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Model Predictive Control of LCL Three-level Photovoltaic Grid-connected Inverter

Cheng Liang[1,2], Engang Tian[1,2], Baobing Pang [1,2], Juan Li[1,2], Yang Yang[1,2]

[1]School of Electrical and Automation Engineering, Nanjing Normal University,

[2]Nanjing, Jiangsu Province, 210042, China

e-mail: liangcheng1031@163.com

Abstract. In this paper, neutral point clamped three-level inverter circuit is analyzed to establish a mathematical model of the three-level inverter in the αβ coordinate system. The causes and harms of the midpoint potential imbalance problem are described. The paper use the method of model predictive control to control the entire inverter circuit [1]. The simulation model of the inverter system is built in Matlab/Simulink software. It is convenient to control the grid-connected current, suppress the unbalance of the midpoint potential and reduce the switching frequency by changing the weight coefficient in the cost function. The superiority of the model predictive control in the control method of the inverter system is verified.

1. Introduction

With the expansion of the world energy crisis and the gradual deterioration of the environmental pollutional problem, the human needs for the development and utilization of new energy are increasing. Solar photovoltaic power generation has attracted more and more attention worldwide because of its widespread distribution, abundant reserves, and high efficiency [2]. To be able to make solar photovoltaic power generation efficient, clean, and friendly, it is necessary to control the strategy of photovoltaic grid-connected inverters in-depth study.

2. The mathematical model of three-level inverter

Photovoltaic grid-connected inverters are the core components of photovoltaic power generation systems. The main function is to convert the direct current generated by solar photovoltaic arrays into alternating current, and access the public power grid for users. Due to the limitation of the device's withstand voltage level, two-level topology inverters are difficult to meet the requirements of high-voltage grid-connected, and neutral point clamped three-level inverters can reduce the voltage stress of the switch and improve the quality of the grid-connected current[3].

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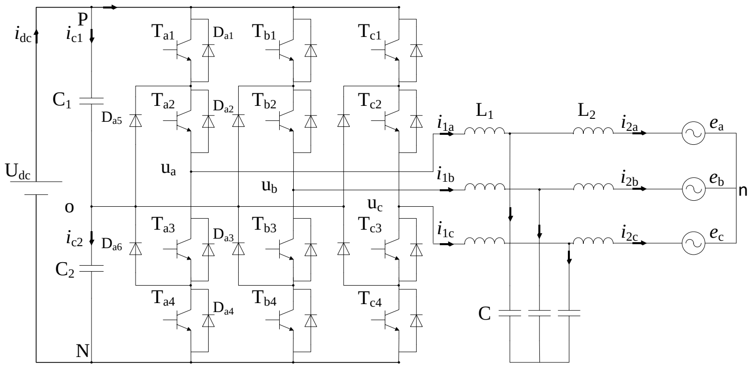

Figure 1. Topology of LCL type NPC three-level grid-connected photovoltaic inverter

In figure 1, the DC side of the NPC three-level inverter consists of two capacitors C_1 and C_2 of the same size. Take the a-phase bridge arm in the three-phase bridge arm of a, b and c as an example. The a-phase bridge arm is composed of four main switching devices T_{a1},T_{a2},T_{a3},T_{a4}, four freewheeling diodes D_{a1},D_{a2},D_{a3},D_{a4} and two clamping diodes D_{a5},D_{a6}. The effect of the clamping diode is to change the point connected to a phase arm to zero. In the LCL filter, L_1 is the inverter side filter inductor, C is the filter capacitor, and L_2 is the grid side filter inductor. Compared with two-level inverters, the maximum voltage that each switching device of an NPC three-level inverter can withstand in the switching process is only half that of a two-level inverter. Therefore, the voltage stress of the switching device in NPC three-level inverter can be greatly reduced to meet the high voltage inverter conditions.

According to the different combinations of the four switching devices on each phase leg of the NPC three-level inverter, there are a total of 16 switching states, of which only three switching states contribute to the circuit.

