Improved two-stage model predictive control method for modular multi-level converter

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Abstract
In recent years, the modular multi-level converter (MMC) has been widely used in high and medium voltage DC transmission systems because of its topological advantages. However, for an MMC with a two-stage model predictive control (TSMPC) method, it is difficult to precisely and reasonably design the weighting factor in the cost function. Here, an improved TSMPC method is proposed which not only can avoid choosing the weighting factor for both first and second stage control but also can raise the output voltage level (OVL) to $2N + 1$ without increasing computation burden. The discrete-time mathematical model of the MMC is first derived. Two circulating current factors are introduced to calculate the optimal number of submodules (SMs) of the upper and lower arms in the first stage control. Secondly, the second stage control calculates the optimal number of SMs through the superior control and forms the optimisation array by adding or subtracting one SM. Then the objective function is developed, and the SMs with the minimum value of the objective function are selected for the final input. Finally, the algorithm of reducing switching frequency (RSF) is applied to achieve the balance of the SM capacitor voltage. The simulation and experimental results verify the effectiveness of the proposed method.

1 | INTRODUCTION

In the last decade, the modular multi-level converter (MMC) has attracted extensive attention from academia and industry. It has advantages such as a modular structure, reduced switching frequency (RSF), high efficiency, low redundancy cost, and good quality of output voltage and current waveform [1–3]. Due to the characteristics of this topology, the MMC is suitable for high-voltage (HV) and medium voltage (MV) applications such as high voltage direct current (HVDC) system [4, 5], MV motor drive [6, 7], static synchronous compensator [8], etc.

The control methods of the MMC can be summarised into three categories, namely, the ac-side output current control (OCC), circulating current control (CCC) and submodule (SM) capacitor voltage control (CVC) [8]. To date, there are already some existing modulation and control strategies that have been designed to control the MMC among which, the model predictive control (MPC) is an advanced control method for the MMC because of its non-linear target system, simple control structure, good dynamic performance, and easy control of multiple variables [9–17].

Among various MPC methods, many researchers and engineers of power electronics focus on the finite control set model predictive control (FCS-MPC) method. The FCS-MPC was first applied to the MMC by Qin, J [18]. In order to realise the control objectives of the ac-side OCC, CCC, and CVC, the objective function optimisation control method is established. However, such a method needs to carry out cycle prediction optimisation for all possible switch states, which inherently leads to a large calculation amount for the control and adjustment of the weight factor. Later, the FCS-MPC is used for the MMC in [19] and the $C_{2N}^N$ switch combinations are considered, where $N$ is the number of SMs and $C_{2N}^N$ means to select $N$ SMs from $2N$ SMs. In reference [20], an MPC with the RSF algorithm is proposed. By introducing a common-mode voltage into the output current model, the harmonic output current is significantly reduced. The output voltage of the...
above-mentioned MPC methods is \(N + 1\) levels, and they are all based on a single-stage MPC (SSMPC).

To reduce the total harmonic distortion (THD) value of the MMC system, in reference [21], by controlling the \((N + 1)^2\) options, the number of SMs inserted into the single-phase bridge arm is no longer fixed as \(N\), and the output voltage level (OVL) is increased to \(2N + 1\). Compared with the SSMPC, the TSMPC can further improve the steady-state performance. Generally, the TSMPC is divided into the first stage control and the second stage control. In the first stage control, the minimum and sub-minimum values of the cost function are calculated, and the corresponding input number of SMs is the output. The second stage control predicts the values of the various states of SMs in the previous control at the next moment and brings them into the cost function to calculate the lowest value of the cost function so as to output the final input SM numbers of the upper and lower bridge arm. In [22], a TSMPC is proposed to evaluate the performance under the same switching state. However, when the number of prediction steps increases, the number of calculations greatly increases. In [23], an MPC method for a multi-step direct prediction and an extrapolation strategy to maintain a small amount of computation are proposed. In [24], a dual-stage MPC is proposed to effectively reduce the calculation amount without weakening the transient response. Further in [25], a simplified rolling optimisation method is proposed to reduce the number of control options to be evaluated. For the abovementioned methods, it is necessary to design the weighting factor to achieve multi-objective control, while the weighting factor is difficult to adjust.

