Hybrid Predictive Control with Simple Linear Control Based Circulating Current Suppression for Modular Multilevel Converters

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Abstract—The modular multilevel converter (MMC) has become a promising topology for widespread power converter applications. However, an evident circulating current flowing between the phases will increase system losses and complicate the heatsink design. This paper proposes a novel hybrid model predictive control method for MMCs. This method utilizes an indirect structure MPC and a sorting algorithm to implement current tracking and capacitor voltages balancing, considerably resulting in reduced calculation burden. In addition, different from the conventional MPC solutions, we add a simple proportional-integral (PI) controller to suppress circulating current through modifying the submodule (SM) inserted number, which is parallel to the MPC loop. This hybrid control solution combines both advantages of MPC and linear control, evidently resulting in improved performance of circulating current. Finally, the MATLAB/Simulink results of an 11-level MMC system verify the effectiveness of the proposed solution.

Index Terms—Circulating current suppression, hybrid predictive control, linear control, modular multilevel converters.

I. INTRODUCTION

Due to their advantageous good modularity, ease of scalability, low harmonics and voltage stress \( \frac{du}{dt} \), modular multilevel converter (MMC) has become a promising topology and are widely used in high-voltage and high-power power electronics applications, e.g. high-voltage direct current (HVDC) transmission and medium-voltage motor drives [1]–[4].

However, a significant drawback of an MMC is the inevitable internal circulating current flowing between the phases [2], due to its physical structure and operational characteristics. The existing internal circulating current will significantly increase system losses and shorten the system life-span, particularly for high-power applications. Apart from circulating current suppression (hereafter referred to as control objective-(a)), good current tracking (hereafter referred to as control objective-(b)) and capacitor voltage balancing (hereafter referred to as control objective-(c)) are the other primary control targets, for both HVDC and medium-voltage motor drives.

Recently, to tackle the above mentioned three control objectives, researchers and engineers have proposed many modulation strategies and different control solutions, most of which are based on conventional proportional-integral (PI) controller or proportional-resonant (PR) controllers [5]–[8]. E.g., the authors in [5] proposed a PI-based multi-goal control solution, which governs the aforementioned three control tasks with three individual PI controllers. Although it is computationally simple, the control performances of each objective will be inevitably coupled and mutually affected. Additionally, as a well-known drawback, the non-decoupling PI controller will lead a steady-state error in tracking a sinusoidal signal. To overcome these drawbacks, the authors in [8] decoupled the three-phase circulating currents and transformed them into a rotating dq-frame. Then the d- and q-components of the circulating currents were controlled separately. However, the complex coordinate transformation process will significantly increase the calculation burden for the processor and there after it is difficult to implement.

The author in [9] proposed a proportional-resonant controller to suppress the harmonic component of circulating current with a selected frequency (twice fundamental frequency). This method can effectively suppress the circulating current and does not require the coordinate transformation process. Nevertheless, the PR-based method requires careful parameters design and predetermined frequency information of the circulating current components [10], which considerably increase the system design difficulty. The authors in [10] presented a dc-link voltage compensation method to suppress circulating current in the MMC, in which only the simple PI controller is used. However, it is difficult to simultaneously include the above-mentioned three control objectives within these solutions, and the system control dynamics are therefore sacrificed to a certain extent via these cascaded (linear) controller-based approaches.

Model predictive control (MPC) has emerged as an effective control alternative for complex and multi-goal power
electronic systems, including the underlying MMC power converters [3]. Different from the aforementioned methods, MPC is inherently suitable to deal with nonlinear dynamics with multiple control targets [11]. It has the chance to directly manipulate switching positions without requiring a modulator, and has therefore very fast dynamic response and straightforward realization. Initially in [12], the authors proposed a direct-structure MPC controller to simultaneously deal with the aforementioned three control targets with a single cost function, with which weighting factors are used to penalize each of these control objectives. The switching state which minimizes the cost will be selected to be assigned to the converter. However, such an MPC solution is impractical to apply to the control of an MMC with many SMs, due to its expensively huge computational burden.

