Control Strategy Research of Based on Resonance Feedforward and Current Estimate of the Photovoltaic Grid Inverter

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Abstract. Due to poor quality of grid-connected current and large impedance value of grid are caused in weak grid environment. Therefore, a control strategy combining multiple resonant feedforward and current estimation method is adopted in this paper. Firstly, in order to make the positive feedback channel have the feedback effect only at the main background harmonics, the low-order harmonics of the grid are extracted by using the method of multi-resonance feedforward control. At the same time, under the premise that the suppression effect of LCL natural resonant frequency remains unchanged, the current estimation method is added into the control strategy, so as to reduce the system cost. Finally, the simulation results show that thus verifying the correctness and effectiveness of the control strategy.

1. Introduction

Due to the large number of power electronic devices and high-power converters in photovoltaic grid-connected systems, the ideal public grid is gradually transformed into a weak grid with low order background harmonics\textsuperscript{[1-2]}. A large number of background harmonics and network impedance values change, resulting in the network voltage and grid-connected current distortion under the weak current network, and then seriously affect the phase margin of the system, and even cause resonance resulting in system instability\textsuperscript{[3]}. Many scholars have studied the impact of grid impedance changes\textsuperscript{[4]} and background harmonic interference\textsuperscript{[5]} on photovoltaic grid-connected system. It is pointed out that the comprehensive effect of grid impedance, control strategy and other factors can make the system operate in a critical stable state under a certain condition and cause resonance\textsuperscript{[6]}. The proportional feedforward control of grid voltage is widely used because it is easy to realize and can effectively restrain the disturbance of grid voltage and prevent the large inrush current during startup\textsuperscript{[7]}. In
order to reduce the cost, adding the error compensation loop of current signal on the basis of proportional feedforward control can achieve the same resonance suppression effect as the grid-connected current double closed-loop control[8]. However, in the weak current network environment, the grid voltage proportional feedforward control may make the system unstable due to the mismatch between the grid impedance and the inverter output impedance[9]. Only when the output impedance and the grid impedance have a certain phase margin at the resonant frequency can the resonance be avoided[10]. Therefore, a resonant feedforward control method is proposed, that is, a band-pass filter is added in the feedforward channel to remove the background harmonics, and the system is stabilized by reducing the coupling between the positive feedback channel and the current loop[11-12]. On this basis, a method of retaining the proportional control link and adding the resonance link is proposed to improve the robustness of the inverter and the ability to suppress the harmonics of the system[13].

On the basis of the above research, a control strategy combining the multi-resonant feedforward with current estimation is proposed in this paper. This method can improve the phase margin of the system and reduce the number of capacitive current sensors. The resonant suppression effect is the same as that of conventional capacitor current feedback while the system cost is reduced. Finally, the correctness and effectiveness of the proposed strategy are verified by simulation.

2. LCL Photovoltaic Grid-Connected Inverter Model

2.1. Structure of LCL Photovoltaic Grid-Connected Inverter

In this paper, the three-phase LCL photovoltaic grid-connected inverter in weak grid environment is taken as the research object, and the system topology is shown in Figure 1.

![Figure 1. Three-phase LCL grid-connected inverter system structure](image)

Where, $U_{dc}$ is the DC bus voltage of the PV array at the front stage of the grid-connected system after being boosted by boost. $L_1$ is the LCL filter inverter side inductance, $C$ is the capacitance in the LCL filter, $L_2$ is the inductance on the network side of the LCL filter, PCC is the Point of Common Coupling point, $Z_g$ is the grid impedance of grid-connected system, $i_{ca}$, $i_{cb}$, $i_{cc}$ respectively are the three-phase current of filter capacitor, and $i_{ga}$, $i_{gb}$, $i_{gc}$ respectively are the three-phase parallel current.

2.2. Equivalent Impedance Model of LCL Photovoltaic Grid-Connected Inverter

This paper only analyzes the interaction between the inverter and the grid from the Perspective of the inner current loop, and takes the d-axis as an example to illustrate. The double closed-loop control block diagram is shown in Figure 2.
In the figure, \(i_g\) is the actual value and \(i_{ref}\) is reference value of grid current, \(G_{pi}\) is the outer loop controller, \(k_c\) is the active damping coefficient and \(K_{pwm}\) is the inverter gain coefficient are shown.