Our aim is to specify the challenges, lead the motivation of this paper, then introduce the philosophy of the proposed method in general. Here, an improved TSMPC method is presented. This method does not need to consider the difficulty of adjusting the weighting factor in the cost function, and the OVL is increased to \(2N + 1\). Besides, the amount of calculation is significantly reduced compared with conventional methods. Here, a discrete mathematical model is first used to predict the state variables in the first stage control. In the ac-side OCC, the number of SMs is not limited to \(N\) to suppress the harmonic circulation and generate \(2N + 1\) levels. In the OCC, the reference value of the circulating current is adjusted by introducing two circulation factors \(\Delta i_{cirj1}\) and \(\Delta i_{cirj2}\). One factor controls the voltage difference of the bridge arm, while the other controls the sum of the bridge arm voltage. According to the discrete mathematical model, the optimal voltage difference and voltage sum of the bridge arm are calculated directly to obtain the number of optimal insertion SMs in the front stage of the TSMPC. Then, in the second stage control, according to the calculation in the previous step, the number of upper and lower SMs are added or subtracted by one SM to establish an optimised array. The value of the ac-side output current and the circulating current at \(k + 2\) time is predicted, and the optimal control scheme is selected by using the objective function so as to determine the final SM numbers. Finally, the SM CVC is balanced by the RSF algorithm. Simulation and experimental results demonstrate the accuracy and effectiveness of the proposed method under steady and transient conditions.

The structure of this article is as follows: In Section 2, the topology and mathematical model of the MMC are introduced. Then in Section 3, we introduce how the traditional TSMPC and the improved TSMPC method are implemented. Next, the simulation and experimental results are given in Sections 4 and 5, respectively. Finally, Section 6 summarises this article.

2 | TOPOLOGY AND MATHEMATICAL MODEL OF THE MMC

Figure 1 shows a three-phase MMC topology. Each phase has an upper arm and a lower arm. Each bridge arm is composed of \(N\) cascaded half-bridge SMs (HBSMs) and a series-connected inductor \(L_F\). The bridge arm inductance \(L_F\) is used to suppress the circulating current. In Figure 1, \(u_{nj}\) and \(i_j\) \((j = a, b, c)\) are the grid voltages and currents. \(u_{nj}\) and \(i_{nj}\) represent the sum of the input SM voltages of the upper and lower bridge arms, while \(i_{pj}\) and \(i_{nj}\) are the currents of the upper and lower bridge arms. \(V_{dc}\) is the dc-side voltage. \(L\) and \(R\) are the ac-side inductance and resistance.

Since the MMC topology is a three-phase symmetrical structure, the single-phase equivalent circuit diagram of the MMC can be obtained by analysing any phase of the MMC. The ac-side output current \(i_j\) and the circulating current \(i_{cirj}\) can be expressed as follows:

\[
i_j = i_{nj} - i_{pj}
\]

\[
i_{cirj} = \frac{i_{pj} + i_{nj}}{2} = i_j + \frac{i_{dc}}{3}
\]

where \(i_{dc}\) is the DC bus current. \(i_{cirj}\) is the circulating current inside the bridge arm, which is composed of a DC component \(i_{dc}/3\) and an evenly circulating harmonic current component \(i_{ej}\).

![Figure 1 Three-phase multi-level converter equivalent circuit topology. SM, submodule](image)
Generally, $i_{cir}$ is set to $i_{dc}/3$ to suppress the harmonic circulating current.

The dynamic characteristics of the SM capacitor voltage are described as follows:

$$C \frac{d u_{xy}}{dt} = S_{xy} i_{xy}$$

where $u_{xy}$ is the voltage of the SM capacitor, and its normal value is $V_{dc}/N$. $C$ is the capacitance of the SM. $x$ is the symbol of the upper and lower bridge arms, represented by $p$ and $n$, respectively. $y$ is the number of SMs, which is $1, \ldots, N$. $S$ is the working state of the half-bridge SM, that is, the input and bypass states. If the on-off voltage drop of the switching device is ignored, the output voltage of the SM is $u_{c}$ when $S_y$ is opened and $S_2$ is closed, and the output voltage of the SM is zero when $S_2$ is opened and $S_f$ is closed.

