Grid-connected Inverter Control Strategy Based On Capacitor Reference Voltage Feedforward

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Abstract. In view of the disadvantage that grid-connected power is not high and the phase margin of the grid-connected current is greatly reduced with the increase of impedance of many grid voltage feedforward control strategies. A grid-connected inverter control strategy based on capacitor reference voltage feedforward is proposed. In this control, the error between the filter capacitor voltage and its reference voltage is combined with the proportional controller as the inner loop control, the error between the inverter side current and its reference current is combined with the current controller as the outer loop control to improve the robustness of the system. The phase difference between grid-connected current and grid voltage is reduced by using capacitor reference voltage feedforward. In addition, by using the grid voltage resonance feedforward, the system can not only retains the ability to suppress harmonics, but also prevents the system's phase margin from decreasing greatly under weak power grid. The proposed strategy has good dynamic performance, it can obtain good grid-connected current quality and high grid-connected power, and it has strong robustness to the change of LCL parameters and the fluctuation of grid voltage. At the same time, it has better adaptability to weak power grid.

1. Introduction

In the pursuit of low-carbon society today, renewable energy, represented by solar energy and wind energy, has gradually attracted wide attention of the world because of its abundant reserves and pollution-free. At present, people use renewable energy through distributed power generation systems, grid-connected inverter as the core device in the system, it is of great significance to study the control strategy of grid-connected inverter.

In the past decades, many scholars have done a lot of research on the current control strategy of grid-connected inverter. Many control schemes are proposed for inverter. The main one is PI control [1]. However, PI control can only track DC signal accurately, and there will be some tracking errors when tracking the sinusoidal AC signal. The AC signal can be converted into DC signal through coordinate conversion to improve the situation that the PI controller cannot accurately track the sinusoidal signal. This technique has been successfully applied to the three-phase inverter, However, in single-phase inverters, this technology not only complicates the controller design but also reduces the transient performance of the inverter system. The resonance control [2], the repetitive control [3]-[4] and the hysteresis control [5] are all good upgrading alternatives for PI control. However, but these methods also reduce the transient response.

Therefore, a new control strategy is proposed by mathematical derivation. The strategy is made up of five cascade controller, they are the voltage resonance feedforward controller which can suppress
the system's phase margin from drastically decreasing under weak grids, the capacitor reference voltage feedforward con- troller which can improve the grid-connected power of the system, the P regulator which can provide active damping to the system, the PI regulator which can generate inverter side reference current.

2. Grid-connected inverter control strategy based on capacitor reference voltage feedforward

The structure diagram of grid-connected inverter is shown in Figure 1. According to [6], the parasitic resistance of the inductor (\( L_1 \) and \( L_2 \)) and the capacitor (\( C \)) is beneficial to the stability of the system and the parasitic resistance is very small. Therefore, to simulate the worst working condition of the system, the parasitic resistance is ignored.

\[
\begin{align*}
1 \mathbf{L} pcc & \quad u_1 \\
1 \mathbf{C} & \quad \mathbf{u} \\
2 \mathbf{L} & \quad g
\end{align*}
\]

Figure 1. The structure diagram of grid-connected inverter

Where: \( C_d \) is the DC-side capacitor, \( L_1 \) is the inverter-side inductor, \( u_{pcc} \) is the coupling point voltage, \( C \) is the filter capacitor, \( u_d \) is DC-link voltage, \( L_2 \) is the grid-side inductor, \( u_g \) is the grid voltage, \( u_c \) is the capacitor voltage, \( u_i \) is the output voltage of the inverter, \( i_g \) is the grid-connected current, \( L_g \) is the grid inductor, \( i_1 \) is the inverter-side current, \( i_c \) is the capacitor current.

According to Figure 1, the differential equation of the inverter system as follow:[7]

\[
\begin{align*}
\frac{d i_1}{dt} & = \frac{1}{L_1} u_1 - \frac{1}{L_1} u_c \\
\frac{d u_c}{dt} & = \frac{1}{C} \\
\frac{d i_2}{dt} & = \frac{u_c}{L_2} - \frac{u_g}{L_2}
\end{align*}
\]  

Where \( u_i = \lambda u_d \), \( L_z = L_2 + L_g \), \( \lambda \) is the duty cycle (switch function), \( u_i \) is the control input of inverter.

