a} \\
u_{b_0} &= L \frac{d}{dt} i_b + R i_b + e_b + u_{n_b} \\
u_{c_0} &= L \frac{d}{dt} i_c + R i_c + e_c + u_{n_c}
\end{align*}
$$

(3)
where $R$ and $L$ are the load resistance and inductance, respectively, $i_{f0}(x = a, b, c)$ is the voltage generated by the inverter, $e_x(x = a, b, c)$ is the electromotive force (EMF) of the load, and $i_x(x = a, b, c)$ is the load current, $u_{f0}$ is the voltage between load neutral point $n$ and inverter neutral point $o$.

Substituting equation (3) into equation (2), the dynamic vector equation of load current is as follows:

$$u = L \frac{di}{dt} + Ri + e$$  \hspace{1cm} (5)

where $u$ is the voltage vector generated by the five-level inverter, $i$ is the load current vector, $e$ is the EMF vector of load.

The fluctuation of the neutral point voltage $u_o$ in 5L-ANPC inverter is determined by the output current $i_o$ of the neutral point and the capacitance value of the upper and lower buses, as shown in:

$$\frac{du_o}{dt} = i_o = \frac{1}{2C}(H_a i_a + H_b i_b + H_c i_c)$$  \hspace{1cm} (6)

where $C$ is the DC side half bus capacitance, and $C = C_{up} = C_{db}$. $H_a, H_b, H_c$ are the three-phase neutral point connection flag variables of inverter, which are defined as:

$$H_x = \begin{cases} 1, & \text{(State}_x = \text{V2 or V3 or V4 or V5)} \\ 0, & \text{(State}_x = \text{V0 or V1 or V6 or V7)} \end{cases}$$  \hspace{1cm} (7)

where $x$ represents phase a, b, or c.

The mathematical model of voltage fluctuation of FC $C_{fx}$ can be described by the following equation:

$$\frac{d\chi_{fx}}{dt} = \frac{i_{fx}}{C_f} = \frac{1}{C_f}H_{fx}\chi_{fx}$$  \hspace{1cm} (8)

where $H_{fx}$ is the FC access flag variable in each phase, $x$ represents phase a, b, or c. which is defined as:

$$H_{fx} = \begin{cases} 1, & \text{(State}_{x} = \text{V1 or V5)} \\ 0, & \text{(State}_{x} = \text{V0 or V3 or V4 or V7)} \\ -1, & \text{(State}_{x} = \text{V2 or V6)} \end{cases}$$  \hspace{1cm} (9)

**C. DISCRETE PREDICTION MODEL OF 5L-ANPC INVERTER**

According to formula (5), the voltage equation in the $\alpha\beta$ coordinate system is

$$u_{\alpha,\beta} = \frac{L}{dt}i_{\alpha,\beta} + Ri_{\alpha,\beta} + e_{\alpha,\beta}$$  \hspace{1cm} (10)

where $u_{\alpha,\beta}$ is the voltage vector generated by the five-level inverter in the $\alpha\beta$ coordinate system, $i_{\alpha,\beta}$ is the load current vector in the $\alpha\beta$ coordinate system, $e_{\alpha,\beta}$ is the EMF vector of load in the $\alpha\beta$ coordinate system.

Applying a sampling period $T_s$, the derivative term of current derivative can be approximately expressed as:

$$\frac{di_{\alpha,\beta}}{dt} = \frac{i_{\alpha,\beta}(k + 1) - i_{\alpha,\beta}(k)}{Ts}$$  \hspace{1cm} (11)

By introducing equation (11) into equation (10), the predictive mathematical model of inverter output current can be obtained:

$$i_{\alpha,\beta}(k + 1) = (1 - \frac{RT_s}{L})i_{\alpha,\beta}(k) + \frac{T_s}{L}(u_{\alpha,\beta}(k) - e_{\alpha,\beta}(k))$$  \hspace{1cm} (12)