According to figure 2 the open-loop transfer function \(G_{ig...igf}(s)\) between the given current \(i_{ref}\) and the grid connected current \(i_g\) is as follows:

\[
G_{ig...igf}(s) = \frac{G_{dcl}(s)G_{p}(s)K_{pwm}}{s^3 l_{c} + s^2 G_{dcl}(s)K_{pwm} + s(l_1 + l_2)}
\]

(1)

The output signal \(i_g(s)\) can be written as:

\[
i_g(s) = \frac{G_{dcl...igf}(s)}{1 + G_{dcl...igf}(s)} \cdot i_{ref}(s) - \frac{G_{dcl...igf}(s)}{1 + G_{dcl...igf}(s)} \cdot u_{g}\).
\]

(2)

Where \(u_{pcc}(s) = u_g(s) + i_g(s)Z_o(s)\), \(Z_o(s) = L_o\), \(L_o\) is the grid inductance.

According to equation (2), the equivalent impedance model of photovoltaic grid-connected inverter can be established. As shown in Figure 3, the left side of PCC point can be equivalent to the parallel connection of current source \(i(s)\) and output impedance \(Z_o(s)\), and the right side of PCC can be equivalent to the series connection of voltage source \(u_g(s)\) and grid impedance \(Z_o(s)\).

\[
i_g(s) = \frac{1}{1 + \frac{Z_o(s)}{Z_o(s)}} \cdot i(s) - \frac{1}{1 + \frac{Z_o(s)}{Z_o(s)}} \cdot u_g(s).
\]

(3)

3. Control of Three-phase LCL Photovoltaic Grid-Connected Inverter

3.1. Control of Multi-Resonance Feedforward

In order to reduce the coupling degree, the multi-resonance feedforward control strategy is adopted, and the control block diagram is shown in Figure 4. The system only achieves all pass...
characteristic at the main low harmonic frequency of grid, and achieves amplitude attenuation characteristic at other resonance frequency bands. It can not only reduce the burden of low frequency regulator, but also improve the system phase margin[13].

$$G_v(s) = \sum_{m=1}^{6} \frac{w_r s}{s^2 + w_r s + ((2m+1)w_o)^2}$$

(4)

Where, 2m+1 is the harmonic frequency, \(w_o\) is the fundamental angular frequency, \(w_r\) is the resonance depth coefficient, and is taken as 15\(\pi\)[13-14].

According to the multi-resonance feedforward control block diagram shown in Fig.4, the open-loop transfer function of the system under multi-resonance feedforward control is as follows:

$$G(s) = \frac{G_d(s)G_p(s)K_{pwm}}{s^3 L_1 (L_2 + L_y) G + s^2 (L_2 + L_y) G_d(s) K_{pwm} k + s(L_1 + L_2 + L_y) - L_2 G_d(s) K_{pwm} h G(s)}$$

(5)

3.2. Current Estimation Control Based on Multi-Resonance Feedforward

In combination with 2.1, this paper proposes a control strategy based on the combination of multi-resonance feedforward control and current estimation. According to the control block diagram of the system based on the control strategy of the combination of multi-resonance feedforward and current double closed loop feedback shown in Fig. 4, it can be concluded that:

$$\begin{align*}
(i_e G_p(s) + u_{pcc} h G_v) K_{pwm} &= u_{inv} \\
u_{inv} - u_{pcc} &= \hat{I}_g(s)(L_1 + L_2)s
\end{align*}$$

(6)

The grid-connected current value after the resonant peak of LCL type filter is suppressed can be estimated, i.e

$$\hat{I}_g(s) = \frac{i_e G_p(s)K_{pwm} + (G_v - 1)u_{pcc}}{(L_1 + L_2)s}$$

(7)

where, \(\hat{I}_g(s)\) is the estimated value of grid current. Suppose that the error between the actual value and the estimated value of the current is \(i_e\). In order to achieve the effect of resonance
suppression, the error current $i_{eq}$ is fed into the control loop after a compensation signal. The control strategy of multi-resonance feedforward based on capacitor current estimation is shown in Figure 5.

![Figure 5. Multi-resonant feedforward control block diagram with current estimation](image)

So the differential equations corresponding to the control block diagram in Figure 8 can be listed as

$$
\begin{align*}
\frac{di}{dt} & = \frac{1}{L_1} \left[ u_{ref} + k_i (i_g - \hat{i}_g) + u_{pcc} G_{pi} k_{pwm} - u_c \right] \\
\frac{di_g}{dt} & = \frac{1}{L_2} (i_g - u_{pcc}) \\
\frac{du}{dt} & = \frac{1}{C} (i_{i1} - i_g) \\
\frac{di_{i1}}{dt} & = \frac{k_{pwm}}{(L_1 + L_2) s} u_{ref} + \frac{G_{pi} - 1}{(L_1 + L_2) s} u_{pcc}
\end{align*}
$$