The state variables are defined as follows:

\[
x_1 = i_1 - i_{1r}, \quad x_2 = u_c - u_{cr}
\]  

Where \( i_{1r} \) and \( i_{2r} \) are respectively the reference current of \( i_1 \) and \( i_2 \), and \( u_{cr} \) is the reference voltage of \( u_c \). Where \( i_{2r} = A \sin 100 \pi t \), \( A \) is the peak value of the reference current, \( u_{cr} = L_2 i_{2r} + u_{pcc} \). \( i_{1r} \) is generated by the error of the grid-connected current and its reference current through PI controller.

Making use of equation (2) can be get equation (3).

\[
\dot{x}_1 = \dot{i}_1 - \dot{i}_{1r} = \dot{i}_{1} - i_{cr} - \dot{i}_{2r}
\]  

According to \( u_c = x_2 + u_{cr} \) and (1), can be get equation(4)[7].

\[
\dot{x}_1 = \frac{1}{L_1} u_1 - \frac{1}{L_1} x_2 - \frac{1}{L_1} u_{cr} - \dot{i}_{2r} - \dot{i}_{cr}
\]  

In order to minimize the error energy of the system, we only need to set the right side of equation (4) as 0. Therefore, it can get equation (5).

\[
u_i = x_2 + u_{cr} + L_1 \dot{i}_{2r} + L_1 \dot{i}_{cr}
\]
By introducing the intermediate input variable $u_{i1}$ into (5), it can be get equation (6).

$$u_i = u_{i1} + u_{cr} + L_i \dot{i}_{cr} + L_v \dot{i}_{cr}$$  \hspace{1cm} (6)

In order to accelerate $x_1$ and $x_2$ convergence, $u_{i1}$ introduces the state feedback gain $k_1$ and $k_2$, it can be get equation (7).

$$u_{i1} = -k_1 x_1 - k_2 x_2$$  \hspace{1cm} (7)

Substitute equation (7) into equation (6), equation (6) can be written as equation (8)[7].

$$u_i = -k_1 x_1 - k_2 x_2 + u_{cr} + L_i \dot{i}_{cr} + L_v \dot{i}_{cr}$$  \hspace{1cm} (8)

According to $i_{cl} = C(du_{cr} / dt)u_i = \dot{u}_{cl}$, the preliminary control duty cycle can be obtained as (9).

$$\lambda = \frac{1}{u_s}\left[-k_1 x_1 - k_2 x_2 + u_{cr} + L_s \frac{d^2 u_{cl}}{dt^2} + L_s \frac{d u_{cl}}{dt}\right]$$  \hspace{1cm} (9)

In this design, PI controller is used to generate the reference current $i_{r1}$ of current $i_1$. The function of PI is as equation (10).

$$G_{pi}(s) = \frac{k_p}{s^2} + \frac{k_i}{s}$$  \hspace{1cm} (10)

According to formula (9), it can be obtain the preliminary control structure diagram 2 of the grid-connected system.

It can be seen from Figure 2 that the second order differential is contained in the capacitor reference voltage feedforward control. In practical engineering applications, the differential link is easier to introduce noise[8]. In this study, low-pass filter $1/ (\tau s + 1)$ is introduced into the capacitor reference voltage feed-forward in order to suppression differential is easy to introduce noise into the system, the $\tau$ is constant time[7]. In addition, there are many harmonics in network voltage, which will lead to the distortion of the grid-connected current of the grid-connected system. The power grid voltage feedforward is widely used because it is effective in suppressing power grid harmonics. However, under the weak grid, the traditional voltage feed-forward will make the phase margin of the system greatly reduce with the increase of the impedance of the power grid, and even lead to the instability of the system. In view of this, the resonant function is introduced into the voltage feedforward to form the resonant feedforward control. The resonance function has frequency selection characteristics, so that the power grid voltage feedforward loop is no longer an all-pass feature. In the middle and high frequency band of the resonant frequency, it has attenuation characteristics, which can improve the phase margin of the system under the weak grid.

