Virtual Submodule Predictive Control method for Power Electronic Transformer based on MMC Structure

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Abstract. In order to achieve flexible and efficient operation of intelligent power distribution, solving the problems of traditional distribution transformer such as large volume and weight, easy to generate harmonics when overload, and need supporting protection equipment to protect it when failure, etc. We propose a power electronic transformer structure based on modular multilevel converter (MMC). Firstly, we consider the multi-dimensional control target of MMC converter to establish a mathematical model. Then a virtual submodule predictive control method is proposed. The method introduces the concept of virtual submodule to realize the optimal switching state rapid mapping and reduce the switching loss of MMC. Finally, the experimental results show that the mmc-based power electronic transformer has excellent dynamic steady-state performance and can effectively overcome the high loss of traditional predictive control.

1 Introduction

Intellectualization is of great significance to improve the reliability, economy, safety and stability of power grid and to realize more efficient and environmentally friendly operation of power system. Distribution transformer is the most important and universal type of equipment in distribution network, which mainly plays the role of transformer and isolation. The traditional distribution transformer has large volume and weight, easy to produce harmonics when overload, and needs supporting protective equipment to protect it when failure occurs. This is far from the smart grid's goals of smart, compatible and high quality power supply. However, the main goals of smart grid in the future, such as high power quality and convenient access to distributed power supply, can be realized or not, mainly depends on the intelligence level of the grid and the performance of electrical equipment. To solve the above problems, we propose a power electronic transformer structure based on MMC. The experimental results show that the mmc-based power electronic transformer has excellent dynamic steady-state performance and can effectively overcome the high loss of traditional predictive control.

2 MMC system modeling

MMC converter is the core component of power electronic transformer. Its topology and simplified circuit are shown in figure 1, which is a three-phase six-bridge structure. Each bridge arm has the same structure, which is composed of multiple half-bridge submodule and bridge arm reactor (Lb) in series. The sum of the input port voltage of each bridge arm submodule constitutes bridge arm voltage (Up, Un), and the number of submodules is determined by the voltage tolerance level of power switching devices, the dc bus voltage, and the number of redundant submodules.

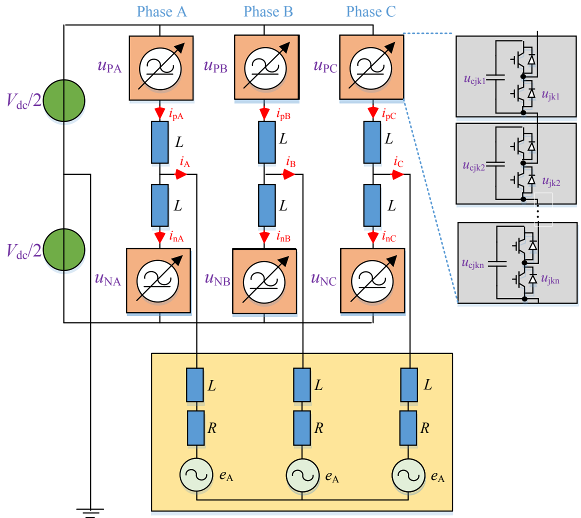

Figure 1. The Simplified circuit of MMC.

The bridge arm port voltage of MMC is composed of three parts: switching state of submodule, capacitor voltage of submodule and voltage drop of bridge arm. To simplify the system model, as shown in figure 1, the sum of capacitor voltage of each bridge arm input submodule is simplified to a dc voltage source (U_{jk}):

$$U_{jk} = \sum_{i=0}^{n} S_{jk} U_{ijk} \qquad (i = 1, 2 \ldots n) \qquad (1)$$

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Where S_{jk}(j=a, b, c; K=p, n) is the switching state of submodule, and U_{ijk} is its corresponding capacitive voltage. Meanwhile, the capacitor voltage of the submodule is determined by its switching state and the current of the attached bridge arm:

$$i_{jk}=C\frac{dU_{ijk}}{dt}\qquad (i=1,2...n) \tag{2}$$

Based on Kirchhoff's voltage law, the relationship between the dc side voltage (V_{dc}), the bridge arm voltage and the network side voltage and current exists as follows:

$$\begin{cases}\frac{V_{dc}}{2}-U_{jp}-e_j=Ri_{sj}+L_g\frac{di_{sj}}{dt}+L_b\frac{di_{jp}}{dt}\\ -\frac{V_{dc}}{2}+U_{jn}-e_j=Ri_{sj}+L_g\frac{di_{sj}}{dt}-L_b\frac{di_{jn}}{dt}\end{cases} \tag{3}$$

Where L_g and L_b are respectively the output end of converter, bridge arm reactor, and R is the equivalent loss resistance of the output end. i_{jp} and i_{jn} are the upper and lower bridge arm current of each phase respectively, and i_{sj} is the output current of the converter.