$n_{A_j}$ and $n_{S_j}$ are used to represent the difference and sum of the input SM numbers of the upper and lower bridge arm and it is expressed as

$$n_{A_j} = n_y - n_y = \sum_{y=1}^{N} (S_{ny} - S_{py})$$

$$n_{S_j} = n_p + n_p = \sum_{y=1}^{N} (S_{py} + S_{ny})$$

According to the voltage and current directions shown in Figure 1, $u_{A_j}$ and $u_{S_j}$ represent the voltage difference and the voltage sum of the upper and lower bridge arms, respectively, and the external and internal dynamic characteristic equations can be deduced as

$$u_{A_j} = 2L_{eq} \frac{d i_j}{dt} + 2R i_j + 2u_{p_j}$$

$$u_{S_j} = V_{dc} - 2L_j \frac{d i_{cir}}{dt}$$

where $L_{eq} = L + L_j/2$, $u_{A_j}$ and $u_{S_j}$ can also be expressed by the following formula:

$$u_{A_j} = u_{n_j} - u_{n_j}$$

$$u_{S_j} = u_{p_j} + u_{p_j}$$

Based on Equation (6), the discrete-time mathematical model of the MMC is derived by using the first-order forward difference approximation method. The ac-side output current and circulating current are obtained as

$$i_j(k+1) = \frac{T_i}{L_{eq}} \left[ u_{xy}(k) - u_{p_j}(k) \right] + \left( 1 - \frac{T_i R}{L_{eq}} \right) i_j(k)$$

$$i_{cir}(k+1) = \frac{T_i}{2L_j} \left[ V_{dc} - u_{S_j}(k) \right] + i_{cir}(k)$$

The capacitor voltage of the SM is calculated as

$$u_{xy}(k+1) = u_{xy}(k) + \frac{T_i}{C} S_{xy}(k) i_{xy}(k)$$

In the discrete-time model, $T_\lambda$ is the sampling period. $i_j(k)$, $i_{cir}(k)$, and $u_{xy}(k)$ are the actual measured values of $k$ time. $i_j(k+1)$, $i_{cir}(k+1)$, and $u_{xy}(k+1)$ are the predicted values of $k+1$ time.

## 3 | TWO-STAGE MODEL PREDICTIVE CONTROL METHOD

### 3.1 | Traditional TSMPC method

The traditional TSMPC approach is shown in Figure 2. The $z$ in the figure is the state variable, which could represent the ac-side current, circulating current, and the bridge arm voltage difference and voltage sum. $\lambda$ is the weighting factor in the cost function.

Firstly, in the first stage control, the values of the ac-side current, circulating current, and the SM capacitor voltage at $k+1$ moment are predicted and brought into the cost function $J_1$. The minimum and sub-minimum values of $J_1$ are calculated, and the corresponding input number of SMs is the output. Secondly, in the second stage control, the values of the ac-side current, circulating current and the SM capacitor voltage at $k + 2$ time of output SMs are predicted. Then the values are brought into the cost function $J_2$ to calculate the minimum value of $J_2$ so as to output the final input SM numbers of the upper and lower bridge arm.

By adjusting the weighting factor of cost functions $J_1$ and $J_2$, multiple control objectives are optimised. According to the constraint conditions, the controller predicts all the switching states and selects the switch states corresponding to the minimum cost function $J_2$ as the SM numbers for conducting. As the weighting factor in the cost function needs to be adjusted...
iteratively, the accurate design is challenged. The designers often set the weighting factor according to their experiences. As a result, the three control objectives are mutually affected. So, it is impossible to realise optimal multiple control objectives at the same time. In conventional TSMPC, the input number of SMs is normally limited to \( N \) and the OVL is the only \( N + 1 \), which affects the steady-state and dynamic-state performances of the system.

### 3.2 Proposed TSMPC method

The weighting factor of the cost function in a traditional TSMPC is difficult to design accurately and the OVL is \( N + 1 \). To solve this problem, here an improved TSMPC method is proposed. Figure 3 shows the principle of the proposed TSMPC. The dark red line, blue line, and the red line in the figure represent the reference value, control options, and the optimal control item of each stage, respectively. It includes two stages: the first stage and the second stage. After meeting the objectives of the ac-side OCC and CCC, the first stage control exports the optimal number of input SMs of the upper and lower bridge arms. In the second stage, through the number of SMs generated in the first stage, one SM is increased or decreased to form an optimised array. By selecting the SMs input that minimises the value of the objective function, the final number of SMs invested is then determined. Finally, combined with the RSF principle, the SM capacitor voltage balance is realised. This method does not need a weighting factor design and does not need to cycle all the switching states. It can also achieve the maximum output of \( 2N + 1 \) levels. The implementation is as follows:

#### 3.2.1 The first stage control

The first stage control is divided into two parts: the ac-side OCC and the CCC. In the ac-side OCC, the number of SMs is not limited to \( N \) to suppress the harmonic generation and control \( 2N + 1 \) levels. In the CCC, the reference value of the circulating current is adjusted by introducing two circulation factors, \( \Delta i_{\text{c}1} \) and \( \Delta i_{\text{c}2} \). The optimal output voltage difference and the voltage sum of the bridge arm are directly calculated so as to calculate the optimal input SM numbers of the upper and lower bridge arm in the first stage control of the TSMPC.

