Highly robust LCL three-phase grid-connected inverter under non-ideal grid

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Abstract. A current-voltage dual-loop grid-connected control strategy for a conventional grid-connected inverter that is susceptible to instability under a non-ideal grid is designed. The effects of grid impedance and fluctuations in this strategy are considered. The influence of power network impedance change on LCL filter is analysed, the small signal model of phase-locked loop is established, and the design methods of system parameters and controller parameters to improve the robustness of the system are given. Finally, through MATLAB/Simulink simulation, current and voltage output of grid-connected inverters and grid-connected current quality parameters are obtained under different working conditions, verifying the correctness and feasibility of theoretical derivation.

1. Introduction

In recent years, renewable energy power generation has developed rapidly. The integration of a large number of renewable energy equipment in the traditional power grid will increase the impedance of the grid and bring disturbance to the common coupling point voltage. Non-ideal grid conditions have a great impact on the stable operation of grid-connected inverters [1].

Currently, the research of grid-connected inverter is mainly based on LCL filter, which has higher high frequency harmonic suppression effect. The grid impedance will change the resonance point, and the stability is difficult to guarantee [2]. Reference [3] designs an active damping scheme of double-current loop based on LCL filter, and designed the system parameters without analyzing the influence of grid impedance on the system. Phase locked loop (PLL) is used to check the phase of side grid voltage. Reference [4] takes single-phase LCL inverter as topology model, establishes small signal model of phase-locked loop, and gives a design method of phase-locked loop parameters.

In this paper, a double closed-loop controller is designed. The influence of grid impedance and grid fluctuation on inverter is analyzed. The design conditions of more robust LCL grid-connected inverter system parameters are given, and its stability is demonstrated and analyzed.

2. LCL grid-connected inverter and control strategy

The control strategy of LCL grid-connected inverter is shown in Figure 1. An active damping control inner loop with LCL filter capacitor voltage as feedback and an external loop control strategy with grid-connected current as feedback are designed in this paper. Where in, the inverter side inductance $L_1$; Grid side inductance $L_2$; Parasitic resistance $R_1, R_2$; Grid induced reactance $L_g$; Inverter output
voltage $u_{abc}$; Filter capacitor voltage $u_{C_{abc}}$; Grid side voltage $u_{gabc}$; Inverter side current $i_{abc}$; Filter capacitance current $i_{C_{abc}}$; grid side current $i_{2abc}$.

**Figure 1.** Schematic diagram of inverter control strategy.

The inverter control and decoupling equation process is shown in equation (1~3). $U_d$, $U_q$, $U_{cd}$, $U_{cq}$, $I_{2d}$ and $I_{2q}$ are state variables.

\[
\begin{align*}
L_1 \frac{d}{dt} i_{1abc} + R_1 i_{1abc} &= u_{abc} - u_{C_{abc}} \\
(L_2 + L_g) \frac{d}{dt} i_{2abc} + R_2 i_{2abc} &= u_{C_{abc}} - u_{gabc} \\
i_{C_{abc}} &= i_{1abc} - i_{2abc} \\
i_{C_{abc}} &= C \frac{d}{dt} u_{C_{abc}}
\end{align*}
\]

\[
\begin{align*}
U_{dq} &= sL_2 i_{dq} + R_1 i_{dq} + U_{C_{dq}} + \omega L_2 I_{2dq} \\
U_{C_{dq}} &= (sL_2 + sL_g + R_2) i_{dq} + U_{g_{dq}} + \omega (L_2 + L_g) I_{2dq} \\
I_{C_{dq}} &= I_{1dq} - I_{2dq} \\
I_{C_{dq}} &= sC U_{C_{dq}} + \omega C U_{C_{dq}}
\end{align*}
\]

\[
\begin{align*}
U_d &= G_w(d) (U_{cd}^* - U_{cd}) - BU_{gd} - DU_{cq} - EU_{gq} \\
U_q &= G_{wq}(d) (U_{cq}^* - U_{cq}) - BU_{gq} + DU_{cd} + EU_{gd} \\
U_{cd}^* &= G_{id} (I_{dref} - I_{2d}) + GU_{gd} - H(U_{cq} - U_{gq}) \\
U_{cq}^* &= G_{iq} (I_{qref} - I_{2q}) + GU_{gq} + H(U_{cd} - U_{gd})
\end{align*}
\]
Where, $G_u$ is the voltage loop control regulator transfer function; $G_i$ is current loop control regulator transfer function.