The resonance function as equation (11).

$$G_{r}(s) = \frac{k_r w_o s}{s^2 + k_r w_o s + w_o^2}$$  \hspace{1cm} (11)

It can be obtained that the improved control duty cycle under resonant feedforward as equation (12).

$$\lambda = \frac{1}{u_s}\left[-k_1 x_1 - k_2 x_2 + \tau^{-1} e^{-\tau \frac{s}{\tau}}(u_{cr} + L_s \frac{d^2 u_{cl}}{dt^2}) + g_t(t)u_{pcc}\right]$$  \hspace{1cm} (12)

According to the $u_{pcc} = L_{ag} (di_2 / dt) + u_{ag}$. The improved control duty cycle of the system under resonance feedforward is equivalent to equation (13).

$$\lambda = \frac{1}{u_s}\left[-k_1 x_1 - k_2 x_2 + \tau^{-1} e^{-\tau \frac{s}{\tau}}(u_{cr} + L_s \frac{d^2 u_{cl}}{dt^2}) + g_t(t)(L_{sc} \frac{di_2}{dt} + u_{ag})\right]$$  \hspace{1cm} (13)

Where: $\tau^{-1} e^{-\tau \frac{s}{\tau}}$ is the antilaplace transform of $1/ (\tau s + 1)$.

According to the (13), the improved control structure diagram of the system is shown in figure 3.
Figure 2. Preliminary control structure of the system

Figure 3. Improved control structure of the system

Where: \( G_1(s) = (1/\tau s + 1)(CL_s s^2 + 1) \)

Figure 3 shows that the control structure of the system is composed of four controllers

1) \( G_f(s) L_s s^2 + u_g \) is the resonant feedforward controller. It can not only suppress the harmonics of the power grid well, but also restrain the phase margin of the system to decrease greatly under the weak power grid, and improve the adaptability of the system to the weak power grid.

2) \( \left( CL_s s^2 + 1 \right) u_{cr} \) is the capacitor reference voltage feedforward controller. It can reduce the phase difference between \( i_2 \) and \( pccu \).

3) \( k_2 x_2 \) is the capacitor voltage P controller which can provide active damping for the control system.

4) \( G_P(s) i_{2r} \) is the PI controller to generate reference current \( i_{1r} \) of inverter side.

3. Performance analysis of the system

3.1. The analysis of system stability under resonant feedforward

The control duty cycle (13) is substituted into the equation (1), and then the Laplace transform is carried out, and then the simplification is carried out. The closed loop transfer function expression (14) of \( i_2 \) as follow:

\[
I_2 = \frac{L_s(L_sC^2 + k_1\tau s^2) + [k_2 G_{nt} + L_s(k_2 + 1)\tau + k_1 G_{nt}]}{D_s^2 + D_s s^2 + D_s s + D_s 0} I_{2r} - \frac{L_s C \tau s^2 + (L_s C + k_1 C \tau - L_s C) s^2 + (k_1 C - \tau G_t + \tau) s + G_t u_g}{D_s^2 + D_s s^2 + D_s s + D_s 0} \tag{14}
\]

\[
D_s = L_s, D_s = L_s, D_s = L_s, D_s = L_s, D_s = L_s, D_s = L_s, D_s = L_s, D_s = L_s, D_s = L_s, D_s = L_s
\]

By introducing equation (10) and equation (11) into equation (14), the closed-loop transfer function (15) between the grid-connected current \( i_2 \) and its reference current \( i_{2r} \) can be obtained.

\[
I_2 = \frac{A_s s^6 + A_s s^5 + A_s s^4 + A_s s^3 + A_s s^2 + A_s s + A_0}{B_s s^2 + B_s s^2 + B_s s + B_s s + B_s s + B_s s + B_s s + B_s s + B_0}
\]
\[ A_6 = L_z L_1 C, \quad A_5 = L_z (k w_o L_1 C + k_2 \tau), \quad A_4 = L_z (L_1 C w_o^2 + k_2 k_1 \tau w_o + k_2 + 1) + k_1 k_1 \tau, \quad A_3 = L_z w_o^2 k_2 \tau + L_z w_o (k_1 k_2 + k_1) + k_1 k_1 \tau + k_1 \tau, \quad A_2 = w_o^2 [L_z (k_2 + 1) + k_1 k_1 \tau] + k_1 k_1 w_o (k_1 \tau + k_1) + k_1 k_1 \tau \]