The ac-side OCC: reverse equation (8) and calculate the reference value of the optimal voltage difference of the bridge arm \( u^*_{\Delta j} \) as follows:

\[
u^*_{\Delta j}(k) = 2u_{nj}(k) + 2\left( \frac{R - L_{eq}}{T_f} \right) i_j(k) + \frac{2T_f}{L_{eq}} i_j(k + 1)
\]  

(11)

To generate the OVL of \( 2N + 1 \), the traditional method cannot be used to calculate the number of SMs inserted into the upper and lower bridge arm because the number of SMs put in by one bridge arm of the MMC is no longer fixed to \( N \).

![Figure 3](image-url) Control principle diagram of improved two-stage model predicitive control

At this time, another method is used to calculate the input SM numbers of the lower bridge arm. Ideally, the capacitor voltage \( u_j \) is equal to its normal value \( \frac{V_{dc}}{N} \). The number of input SMs \( n_{pj1} \) of the upper bridge arm is written as

\[
n_{pj1} = \text{round} \left( \frac{V_{dc} - u_j}{2V_{dc}/N} \right)
\]  

(12)

Then write out the ideal ac-side OCC level \( j \) as follows:

\[
level_j = \frac{\text{round} \left( \frac{Nn_{pj1} V_{dc}}{V_{dc}} \right) - n_{nj1} - n_{pj1}}{2}
\]  

(13)

Therefore, in order to produce the ideal normalised OVL of the ac-side, the number of SMs input by the lower arm \( n_{nj1} \) is given by Equations (12) and (13) and is provided as

\[
n_{nj1} = 2level_j + n_{pj1}
\]  

(14)

CCC: The balance of the circulating current and the SM capacitor voltage cannot be properly controlled simultaneously but can be realised by adjusting the reference value of the circulating current. Two circulation factors \( \Delta i_{\text{c1}} \) and \( \Delta i_{\text{c2}} \) are introduced in this paper. One controls the voltage difference of the bridge arm and the other controls the sum of the bridge arm voltage. Unlike any previous work, the circulation factor is no longer generated by PI control, but it is directly calculated by the discrete mathematical model of the MMC. In general, when the CVC is not considered, the reference value of the circulating current is set as \( i_{dc}/3 \). Here, the circulation base is set as \( i_{\text{c1}} \) and \( i_{\text{c2}} \), where \( i_{\text{c1}} = i_{dc}/3 + \Delta i_{\text{c1}} \) and \( i_{\text{c2}} = i_{dc}/3 + \Delta i_{\text{c2}} \). According to Equation (10), the sum SM capacitor voltages of the upper and lower bridge arms are obtained, and the addition and subtraction operations are performed to get the difference of voltage between the bridge arm \( u_{\Delta j}(k + 1) \) and the sum of the bridge arm voltage \( u_{\Delta j}(k + 1) \):
\[ u_{\Delta j}(k + 1) = \sum_{j=1}^{N} [u_{cjy}(k + 1) - u_{cpp}(k + 1)] \]  

(15)

\[ u_{\Sigma j}(k + 1) = \sum_{j=1}^{N} [u_{cpp}(k + 1) + u_{cjy}(k + 1)] \]  

(16)

It can be seen from reference [10] that the voltage of any phase bridge arm in the MMC three-phase bridge arm varies from 0 to 2\(V_{dc}\). So the reference values of \(u_{\Delta j}(k + 1)\) and \(u_{\Sigma j}(k + 1)\) are set to 0 and 2\(V_{dc}\), respectively. The following formulas are given according to the reference values of the bridge arm voltage, circulating current, and the ac-side current measurement:

\[ 0 = u_{\Delta j}(k) + m u_{\Delta j}(k) i_{cirj}(k) - \frac{1}{2} m n s_{\Sigma j}(k) i_{j}^{*}(k) \]  

(17)

\[ 2V_{dc} = u_{\Sigma j}(k) + m n s_{\Sigma j}(k) i_{cirj}(k) - \frac{1}{2} m n u_{\Sigma j}(k) i_{j}^{*}(k) \]  