3. Analysis of factors affecting system stability

3.1. Stability analysis of LCL filter

The LCL filter transfer model is shown in Figure 2. Parasitic resistance is omitted in the analysis below.

$$
A = \frac{(c^2 + e^2)(ab - df + 1) + ac - ef}{c^2 + e^2}
$$

$$
B = \frac{ac + ef}{c^2 + e^2}
$$

$$
D = \frac{(c^2 + e^2)(ab + df) + cf - ae}{c^2 + e^2}
$$

$$
E = \frac{ae - cf}{c^2 + e^2}
$$

$$
F = \frac{c^2 + e^2}{c}
$$

$$
G = 1
$$

$$
H = \frac{e}{c}
$$

$$
I = \frac{a\lambda + R_1}{sL_1}
$$

$$
J = sL_2 + sL_s + R_2
$$

$$
k = \omega C
$$

$$
l = e\left(L_2 + L_s\right)
$$

$$
m = \omega L_4
$$

Where, $G_u$ is the voltage loop control regulator transfer function; $G_i$ is current loop control regulator transfer function.

The open loop transfer function can be obtained from the transfer model of LCL filter [5].

$$
G_{LCL}(s) = \frac{i_2(s)}{u_{im}(s)} = \frac{1}{L_1(L_2 + L_s)Cs^3 + (L_1 + L_2 + L_s)s} = \frac{1}{(L_1 + L_2 + L_s)s} \frac{\omega_r^2}{s^2 + \omega_r^2}
$$

Where, $\omega_r = \sqrt{\left(L_1 + L_2 + L_s\right)\frac{1}{L_1(L_2 + L_s)C}}$.

When the electrical impedance changes, the resonance point is offset. Figure 3 shows that the resonance peak is affected by the change of power grid impedance, which affects the stable operation of grid-connected inverter control system.

3.2. Small signal model of PLL

Each state quantity of the grid is composed of steady-state quantity and disturbance quantity [6]. According to Lyapunov first method first method, for the dynamic system of equilibrium point, a new vector $x = x - x_i$ is introduced. When exploring the stability of the system, only the stability at the origin needs to be studied [7].
Due to the fluctuation of power grid, there is a certain phase difference between the control signal and the sampling signal. The phase difference $\theta$ between the control signal $U'$ and the system signal $U$ is not zero [8]. As shown in equation (5).

$$
\begin{bmatrix}
U' + U
\end{bmatrix} =
\begin{bmatrix}
\cos(0 + \tilde{\theta}) & \sin(0 + \tilde{\theta}) \\
-sin(0 + \tilde{\theta}) & \cos(0 + \tilde{\theta})
\end{bmatrix}
\begin{bmatrix}
U' + U
\end{bmatrix}
$$

(5)

According to equation (5), the corresponding relationship of disturbance signals can be obtained by separating the basis quantity from the disturbance quantity, as shown in equation (6).

$$
\begin{bmatrix}
u_d^c \\
u_q^c
\end{bmatrix} \approx \begin{bmatrix}
u_d^s + U_q^s \tilde{\theta} \\
u_q^s + U_q^s \tilde{\theta}
\end{bmatrix}
$$

(6)

Where, $\sin(\tilde{\theta}) \approx \tilde{\theta}$.

According to Figure 4, the loop gain can be obtained, as shown in equation (7).

$$
\tilde{\theta} = u_q^s G_p(s) \frac{1}{s}
$$

(7)

Small signal disturbance function can be obtained by substituting equation (7) into equation (6), as shown in equation (8).

$$
\tilde{\theta} = \frac{G_p(s)}{s + U_q^s G_p(s)} u_q^s
$$

(8)

The small signal open-loop transfer function of phase-locked loop is shown in equation (9).

$$
G_{PLL} = \frac{\tilde{\theta}}{u_q} = \frac{G_p(s)}{s + U_q^s G_p(s)}
$$

(9)

3.3. Control model of grid-connected inverter system

The control transfer block diagram with small signal disturbance of PLL is shown in Figure 5.