Where, $h_i = 1/k_{pwm}$, $u_{pcc} = u_g + i_g L$. The system state variable is selected as the current $i_{i1}$, the grid-connected current $i_g$, the filter capacitor $u_c$, and the estimated current flowing through the filter inductor $L_1$. The system state variables are the current $\hat{i}_g(s)$ flowing through the filter inductor $L_1$, the input is the power grid voltage $u_g$, and the output $U_{cref}$ of controller $G_{pi}$. The system equation of state can be written as

$$
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Dx
\end{align*}
$$

where:

$$
A = \begin{bmatrix}
0 & \frac{1}{L_1 (k_i + G_{pi} G_{Gc})} & \frac{1}{L_1} & \frac{k_{pwm} G_{Gc}}{L_1} \\
0 & \frac{L_2}{L_1} & \frac{1}{L_2} & 0 \\
\frac{1}{C} & \frac{1}{L_2} & 0 & 0 \\
0 & \frac{L_2 (G_{pi} - 1)}{(L_1 + L_2)s} & 0 & 0
\end{bmatrix}
$$

$$
B = \begin{bmatrix}
\frac{1}{L_1} & G_{pi} G_{Gc} & \frac{L_1}{L_1} \\
0 & \frac{1}{L_2} & 0 \\
0 & 0 & \frac{k_{pwm}}{(L_1 + L_2)s} G_{pi} (G_{pi} - 1) & \frac{L_1}{(L_1 + L_2)s}
\end{bmatrix}
$$
\[
\begin{bmatrix}
\dot{x} = \begin{bmatrix} i_t & i_{g} & u_{c} & i_{g} \\ u = \begin{bmatrix} u_{ref} & u_{g} \end{bmatrix} \end{bmatrix}
\end{bmatrix}^{T}
\]

By substituting \( D = [0 \ 1 \ 0 \ 0] \) into \( W(s) = D(sI - A)^{-1}B \) and ignoring the grid voltage \( u_{g} \).

In order to reduce the influence of grid voltage \( U_{g} \) on the steady-state error and THD of system grid-connected current, the control strategy combining proportional feedforward control and current estimation method is the system open-loop transfer function as follows:

\[
G(s) = \frac{G_{t_m}(s)G_{p}(s)K_{p}}{G_{t_m}(s)K_{p}Z_{c} + (Z_{c} + Z_{2})Z_{c} + Z_{c}Z_{2}}
\]

where \( h_{g} \) is the proportional feedforward coefficient.

4. Simulation Analysis and Verification

In this paper, the simulation model of three-phase LCL grid connected inverter is built in Matlab/Simulink for verification. The simulation parameters are shown in Table 1.

| Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|
| \( U_{1} \)/V | 750 | \( L_{1} \)/mH | 0.6 |
| \( U_{g} \)/V | 380 | \( L_{2} \)/mH | 0.9 |
| i/A | 30 | C/\( \mu \)F | 21.92 |
| \( f_{o} \)/Hz | 50 | \( f_{s} \)/kHz | 10 |

![Simulation waveforms](image)

(a) proportional feedforward + current estimation method
(b) multi resonance feedforward + current estimation method

**Figure 6.** Grid-connected current waveform
Figure 7. Total harmonic distortion

Figure 8 shows the grid-connected current waveform when a given current step disturbance occurs in the case of weak current network. It can be seen from the figure that when \( t=0.05 \)s, given the step signal, the current changes rapidly from 20A to 30A, and the given current is tracked quickly, which shows that the proposed control strategy of multi-resonance feedforward combined with current estimation has good stability.

Figure 8. The grid-connected current waveform with a given step disturbance

This method not only improves the phase margin of the system, but also increases the stability range of the system. Moreover, due to the addition of multi-resonance feedforward, the main low order harmonics are extracted and well suppressed. In other words, the feed-forward control strategy of grid connected current plus multi resonance can reduce the system cost and steady-state error of grid connected current, and improve the adaptability of the system to weak grid and main low order harmonics.

5. Conclusion

By adopting the multi-resonance feedforward control method, the phase margin of the system is improved and the coupling degree between the positive feedback channel and the current loop is reduced. At the same time, the superposition current estimation method can suppress the natural resonant frequency of LCL without using the capacitive current sensor, reduce the system cost, and improve the adaptability of the system to the grid impedance and low order background harmonics in the weak grid environment. Finally, the correctness and effectiveness of the control
strategy based on the combination of multi-resonance feedforward and current estimation are verified by Matlab/Simulink simulation.

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