In [13], an indirect MPC was proposed, which employs the SM inserted number as the input instead of all possible switching states, resulting in evidently reduced computational efforts. Additionally, a so-called “sorting algorithm” [3] is used to balance capacitor voltage. The authors in [14] proposed a sequential structure MPC method, in the frame of the indirect MPC solution. This solution is very interesting to apply MPC for MMCs. In [15], the authors compared the performances of the existing MPC methods and the PIR controller for MMCs. The results show that the MPC method has better current tracking performance and dynamic response. However, the PIR controller presents lower circulating current oscillations than the MPC method. This is because, with either the direct MPC or indirect MPC with sequential optimization mode, it will inevitably sacrifice the circulating current suppression performance, due to the restricted and weighted control efforts allowed to this control objective (i.e., control objective-(a)) within the cost function(s). Different from the sequential mode MPC solution, the author in [16], [17] proposed a parallel MPC method to govern multiple objectives without designing the weighting factors, which avoids the weighted control efforts between these goals.

Inspired by the parallel-structure control solution, we propose a new hybrid MPC solution with parallel structure for MMCs, i.e., an indirect MPC is employed to deal with the control objectives of (b) and (c), while control objective-(a) is governed via a simple PI controller. Thus, both the advantages of MPC in dealing with multiple control objectives, and the properties of a computationally efficient linear controller with better circulating current performance are combined together. The major contributions of this paper are collected as follows.

(i) Different from the conventional MPC method, we parallelly add a PI controller in the frame of the indirect MPC solution, resulting in considerably reduced computational efforts and improved performance of circulating current (see Fig.6 in Sec. V) for modular multilevel converters.

(ii) Compared to the sequential optimization mode in the existing MPC methods, the proposed hybrid MPC with hybrid and parallel structure will simultaneously include the three control targets without performance deterioration (see Fig.5 (a), Fig.6 - Fig.8 in Sec. V).

(iii) A very thorough modeling of MMCs with half-bridges and a detailed comparison investigation of the proposed hybrid MPC and the classical MPC approaches are carried out, and verified with simulation results for an 11-level MMC topology, considering both the steady-state and transient control performances.

This paper is structured as follows: Sec. II states the principle and mathematical models of an MMC. Sec. III revisits the indirect MPC method. In Sec. IV, the proposed hybrid MPC solution, combined with a linear circulating current suppression control loop, is presented. Sec. V reports the comparative results and their analysis. Finally, Sec. VI concludes this work.

II. PRINCIPLE AND MATHEMATICAL MODEL OF THE MMC

A. Operational Principle of an MMC

Fig. 1 shows a simplified three-phase MMC system, where each phase-j (j = a, b, c) leg comprises an upper arm and a lower arm. Each arm consists of \( N \) identical submodules and an arm inductance \( L_{arm} \) connected in series. The arm inductances provide passive current control and suppress the circulating current flowing in the arm. The most widely used submodule type is the half-bridge SM, which is composed of a capacitor and two IGBTs switches, \( S_x \) and \( S_x \) (x = 0, 1, ..., 2N). The half-bridge SM can provide two voltage levels at its output terminals, i.e. zero or \( U_c \) (capacitor voltage of the SM), which depends on the switching states of the two IGBTs.

Assuming that the capacitor voltages of all SMs are balanced, the capacitor voltage \( U_c \), the upper and lower arm voltage \( U_{pj} \) and \( U_{nj} \) and the output voltage \( U_j \) of phase-j can be written as

\[
\begin{align*}
U_c &= \frac{U_{dc}}{N} \\
n_{pj} &= N_{pj} \\
n_{nj} &= N_{nj} \\
U_j &= U_{nj} - U_{pj} \\
U_j &\approx \frac{U_{nj} - U_{pj}}{2}
\end{align*}
\]

where \( N_{pj} \) and \( N_{nj} \) represent the number of SMs inserted into the upper and lower arms respectively. According to (1), the
output levels of \( N \) SMs in the same arm can constitute an \((N + 1)\)-level output voltage waveform. For a selected voltage level, redundant switching states will always exist, which provides the possibility of circulating current suppression and capacitor voltage balancing [3], [18].

B. Modeling and Circulating Current Analysis

Fig. 2 shows the equivalent model of an MMC system, which describes the current paths and uses an equivalent voltage source to represent the output voltage of each arm. According to Fig. 1, Fig. 2, KVL and KCL, the equations describing current and voltage of phase-\( j \) can be written as

\[
i_j = i_{pj} - i_{nj},  \tag{2}
\]

\[
i_{nj} = i_{njl} + \frac{i_{njc}}{3} = i_{njl} + \frac{i_{njc} + i_{nj}}{2}, \tag{3}
\]

\[
\begin{align*}
    &u_{pj} + L_{arm} \frac{di_{pj}}{dt} + L \frac{di_j}{dt} + i_j R + u_j = \frac{U_{dc}}{2}, \\
    &u_{nj} + L_{arm} \frac{di_{nj}}{dt} - L \frac{di_j}{dt} - i_j R - u_j = \frac{U_{dc}}{2}
\end{align*} \tag{4}
\]