The relationships between i_{jp}, i_{jn}, i_{sj}, dc side current (i_{dc}), and interphase circulation (i_{zj}) are as follows:

$$\begin{cases}i_{jp}=\frac{i_{dc}}{3}+\frac{i_{sj}}{2}+i_{zj}\\ i_{jn}=\frac{i_{dc}}{3}-\frac{i_{sj}}{2}+i_{zj}\end{cases} \tag{4}$$

3 The principle of FCS-MPC

Figure 2 is a finite control set model predictive control (FCS-MPC) principle diagram. FCS-MPC is a derivative of MPC in the field of power electronics. It is based on a finite number of switching states of the converter. FCS-MPC establishes the prediction model of the controlled object, predicts the future state of the controlled system according to the input and output, and selects the optimal switching state, so as to achieve the purpose of high-precision control of the controlled system.

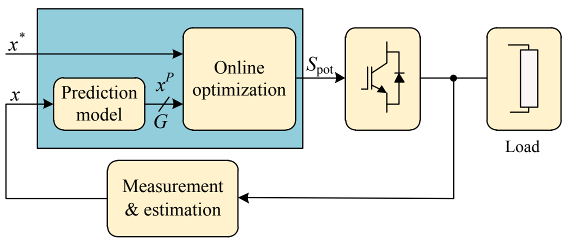

Figure 2. Schematic diagram of FCS-MPC strategy.

3.1 Discrete prediction model

For the power electronic transformer system with MMC structure, FCS-MPC is based on the system mathematical model to predict and optimize the future state, so as to select the optimal submodule switching state to achieve multi-objective control. In order to obtain the prediction model of the controlled system effectively, the mathematical model of the system should be discretized. If the sampling period of the digital control system is small enough, then:

$$\frac{d\Gamma}{dt}=\frac{\Gamma(k+1)-\Gamma(k)}{T_s} \tag{5}$$

Where Γ is any control variable of MMC system.

By substituting equation (5) into equation (4) and carrying out discretization, it can be concluded that the mathematical model of MMC system in the discrete domain is:

$$\begin{cases}i_{sj}(k+1)=\frac{1}{K_2}[K_1i_{sj}(k)-e_j(k+1)+\frac{U_{jn}(k+1)-U_{jp}(k+1)}{2}]\\ K_1=\frac{L_b/2+L_g}{T_s}\qquad K_2=R+K_1\end{cases} \tag{6}$$

Similarly, based on equation (2), the capacitor voltage of the submodule can be predicted to be

$$U_{ijk}(k+1)=U_{ijk}(k+1)+\frac{S_{ijk}T_s}{C}i_{jk} \tag{7}$$

The predicted circulating current of each phase in MMC converter system is

$$i_{zj}(k+1)=\frac{T_s}{2l_b}[U_{dc}-U_{jn}(k+1)-U_{jp}(k+1)]+i_{zj}(k) \tag{8}$$

Thus, according to equations (6), (7) and (8), discrete prediction model of MMC system can be completed.

3.2 The online optimization

In order to complete the online optimization of the system, FCS-MPC introduces the cost function normalized control concept based on the system control requirements, establishes the objective equation of weight factor, converts multiple control problems into a single online objective equation to solve problems, and establishes the objective equation as follows

$$\begin{aligned}J_{jmin}&=\lambda_1\left|i_{sj}^*-i_{sj}(k+1)\right|\\&+\lambda_2\sum_{i=0}^{n}\left|U_{ijk}^*-u_{ijk}(k+1)\right|\\&+\lambda_3\left|i_{zj}^*-i_{zj}(k+1)\right|\end{aligned} \tag{9}$$

Where λ_1, λ_2 and λ_3 is the weight factor of the cost equation. The solution is solved online by adjusting the value of λ_1, λ_2 and λ_3 to optimize the model predictive control strategy.