According to Kirchhoff's voltage and current law, the inverter side inductance L_1, the grid side inductance L_2, and the filter capacitance C in the abc coordinate system satisfy the following state equations, where $k = a, b, c$.

$$\begin{cases} L_1 \dfrac{di_{1k}}{dt} = u_k - u_{ck} \\ L_2 \dfrac{di_{1k}}{dt} = u_{ck} - e_k \\ C \dfrac{du_{ck}}{dt} = i_{1k} - i_{2k} \end{cases} \tag{1}$$

The state equations of the three-level inverter in the αβ two-phase stationary coordinate system is obtained by using the Clark transform.

$$\begin{cases} L_1 \dfrac{di_{1\alpha,\beta}}{dt} = u_{\alpha,\beta} - u_{c\alpha,\beta} \\ L_2 \dfrac{di_{1\alpha,\beta}}{dt} = u_{c\alpha,\beta} - e_{\alpha,\beta} \end{cases} \tag{2}$$

3. Causes and hazards of the midpoint potential unbalance

The problem of midpoint potential unbalance is a prominent problem in the NPC three-level inverter circuit. The two voltage-dividing capacitors on the DC side of the NPC three-level inverter circuit cause the midpoint potential to fluctuate during charging and discharging. When the amplitude of the midpoint potential fluctuation is large, the harmonic content of the output waveform will increase, resulting in a poorer quality of the output waveform, and the fluctuation will become three times of the fundamental frequency, which reduces the output efficiency of the inverter [4]. Therefore, in the NPC three-level inverter circuit must use appropriate control strategies to solve the midpoint potential unbalance.

At present, the main factors that affect the midpoint potential unbalance are the following:

- two voltage divider capacitors on the DC side cause fluctuations in the midpoint potential during charging and discharging;
- dc-side bus capacitance can not be exactly the same in the parameter characteristics, it will also cause the midpoint potential unbalance;
- power factor of the load is also an important factor affecting the midpoint potential.

The harm caused by the midpoint potential unbalance to the inverter system mainly includes:

- output voltage and current waveform of the inverter produces a certain degree of distortion;
- switch components of the inverter system are subjected to the unbalanced voltage;
- voltage fluctuations reduce the lifetime of the DC bus capacitors.

4. Model predictive control of NPC three-level photovoltaic grid-connected inverter

MPC has the characteristics of intuitive modeling, low dependence on system model, easy to handle system constraints, direct control and strong stability [5]. Through on-line tuning and optimization of system parameters, the immunity of the controlled system is greatly improved. The system has also become more stable. In this section, the MPC of NPC three-level photovoltaic grid-connected inverters is studied in detail. The discrete-time model and cost function of the three-level inverter are given, and the simulation is carried out for analysis.

4.1. Discrete-time model

Discrete time equations can be obtained by applying the Euler formula to discrete equation (2):

$$\begin{cases} i^p_{1\alpha,\beta}(k+1) = \dfrac{T_s}{L_1}\Big(u_{\alpha,\beta}(k) - u_{c\alpha,\beta}(k)\Big) + i_{1\alpha,\beta}(k) \\ i^p_{2\alpha,\beta}(k+1) = \dfrac{T_s}{L_2}\Big(u_{c\alpha,\beta}(k) - e_{\alpha,\beta}(k)\Big) + i_{2\alpha,\beta}(k) \end{cases} \tag{3}$$

Suppose $i^p_{2\alpha,\beta}(k+1) - i_{2\alpha,\beta}(k) = i^p_{1\alpha,\beta}(k+1) - i_{1\alpha,\beta}(k)$, by Formula (3) available:

$$i^p_{1\alpha,\beta}(k+1) = \frac{T_s}{L_1+L_2}\Big(u_{\alpha,\beta}(k) - e_{\alpha,\beta}(k)\Big) + i_{1\alpha,\beta}(k) \tag{4}$$

Because the midpoint potential of the NPC three-level inverter is unbalanced, the midpoint potential needs to be controlled.

The current in the DC side capacitor C_1, C_2 is:

$$i_{C1,2} = C_{1,2}\frac{du_{C1,2}}{dt} \tag{5}$$

The corresponding discrete-time equation is:

$$u^p_{C1,2}(k+1) = \frac{T_s}{C_{1,2}} i_{C1,2}(k) + u_{c1,2}(k) \tag{6}$$

In equation (6), $u_{c1,2}(k)$ is the voltage value of the DC side capacitor C_1, C_2 at time t_k, and $u^p_{C1,2}(k+1)$ is the voltage prediction value of C_1, C_2 at t_{k+1},the value of the current $i_{C1,2}(k)$ depends on the switching state of the inverter and the value of the output current.

4.2. Cost function

The cost function is a core part of the model predictive control and plays a role of planning and decision-making in the controller. It is the key to dealing with multi-variable and multi-constraint problems.