where \( i_j \) and \( i_e \) represent the AC output current and the circulating current, respectively, while \( i_{pj}, i_{nj}, u_{pj}, u_{nj} \) and \( u_j \) are the currents and voltages of the upper and lower arms, respectively. The circulating current consists of the dc and ac components. The dc component represents (outer circulating current) the energy supplied from the dc-side to ac-side. The ac components (internal circulating current, most with twice fundamental frequency) are caused by unbalanced three-phase voltages, which merely flow between the three phases and will not influence the output current. The internal circulating current will significantly increase system losses and heat, and it should be effectively eliminated suppressed.

Based on (2)-(4), the equations of output current and circulating current can be written as

\[
(L_{arm} + 2L) \frac{di_j}{dt} + 2i_j R = u_{nj} - u_{pj} - 2u_j, \tag{5}
\]

\[
2L_{arm} \frac{di_{nj}}{dt} = U_{dc} - (u_{nj} + u_{pj}). \tag{6}
\]

III. INDIRECT MPC FOR THE MMC

In this section, the indirect structure sequential MPC is developed as a preliminary demonstration and the foundation of the proposed hybrid MPC solution.

- First Stage: Current Control
  - Cost Fun \( J_i \) Minimization
  - \( N_{arm} \) Sorting Algorithm
  - MPC Current Control Loop

- Second Stage: Circulating Current Control
  - \( N_{arm} \) Sorting Algorithm
  - PI-based Circulating Current Loop

(a) The indirect MPC algorithm with sequential optimization mode

(b) The proposed hybrid MPC solution with parallel-loop control.

Fig. 3. The block diagrams of the indirect MPC and the hybrid MPC.

Primarily, utilizing the first order forward Euler method, the discrete-time equation of output current and circulating current can be written as

\[
i_j(k+1) = \frac{1}{2T_e R + 2L + L_{arm}}((L_{arm} + 2L) \cdot i_j(k)) + T_e (u_{nj}(k+1) - N_{pj}(k+1) - 2u_j(k)), \tag{7}
\]

\[
i_j(k+1) = i_j(k) + \frac{T_e}{2L_{arm}}(U_{dc} - u_{nj}(k+1) - u_j(k+1)). \tag{8}
\]

In (7) and (8), \( u_{pj}(k+1) \) and \( u_{nj}(k+1) \) are the predicted values of output voltages of the upper and lower arm in the next period, which are determined by the switching states of all SMs. The initial MPC solutions proposed in [12] consider all possible switching states in the cost functions to regulate three control targets, which are impractical for the control of an MMC due to the significantly increased computational burden with the increased SMs. The indirect structure MPC proposed in recent years effectively reduce the computational effort of the MPC algorithm for MMCs. Thereafter, we will discuss the principle and implementation of this concept in the following.

Under the assumption that the all SM capacitor voltages are balanced, the expression of output current and circulating current can be rewritten as

\[
i_j(k+1) = \frac{1}{2T_e R + 2L + L_{arm}}((L_{arm} + 2L) \cdot i_j(k)) + T_e (N_{nj}(k+1) - N_{pj}(k+1)) \cdot U_e - 2u_j(k)), \tag{9}
\]

\[
i_j(k+1) = i_j(k) + \frac{T_e}{2L_{arm}}(U_{dc} - (N_{pj}(k+1) + N_{nj}(k+1)) \cdot U_e). \tag{10}
\]

To optimize the output current and the circulating current,
then the cost functions are built as

\[ J_i = |i_i'(k) - i_i(k+1)|, \quad (11) \]

\[ J_z = \left| \frac{i_z(k)}{3} - i_z(k+1) \right|. \quad (12) \]

Different from the conventional MPC solutions, the indirect structure MPC method is implemented through selecting the predicted SM inserted number, \( N_{p1} \) and \( N_{n1} \), in the next period instead of all possible switching states, which is why we call it ‘indirect MPC’. The SM inserted number, \( N_{p1} \) and \( N_{n1} \), of the upper and lower arm merely need \( N+1 \) calculations instead of \( C_{2N}^N \), which significantly reduce the calculation burden and make it possible to apply the MPC in MMCs. In addition, the cost functions of the output current and circulating current are separated as (11) and (12), and then the multiple targets control is realized in a sequential mode, which avoids the tedious weighing factor design.

Fig. 3 (a) shows the block diagram of the indirect MPC, and the following steps summarize the indirect MPC strategy.