The open-loop transfer function of the system can be obtained as follows:

\[ G(s) = \frac{I_r(s)}{I_L(s)} = \frac{A_s^4 + A_s^3 + A_s^2 + A_s + 1}{C_s^4 s^4 + C_s^3 s^3 + C_s^2 s^2 + C_s s + C_0} \]  

Where: \( C_1 = B_1, \quad C_6 = B_6 - A_6, \quad C_5 = B_5 - A_5, \quad C_4 = B_4 - A_4, \quad C_3 = B_3 - A_3, \quad C_2 = B_2 - A_2, \quad C_1 = B_1 - A_1, \quad C_0 = B_0 - A_0 \)

Then, the open-loop transfer function of the system can be obtained as follows:

\[ A_6 = k_1 w_o^2 (k_1 + k \tau) + k_1 k_1 k_1 w_o, \quad A_4 = k_1 k_1 w_o^2 \]

Figure 4. Open loop bode diagram of the system with \( L_g = 3 \text{mH} \) and \( L_g = 4 \text{mH} \)

Figure 5. Closed loop bode diagram with constant and 20% increase in LCL parameters

According to formula (16), the system open-loop Bode diagram can be drawn. From figure 4, it can be known that the influence of grid impedance on the system is mainly in the middle frequency band. When \( L_g = 3 \text{mH} \), the phase margin of the system is 39.1°, when it is increased to \( 4 \text{mH} \), the phase margin is also 39.1°. The phase margin of the system does not decrease with the \( L_g \) increase under grid voltage resonance feedback control, it is shown that the voltage resonance feedforward can suppress the phenomenon that the system phase margin decreases rapidly as the inductance \( L_g \) increases. In addition, the open-loop gain of the system hardly changes with the increase of the \( L_g \), indicating that the steady-state error of the designed control system is not affected by the power grid perceptual impedance. It can also be seen from the figure 4 that the shear frequencies of the system are both 15200Hz when \( L_g \) is 3mH and 4mH , that is, with the increase of \( L_g \), the shear frequency of the system does not decrease, that is, the system still has better grid harmonic suppression capability under weak grid. To sum up, it shows that the system has a relatively strong adaptability to the weak power grid.

3.2. The robustness analysis of system to parameters

According to equation (15), the closed-loop transfer function bode Figure 5 can be drawn when the filter parameter is unchanged or the filter parameter is increased by 20%. From figure 5 , the grid current has almost no steady-state error (0-dB amplitude) at the fundamental frequency when the filter parameters are unchanged or the parameters are increased by 20%. This is shown that the system has strong robustness to the fluctuation of LCL parameters, and this also shows that the system have better tracking performance.
4. Simulation verification

In order to verify the effectiveness of the strategy, Matlab software was used to build the simulation model of feedforward control strategy based on capacitor reference voltage. Set the given value of grid-connected current as \( i_2 = 20 \sin(100 \pi t) \), \( u_d = 400 \text{V} \), the effective value of grid voltage is 220V, \( f_s = 50 \text{Hz} \), \( f_w = 20000 \text{Hz} \). In order to facilitate observation, the coupling point voltage is reduced to 0.3 times before entering the oscilloscope. The parameters as: \( k_1 = 53 \), \( k_2 = 80 \), \( k_i = 19000 \), \( k_p = 1 \), \( \omega_o = 314 \text{rad}/s \), \( k_r = 1 \), \( \tau = 0.011 \text{ms} \), \( L_4 = 2 \text{mH} \), \( L_2 = 0.6 \text{mH} \), \( C = 6 \text{uF} \).

The simulation waveform diagram of the coupling point voltage \( u_{pcc} \) and grid-connected current \( i_2 \) and the fast Fourier transform (FFT) analysis diagram of \( i_2 \) for the system based on the capacitor reference voltage feedforward under the ideal power grid \( L_g = 0 \) are shown in Figure 6. It can be seen from (a) that \( u_{pcc} \) and \( i_2 \) are all relatively smooth sine wave, and it can be seen from (a) that the total harmonic distortion rate (THD) of \( i_2 \) is only 0.51%, which is far less than 5% of the international standard. The above analysis shows that the system has good grid-connected current quality.