4 Virtual submodule fast MPC

4.1 Expected output voltage prediction

In view of the problem of low realization degree caused by the excessive computation load in the process of applying the model predictive control strategy to multilevel complex topology structure mentioned above. The expected output voltage prediction technique is used to replace the direct current prediction scheme adopted by the FCS-MPC strategy. Compared with the FCS-MPC strategy, multiple current predictions are made for different submodule switching schemes in the prediction link. The VSF-MPC strategy only needs to predict the expected output voltage once to achieve the target of given power tracking.

To achieve controllable tracking output power of the converter, the output current is required to be infinitely approximated to the given ($i(k+1)=i^*$) in the next unit period. By sorting out equation (7), the expected output voltage of the converter can be obtained according to the feedback state of the system:

$$\begin{cases} u_{\mathrm{Oj}}(k+1)=e_{\mathrm{j}}(k)-K_1 i_{\mathrm{sj}}(k)+K_2 i_{\mathrm{sj}}^* \\ K_1=\dfrac{(L_{\mathrm{b}}/2+L_{\mathrm{g}})}{T_{\mathrm{s}}} \qquad K_2=K_1+R \end{cases} \tag{10}$$

Where u_{Oj} is the virtual predicted output voltage of the converter. According to equation (3) and the output voltage of each phase of the converter and U_{jk}, the predicted $U_{\mathrm{jk}}(k+1)$ of each bridge arm can be obtained.

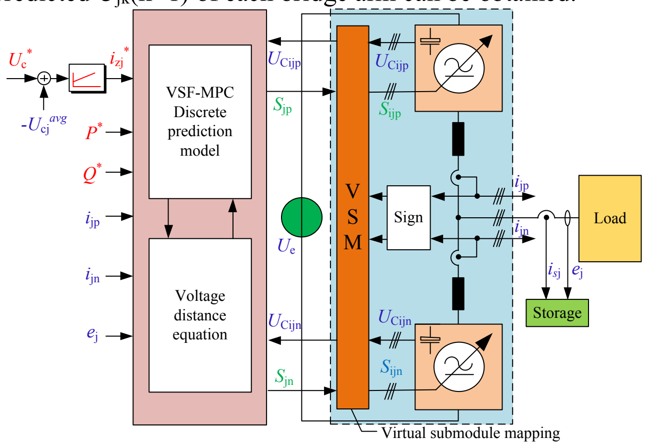

Figure 3. Control block diagram of VSR-MPC.

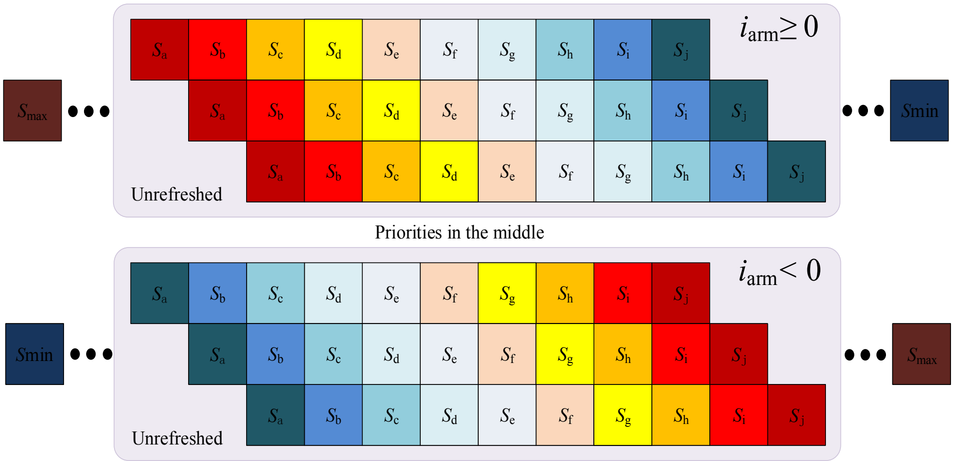

Figure 4. The rules of virtual submodule mapping.

In order to effectively suppress the internal circulation of MMC system, realize the capacitance voltage balance of each bridge arm submodule, and reduce its fluctuation amplitude, as shown in figure 3, the average capacitance voltage control and circulation suppression control of submodules are introduced in the prediction of submodule switching number.

