Study of Modular Multilevel Converter in AC/DC Hybrid Distribution Network

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Abstract. The AC/DC hybrid power system plays an important role in the intelligent distribution network with the advantages of large power supply radius and capacity, low line cost and convenient distributed access. In this paper, a modular multilevel converter based on AC-DC side of AC/DC hybrid distribution network is exploited. An improved MPC sub-module capacitor voltage balance control method is proposed to reduce the calculation burden of MPC. The cost function is defined for phase currents, circulating currents, and sub-modules capacitor voltages. The weight factors of the cost function are eliminated, and the sub-module capacitor voltage control algorithm is improved to reduce the computational complexity of MPC. Not all cost functions for possible switching states combinations of MMC are calculated using improved method. The effectiveness of proposed improved method is evaluated based on 11 levels MMC system using Matlab/Simulink.

1. Introduction

At the end of the 20th century, with the development of power electronics technology, control technology and DC power supply technology, DC distribution network has been developed rapidly. Compared with AC distribution network, DC distribution network has significant advantages in distributed energy access, improving system efficiency, reducing line loss and operation cost, and increasing system capacity. If the two combination, will make the medium-low-voltage distribution network technology more flexible, better reliability [1].

Modular Multilevel Converter is a promising topology first proposed by A.Lesnicar and R.Marquardt of Federal Defense Force University in Munich, Germany in 2003. Compared with two-level and three-level converter, it has the characteristics of modular design, expansibility, high efficiency and high quality waveform [2]. Up to now, the topology is widely used in high voltage and high power applications, such as HVDC transmission system [3][4], static synchronous compensator[5][6], DC distribution network[7], motor drive application [8][9] and so on.

Modular Multilevel Converter require simultaneous control of phase current, internal circulation, and sub-module capacity voltages. therefore, they have more complex control strategy[10]. Over the past few years, the research on the control strategy of modular multilevel converter is mainly classical control method and pulse width modulation[11]-[13]. An open loop classical control method based on reference input and output voltage control Modular Multilevel Converter is proposed in[14]. For the modular multilevel converter, it is difficult to control the circulation suppression and maintain the capacitor...
voltage balance. There are many corresponding[15][16] to study it. The proportional integral (PI) controller is designed and adjusted by classical control method, and is used to control the circulation suppression of modular multilevel converter and the capacitor voltage balance control[17][18] of submodule.

Each control target corresponds to a PI controller in the classical control method, which makes its parameter adjustment more complicated. However, with the development of microprocessor, model predictive control is applied to power electronics and power drive[19]. Model predictive control can eliminate PI controller and save complex controller design process. Compared with the traditional control method, the model predictive control is easy to contain nonlinear characteristics and has the ability to deal with multiple variables because of its fast dynamic response[20][21]. As a result, scholars at home and abroad pay great attention to the of modular multilevel converter control[22].

For the first time, the model predictive control is successfully applied to the control of the modular multilevel converter in [23]. a number of control objectives of the modular multilevel converter, including phase current, circulation, and sub-module capacity voltage, are implemented through an objective function to calculate all possible switching state combinations of the sub-modules. When the number of sub-modules per bridge arm of a modular multilevel converter is N, the number of all possible switching state combinations of sub-modules needs to be considered in the model predictive control strategy. Therefore, with the increase of the number of sub-modules, the computational complexity of model predictive control will increase. in order to solve the computational complexity problem faced by the model predictive control strategy, proposes an improved model predictive control method with 22N switching state combinations for modular multilevel converter control. A predictive control control[24] packet sorting optimization model is proposed to control Modular Multilevel Converter, which can reduce the computational cost by grouping switch state combinations. another way to reduce computational complexity is the voltage level-based model predictive control method, which divides multiple targets of Modular Multilevel Converter into different controller corresponding to the objective function. A predictive control method based on indirect finite control set model for modular multilevel converter control is proposed the [26][27]. Combined with the traditional sub-module capacitor voltage sequencing balance control strategy. A three model predictive control controller is established in [28] to control the AC current, circulation and capacitance voltage of the modular multilevel converter by selecting the optimal value of the objective function.