By discretizing equation (6) with the same method, a mathematical model for predicting the neutral point voltage fluctuation of 5L-ANPC inverter can be obtained:

$$u_o(k + 1) = \frac{T_s}{2C}(H_a i_a(k) + H_b i_b(k) + H_c i_c(k)) + u_o(k)$$  \hspace{1cm} (13)

By discretizing equation (8), a mathematical model for predicting the voltage fluctuation of FCs in each leg of 5L-ANPC inverter is obtained:

$$u_{fx}(k + 1) = |\frac{T_s}{C_f}H_{fx}\chi_{fx} + u_{fx}(k) - U_f^*|$$  \hspace{1cm} (14)

where $U_f^*$ represent the setting voltage of FC.

The average number of switching actions of the system at the next moment is $f_{\text{switch}}$:

$$f_{\text{switch}} = \frac{12}{J} \sum_{i=1}^{12} (f_{sa} + f_{sb} + f_{sc}) / 36$$  \hspace{1cm} (15)

where: $f_{sa}, f_{sb}$ and $f_{sc}$ represent the action times of three-phase switching devices respectively.

The control strategy also uses an estimation of the future reference current. Depending on the sampling time applied and the computational constrains, the estimation can be obtained by a second-order extrapolation given by:

$$i_{\alpha,\beta}^*(k + 1) = 3i_{\alpha,\beta}^*(k) - 3i_{\alpha,\beta}^*(k - 1) + i_{\alpha,\beta}^*(k - 2)$$  \hspace{1cm} (16)

**IV. OPTIMIZATION OF SWITCHING STATES OF 5L-ANPC INVERTER**

In order to reduce the number of rolling optimizations, it is necessary to optimize all switching states of 5L-ANPC inverter. The switching states that do not meet the output requirements of the inverter are deleted in advance, and the effective switching states are involved in the rolling optimization control.

In view of the above objectives, it is necessary to put forward requirements for the voltage output of the inverter, which should meet the following two conditions:

1) Each phase output voltage of the inverter shall not jump more than one level, and the output level of each phase voltage shall not exceed the output level range of the inverter;
The output line voltage cannot jump more than one level too.

If the output voltage does not meet the two conditions given in this paper, there will be cross-level jump, which will lead to the decrease of output level and the increase of output harmonic. For 5l-anpc inverter, switching chaos will occur when switching state, which will lead to system failure.

According to the above two requirements, the effective switching state of the inverter can be calculated at the next moment. If the current output switch state is \([s_a(k), s_b(k), s_c(k)]\), and the first condition is satisfied, the output switching state at the next moment is as follows:

\[
\begin{bmatrix}
s_a(k+1) \\
s_b(k+1) \\
s_c(k+1)
\end{bmatrix} = \begin{bmatrix}
s_a(k) \\
s_b(k) \\
s_c(k)
\end{bmatrix} + \begin{bmatrix}
s_{ja} \\
s_{jb} \\
s_{jc}
\end{bmatrix}
\]  
(17)

where: \(s_x\) represents the level jump variable of x, where x represents phase a, b, or c. \(|s_x| \leq 1\), and \(0 \leq s_x(k+1) \leq 4\).

According to the above formula, the calculation formula of line voltage at the next moment can be deduced:

\[
\begin{bmatrix}
s_{ab}(k+1) \\
s_{bc}(k+1) \\
s_{ca}(k+1)
\end{bmatrix} = \begin{bmatrix}
s_{ab}(k) \\
s_{bc}(k) \\
s_{ca}(k)
\end{bmatrix} + \begin{bmatrix}
s_{ja} - s_{jb} \\
s_{ja} - s_{jc} \\
s_{jb} - s_{jc}
\end{bmatrix}
\]  
(18)

According to the calculation of five-level inverter, the number of all switching states is 125, the maximum number of switch states meeting the first condition is 27, and the maximum number of switching states satisfying both conditions is 15. A conclusion is drawn that the traditional MPC method needs to calculate 125 times each time, while the proposed method only needs to calculate 15 times at most, which can save 88% of the calculation time and improve the computational efficiency of the processor. Figure 4 shows the switching state diagram of five-level inverter, in which the state represented by box represents all switching states of five-level inverter, and the state represented by solid dot is the optimized switching state satisfying two conditions.