(18)

where \(m = T_{s}/C\). Equations (17) and (18) are used to calculate the two circulation factors, \(\Delta i_{cirj1}\) and \(\Delta i_{cirj2}\). Further simplification shows that the difference between the upper and lower bridge arm SMs \(n_{\Delta j} = 2\text{level}_{j}\), and the total SMs input \(n_{\Sigma j}\) is replaced by \(N\). Therefore, \(\Delta i_{cirj1}\) and \(\Delta i_{cirj2}\) can be calculated as

\[ \Delta i_{cirj1} = -\frac{1}{2m\text{level}_{j}} u_{\Delta j}(k) - \frac{i_{dc}}{3} + \frac{N}{4\text{level}_{j}} i_{j}^{*}(k) \]  

(19)

\[ \Delta i_{cirj2} = -\frac{1}{mN} u_{\Sigma j}(k) + \frac{\text{level}_{j}}{N} i_{j}^{*}(k) + \frac{2}{mN} V_{dc} - \frac{i_{dc}}{3} \]  

(20)

Considering the CVC of the bridge arm and the whole system, if the results calculated by Equations (19) and (20) are directly brought into the reference value of the circulating current, even harmonic component will be introduced, which is unfavourable to the whole system control. Thus, a circulating current restrictor is added. The amplitude is designed according to the steady-state requirements of the capacitor voltage. The reference value of the circulating current is finally expressed as

\[ i_{cirj}^{*}(k + 1) = \frac{i_{dc}}{3} + \text{Restrictor}(\Delta i_{cirj1} + \Delta i_{cirj2}) \]  

(21)

The reference value of the circulating current \(i_{cirj}^{*}(k + 1)\) in Equation (9) is changed to its reference value, and the reference value of the optimal voltage sum of the bridge arm \(u_{\Sigma j}(k)\) is calculated by inverse deduction:

\[ u_{\Sigma j}(k) = V_{dc} - \frac{2L_{f}}{T_{s}} [i_{cirj}^{*}(k + 1) - i_{cirj}(k)] \]  

(22)

The total input SM numbers of the bridge arm \(n_{\Sigma j}(k)\) is obtained by dividing the bridge arm voltage by the average capacitor voltage of the SM, and it is rounded by the nearest level control (NLC) expressed as

\[ n_{\Sigma j}(k) = \text{round} \left( \frac{u_{\Sigma j}(k)}{V_{dc}/N} \right) \]  

(23)

To avoid affecting the control of the ac-side current measurement during the CCC, the number of SMs of the bridge arm input or bypass should be the same when the upper and lower bridge arms carry out the CCC. Therefore, the number of SMs \(n_{pj2}\) and \(n_{nj2}\) finally put into the operation of the upper and lower bridge arms are as follows:

\[ n_{pj2} = n_{pj1} + \frac{n_{\Sigma j}(k) - (n_{nj1} + n_{pj1})}{2} \]  

(24)

\[ n_{nj2} = n_{nj1} + \frac{n_{\Sigma j}(k) - (n_{nj1} + n_{pj1})}{2} \]  

(25)

After calculating the number of SMs of the optimal control input, the implementation of the first stage control is described in the following steps, and the flow chart is shown in Figure 4.

1. The ac-side output current \(i_{j}(k)\), circulating current \(i_{cirj}(k)\), and the SM capacitance voltage \(u_{cjy}(k)\), respectively, are measured at \(k\) time.
2. According to Equations (12)–(14), the number of SMs \(n_{pj1}\) and \(n_{nj1}\) for the upper and lower arms of the ac-side OCC are calculated.
3. The two circulation factors \(\Delta i_{cirj1}\) and \(\Delta i_{cirj2}\) are calculated by Equations (15)–(20), and the reference value of the circulating current \(i_{cirj}^{*}(k + 1)\) is calculated with a current limiter.
4. The reference value of the optimal voltage sum of the bridge arm \(u_{\Sigma j}(k)\) is calculated by the inversion of Equation (9), and the total number of SMs input by the upper and lower bridge arms is calculated according to Equation (23).
5. Combined with the number of SMs put into the ac-side, the number of SMs \(n_{pj2}\) and \(n_{nj2}\) of the upper and lower bridge arms finally put into the first stage control are calculated according to Equations (24) and (25).

Compared with the method in [22], the first stage control proposed here does not need to select the optimal input number of SMs through the cost function, thus avoiding the selection of weighting factors. Moreover, with the increase in the number of SMs, the calculated amount is further reduced. In terms of the OVLs, the THD performance of the MMC is improved by increasing \(N + 1\) levels to \(2N + 1\) levels.
3.2.2 | The second stage control

Any digital control system will have a common problem, and there will be latency caused by a sampling period delay. Therefore, compensation is required. Otherwise, the performance of the control system cannot be guaranteed. This delay can be easily compensated by predicting the value at \( k + 2 \) time as an advantage of the MPC scheme. The number of the optimal input SMs is calculated in the first stage control. The number of the upper and lower bridge arm SMs is added or subtracted by one SM to form an optimal control group. The control options are shown in Table 1.

