Research on Control Strategy of Z-source Photovoltaic Grid-connected Inverter Based on Sliding Mode Control

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Abstract. This paper proposes a photovoltaic grid-connected inverter based on a Z-source NPC three-level topology to achieve buck-boost control and improve the transmission efficiency of the system. In view of the instability of the output power of the photovoltaic system, which affects the output of the grid-connected inverter, this paper proposes a dual closed-loop sliding mode control strategy. The DC bus voltage outer loop of this strategy adopts traditional sliding mode control and grid-connected current inner loop adopts PI control to weaken the system chatter. The anti-interference ability of photovoltaic grid-connected system and harmonic content of grid-connected current were studied through the Matlab/Simulink simulation platform. The results show that the control strategy can effectively improve the robustness of the system and reduce the harmonic content of grid-connected current.

1. Introduction

With the gradual decrease of fossil energy and the increasingly serious environmental problems, the development and utilization of renewable energy has become a hotspot of current energy research, especially microgrid technology that focuses on distributed power sources such as solar energy and wind energy. The inverter is the core equipment in the microgrid and the bridge between the distributed power supply and the power grid. The research on the topology of the new inverter and the grid connection control strategy is a hot spot in the microgrid technology. With the continuous research of scholars at home and abroad, Professor Peng Fangzheng proposed the Z-source inverter, which uses a passive network built by inductors and capacitors to replace the DC/DC conversion in traditional photovoltaic grid-connected systems. The DC side and the inverter side are coupled together to realize power transmission and buck-boost control, which greatly improves the transmission efficiency of the system. Therefore, this article applies the Z-source NPC three-level topology to the photovoltaic grid-connected system.

In order to ensure that the output voltage and the grid voltage are in the same frequency and phase, and to ensure that the output current harmonics of the grid-connected output are small, and to improve the power quality, the photovoltaic module is connected to the grid through the inverter. Control Strategy. Although Z-source inverter is a new type of inverter topology, the grid-connected control method it uses is still the mainstream grid-connected control technology of traditional inverters. At present, in addition to the traditional PID control, single closed-loop control and voltage and current double closed-loop control, there are hysteresis control, proportional resonance control, and repetitive control. This paper proposes a double closed-loop sliding mode control strategy. Compared with traditional PI control, this control strategy has fast dynamic response and good anti-interference ability.
2. The working principle and mathematical model of Z source NPC three-level inverter

2.1 Analysis of working state of Z source NPC three-level inverter

In the topology of the Z-source NPC three-level inverter shown in Figure 1, the DC power supply voltage is \( U_{dc} \). CS1 and CS2 are the voltage dividing capacitors of the DC power supply, and their values are \( C_{S1} = C_{S2} = C_s \). The Z source network is composed of capacitors \( C_1, C_2 \) and inductors \( L_1, L_2 \), \( V_i \) is the output voltage of the Z source network.

![Figure 1. Z source NPC type three-level inverter topology.](image)

The traditional NPC three-level inverter single-phase output voltage has three states: P state, O state and N state. When \( SA_1 \) and \( SA_2 \) are on and \( SA_3 \) and \( SA_4 \) are off, the phase voltage is output \( V_{an} = U_{dc}/2 \), is P state. When \( SA_2 \) and \( SA_3 \) are on and \( SA_1 \) and \( SA_4 \) are off, the phase voltage is output \( V_{an} = 0 \), is O status. When \( SA_3 \) and \( SA_4 \) are on and \( SA_1 \) and \( SA_2 \) are off, the phase voltage is output \( V_{an} = -U_{dc}/2 \), is N state. On the basis of these working states, the Z source NPC three-level inverter adds a through state to realize the circuit's boost function. There are three states for the pass-through state: Upper Shoot-through(UST), Lower Shoot-through(LST) and Full Shoot-through(FST). Table 1 shows the size of the switch tube that the structure is turned on in these five working states, the output phase voltage and the midpoint current.

| Operating mode | Conduction device | Phase voltage | Neutral current |
|----------------|------------------|---------------|----------------|
| P              | SA1,SA2,VD1,VD2  | \( U_{dc}/2 \) | 0              |
| O              | SA2,SA3,VD1,VD2  | 0             | exist          |
| N              | SA3,SA4,VD1,VD2  | \( -U_{dc}/2 \) | 0              |
| UST            | SA1,SA2,SA3,VD1  | 0             | exist          |
| LST            | SA2,SA3,SA4,VD2  | 0             | exist          |

2.2 Mathematical model of Z source NPC three-level inverter

In order to accurately control the Z-source NPC three-level inverter and ensure the quality of the output waveform, it is necessary to analyze its equivalent circuit to establish an accurate mathematical model. The equivalent circuit in the non-through state is shown in Figure 2. Assuming \( U_{L1}=U_{L2}=U_L, U_{C1}=U_{C2}=U_C, U_N = 0 \), then \( U_{N+} = U_i/2, U_{N-} = -U_i/2 \). According to KVL:

\[
U_{dc} = U_i - U_L
\]  
\[
U_{dc} = U_L + U_c \tag{2}
\]

Simultaneous (1) and (2):

\[
U_{dc} = 2U_c - U_i \tag{3}
\]
Figure 2. Non-through state equivalent circuit.