Taking the current switching states \((2,2,2)\) as an example, if not optimized, the five-level inverter can output 27 switching states. After optimizing, the number of switching states satisfying two conditions is 15. Figure 5 is the switching state optimization diagram of five-level inverter, in which the dotted line represents the optimized switching state meeting condition 1 but not condition 2, and the solid line represents the switching state that can be output at the next moment after optimization control.

V. MODEL PREDICTIVE CONTROLLER FOR 5L-ANPC INVERTER

A. DESIGN OF MODEL PREDICTIVE CONTROL SYSTEM FOR 5L-ANPC INVERTER

Figure 6 shows the block diagram of O-MPC system for 5L-ANPC inverter. In order to accurately predict and control the neutral point potential, the voltage of floating capacitor and the expected output load current, the voltage and load current of each capacitor should be sampled in real time. Then, according to the switch state of the inverter output at the current moment, the optimized switch state is selected by the switch state optimization controller and substituted into the prediction model, i.e. (12), (13), (14), (15). Then the predicted value of the required control target is obtained. Finally, the switching state with the smallest value function is selected to output and the optimal control target is obtained.

The design objectives of 5L-ANPC inverter predictive controller are as follows:

1) Load current reference trajectory tracking;
2) Balance control of neutral point potential;
3) Balance control of FCs;
4) Reduce the switching frequency.
Using the value function, the above control objectives can be described by formula:

\[ J = K_i |i_a(k + 1) - i_a(k)| + |i^p(k + 1) - i^p(k)| \]
\[ + K_o |u_o(k + 1)| + u_f(k + 1)| + u_{switch}(k + 1)| \]
\[ + K_n f_{switch} \]  
\[ (19) \]

where \( K_i, K_o, K_f \) and \( K_n \) are the weight factors of load current, neutral point potential deviation, the voltage deviation of three-phase FCs and switching frequency optimization.

The O-MPC method flow chart of 5L-ANPC inverter is given in Figure 7. Firstly, the voltage and load current on each capacitor are measured and sampled, and the final optimized switch state and its number are determined according to formula (17) (18). Then, the rolling optimization stage is started. The load current and capacitor voltage are obtained through formula (12), (13), (14) and (15) respectively for each optimized switching state. Finally, the optimal switching state obtained by equation (19) is applied to the converter.

**B. DESIGN METHOD OF WEIGHT FACTORS**

The role of the weight factor is to adjust the proportion of the control objective in the value function. When the value of the weight factor \( K \) is larger, it means that the corresponding control objective has a greater proportion in the value function, which means that the target has a greater priority. When the value of \( K \) is smaller, it means that the proportion of the corresponding control objective in the value function is smaller. In the actual system, the satisfactory control effect can be achieved by setting the weighting coefficient \( K \) flexibly.

In order to alleviate the conflict between different indexes and realize the global optimization that takes the interests of all indexes into account, this paper designs the value function based on the satisfactory optimization method.

According to the importance of control objectives, we divide the priority of control objectives, and adopt the idea of hierarchical optimization to design the weight coefficient of each control objective within the satisfaction range. Specifically, all control objectives are divided into different levels according to different priorities, and the control of each target is realized according to the order of priority from high to low. The determination of weight factor takes the control objective to reach the set control range as the goal, that is to achieve the satisfactory control of the objective. The weight factors of other control objectives are determined in turn.