Equivalently simplify the model of Figure 5 is shown in Figure 6.
Where,
\[
G_1(s) = \frac{G_i(s)G_u(s)K_{PWM}}{G_u(s)K_{PWM}H_u + ab + 1} \\
G_2(s) = \frac{G_i(s)G_u(s)K_{PWM}}{cG_i(s)K_{PWM}H_u + abc + c + a}
\]

Therefore, the loop gain \(T(s)\) of the system is shown in equation (11).
\[
T(s) = G_1(s)G_2(s)H_i = \frac{G_i(s)G_u(s)K_{PWM}H_i}{cG_i(s)K_{PWM}H_u + abc + c + a}
\]

The grid-connected current function with phase-locked loop disturbance is given by equation (12).
\[
i_2(s) = \left[ \frac{1}{H_i} + \frac{T(s)}{1 + T(s)} \right] \frac{G_{PLL}I_mH_{si}}{1 + T(s)} - \frac{G_2(s)}{1 + T(s)} u_{PCC}
\]

4. System parameter design

4.1. Filter parameters
Grid-connected inverter steady-state network side vector [9-11], as shown in Figure 7.

The grid-connected inverter has different operating states at different positions of a, b, c, and d. The worst case stability is c point. When using SVPWM control, the upper limit of the design of the inductor should be
\[
L_i + L_2 \leq \frac{V_s}{\sqrt{3}E_p} \omega I_{LP}
\]

Where, \(E_p\) is the voltage peak; \(I_{LP}\) is the peak of the inductor current.

In the design of the wave device, the capacitance capacity generally does not exceed 5% of the rated power [12], as shown in equation (14).
\[
3U_c^2 \omega C \leq 5\% P_n
\]

Where, \(U_c\) is the capacitor voltage; \(P_n\) inverter rated power.

4.2. Current loop PI parameters
According to the system open loop transfer function:
\[
|T(j2\pi f_c)| = \frac{|G_i(s)G_u(s)K_{PWM}H_i|}{|cG_u(s)K_{PWM}H_u + abc + c + a|}
\]

The loop gain amplitude at the cutoff frequency is 1, i.e., \(|T(j2\pi f_c)| = 1\), and \(|G_i(j2\pi f_c)| = K_P\). In the low frequency band, the influence of differential on the system can be ignored[13-16]. The approximate calculation can be obtained:
\[ K_p \approx \frac{2\pi f_c}{H_{PWM} G_n G_d} (L_1 + L_2 + L_3) \]

After obtaining \( K_p \), you can get the range of values of \( K_i \). As in (18).

\[ K_i > K_{i, \gamma_0} = \frac{2\pi f_c}{K_{PWM} H G_2 G_d} \left[ \frac{4\pi^2 \left( L_1 + L_2 + L_3 \right)^2}{10^{20} f_0^2} - f_c^2 \right] \tag{17} \]

The value range of \( K_i \) is different under different delay conditions. The three curves in the Figure 8 show the change of the value \( K_i \) of different delay. The shaded part is the range of values of \( K_i \) when the delay is maximum.

![Figure 8. \( K_i \) range of values.](image)

![Figure 9. DC bus voltage and index.](image)

5. Simulation experiment verification

In this paper, the model of LCL three-phase photovoltaic grid-connected inverter system is built in Matlab/Simulink. Parameters of three-phase LCL type grid-connected inverter: output power \( P_n = 100 \text{ kW} \), fundamental frequency \( f_0 = 50 \text{ Hz} \), inverter output line voltage \( U_{abc} = 380 \text{ V} \), DC bus voltage \( V_{dc} = 730 \text{ V} \), filter parameters \( L_1 = 0.16 \text{ mH} \), \( L_2 = 0.1 \text{ mH} \), \( C = 10 \text{ \mu F} \). The stability of the DC bus voltage is a prerequisite for stable system output. Figure 9 shows the DC bus voltage and index.

Figure 10 and figure 11 respectively show the current output waveform of the traditional control strategy and the control strategy in this paper. The traditional control is based on the ideal grid conditions. According to the waveform, when the grid fluctuates and impedances, its output cannot meet the requirements. The control strategy of the above conditions can output ideal current waveform.

![Figure 10. The output current of traditional control strategy.](image)

![Figure 11. The output current of the control strategy in this paper.](image)
The amount of current harmonics is an important indicator of power quality. As shown in figure 12, the grid-connected current THD is 2.18%, which meets the grid connection requirement of THD≤5%.

![Grid-connected current THD spectrum.](image)

**Figure 12.** Grid-connected current THD spectrum.

Voltage and current output waveform under different working conditions, Grid-connected inverter output when command current ramps and abrupt changes is shown in Figure 13 and 14. It can be proved that the control strategy designed in this paper can satisfy the influence of extreme conditions on the system while solving the influence of the two factors of power grid impedance and power grid fluctuation.