A predictive control strategy for AC / DC hybrid distribution network using an improved modular multilevel converter sub-module capacitor voltage balance model is proposed. By improving the sub-module capacitor voltage balance control introduced, the number of switching state combinations is reduced and the computational complexity is reduced. Select an open sub-module at each rolling optimization of the objective function and repeat the selection according to the number of output voltage levels to determine the switching state of all sub-modules. Each bridge arm chooses to open the minimum number of sub-modules is 0, the maximum number is N/2, can effectively reduce the controller hardware and software resources. Finally, the simulation platform is established in the MATLAB/Simulink software, and the simulation analysis is carried out to verify the correctness of the proposed scheme.

2. Model predictive control strategy

2.1. Basic structure of modular multilevel converter

Figure 1 shows a three-phase modular multilevel converter topology. As can be seen from Figure1, the multilevel converter consists of three phase units, each of which can be divided into two bridge arms, upper and lower (represented by subscript u and l). N sub-modules connected in series with inductors form a bridge arm. Lam represents the bridge arm inductance that suppresses the circulation. the AC side of the modular multilevel converter is connected with the resistor R and inductor L the basic constituent unit of the modular multilevel converter is a sub-module (consisting of two IGBT (T1 and
T2) parallel diodes and dc energy storage capacitance C). If the sub-module is bypassed, its output voltage is zero; when the sub-module is put into operation, its output voltage is UC capacitance voltage.

![Figure 1. Three-phase MMC circuit topology](image)

### 2.2. Mathematical model of modular multilevel converter

According to the topology of the three-phase modular multilevel converter shown in Figure 2, the voltage equation can be obtained

\[
\begin{align*}
\frac{U_{dc}}{2} - v_{aj} - L_{arm} \frac{di_{aj}}{dt} + L \frac{di_j}{dt} + R_i \cdot i_{aj} &= 0 \\
-\frac{U_{dc}}{2} + v_{j} + L_{arm} \frac{di_{aj}}{dt} + L \frac{di_j}{dt} + R_i \cdot i_j &= 0
\end{align*}
\]

where the j is the A,B,C three phase units of the modular multilevel converter system. The \(v_{aj}\) is the AC side voltage and the \(U_{dc}\) is the dc side voltage. The \(v_{aj}\) and the \(v_j\) represent the controllable voltage sources of the upper and lower arm voltage, respectively.

By establishing the voltage equation of three-phase modularized multilevel converter, the upper and lower arm currents are obtained

\[
\begin{align*}
i_{aj} &= \frac{i_j + i_{aj}}{2} + i_{aj} \\
i_j &= \frac{i_j + i_{aj}}{2} + i_{aj}
\end{align*}
\]

The \(i_{aj}\) represents the circulation of j phase, and the \(i_j\) and \(i_{dc}\) are phase current and DC side current respectively.
According to (3) and (4), the relationship between internal unbalanced current, phase current and bridge arm current is

\[ i_{\text{diff}} = \frac{i_{uj} + i_{lj}}{2} = i_{uj} + \frac{i_{lj}}{3} \]  

(5)

\[ i_j = i_{uj} - i_{lj} \]  

(6)

Among them, the \( i_{\text{diff}} \) is the internal unbalanced current.

The external and internal dynamic characteristic equations of modularized multilevel converter system can be obtained by (1)-(6) as

\[ v_j - v_{ui} + L_{am} \frac{di_j}{dt} + 2L \frac{di_j}{dt} + 2Ri_j - 2v_{uj} = 0 \]  

(7)

\[ \frac{U_{dc}}{2} - v_{uj} + v_{lj} - L_{am} \frac{di_{\text{diff}}}{dt} = 0 \]  

(8)

Adjust the phase current of the modular multilevel converter to track the reference current. By using the forward Euler formula and the \( T_s \) as the sampling period, the phase current and the internal unbalanced current are discretized. The discrete time models are as follows

\[ i_j(t+T_s) = A \frac{v_j(t+T_s) - v_{uj}(t+T_s)}{2} + A' \frac{i_j(t)}{T_s} \]  