Give a specific form of the cost function g:

$$\begin{gathered} \mathrm{g} = \left|i^*_\alpha(k+1) - i^p_{1\alpha}(k+1)\right| + \left|i^*_\beta(k+1) - i^p_{1\beta}(k+1)\right| + \\ \lambda_{dc}\left|u^p_{C1}(k+1) - u^p_{C2}(k+1)\right| + \lambda_n n_c \end{gathered} \tag{7}$$

In equation (7), $i_\alpha^*(k+1)$ and $i_\beta^*(k+1)$ are real and imaginary parts of the reference current vector i^* at time t_{k+1},$i_{1\alpha}^p(k+1)$ and $i_{1\beta}^p(k+1)$ are the real and imaginary parts of the predicted current vector i^p at the inverter side at time t_{k+1}, λ_{dc} is the weight coefficient of the midpoint potential balance and λ_n is the weight coefficient of the frequency of the switch,n_c is the switching times of the switching tubes that are switched from the current switch state to the switch state at a certain time in the future. The specific expression is:

$$n_c = |S_a(k) - S_a(k-1)| + |S_b(k) - S_b(k-1)| + |S_c(k) - S_c(k-1)| \quad (8)$$

In equation (8),$S_a(k-1)$,$S_b(k-1)$ and $S_c(k-1)$ indicate the switching state at the time of the previous sampling cycle, $S_a(k)$,$S_b(k)$ and $S_c(k)$ indicates the switch state at time t_k.

4.3. Results and analysis of the simulation

Using Matlab/Simulink to build the simulation model of the model predictive control system of NPC three-level photovoltaic grid-connected inverter, as shown in Fig. 2, the system model is mainly composed of the part of model predictive control, NPC three-level inverter, LCL filter and the three-phase power grid.

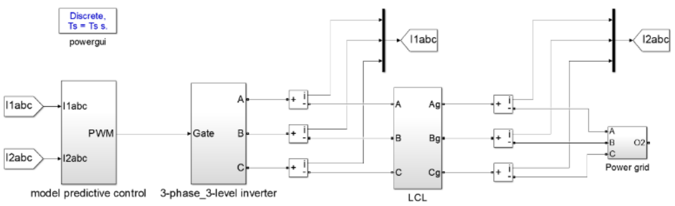

Figure 2. the simulation model of NPC three-level photovoltaic grid-connected inverter system in model predictive control

To analyze the effects of grid-connected current control on the inverter-side and the grid-side, we need to make $\lambda_{dc} = \lambda_n = 0$ in the cost function expression. At this point, the predicted control current waveform of the NPC three-level photovoltaic grid-connected inverter model is shown in Figure 3. It can be seen from the figure that the grid-connected current waveform are good both on the inverter-side current and the grid-side.

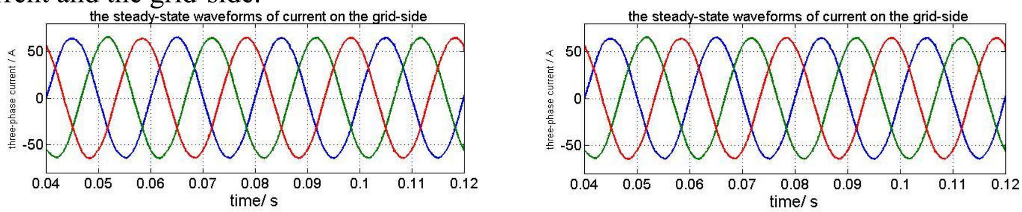

Figure 3. the steady-state waveforms of current on the inverter-side and the grid-side

Next, we study the effect of grid current tracking under dynamic model control. From Fig.3, it can be found that both the inverter-side current and the grid-side current can follow the reference current well at the steady state. At time t = 0.12s, the active power of the grid is reduced to 0.7 times the original power. As can be seen from Fig.4, both the inverter-side current and the grid-side current can quickly follow the reference current and the dynamic response is faster.

