A Method for Improving Robustness of Grid-Connected Inverter System with Control Delay

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Abstract. In the grid-connected inverter system, due to the existence of digital control delay, the inverter presents the characteristic of negative damping. The traditional damping method is usually the form of capacitive current feedback, but the stability margin of the system is very low. Passive damping can improve the stability margin of the system, but it increases the loss of the system and reduces the high-frequency attenuation characteristics of the filter. Therefore, this paper considers the use of active + passive damping, while ensuring the system phase margin, reducing the loss as far as possible, improving the filter's high-frequency filtering characteristics. Finally, the simulation model is built in Matlab/Simulink, and the correctness of the theoretical analysis is verified by simulation.

1. Introduction
In recent years, with the large-scale development and application of renewable energy such as solar energy and wind energy, more and more distributed energy sources have been integrated into the power grid to replace traditional fossil energy sources [1]. Among them, the grid-connected inverter is a key interface for distributed generation, which has a very important impact on the stability of the grid-connected system [2]. How to improve the stability of the grid-connected inverter system has become the focus of attention [3].

In order to suppress the high-frequency switching harmonics generated by PWM control, the grid-connected inverter generally uses an LCL filter [4]. However, the amplitude-frequency response of the LCL filter has a resonant peak, and its phase will have a -180° transition at the resonant frequency. If it is not damped, it may cause grid current oscillation and even cause grid-connected inverter instability [5].

Damping method of the resonant peak of the LCL filter can be passively damped or actively damped [6]. The former is simple and reliable, but introduces losses. The latter do not introduce losses, but need to introduce state variable feedback. When active damping is used, due to the influence of control delay, the capacitive current feedback will no longer be equivalent to a virtual resistor connected in parallel with the filter capacitor, but a virtual impedance that varies with frequency [7]. While the equivalent virtual impedance damping the resonant peak, changes the frequency of the system loop gain resonance spike, thereby affecting the stability of the system. Reference [8] pointed out that the negative resistance effect is the intrinsic mechanism of self-excited oscillation in the power system. Reference [9] pointed out that if the conductance characteristics of all grid-connected
inverters are positive, the grid-connected system is stable; if there is an inverter with negative damping characteristics, the grid-connected system has resonance risk.

Based on the impedance stability criterion, the paper studies the method of using active + passive damping to improve the robustness of grid-connected inverters to the grid. Firstly, considering the influence of digital control delay, an equivalent model of LCL-type grid-connected inverter using capacitive current feedback active damping and grid-connected current feedback is established. Then, the active + passive damping method is proposed to improve the stability margin of the system, and the advantages and disadvantages of using different damping methods are compared and analyzed. Finally, the simulation results verify the correctness of the conclusions by building a simulation model in Matlab/Simulink.

2. System Model of LCL Grid-Connected Inverter

The system structure diagram of LCL type single-phase grid-connected inverter is shown in Figure 1. $H_1$ is a capacitance current feedback coefficient; $H_2$ is a grid current feedback coefficient; $i^*_2$ is a grid connected current instruction, which can be multiplied by the phase angle sin θ generated by the phase locked loop (PLL) in the system and the given amplitude $I^*$ of the grid connected current; $G_i(z)$ is the transfer function of the controller; $v_M$ is the modulation signal output by the controller; SPWM is the modulation (sinusoidal pulse width modulation).

![Figure 1. The control structure diagram of a single grid-connected inverter](image)

According to the control strategy of inverter shown in Fig. 1, the control block diagram of the grid-connected inverter can be obtained, as shown in Figure 2. $K_{pwm}$ is the transfer function of the modulation signal to the output voltage of the inverter arm. It is equal to the ratio of the $V_{dc}$ of the DC side voltage to the $V_{tri}$ of the triangular carrier amplitude: $K_{pwm}=V_{dc}/V_{tri}$. $G_d(s)$ is a transfer function expression considering the one-shot delay $e^{sT_d}$ introduced by the digital control and the half-beat delay $(1-e^{sT_s})/s$ introduced by the zero-order keeper [17]. In the Nyquist frequency, the expression can be approximated as: $G_d(s) \approx e^{-1.5sT_d}$. $T_s$ is the sampling cycle.