**Step 1:** In the first stage, the different results of cost function \( J_i \) with all possible SM inserted numbers are calculated and evaluated based on (9) and (11).

**Step 2:** Then the optimal SM inserted numbers \( N_{p1} \) and \( N_{n1} \) which can minimize the cost function \( J_i \) are selected. Then \( N_{p1} \) and \( N_{n1} \) are simultaneously superimposed with a margin \( K \) \((K = [-k,\ldots,0,\ldots,K])\) to increase the selection range for the second stage.

**Step 3:** Thereafter, in the second stage, the optimal \( N_{p2} \) and \( N_{n2} \) are respectively selected in the interval \([N_{p1} - k,\ldots,0,\ldots,N_{p1} + k]\) and \([N_{p2} - k,\ldots,0,\ldots,N_{p2} + k]\), where the \( k \) is determined by practical requirements. In this way, according to (1), the simultaneously superimposed margin \( K \) on \( N_{p1} \) and \( N_{n1} \) will not affect the output current control in the first stage.

**Step 4:** Finally, a sorting algorithm is utilized to balance the capacitor voltages and output switching signals.

This solution is promising for MPC applied in MMCs due to the smaller calculation requirements and straightforward design. Nevertheless, in this way, the hierarchical optimization mode will merely show excellent output current performance, but inevitably restrict the selection range and sacrifice the control effect for the second stage circulating current control.

**IV. PROPOSED HYBRID MPC WITH LINEAR CONTROL**

In this section, the proposed hybrid MPC is developed, which is combined with a linear control loop (PI controller-based) to eliminate/suppress the circulating current. Different from the indirect MPC introduced in III, this hybrid MPC adopts the parallel-loop structure to realize multiple targets control instead of sequential optimization mode, where the output current tracking and circulating current suppression is implemented by the indirect MPC and PI-based control loop respectively. The PI-based control loop is based on the averaging control concept proposed in [5].

The block diagram and float chart of the proposed hybrid MPC solution are shown in Fig. 3 (b) and Fig. 4 respectively, and the operation principle is explained as follows.

**Step 1:** In the MPC loop, same as before, the current tracking is realized based on (7) and (9). Then the selected optimal SM inserted number \( N_{p1} \) and \( N_{n1} \) is selected and sent to the sorting algorithm.

**Step 2:** In the PI-based control loop, the front-end PI controller maintains the average voltage \( \bar{U}_c \) of phase-j to the reference \( U_{c}^* \) \((U_{dc}/N)\), and generates the circulating current reference \( i_z^* \) for the post PI controller.

**Step 3:** Then the post PI controller calculates the real circulating current value based on (3) and maintains it to the reference value \( i_z^* \), through which the circulating current will be suppressed effectively. The outputs of the PI-based loop, \( i_z^* \), is also sent to the sorting algorithm to regulate the SM inserted number.

**Step 4:** Finally, the SM inserted numbers generated from the MPC loop are superimposed with the modified values \( u_z^* \) (after being rounded). Then the sorting algorithm is used to balance the capacitor voltages and output switching signals.

**V. VALIDATION**

In this section, we establish an 11-level \((N=10)\) MMC MATLAB/Simulink model to verify the effectiveness of the
proposed hybrid MPC solution. Both the indirect MPC and hybrid MPC solutions are implemented in the simulation model, and the comparison study focusing both on steady-state and dynamic performance is carried out. The parameters of the 11-level MMC system are summarized in Table I.

| Parameters                     | Value           |
|-------------------------------|-----------------|
| DC-link Voltage: \( U_{dc} \) | 1000 V          |
| Number of SMs in Each Arm: \( N \) | 10              |
| SM Capacitor: \( C_{sm} \)  | 5 mF            |
| Arm Inductance: \( L_{arm} \) | 3 mH            |
| Grid Resistance: \( R \)     | 30 Ω            |
| Grid Inductance: \( L \)     | 20 mH           |
| Grid Voltage Amplitude: \( U_g \) | 220 V        |
| Grid Current Amplitude: \( I_g \) | 10 A          |
| Sample Time: \( T_s \)       | 25 µs           |
| Margin in indirect MPC: \( k \) | 2               |
| PI parameters in hybrid MPC: \( K_{p1} \), \( K_{i1} \) , \( K_{p2} \), \( K_{i2} \) | 5, 1; 2, 0.5 |

A. Comparison of the steady-state performance

The steady-state performances of the indirect MPC and proposed hybrid MPC is indicated by output current, voltages, circulating current, arm current and capacitor voltages. Fig. 5-7 illustrate the corresponding results.