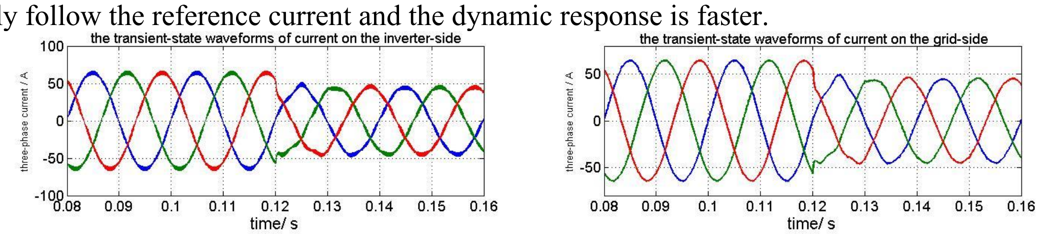

Figure 4. the transient-state waveforms of current on the inverter-side and the grid-side

The midpoint potential unbalance will increase the lower harmonics of the output voltage, reduce the quality of the output waveform, produce three times the fundamental frequency of AC fluctuations, affecting the inverter output efficiency and other issues. As shown in Fig. 5, the weight coefficient $\lambda_{dc} = 0.1$ is added at time t=0.12s to balance the midpoint potential. Before adding the balance control of the midpoint potential, the average absolute error of the DC side capacitors C_1 and C_2 is 9.835V. Capacitance voltage midpoint potential fluctuations are relatively large, after adding the midpoint potential balance control, the DC potential voltage fluctuations in the capacitor voltage is significantly reduced, the inverter output voltage peak almost unchanged, the current tracking error is small.

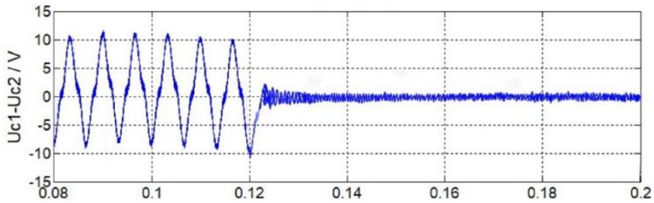

Figure 5. the waveform of the midpoint potential fluctuation

The higher the switching frequency, the higher the switching losses. Therefore, the reduction of switching frequency is very important. As shown in Fig.6, the weight coefficient $\lambda_n = 0.06$ is added at time t=0.06s to control the reduction of the switching frequency. Compared with the case where the switching frequency control is not added, the switching frequency is reduced, the current tracking effect and the midpoint potential balance control effect have hardly changed, the control performance of the entire photovoltaic grid-connected inverter system is good.

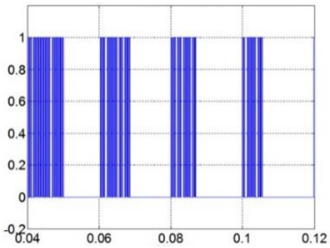

Figure 6.the drive signal waveform of T_{a1}

5. Conclusion

Based on the basic principles of model predictive control, this paper establishes the discrete-time model and cost function of NPC three-level photovoltaic grid-connected inverter in αβ coordinate system. The simulation model of the system is built using Matlab/Simulink software and simulation analysis is performed, including the current control performance on the steady-state and transient-state, the effect of the midpoint potential balance control and the reduction of the switching frequency. From the simulation results, the model predictive control technology can well control the grid-connected current, neutral point potential balance and reduce the switching frequency by changing the weight coefficient. The three-level photovoltaic grid-connected inverter has been optimized.

6. References

[1] Xia C, Liu T, Shi T, et al. A Simplified Finite-Control-Set Model-Predictive Control for Power Converters[J]. IEEE Transactions on Industrial Informatics, 2017, 10(2):991-1002.
[2] Jansen M. Intergovernmental Panel on Climate Change (IPCC)[J]. Encyclopedia of Energy Natural Resource & Environmental Economics, 2013, 26(2):48-56.

IOP Conf. Series: Earth and Environmental Science **153** (2018) 042023 doi:10.1088/1755-1315/153/4/042023

[3] Teodorescu R, Blaabjerg F, Liserre M, et al. Proportional-resonant controllers and filters for grid-connected voltage-source converters[J]. IEE Proceedings - Electric Power Applications, 2006, 153(5):750-762.
[4] Zmood D N, Holmes D G. Stationary frame current regulation of PWM inverters with zero steady-state error[J]. Power Electronics IEEE Transactions on, 2003, 18(3):814-822.
[5] Young H, Rodríguez J. Comparison of finite-control-set model predictive control versus a SVM-based linear controller[C]// European Conference on Power Electronics and Applications. IEEE, 2013:1-8.