In order to evaluate the prediction performance when \( t = (k + 2)T_s \), the objective function \( J \) is defined as

\[
J = \left| i_j^*(k + 2) - i_j(k + 2) \right| + \left| i_{cirj}^*(k + 2) - i_{cirj}(k + 2) \right|
\]

(26)

where \( i_j^*(k + 2) \) and \( i_{cirj}^*(k + 2) \) are the reference values of the ac-side current and circulating current at \( k + 2 \) time, \( i_j(k + 2) \) and \( i_{cirj}(k + 2) \), are the predicted values of the ac-side current and circulating current at \( k + 2 \) time, respectively. The value of \( k + 2 \) time is extrapolated by using the third-order Lagrange extrapolation algorithm. Taking the ac-side measured output current as an example, the formula is as follows:

\[
i_j^*(k + 2) = 4i_j^*(k + 1) - 6i_j^*(k) + 4i_j^*(k - 1) - i_j^*(k - 2)
\]

(27)

Since the SM capacitor voltage changes relatively slowly, the objective function does not need to include the quantities of the single capacitor voltage ripple control. After evaluating the five control options, the minimum objective function is selected to output the number of SMs, \( n_{pj3} \) and \( n_{nj3} \), for the optimal input of the upper and lower bridge arms.

After deriving the number of input SMs, the RSF algorithm is used to generate the switching signal. In the RSF capacitor voltage balance algorithm, the previously used SM will not be re-applied for the next period. In case the SM was not used in the previous period, the bypassed SM will be selected and put in. The flowchart of the proposed second stage control is shown in Figure 5. By using the proposed TSMPC method, the OVL is increased and the amount of calculation can be reduced.

### 3.3 | Comparison between different MPC methods

For the traditional SSMPC method, multi-objective control depends on the steps of cost function minimisation. It is necessary to predict the values of \( i_j(k + 1), i_{cirj}(k + 1), \) and \( u_{cirj}(k + 1) \) for each control option. The optimal control scheme is selected by comparing the values of each cost function. With the increasing number of control options, the amount of calculation will also increase. In addition, the weighting factor in the cost function is not easy to be determined in [7].

Meanwhile, the traditional TSMPC methods, whether in the first stage control or the second stage control, rely on the cost function. In both the methods represented in [22, 25], although the control options are further reduced, the selection of the weighting factors in the cost function should be considered, and the OVL is only \( N + 1 \).

In contrast, the proposed TSMPC with low computational complexity does not need to consider the problem that the weighting factor is difficult to set. In the first stage control, by introducing two circulation factors \( \Delta i_{cirj1} \) and \( \Delta i_{cirj2} \), the optimal voltage difference and the voltage sum of the bridge arms are directly calculated. So, the optimal number of input SMs of the first stage control is calculated. In the second stage control, according to the optimal number calculated in the early stage, the number of upper and lower SMs is added or subtracted by one SM to determine an optimisation group. The reference value of the ac-side current and circulating current at \( k + 2 \) moment is calculated, which is substituted.
into the objective function to calculate the minimum value of the objective function and the number of SMs finally put into the output.

In order to quantitatively analyse the computational complexity of the proposed control method, Table 2 lists the comparison of the number of control options and the output level of different MPC methods. With the increase in the number of SMs, the amount of calculation will increase considerably. However, no matter how many SMs grow, the control options are always five and the OVL is $2N + 1$.

## 4 | SIMULATION RESULTS

In order to verify the correctness and feasibility of the control strategy, the system simulation model shown in Figure 1 is established in Matlab/Simulink, and the control algorithm block diagram is shown in Figure 6. To facilitate the analysis, the MV system with 8 kV ac-side is selected, and the simulation parameters are given in Table 3. The control method proposed here is compared with the traditional TSMPC method, and the system parameter settings are consistent.

As shown in Figure 6, the control structure of the system mainly includes the calculation of the three-phase current setting value and the two-stage control to obtain the optimal number of SMs for the upper and lower bridge arm input and the SM capacitor voltage RSF control. The optimal output level number of the two-stage control is obtained according to the control method proposed here.