Figure 3. Through state equivalent circuit.

In the through-equivalent circuit, there are an upper through-equivalent circuit and a lower through-equivalent circuit, as shown in Figure 3 (a) and (b), respectively. Since the midpoint potential is 0, In the UST equivalent circuit, $U_{N+} = 0$. In the LST equivalent circuit, $U_{N-} = 0$. According to KVL:

**UST state:**

\[ U_L = 0.5U_{dc} \]  \hspace{1cm} (4)

\[ -U_{N-} = U_c - U_L = U_i \]  \hspace{1cm} (5)

**LST state:**

\[ U_L = 0.5U_{dc} \]  \hspace{1cm} (6)

\[ U_{N+} = U_c - U_L = U_i \]  \hspace{1cm} (7)

In a switching cycle $T_s$, assuming that the total shoot-through time is $T_0$, according to the principle of inductance volt-second balance, the average voltage $\bar{U}_L$ of the inductor in the Z source network in one switching period is 0:

\[ \bar{U}_L T_s = 0.5U_{dc}T_0 + (U_{dc} - U_c)(T_s - T_0) = 0 \]  \hspace{1cm} (8)

Organized:

\[ U_c = \frac{T_s - 0.5T_0}{T_s - T_0} U_{dc} \]  \hspace{1cm} (9)

Substituting eq.(9) into eq.(3), eq.(5) and eq.(7) respectively, the output voltage of the Z source network can be obtained:

\[ U_i = \frac{1}{1 - d_0} U_{dc} \]  \hspace{1cm} (10)

\[ U_i = \frac{1}{2(1 - d_0)} U_{dc} \]  \hspace{1cm} (11)
Eq.(10) is the output voltage formula in the non-through state, and eq.(11) is the output voltage formula in the through state. In the formula, \( d_0 = T_0 / T_s \) represents the through duty cycle. Assuming that the boost factor \( B = 1 / (1 - d_0) \), the output voltage amplitude:

\[
U_A = BMU_{dc}
\]

In the formula (12), \( M \) is the modulation ratio. When \( BM > 1 \), the inverter works in boost mode. When \( BM < 1 \), the inverter works in buck mode.

3. Grid connection control strategy

This article uses a double closed-loop control strategy, the overall control block diagram shown in Figure 4. In the figure, the voltage outer loop uses the exponential approach law to solve the reference value of the current loop \( i_d^* \). The current inner loop uses the traditional PI algorithm to solve the controlled voltage signal \( u_d \) and \( u_q \). At the same time, the active damping method is used to obtain the control signal \( u_\alpha \) and \( u_\beta \) in the two-phase static coordinate system through inverse Park transformation.

From eq.(10) and eq.(11), we know that the Z-source inverter controls the output voltage by changing the size of the through duty cycle \( d_0 \). Therefore, in order to use the output power of the photovoltaic module for maximum efficiency, it is necessary to obtain the through duty ratio \( d_0 \) through the MPPT algorithm for buck-boost control. Finally, the SVPWM modulation method is used to generate a pulse signal to control switch to turn on and turn off.

![Figure 4. Control structure diagram of Z-source grid-connected system.](image)

3.1 Design of sliding mode controller

Sliding mode control is a nonlinear control method. It can be combined with the current state of the system to make corresponding changes to force the system to perform sliding mode movement along the specified state trajectory to achieve the desired control goal. The sliding mode surface \( s(x) = 0 \) divides the state space of the system into \( s(x) > 0 \) and \( s(x) < 0 \). The basic principle of sliding mode control is to transfer all the state points of the system to the sliding mode. On the surface, it gradually stabilizes on the sliding surface. The sliding mode surface \( s(x) = 0 \) is the core of the sliding mode controller, which needs to meet the accessibility condition \( \dot{s} s' \leq 0 \). Only the sliding surface that meets the accessibility conditions can make the system reach the sliding surface in a limited time at a state point other than the sliding surface.

In a three-phase grid-connected inverter system, the active power \( P_g \) and reactive power \( Q_g \) on the grid side are:

\[
P_g = 1.5(u_{gd}i_{gd} + u_{gq}i_{gq})
\]
\[ Q_g = 0.5(u_{gd}i_{gq} - u_{gq}i_{gd}) \]  

(14)

Considering that the inverter is in the ideal rotating coordinate, with reference to \( u_{gq} = 0 \) in the grid voltage, the active power regulation control current \( i_{gq} \) and the reactive power control current \( i_{gd} \):

\[ i_{inv}u_{dc} = 1.5u_{gd}i_{gd} \]  

(15)

\[ \frac{du_{dc}}{dt} = \frac{1}{C_{dc}}(i_{pv} - \frac{3u_{gd}i_{gd}}{2u_{dc}}) \]  

(16)

Where: \( u_{dc} \) is the DC side voltage. \( i_{inv} \) is the current flowing into the inverter. \( C_{dc} \) is the DC side capacitance. \( i_{pv} \) is the output current of the photovoltaic cell.