Take 5L-ANPC inverter control system as an example. Firstly, three control objectives of the system are determined: the output level does not jump across levels, the control of the FC voltage, the control of the neutral point voltage and the control of the switching frequency. Secondly, the priority of the three control objectives is determined, as shown in Table 2. In the optimization process, objective satisfaction replaces the optimal one, in exchange for more control freedom, so that lower priority control targets participate in the optimization process.

When the control objectives conflict, the conflicting targets can be prioritized again. In this way, all targets can be divided according to different priorities, so there will be no conflict.
FIGURE 8. The surface constrained by weight factors $K_i$, $K_f$ and $K_n$.

FIGURE 9. Taking switch state 400 as an example, the specific flow chart of the O-MPC optimization.

In this paper, because the control objectives of neutral point potential voltage and FC voltage are both 5% of the set voltage, the priority of the two control objectives is set as the same.

Taking 5L-ANPC as an example, in order to simplify the calculation, the number of weight factors can be simplified because the control priority of floating capacitor voltage and neutral point voltage is the same. Let $K_0 = K_f$, then the weight factors are only three $K_i$, $K_f$, $K_n$. The constraint relations of the three weight factors are as follows: $K_i + K_f + K_n = 1$. According to the priority division in Table 2, the priority of current control is higher than that of floating capacitor voltage and neutral point voltage, while the priority of switching frequency control is the lowest. It can be seen that $K_f > K_i > K_n$. Thus, the selection range of weight coefficient can be greatly simplified, and the weight coefficient diagram meeting the above conditions is shown in Figure 8. Then the algorithm can be further optimized in the actual experiment to get the weight factors which can meet the system requirements.

If the current switch state is 400, the process of selecting the optimal switch state is shown in Figure 9.

C. DESIGN METHOD OF DELAY COMPENSATION

Ideally, the controller sampling, calculation and output should be completed at the same time point. However, the actual digital processing system needs to consume a certain amount of calculation time when executing the code, resulting in the mismatch between the pulse action time and the sampling time, which affects the control effect and causes the control results to produce errors. Especially in the multilevel transformation, due to the number of rolling optimizations, the above problems are particularly prominent.

A simple solution to compensate for this delay is to consider the calculation time and apply the selected switching state after the next sampling instant. In this way, the control algorithm is modified as follows: 1) Measurement of the load currents. 2) Application of the switching state. 3) Estimation of the value of the currents at time $t_k - 1$, considering the applied switching state. 4) Prediction of the load currents for the next sampling instant $t_k + 1$ for all possible switching states. 5) Evaluation of the cost function for each prediction. 6) Selection of the switching state that minimizes the cost function.

The schematic diagram is shown in Figure 10. The specific steps are as follows:

1) Output the switch state calculated from the previous beat;
2) System AD sampling;
3) Delay compensation;
4) Query optimization switch sequence;
5) Online optimization.

VI. EXPERIMENTAL VERIFICATION

To verify the effectiveness of the proposed control strategy, the 5L-ANPC inverter experimental prototype is built for experimental verification, as shown in Figure 11. The core controller of the experimental platform uses DSP TMS320C28346 and FPGA Spartan 6. FPGA is mainly used...
in the calculation of rolling optimization in O-MPC algorithm. The IGBT adopts Infineon FF300R12MS4, and uses three-phase resistive load to replace the motor. The specific parameters of the experiment are shown in Table 3.

In order to improve the utilization rate of DSP, the whole rolling optimization process of predictive control is completed in FPGA. Referring to the flow chart of the O-MPC in Figure 7, the specific implementation steps in FPGA are as follows: 1) FPGA obtains the real-time data of actual current, neutral point voltage and three-phase floating capacitor from DSP; 2) simplify the switch state involved in rolling according to the method mentioned in the Section IV; 3) calculate the value function $J$ corresponding to each switch state; 4) select the switch state corresponding to the minimum value function $J$ and send it back to DSP.