(9)

\[ i_{\text{diff}}(t+T_s) = B[\frac{v_j(t+T_s) + v_{uj}(t+T_s)}{2}] + i_{\text{diff}}(t) \]  

(10)

While

\[ v_{uj}(t+T_s) = \frac{v_j(t+T_s) - v_{uj}(t+T_s)}{2} \]  

(11)

Among them, \( A = 1/(A' T_s + R), A' = L / 2 + L, B = T_s / 2L_{am} \), \( i_j(t) \) represents the measured value of the phase current. Under ideal conditions, the AC-side active power and DC-side active power of the modularized multilevel converter are equal

\[ P_{ac} = P_{dc} = U_{dc} * i_{dc} \]

(12)

\[ i'_{dc} = \frac{P_{dc}}{U_{dc}} \]

(13)

According to [23], the capacitance voltage predicted by input and removal of sub-modules is

\[ U_{ui}(t+T_s) = \begin{cases} U_{ui}(t) + \frac{L_{ui}(t)}{C} \omega_1 T_s \\ U_{ui}(t) \end{cases} \]

(14)

where \( i_{um}(t) = i_{uj}(t) \) or \( i_{lj}(t) \) is the measured value of the bridge arm current at a time of \( t \). According to (9), (10) and (14), the objective function of a modular multilevel converter is

\[ J = \omega_1 \left[ (t+T_s) - i_j(t+T_s) \right]^2 + \omega_2 \left[ i_{\text{diff}}(t+T_s) \right]^2 + \omega_3 \sum_{i=1}^{N} \left( \frac{U_{ui}(i)}{N} - U_{ui} \right)^2 \]

(15)

where \( i_{j}(t+T_s) \) and \( i'_{dc} \) are the phase current and dc reference values, \( \omega_1, \omega_2 \) and \( \omega_3 \) are the weight coefficients of the objective function.

All possible switching state combinations for the next sampling period are predicted based on the output voltage of the modular multilevel converter. The switching state of each sub-module of the modular multilevel converter is predicted according to the next sampling period, and the corresponding phase current, circulation and sub-module capacitance voltage objective function values are calculated. Finally, the switch state corresponding to the minimum value of the objective function is taken as the switch state of the next control period.
The traditional model predictive control structure is simple and has good dynamic performance, but $C_{2N}^N$ possible switching state combinations must be considered for each bridge arm with a modular multilevel converter with $N$ sub-modules. Therefore, with the increase of the number of sub-modules, the traditional model predictive control is difficult to control the modular multilevel converter due to the increase of computational complexity. In addition, it is difficult to determine the weight coefficient of the objective function, and most of them are selected according to experience, which further affects the control effect of the modular multilevel converter.

3. Improved model prediction control method for modular multilevel converter

Three corresponding model predictive control controllers are established for phase current, internal circulation and capacitor voltage of modular multilevel converter. The proposed method eliminates the weight coefficient, and the structure is simple and easy to be digitized. The objective function of phase current of a modular multilevel converter is expressed as

$$J_i = \left| j_i(t + T_s) - j_i(t + T_s) \right|$$

where the output voltage reference value of the modular multilevel converter can be expressed as

$$v_{oj}^* = \frac{v_o - v_u}{2} = \frac{1}{2} \left( \sum_{j=1}^{N} U_{dc} S_{j} - \sum_{j=1}^{N} U_{dc} S_{j} \right)$$

can be rewritten

$$v_{oj}^* = \frac{U_{dc}}{N} \left[ \frac{N}{2}, \frac{N-1}{2}, \cdots, \frac{N-1}{2}, \frac{N}{2} \right]$$

where $S_{ij}$ and $S_{ujj}$ represent the switching state of the sub-module.