![Figure 2. The control block diagram of single grid-connected inverter](image)

According to the control block diagram shown in figure 2, the Norton equivalent model of the grid-connected inverter can be obtained, as shown in Figure 3. $i(s)$ is the equivalent current source output current, which can be expressed as $i(s)=G_d(s)i^*_2$, $Y_d(s)$ as inverter output admittance, $Z_d(s)$ as grid impedance and $v_d(s)$ as grid voltage.
\[ G_i(s) = \frac{H_iG_i(s)K_{pum}G_d(s)}{L_iL_2C \cdot s^3 + K_{pum}G_d(s)H_iL_1L_2C \cdot s^2 + (L_1 + L_2)s + H_2G_i(s)K_{pum}G_d(s)} \]  

(1)

\[ Y_p(s) = \frac{L_0C \cdot s^2 + K_{pum}G_d(s)H_1C \cdot s + 1}{L_iL_2C \cdot s^3 + K_{pum}G_d(s)H_iL_1L_2C \cdot s^2 + (L_1 + L_2)s + H_2G_i(s)K_{pum}G_d(s)} \]  

(2)

Figure 3. The Norton equivalent model of a single grid-connected inverter

3. Stability Analysis of LCL Grid-Connected Inverter

The grid-connected current \( i_2(s) \) expression can be obtained from the grid-connected inverter Norton equivalent model:

\[ i_2(s) = \frac{1}{1 + Z_p(s)/Z_o(s)} \left( i_o(s) - \frac{u_g}{Z_o(s)} \right) \]  

(3)

Equation (3) shows that the stability of the grid-connected current \( i_2(s) \) is determined by two parts: \( i_o(s)/Z_o(s) \) and \( Z_p(s)/Z_o(s) \). The former part is only related to the stability of the inverter itself, and the latter part depends on whether the \( Z_p(s)/Z_o(s) \) satisfies the Nyquist stability criterion.

According to the Nyquist stability criterion, the phase difference at the intersection of the amplitude-frequency curve of the grid impedance \( Z_g(s) \) and the grid-connected inverter output impedance \( Z_o(s) \) is less than 180°, and the system is stable. In order to ensure the robustness of the system, it is generally necessary to leave a certain phase margin in actual design. Figure 4 shows the intersection of the inverter output impedance \( Z_o(s) \) and the grid impedance \( Z_g(s) \) when the LCL grid-connected inverter uses the PR controller. See Table 1 in Section 4 for details. As can be seen from the figure 4, the phase-frequency curve of the output impedance of the inverter have a frequency band lower than -90° \( (f_1, f_2) \). When the grid impedance \( Z_g \) is a pure inductance, its phase is always 90°. When the frequency at the intersection of the amplitude-frequency curves of \( Z_g(s) \) and \( Z_o(s) \) falls between \( (f_1, f_2) \), the phase difference between the two is greater than 180°, and the system will be unstable.
In order to get the relationship between frequency $f_1$ and $f_2$, we need to further analyze the output impedance of the inverter. In the frequency band $(f_1, f_2)$, the inverter output impedance phase is lower than 90°, which indicates that the inverter output impedance exhibits a negative damping characteristic in the frequency band. That is the real part of the output impedance is negative. We will analyze the real part of the transformer output impedance. 

By simplifying Equation 2, we can get the real-body expression of the output impedance of the inverter in the frequency domain (where $x=1.5T_{sw}$):

$$R(Z_{o}(jw)) = \frac{K_{pon} \cos x[K_pH_2 + w^2L_tC(H_1 - K_pH_2)]}{(1 + wC\sin xH_1K_{pon} - wL_c)^2 + (wCH_1K_{pon} \cos x)^2}$$

(4)

Let $K_{pon} \cos x[K_pH_2 + w^2L_tC(H_1 - K_pH_2)] = 0$, we can get that:

$$w_1 = \frac{K_pH_2}{\sqrt{L_tC(\overline{H_1} + K_pH_2)}}, \quad w_2 = \frac{w}{6}$$

(5)

It can be seen from the above analysis that the angular frequency $w_2$ corresponding to $f_2$ is fixed and only related to the system control delay, and the angular frequency $w_1$ corresponding to $f_1$ varies with the parameter of the system. Only when $w_1 = w_2 (f_1 = f_2)$, the phase frequency characteristics of the output impedance of the entire inverter are at -90° and above. However, if the grid impedance and the inverter output impedance cross at this frequency $f_2$, the phase margin of the system is 0°, and the robustness of the system is poor. The traditional capacitive current feedback will not be applicable to the system presence control delay. Therefore, in order to increase the system damping and improve the stability margin and robustness of the system, consider the passive + active damping method.

4. Improve system robustness

It can be seen from the above analysis that the purely capacitive active current damping form, the phase margin of the system is up to 0°, and the system is critically stable. In order to ensure the system remains stable under system parameters and external disturbances, it is necessary to improve the stability margin of the system. Therefore, this paper considers the double damping form of capacitor string resistor and capacitor current feedback, so that the inverter will not have negative damping characteristics in the whole frequency range, and it can also improve the stability margin of the system, as shown in Figure 5.
According to the inverter control strategy shown in Figure 5, we can get the output impedance of the inverter at this time:

\[
Z_{v1}(s) = \left\{ \frac{(L_1 + L_2) + R_{CH} G_1(s) K_{PWM} G_p(s)}{L_1 C s^2 + (K_{PWM} G_p(s) H C + R C)s + 1} \right\} \cdot \left( (L_1 + L_2) + R C C H G_1(s) K_{PWM} G_p(s) H C + R C \right) s + 1
\]