Figure 12 shows the dynamic experimental waveforms of 5L-ANPC inverter under the proposed O-MPC method. It can be seen from the figure that the level jump of phase voltage is one level and there is no cross-level jump. Furthermore, it is explained that the switch state optimization described in Section IV has achieved the expected control effect; it can also be seen from the figure that the deviation of floating capacitor voltage and neutral point potential of phase A is small, and both can be stably controlled when the load changes suddenly, which proves that the control theory in Section V has good dynamic and steady-state control effect.

Figure 13 shows the dynamic waveforms of 5L-ANPC inverter under the proposed O-MPC method. It can be seen from Figure 13 (a) that there is no cross-level jump in line voltage level jump, which further verifies the control effect of switch state optimization described in Section IV. Figure 13 (b) shows the given and actual load current waveforms of phase A, which can keep good sinusoidal degree before and after the load current mutation. At the same time, the load current can quickly track the given value after the given current mutation, which shows that the proposed O-MPC method of 5L-ANPC inverter has good robustness ability and fast dynamic response ability.

Figure 14 shows the average switching frequency of 5L-ANPC inverter model predictive control when the weight factor $K_n$ changes. Compared with Figure 14 (a) and (b), it can be seen that when the weight factor $K_n$ changes, the average switching frequency of the system changes. At the same time, with the increase of the weight coefficient, the proportion of the optimization of the average switching frequency in the whole value function is increasing, and then the average switching frequency is reduced.

Figure 15 shows the experimental waveforms of neutral point voltage and floating capacitor of 5L-ANPC inverter under the proposed O-MPC method. It can be seen from Figure 15 (a) that there is no cross-level jump in line voltage level jump, which further verifies the control effect of switch state optimization described in Section IV. Figure 15 (b) shows that the given and actual load current waveforms of phase A, which can keep good sinusoidal degree before and after the load current mutation. At the same time, the load current can quickly track the given value after the given current mutation, which shows that the proposed O-MPC method of 5L-ANPC inverter has good robustness ability and fast dynamic response ability.
From the figure, we can see that the traditional MPC method and the O-MPC method are shown in Figure 17.

The neutral point voltage tends to balance quickly. If the neutral point potential is extremely unbalanced, and after the control is applied, the voltage of the neutral point potential will all within 5% through the optimization of the no weight factor, and the satisfactory optimization control effect is achieved.

The time of one calculation cycle under the traditional MPC method and the O-MPC method are shown in Figure 17. From the figure, we can see that the traditional MPC needs about 8 µs, while the proposed control strategy only needs 2 µs, saving 6 µs, saving about 80% of the time. It can be seen that the proposed control strategy can significantly improve the computing efficiency of the processor.

FIGURE 17. The time of one calculation cycle. (a) under the traditional MPC method. (b) under the proposed O-MPC method.

VII. CONCLUSION

In this paper, an O-MPC method was proposed to shorten the computation time of the predictive control algorithm and improve the multi-objective performances for five-level ANPC inverter. By establishing the switching state of the inverter and the set constraints, the number of switching states participating in dynamic optimization is successfully reduced. Taking 5L-ANPC inverter as an example, the number of switch states participating in rolling optimization is reduced from 125 to 15, which saves more than 80% of the calculation time compared with the traditional MPC. In order to solve the conflict problem of multiple control objectives, all control objectives are divided into different levels according to different priorities, and the control of each target is realized based on the order of priority from high to low. The value of the weight factor is not based on the optimal value of a single target, but the optimal value when multiple control targets are satisfied. This method has improved the multi-objective performance of the control system effectively.

REFERENCES

[1] N. D. Dao and D.-C. Lee, “Operation and control scheme of a five-level hybrid inverter for medium-voltage motor drives,” IEEE Trans. Power Electron., vol. 33, no. 12, pp. 10178–10187, Dec. 2018, doi: 10.1109/TPEL.2018.2811182.