![Figure6. Simulation waveforms of u_{pcc} and i_2 under ideal power grid](image)

![Figure7. Simulation waveforms of u_{pcc} and i_2 under L_g=3mH](image)

![Figure8. Simulation waveform of u_{pcc} and i_2 with given change of reference current under L_g=3mH](image)
In figure 9, (a) and (b) are the simulation waveforms of $u_{pcc}$ and $i_2$ of the system under feedforward with and without capacitor reference voltage, respectively. It can be seen from the figure 9 that the phase difference of $u_{pcc}$ and $i_2$ with capacitor reference voltage feedforward is less than that without capacitor reference voltage feedforward. The above clearly shows that the capacitor reference voltage feedforward can reduce the phase difference between $u_{pcc}$ and $i_2$ and improve the grid-power of the system. In addition, from figure (a) that the system with reference voltage feedforward has a minimal phase difference between $u_{pcc}$ and $i_2$.

This control method is compared with the previous control method [9]. In the literature [9], the phase margin was 42.5° when the grid impedance was $L_g = 1 \text{mH}$, which was reduced to 35° at 2mH and 15.6° at 4mH. In this paper, the phase margin is always 39.1°at $L_g = 3 \text{mH}$ and $L_g = 4 \text{mH}$. This shows that the proposed control method has excellent performance, which is better than or comparable to the previous control methods.

5. Experimental results

In this paper, a grid-connected experimental platform is built to experiment and analyze the grid-connected system[10]. The processor of the experimental platform is DSP-TMS320F28335. Due to limited experimental conditions and safety considerations, the voltage level was lowered in the experiment. In this experiment, the peak value of the grid voltage is 130V, and the peak value of the grid-connected current is set to 7A.

Figure 10 shows the experimental waveform diagram of the coupling point voltage $u_{pcc}$ and grid-connected current $i_2$ for the system based on the capacitor reference voltage feedforward under the ideal grid $L_g=0$. It can be seen from the figure that $u_{pcc}$ and $i_2$ are all relatively smooth sinusoidal waveforms, and the grid-connected current can well follow its reference current. At the same time, the phase difference between $u_{pcc}$ and $i_2$ is small. These indicate that the system has good grid-connected current quality and high grid-connected power under an ideal grid.

Figure 11 shows the experimental waveform diagram of $u_{pcc}$ and $i_2$ under the weak grid $L_g=3.4\text{mH}$. 

(a)With capacitor reference voltage feedforward    (b)Without capacitor reference voltage feedforward

Figure 9. The simulation waveforms of $u_{pcc}$ and $i_2$ under feedforward with and without capacitor reference voltage

Figure 10. The experimental waveform diagram of $u_{pcc}$ and $i_2$ under the ideal grid $L_g=0$.

Figure 11. The experimental waveform diagram of $u_{pcc}$ and $i_2$ under the weak grid $L_g=3.4\text{mH}$. 

Figure 11 shows the experimental waveform diagram of \( u_{pcu} \) and \( i_2 \) for the system under weak power grid \( L_g = 3.4 \text{mH} \). It can be seen from the figure 11 that the waveforms of \( u_{pcu} \) and \( i_2 \) under \( L_g = 3.4 \text{mH} \) are still standard sinusoidal waveforms, and the grid-connected current can well follow its reference current. This show that the system has good adaptability to weak power grids.

6. Conclusion

Based on the research of grid-connected inverter system, a new grid-connected inverter control method based on capacitor reference voltage feedforward is proposed in this paper. In view of the fact that the phase margin of the traditional power grid voltage feedforward will sharp decline under weak power grid, the resonant feedforward control of the power grid voltage is proposed to prevent the phase margin from sharp decline. In addition, the capacitor reference voltage feedforward is used to reduce the phase difference between grid-connected current and grid-connected voltage. The effectiveness of the proposed control strategy is verified by simulation and experiment. The control system has good performance in weak power grid.

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