![Waveforms under different working conditions.](image)

**Figure 13.** Working condition 1. **Figure 14.** Working condition 2.

6. **Conclusions**
Under non-ideal grid, grid impedance, grid fluctuation and other factors put forward higher requirements for the control of grid-connected photovoltaic inverter. In this paper, based on the LCL type three-phase grid-connected inverter, the influence of changes in grid parameters on photovoltaic grid-connected inverter is considered. A double closed loop controller with current - capacitance voltage on the network side is designed. The parameters are calculated according to the constraint conditions and the simulation model is built. The simulation results show the output of the inverter under the condition of sudden or slow change of command current and change of power grid impedance. The validity, stability and robustness of the controller design scheme are proved.
References

[1] He Y, Chung H S H, Lai C T 2018 Active Cancelation of Equivalent Grid Impedance for Improving Stability and Injected Power Quality of Grid-Connected Inverter Under Variable Grid Condition IEEE Transactions on Power Electronics 33(11) 9387-9398

[2] Gao Fengyang, Du Qiang, Qiao Wei, Qiang Guodong 2018 Decoupling control of LCL three-phase photovoltaic grid-connected inverter with inverter-side current feedback Power System Protection and Control 46(09) 122-128

[3] Li Zebin, Luo An, Tian Yuan 2014 Control method of current inner loop of LCL photovoltaic grid-connected inverter Power System Technology 38(10) 2772-2778

[4] Wu Heng, Yan Xinbo, Yang Dongsheng 2014 Study on the Influence of Phase-Locked Loop on the Stability of LCL Grid-Connected Inverter under Weak Grid Condition and Parameter Design of Phase-Locked Loop Proceedings of the CSEE 34(30) 5259-5268

[5] Yang Wei, Chen Yandong, Zhou Leming 2018 Influence and stability analysis of small-interference modeling of three-phase LCL grid-connected inverter under weak grid Proceedings of the CSEE 38(13)

[6] Yin J, Duan S, Liu B 2013 Stability analysis of grid-connected inverter with LCL filter adopting a digital single-loop controller with inherent damping characteristic IEEE Transactions on Industrial Informatics 9(2) 1104-1112

[7] Pan D, Ruan X, Wang X, et al 2018 A Highly Robust Single-Loop Current Control Scheme for Grid-Connected Inverter With an ImprovedLCLFilter Configuration IEEE Transactions on Power Electronics 33(10) 8474-8487

[8] Saïd-Romdhane M B, Naouar M W, Slama-Belkhodja I and Monmasson E 2016 Robust active damping methods for LCL filter-based grid-connected converters IEEE transactions on power electronics 32(9) 6739-6750

[9] Zhang Xing, Zhang Chongxi 2017 PWM Rectifier and Its Control. Mechanical Industry Press 272-273

[10] Zhang X, Xia D, Fu Z, Wang G and Xu D 2018 An improved feedforward control method considering PLL dynamics to improve weak grid stability of grid-connected inverters IEEE Transactions on Industry Applications 54(5) 5143-5151

[11] Guan Y, Wang Y, Xie Y, Liang Y., Lin A and Wang X 2018 The Dual-current Control Strategy of Grid-connected Inverter with LCL Filter IEEE Transactions on Power Electronics

[12] Jia L, Ruan X., Zhao W, Lin Z and Wang X 2018 An Adaptive Active Damper for Improving the Stability of Grid-Connected Inverters Under Weak Grid IEEE Transactions on Power Electronics 33(11) 9561-9574

[13] Khajehoddin S A, Karimi-Ghartemani M, Jain P K 2011 A control design approach for three-phase grid-connected renewable energy resources IEEE Transactions on Sustainable Energy 2(4) 423-432

[14] Yang Wei, Chen Yandong, Zhou Leming, et al. 2018 Influence and stability analysis of small-interference modeling of three-phase LCL grid-connected inverter under weak grid Proceedings of the CSEE 38(13)

[15] Zhang X, Xia D, Fu Z., Wang G and Xu D 2018 An improved feedforward control method considering PLL dynamics to improve weak grid stability of grid-connected inverters IEEE Transactions on Industry Applications 54(5) 5143-5151

[16] Xu J, Xie S, Zhang B and Qian Q. 2018 Robust Grid Current Control With Impedance-Phase Shaping forLCL-Filtered Inverters in Weak and Distorted Grid IEEE Transactions on Power Electronics 33(12) 10240-10250