[2] E. Burguete, J. Lopez, and M. Zabaleta, “New five-level active neutral-point-clamped converter,” IEEE Trans. Ind. Appl., vol. 51, no. 1, pp. 440–447, Jan. 2015, doi: 10.1109/TIA.2014.2334737.

[3] P. Barbosa, P. Steimer, J. Steinke, M. Winkelkemper, and N. Celanovic, “Active-neutral-point-clamped (ANPC) multilevel converter technology,” in Proc. Eur. Conf. Power Electron. Appl., 2005, pp. 1–10.

[4] F. Kieferndorf, M. Basler, L. A. Serpa, J.-H. Fabian, A. Coccia, and G. A. Scheuer, “A new medium voltage drive system based on ANPC-5L technology,” in Proc. IEEE Int. Conf. Ind. Technol., Vitia del Mar, Chile, Mar. 2010, pp. 643–649.

[5] M. Narimani, B. Wu, V. Yaramasu, and N. R. Zargari, “Finite control-set model predictive control (FCS-MPC) of nested neutral point-clamped (NNPC) converter,” IEEE Trans. Power Electron., vol. 30, no. 12, pp. 7262–7269, Dec. 2015, doi: 10.1109/TPEL.2015.2396033.

[6] B. Stellato, T. Geyer, and P. J. Goulart, “High-speed finite control-set model predictive control for power electronics,” IEEE Trans. Power Electron., vol. 32, no. 5, pp. 4007–4020, May 2017, doi: 10.1109/TPEL.2016.2584678.
ZHAN LIU (Member, IEEE) was born in Xiaoxian, Anhui, China, in 1989. He received the B.S. degree in electrical engineering and automation, the M.S. degree in power electronics and power drives, and the Ph.D. degree in electrical engineering from the China University of Mining and Technology, Xuzhou, China, in 2011, 2013, and 2016, respectively. Since 2017, he has been a University Lecturer with the School of Electrical Engineering and Automation, Jiangsu Normal University, China, where he is responsible for the National Natural Science Foundation of China. His research interests include power electronics, modern control theory, model predictive control, and multilevel converter.

ZHENGLONG XIA (Member, IEEE) received the B.S. degree in electrical engineering and automation, the M.S. degree in power system and automation, and the Ph.D. degree in power electronics and power drives from the China University of Mining and Technology, in 2005, 2008, and 2014, respectively. Since 2014, he has been an Associate Professor with the Department of Electrical Engineering and Automation, Jiangsu Normal University, China, where he is responsible for the Youth Fund of the Foundation Research Project of Jiangsu. Since 2019, he has been a Visiting Scholar with Aalborg University, Denmark. He has published more than 40 journal articles in the fields of power quality management and fault diagnosis. His research interests include reactive compensation of power systems, fault diagnosis, and circuit theory and systems.

DAN LI was born in Xuzhou, Jiangsu, China, in 1986. He received the M.S. degree in electronics engineering from the China University of Mining and Technology, Xuzhou, China, in 2019. His current research interests include automation control system, modulation strategy, and system improvement.

YU WANG was born in Xuzhou, Jiangsu, China, in 1989. He received the M.S. degree in electronic engineering from the China University of Mining and Technology, Xuzhou, China, in 2016. His current research interests include automation control system, modulation strategy, and system improvement.

FEI LI (Member, IEEE) was born in Xuzhou, Jiangsu, China, in 1982. He received the B.S. degree in electrical engineering and automation from the China University of Mining and Technology, Xuzhou, China, in 2005, the M.S. degree in electronic engineering from the University of Duisburg–Essen, Germany, in 2009, and the Ph.D. degree in power electronics and electrical drive from the China University of Mining and Technology, in 2017. He is currently working with the School of Electrical Engineering and Automation, Jiangsu Normal University, Xuzhou, as a University Lecturer. His current research interest includes power electronic converters for electric drives and power quality.