The phase current control flow chart is shown in Figure 2, Figure 3 shows the flow chart of circulation control, and Figure 4 shows the improved sub-module capacity voltage balance control flow:

![Flowchart of the ac-side current control](image)

The voltage reference value of the upper and lower bridge arms of the modular multilevel converter

$$v_{oj}^* = \frac{U_{dc}}{2} - v_{oj}^*$$

(19)
\[ v^*_{\text{dc}} = \frac{U_{\text{dc}}}{2} + v^*_{\text{ul}} \]  

(20)

can be rewritten

\[ v^*_{\text{dc}}, v^*_{\text{ul}} = \frac{U_{\text{dc}}}{N} \{0, 1, 2, \ldots, N-1, N\} \]

(21)

The predicted internal unbalanced current value is (10). The loop suppression is realized by \( U_{\text{diff}} \) level, \( U_{\text{diff}} \) as

\[ U_{\text{diff}} = \frac{U_{\text{dc}}}{2} \{-1, 0, 1\} \]

(22)

Therefore, the internal unbalanced current is:

\[ i_{\text{diff}}(t+T_s) = B[U_{\text{dc}} - \{v^*_{\text{g}}(t+T_s) + v^*_{\text{ul}}(t+T_s) + 2v_{\text{diff}}\}] + i_{\text{diff}}(t) \]  

(23)

\[ J_{\min} = \infty \]

\[ J_2 < J_{\min} \]

\[ v_{\text{diff}}(t+T_s) = k^* \left[ \frac{U_{\text{dc}}}{N} \right] \]

\[ i_{\text{diff}}(t+T_s) = \text{calculated according to formula} \]

\[ k=1 \]

\[ k=U_{\text{diff}} \text{ return loop} \]

\[ \text{Adapt} i_{\text{diff}} \]

\[ v_{\text{diff}}, v_{\text{ul}} \text{ calculated according to formula} \]

\[ N_{uj} \text{ and } N_{lj} \text{ of sub-modules input from upper and lower bridge arms} \]

\[ N_{uj} = \frac{v_{\text{diff}}}{U_{\text{dc}} / N} \]

(27)

\[ N_{lj} = \frac{v_{\text{diff}}}{U_{\text{dc}} / N} \]

(28)

Figure 3. Flowchart of the circulating current control

The objective function of the internal unbalanced current is:

\[ J_2 = \left| i_{\text{diff}}(t+T_s) - \frac{i_k}{3} \right| \]

(24)

Because of the control of the circulation, the reference voltage of the upper and lower arm of the bridge becomes:

\[ v_{\text{diff}}^* = v_{\text{diff}}(t+T_s) + v_{\text{diff}} \]

(25)

\[ v_{\text{ul}}^* = v_{\text{ul}}(t+T_s) + v_{\text{diff}} \]

(26)

Number \( N_{uj} \) and \( N_{lj} \) of sub-modules input from upper and lower bridge arms

Modular multilevel converter sub-module capacitor voltage objective function
The improved sub-module capacitor voltage balancing control is shown in Figure 4. As shown in Figure 4, if \( N_{uj} (N_{lj}) \) is equal to 0, all sub-modules are put in, resect all sub-modules if \( N_{uj} (N_{lj}) \) is equal to \( N \), then, the sub-module switch state combination is determined by rolling optimization. when \( N_{uj} (N_{lj}) > N/2 \), only the \( N_{uj} (N_{lj}) \) - \( N/2 \) sub-modules need to be selected input while removing all remaining sub-modules; when \( N_{uj} (N_{lj}) \leq N/2 \), only the \( N_{uj} (N_{lj}) \) sub-modules need to be selected input while removing all remaining sub-modules. hence, the number of switching state combinations of each bridge arm through the sub-module selected by the objective function is between 0 and \( N \times N/2 \). Finally, the average number of switching states considered by the sub-modules of each phase unit is \( N \times N/2 \).

The number of all possible switching state combinations of sub-modules for a single phase unit is listed in Table 1. where \( M_{uj} \) and \( M_{lj} \) represent the number of switching state combinations of sub-modules of upper and lower bridge arms of Modular Multilevel Converter, respectively.