4.2 Virtual submodule mapping

The voltage stabilizing strategy of virtual submodule includes the following steps:

1) Build Submodule Virtual Switching State: The submodule virtual switching state is shown in figure 4.

2) Priority Classification of Submodules of MMC System: In the voltage regulation link of MMC system, priority classification is carried out based on the capacitance voltage of submodules and the current direction of bridge arm. The maximum and minimum priority modules are screened out and their Numbers are refreshed.

3) Actual Submodule Mapping: After step 2, the priority sequence number of the refreshed submodule can be obtained, and the switching state of the virtual submodule can be mapped to the actual submodule by referring to the priority sequence number.

5 Experimental verification and analysis

In order to verify the effectiveness of the VSF-MPC method in power electronic transformer with MMC structure, the steady-state and dynamic performance of the 50kW simulation test prototype was experimentally verified.

The phase angle adjustment test results of MMC system are presented in figure 5. There is a 30° phase angle difference between the transmission terminal voltage and the receiving terminal voltage at the initial moment, and the two-terminal grid interconnection at the moment of 0.04s. Figure 5(a) shows the branch current of the MMC module, the current of the transmission line and the output line voltage of the side-unit. It can be seen that, after the interconnection of the two-terminal large phase difference power grid, the current of the transmission line rapidly and smoothly increases to about

25A due to the correction function of poly phase Angle of the MMC system, and the double-terminal power grid has no over-current shock problem. The local amplification result after the connection is shown in figure 5(b). Similarly, figure 6 shows the test results of transformer impedance regulation under MMC structure. Considering the length of the article, we will not describe it in detail here.

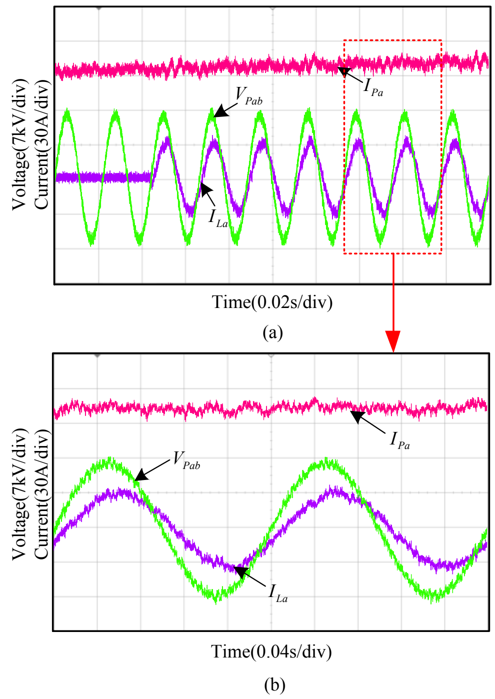

Figure 5. Phase Angle adjustment test results.

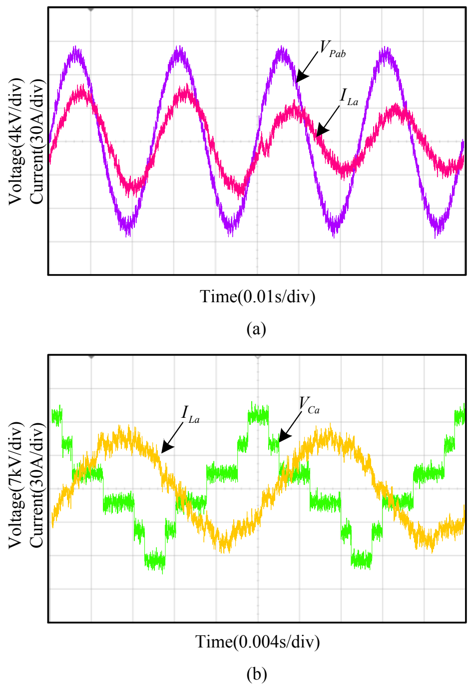

Figure 6. Impedance adjustment test results.

6 Conclusion

In order to achieve flexible and efficient operation of intelligent power distribution, solving the problems of traditional distribution transformer such as large volume and weight, easy to generate harmonics when overload, and need supporting protection equipment to protect it when failure, etc. We propose a power electronic transformer structure based on modular multilevel converter (MMC). The experimental results show that the mmc-based power electronic transformer has excellent dynamic steady-state performance and can effectively overcome the high loss of traditional predictive control.

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