### 4.1 | Traditional TSMPC method

The traditional TSMPC method in reference [25] is shown in Figure 2. The weighting factors $\lambda_1$, $\lambda_2$, $\lambda_3$ and $\lambda_4$ of the ac-side current, circulating current and the bridge arm SM capacitor voltage in cost function $J_1$ and $J_2$ need to be adjusted iteratively to determine the optimal value. The weighting factor in the cost function needs to be adjusted continually. Hence, it is challenging to design accurately, and the three control objectives will affect each other. So it is difficult to achieve the optimal control of each objective. According to reference [26], the selection of weighting factors is finally determined as...
Table 3: Simulation parameters of the MMC system

| Parameters                                      | Values |
|------------------------------------------------|--------|
| Grid voltage $u_a$/kV                          | 8      |
| DC-link voltage $V_d$/kV                       | 20     |
| Normal value of capacitor voltage $u_c$/kV     | 2      |
| The ac-side inductance $L_a$/mH                | 2      |
| The ac-side resistance $R_a$/Ω                 | 0.01   |
| Arm inductance $L_a$/mH                        | 20     |
| SM capacitance C/mF                            | 3.5    |
| Number of submodules per arm $N$               | 10     |
| Power factor angle $\varphi$/$^\circ$         | 0      |
| Control cycle $Ts$/μs                          | 100    |

Abbreviation: MMC, modular multilevel converter.

Figure 7: Traditional two-stage model predictive control method. (a) The output current and given value of the ac-side, (b) Three-phase ac-side output currents, (c) AC component of three-phase circulating currents, (d) Phase submodule capacitor voltages.

$\lambda_1 = 1$, $\lambda_2 = 0.5$, $\lambda_3 = 2 \times 10^{-5}$ and $\lambda_4 = 8 \times 10^{-5}$. The initial operation of the system is steady. Given the active power $P^* = 8$ MW and reactive power $Q^* = 0$ MW, when $t = 0.3$ s, the active power $P^*$ suddenly changes to 4 MW. The simulation results of the system are shown in Figure 7 and Figure 8.

Figure 7 shows the output current and given value of the ac-side, three-phase ac-side output currents, AC component of the three-phase circulating currents, and all the SM capacitance voltages of the upper and lower bridge arm. It can be seen from Figure 7(a) and Figure 7(b) that the output current of the ac side changes with the given value, and the tracking performance is good. The THD of the three-phase output current is 2.36% in Figure 11(b). The circulating current fluctuates wildly and contains the second harmonic, as shown in Figure 7(c).

Although the fluctuation amplitude of the capacitor voltage of

Figure 8: Traditional two-stage model predictive control method. (a) Trigger signal of submodules (SMs) and (b) Input number of SMs.

Figure 9: Improved two-stage model predictive control method. (a) The output current and given value of the ac-side, (b) Three-phase ac-side output currents, (c) AC component of three-phase circulating currents, (d) Phase submodule capacitor voltages.
the SM is less than 8%, its dynamic performance is not very good, as shown in Figure 7(d).

Figure 8 shows the trigger signal and input number of SMs. According to the calculation of the SM trigger signals, the MMC average switching frequency of the traditional TSMPC method is 175 Hz, as shown in Figure 8(a). Because the number of input SMs is limited to \( N \) in Figure 8(b), the OVL is only \( N + 1 \). The THD of the ac-side output voltage is 19.38% in Figure 11(a).

4.2 Proposed TSMPC method

To solve the above problems, a TSMPC method is proposed and verified by simulation. With the same simulation parameters as the traditional TSMPC, the system simulation results are shown in Figure 9 and Figure 10.

Figure 9 shows the output current and given value of the ac-side, three-phase ac-side output currents, AC component of the three-phase circulating currents, and the SM capacitance voltages of the upper and lower bridge arms. Compared with Figure 7(a), it can be seen that the ac-side output current tracking accuracy is higher in Figure 9(a). The THD can be reduced to 0.82% in Figure 11(d). It can quickly respond to the system step change with a promised dynamic performance, as shown in Figure 9(b). Here, the two circulation factors are set to 1. Compared with the circulation in Figure 7(c), the AC component of the three-phase circulating currents are better controlled, achieving a better suppression effect in Figure 9(c). The problem of energy imbalance between the bridge arms is reduced so that the SM can be electrically powered and the capacitance-voltage fluctuation decreases in Figure 9(d).