### Table 1. Number of switching state combinations

| \( N_{uj}, N_{lj} \) | \( M_{uj}, M_{lj} \) | Total Quantity |
|----------------------|------------------|----------------|
| 0,0                  | 0,0              | 0              |
| 1,N-1                | 1\times N, 1\times N | 2\times N      |
| 2,N-2                | 2\times N, 2\times N | 4\times N      |
| \ldots               | \ldots           | \ldots         |
| N/2,N/2              | N/2\times N, N/2\times N | N\times N      |
| \ldots               | \ldots           | \ldots         |
Table 2 shows the number of switching states of each phase of a modular multilevel converter using different model prediction control methods.

| Control Strategy | Number Of Switch State Combinations |
|------------------|-------------------------------------|
| Document [23]    | $c_{2N}^N$                           |
| Document [24]    | $2^{2N}$                            |
| This text        | $N \times N/2$                      |

4. System simulation analysis
A three-phase modular multilevel converter simulation system with 11 levels is built by MATLAB /Simulink in order to evaluate the performance of the model predictive control strategy. The modular multilevel converter system is shown in Figure 1, and the simulation parameters are shown in Table 3. Figure 5 shows the control flow of the model predictive control strategy.

Table 3. Simulation parameters

| Project                          | Parameter                  |
|----------------------------------|----------------------------|
| AC side voltage                  | 10 kV                      |
| Ac frequency                     | 50 Hz                      |
| DC side voltage                  | 20 kV                      |
| Sub-module voltage               | 2 kV                       |
| Capacitance of Sub-modules       | 0.009 F                    |
| AC side inductance               | 1.5 mH                     |
| AC side resistance               | 0.04 ohm                   |
| Bridge arm inductance            | 18 mH                      |
| Number of sub-modules of bridge arm | 10                        |
| Sampling period                  | 50 us                      |

The expression[23] of active and reactive power of AC system into modular multilevel converter
\[ P = \frac{3}{2} v_d i_d \]  
\[ Q = -\frac{3}{2} v_d i_q \]  

Among them, \( i_d \), \( i_q \) and \( v_d \), \( v_q \) are AC side d-q current and voltage, respectively. AC voltage known, The reference current of the \( d \) and \( q \) axis is calculated according to the reference active and reactive power \( P^* \) and the \( Q^* \) pass is (30) and (31) respectively. Then, The model predictive controller calculates the driving signal to control the modular multilevel converter according to the reference current.

The simulation results of the dynamic characteristics of the modular multilevel converter transmitted by changing the reference values of active and reactive power are shown in Figure 6. The initial value of active and reactive power reference is set to 0. When \( t = 0.3 \) s, the active power reference value is from 0 step to 3 MW; When \( t = 1.2 \) s, the active power reference value changes from 3 to 10 MW; at \( 1.8 \) s, the active power reference value drops to 5 and the reactive power remains at 0. It can be observed from the simulation results that the reference power is accurately tracked by the modular multilevel converter. Figure 6 (a) is the dynamic waveform of active and reactive power of the modular multilevel converter, which will be amplified \( t = 1.2 \) s. It can be seen that the model predictive control controller has fast response speed and good dynamic performance.

Figure 6 (b) and (c) are the wave forms of the phase current and AC side voltage of the modular multilevel converter. Figure 6 (d) and 6(e) are dc side current and upper bridge arm current. Figure 6(f) is the circulation waveform of A phase. The capacitance voltage waveform of the upper arm sub-module of the A phase is shown in Fig. 6(g). It is observed from this figure that the capacitance voltage of the sub-module is well controlled and stabilized at the corresponding reference value.
5. Conclusion

In this paper, the research work of medium voltage side AC converter DC power electronic converter in DC mixed medium / low voltage distribution network is carried out, and the following conclusions are obtained:

- An improved predictive control strategy of the sub-module capacitor voltage balance control model is proposed. The objective functions of the phase current, circulation and sub-module capacitor voltage of the modular multilevel converter are established. The optimal switching state combination is selected by rolling optimization, which eliminates the weight coefficient and simplifies the traditional model predictive control strategy.
- It reduces the state combination of the predicted sub-module switch and reduces the computational complexity of the algorithm.
- The improved model predictive control strategy has good steady-state and dynamic characteristics by constructing a 11-level modular multilevel converter system in Matlab/Simulink environment.

6. Reference

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Acknowledgements

This research was supported by the kjcb-2020-33 program through the State Grid Hebei Electric Power Co., Ltd project.