Figs. 5 (a) and (b) compare the output performances of the two methods, including the output currents and output voltages of the MMC. The amplitude of the reference current is set to 10 A and the simulation time is from 0.26 s to 0.3 s. As we can see, the output currents both of the indirect MPC and the proposed hybrid MPC are perfectly following their references and the THD of current are similar, 0.48% and 0.43% respectively. The output voltages both of the two methods show a step waveform with 11 \((N+1)\) levels.

In order to clearly observe the internal circulating current (ac component), we use a high-pass filter to remove the dc component \( i_{ch} \), where the pass band edge frequency is set to 1 Hz. As shown in the top of Fig. 6, the amplitude of circulating current is close to 10 A and the indirect MPC shows poor circulating current performance. The bottom of Fig. 6 shows the circulating current suppressing performance of the proposed hybrid MPC. The amplitude of the circulating current is reduced to about 2 A, which verifies the effectiveness of the hybrid MPC in circulating current suppression. Although the presence of the evident harmonic components in the circulating current, it reflects the frequent corrective action of the PI controller and the harmonic components will not degrade the output power quality according to the analysis in the Sec. II.

Figs. 7 (a) and (b) show the arm currents and capacitor voltages of the upper and lower arm of phase-a. In order to more clearly observe the steady-state arm currents and capacitor voltages, the simulation time is set from 0.26 s to 0.36 s. As shown in Fig. 7 (a), thanks to the considerably suppressed circulating current, it is observed that the arm currents of the hybrid MPC have lower ripple value (from -2 A to 9 A) than the indirect MPC (from -10 A to 15 A), and also has fewer harmonic components and smoother waveform. In addition, as shown in Fig. 7 (b), compared to the indirect MPC, the proposed hybrid MPC also has smoother capacitor voltages waveform, and the ripple amplitude is reduced from 4 V to 1 V (the voltage fluctuation from 4% to 1%).

All the results of the comparative analysis on the steady-state performance are summarized in the Table II. The lower circulating currents, smoother arm currents and capacitor voltages confirm the considerably improved steady-state performance of the proposed hybrid MPC.
B. Comparison of the dynamic performance

The dynamic performances of the indirect MPC and the proposed hybrid MPC are also tested in this section. Figs. 8 (a) and (b) show the output current and circulating current when a step of current amplitude reference (from 10 A to 5 A) occurred at 0.275 s. As can be seen, both methods show fast output current tracking response in the transient state, which confirms the good dynamic performance of MPC technique. However, as shown in the bottom of Figs. 8 (a) and (b), different from the indirect MPC method, the circulating current amplitude of the hybrid MPC decreased rapidly as the output current decreased, which reflects the better tracking and control ability for the circulating current of the proposed hybrid MPC method.

| THD (%) | $i_{cm}$ (A) | $\Delta u_c$ (%) |
|---------|-------------|------------------|
| IMPC    | 0.48        | 10               |
| HMPC    | 0.43        | 2                |

Fig. 7. Simulation results of (a) arm currents and (b) capacitor voltages.

VI. CONCLUSION

The modular multilevel converter has emerged as a promising topology and been widely employed in the areas of e.g. high-voltage direct current transmission systems, and medium-voltage motor drives. Due to its physical structure and the operation principles, multiple control objectives shall be well controlled simultaneously to achieve good potential of this topology. Among these control objectives, circulating current suppression is important. Predictive control, thanks to its very good properties of inclusion of multiple control objectives, fast control dynamics, and simple concept, has become a very good alternative in dealing complex (nonlinear) power electronic systems. However, very high computational efforts as well as sacrificed circulating current suppression control performances appear as two of the shortcomings.

This paper presents a novel hybrid MPC solution to improve the unsatisfying performance of circulating current suppression in the conventional MPC method. In the frame of the indirect MPC, we add a simple PI controller to suppress circulating current and adopt a parallel-loop structure to realize multiple targets control, which combines both the advantages of MPC and linear control. The proposed method does not require complex weighting factor design and has lower computational efforts, while achieves even better steady state control performances (the circulating current amplitude and the capacitor voltage ripple value are reduced from 10 A to 2 A, 4% to 1% respectively) with similarly fast control dynamics, in comparison with the classical predictive control approach.

Future work will focus on the extension of the proposed solution to back-to-back HVDC systems and four-quadrant medium voltage drives, with modular multilevel converters.

Fig. 8. Simulation results of dynamic performance of (a) the indirect MPC and (b) the proposed hybrid MPC.
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