Figure 10 shows the trigger signal and input number of SMs. According to the SM trigger signals of the converter in Figure 10(a), the MMC average switching frequency of the improved TSMPC method is 226 Hz. Compared with the traditional TSMPC, although the MMC average switching frequency has increased, its circulating current ripple is smaller. Because the total number of input SMs in each phase is not limited to \( N \), the maximum level output of \( 2N + 1 \) can be achieved, as shown in Figure 10(b). The THD of the ac-side output voltage can be reduced to 12.44% in Figure 11(e).

5 EXPERIMENTAL VALIDATION

To verify the correctness of the control method in this article, a semi-physical real time hardware-in-the-loop simulation test platform was built, as shown in Figure 12. The chassis on the right of the picture is the StarSim real time simulator of Far Wide Energy, and to the left of the picture is the DSP controller of the real inverter. The DSP is mainly responsible for the process of prediction and optimisation.

Users can use MATLAB’s Simulink tool to load the MMC model they built and run it with the DSP controller through physical wiring in a closed loop. The feature of the StarSim real time simulator is that it can use a field programmable gate array (FPGA) to realise 1 \( \mu \)s small step simulation of arbitrary topology. Execute the sorting algorithm of the SM capacitor voltage balance through FPGA, and distribute multiple pulse signals to control the switching state of the SM. The experimental parameters are shown in Table 4.
5.1 Steady-state and dynamic-state performances of the traditional TSMPC method

Figure 13 is the verification result of steady-state and dynamic-state performances of the traditional control strategy on the real-time simulation experiment platform (real-time waveform observed by the oscilloscope).

Figure 13(a) are the grid voltage and the ac-side output current waveform of the converter, Figure 13(b) is the upper and lower arm current and the AC component of the circulating current waveform, Figure 13(c) is the SM capacitor voltage waveform, Figure 13(d) is the output voltage level waveform. Before 200 ms, the reference value of the output current is set to 6 A. The actual output current completely follows its reference value, as shown in Figure 13(a). The THD of the output current is 3.41%. As shown in Figure 13(b), the ripple of the AC component of the harmonic circulation has not been well suppressed. It can be seen in Figure 13(d) that the OVL is only five due to the limited input number of SMs. The THD of the ac-side output voltage is 19.32%.

In order to verify its dynamic performance, the reference value of the output current is reduced by 50% at 200 ms. The output current reaches the reference value of its change within about 0.6 ms. The effect of circulation is worse than that in steady state. It can be seen from Figure 13(d) that the SM capacitor voltage can be kept balanced whether it is in steady-state or dynamic-state performances.

5.2 Steady-state and dynamic-state performances of the proposed TSMPC method

The steady-state and dynamic-state performances of the MMC by using the proposed TSMPC are displayed in Figure 14.
Similarly, the reference value of the output current is set to 6 A. It can be seen from Figure 14(a) that the control method in this paper can operate stably, and the ac-side output current waveform is of good quality. The THD of the output current is 1.91%. Due to the introduction of the circulation injection method, the two circulation factors ΔI_{circ1} and ΔI_{circ2} are set to ±0.2 A, respectively. It can be seen from Figure 14(b) and 14(c) that the ripple of AC component of circulating current is small, and the SM capacitor voltage achieves balance. Since the number of SMs is not limited to N, it can be seen from the OVL waveform of Figure 14(d) that the output is nine levels, which realises 2N + 1 levels, thereby better suppressing the harmonics. The THD of the ac-side output voltage can be reduced to 11.41%.

The reference value of the ac-side output current is reduced by 50%, which verifies its good dynamic performance. The ac-side output current can be quickly adjusted to its new reference value. Compared with the traditional TSMPC, the ripple of the AC component of the circulating current is smaller, which helps to reduce the power loss of the MMC. As shown in Figure 14(c), the SM capacitor voltage keeps a good balance during steady-state and dynamic-state performances.

6 | CONCLUSION

Here, an improved TSMPC method without considering the difficulty of adjusting the weighting factor in the cost function is proposed. The performance and effectiveness of the method are verified by using massive MMC three-phase simulations and a single-phase hardware-in-the-loop experiment. Compared with the traditional TSMPC method, it has the following advantages:

1. In the first stage control, the ac-side OCC and CCC are decoupled without interaction. It avoids the problem that the weighting factor of the cost function is difficult to adjust in the second stage control.
2. In the ac-side OCC of the first stage control, the number of input SMs is not limited to N, and the OVL is increased to 2N + 1.
3. In the second stage control, the five control options for optimisation are sufficient, which are irrelevant to the number of SMs. In this way, the amount of calculation can be greatly reduced.

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