Define the voltage tracking error as:

\[ e = u_{dc} - u_{dc}^* \]  

(17)

Since the reference voltage \( u_{dc}^* \) is a constant, the derivative of eq.(17) is consistent with eq.(16). Because the control period of the MPPT algorithm in the photovoltaic system changes slowly, in order to compensate for the uncertainty of the system, the sliding mode surface is designed as:

\[ S_V = e + \lambda \int_0^te d\tau = 0 \]  

(18)

Since the error derivative will increase the signal-to-noise ratio in the actual system, the sliding mode surface (18) is selected as the integral term. Using the exponential approach law, the final voltage outer loop equation of sliding mode control is:

\[ i_d^* = i_{gd} = \frac{3C_{dc}u_{dc}}{2u_{gd}}[\lambda_e + \alpha S_V + \beta \text{sgn}(S_V) + \frac{i_{pv}}{C_{dc}}] \]  

(19)

Where: \( i_d^* \) is the d-axis current reference value of the current inner loop. \( \lambda_e \) is a proportional term. \( \alpha S_V + \beta \text{sgn}(S_V) \) is the sliding surface to compensate the uncertainty of the system. \( \frac{i_{pv}}{C_{dc}} \) is the known dynamics of the compensation system.

Define the Lyapunov function as \( V = 0.5S_V^2 \), and derive it:

\[ V' = S_V S_V' = -S_V[\alpha S_V + \beta \text{sgn}(S_V)] \]  

(20)

The condition for the system to run stably is that the derivative of the Lyapunov function is less than 0, and the control strategy of this paper only needs to be \( \alpha > 0 \) and \( \beta > 0 \) to satisfy this condition.

4. Simulation analysis

In order to analyze the feasibility of the grid-connected control strategy adopted, a simulation model was built in Matlab/Simulink. The main system parameters are set as follows: DC side reference voltage \( U_{dc}^* = 600V \), three-phase grid voltage effective value is 220V, Z source network inductance \( L_1 = L_2 = 0.15mH \), capacitor \( C_1 = C_2 = 2.262mF \), grid side inductance \( L = 1.5mH \), resistance \( R = 0.05\Omega \). Parameter setting of sliding mode controller (SMC): \( \alpha = 2.5, \beta = 2000 \).

Figure 5(a) and Figure 5(b) are three-phase grid-connected current waveforms under PI control and sliding mode control, respectively. It can be seen from the figure that the three-phase grid-connected current under PI control takes a long time to reach steady state, while the three-phase grid-connected current under sliding mode control can reach within about 1 cycle within the allowable range Steady state, and at the moment of start-up, PI control will generate larger current, while sliding mode control will not generate larger current.

Figure 6 and Figure 7 are the FFT analysis results of the B-phase grid-connected current of PI control and sliding mode control, respectively. It can be seen from the figure that the grid connection standard, but the harmonic distortion rate of grid connection current under sliding mode control is significantly lower than PI control.
Figure 5. Three-phase grid-connected current waveform

(a) PI control  (b) Sliding mode control

Figure 6. Harmonic distortion rate of grid-connected current under PI control

Figure 7. Harmonic distortion rate of grid-connected current under sliding mode control
Figures 8(a) and 8(b) are the DC link voltage waveforms of PI control and sliding mode control, respectively. It can be seen from the figure that in PI control, the DC link voltage only reaches the steady state value in 0.2 ~ 0.3s, while in sliding mode control, the DC link voltage can reach the steady state value in about 0.05s. When the photovoltaic system reduces the output power at 0.5s, the DC link voltage will drop. PI control takes about 0.1s to make the system return to the steady state value again, while sliding mode control takes about 0.01s. Can make the system return to the steady state value again.

5. Conclusion
This paper replaces the traditional two-stage photovoltaic grid-connected inverter topology with the single-stage topology of the Z-source NPC three-level inverter, which improves the energy conversion efficiency of the system. Based on the traditional double closed-loop PI control, the outer loop voltage PI was changed to sliding mode control, and a simulation model was built in Matlab / Simulink. The simulation results show that compared with the traditional double closed-loop PI control strategy, the double closed-loop control strategy with sliding mode control not only has good robustness and stability, high control accuracy, excellent dynamic steady-state performance, anti- The advantages such as strong interference ability also reduce the harmonic distortion rate of grid-connected current.

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