From the third section analysis, we can see that when the active damping of capacitive current feedback is used, the stability margin of the system is the largest when \( w_1 = w_2 \), and the size of \( H_1 \) is:

\[
H_1 = K_p H_2 - \frac{K_p H_2 9}{C L C^2 \pi^2 f_0^2}
\]

From the system parameters in Table 1 of Section 4, \( H_1=0.0712 \) is obtained at this time. The following is a Bode plot of the inverter output impedance as a function of resistance \( R_1 \) when \( H_1 = 0.0712 \), as shown in Figure 6. It can be seen from Fig. 6 that as the \( R_1 \) increases, the high-frequency phase of the inverter output impedance increases. Considering that in the most severe case (the grid impedance is purely inductive), to ensure that the phase margin at the intersection frequency of the inverter output impedance is greater than 30°, the minimum series resistance \( R_1 = 1 \, \Omega \) under this condition is taken.

**Figure 5.** Grid-connected inverter control structure diagram for active + passive damping

**Figure 6.** Bode diagram of inverter output impedance as variety of \( R_1 \) when \( H_1=0.0712 \)
Draw the Bode plot of the output impedance of the inverter with the capacitive current feedback coefficient when \( R_1 = 1 \, \Omega \), as shown in Figure 7. As can be seen from Fig. 7, as the capacitance current feedback coefficient increases, the phase at the high frequency of the inverter output impedance first increases and then decreases, and the phase frequency characteristic curve of the inverter output impedance intersects at the frequency \( f_2 \). The phase margin is maximized near \( H_1 = 0.07 \), which is consistent with the above analysis.

![Bode Diagram](image)

**Figure 7.** Bode diagram of inverter output impedance with variety of \( H_1 \) when \( R_1 = 1 \, \Omega \)

Figure 8 is the Bode diagram of the output impedance of the inverter with variety of series resistance \( R_1 \) when a passive damping mode of a capacitor series resistor is employed. It can be seen from the figure that as the resistance \( R_1 \) increases, the high-frequency phase of the inverter output impedance will increase. Considering that in the most severe case (the grid impedance is purely inductive), to ensure that the phase margin at the intersection frequency of the inverter output impedance is greater than 30°, the minimum series resistance \( R_1 = 3 \, \Omega \) under this condition is taken.

![Bode Diagram](image)

**Figure 8.** The bode diagram of inverter output impedance as a function of \( R_1 \) during passive damping

When using different damping methods, the bode diagram of the filter is shown in Fig. 9.
It can be seen from the figure that the attenuation of the high-frequency harmonics of the active damping and the passive + active damping filter are almost the same. The damping of the capacitor string resistor will weaken the high-frequency harmonics attenuation ability of the LCL filter.

5. Simulation

In order to verify the above analysis, a simulation circuit model is built on the Matlab/Simulink platform, and the specific parameters are shown in Table 1. When the different damping modes are used, the grid-connected current of the inverter output is as follows.

| Parameter  | Value | Parameter  | Value | Parameter  | Value | Parameter  | Value |
|------------|-------|------------|-------|------------|-------|------------|-------|
| $U_d/V$    | 360   | $f_s/k$Hz  | 20    | $L_2$/$m$H | 0.09  | $H_{2,1}$  | 0.15  |
| $U_g/V$    | 220   | $f_{sw}/k$Hz | 10    | $C/\mu$F  | 10    | $K_p$      | 0.6   |
| $f_o/Hz$   | 50    | $L_1$/$m$H | 0.85  | $V_{ni}/V$ | 4.5   | $K_r$      | 65    |

When passive damping is used ($R_1=1\Omega$), the grid-connected inverter current waveform is shown in Figure 10. At this time, the phase of the inverter output impedance is in the frequency range below -90°. When the grid impedance $L_g=0.6mL$, the output impedance of the inverter is intercepted within the frequency range. The current contains a lot of harmonics and the system is unstable.

Figure 9. The bode diagram filter characteristics

Figure 10. $R_1 = 1 \Omega$, the grid-connected current waveform of the inverter output
When the active damping + passive damping mode is adopted \((H_1=0.0712, R_1=1\Omega)\), the inverter grid-connected current waveform is shown in Figure 11. The output grid-connected current has no resonance and the system is stable.

![Figure 11. \(H_1=0.0712, R_1=1\Omega\), the current waveform of the inverter output](image)

The literature [10] gives the loss calculation expression caused by the damping resistance:

\[
P_{loss} = \sum_{h=1}^{\infty} i_{h}(h^2) R_1 \left( \frac{-w^2 L_c C}{1+jwR_1C} \right)^2
\]  

(8)

It can be seen from the expression that the loss caused by the damping resistance is related to the size of the resistor itself, the harmonic content of the current on the grid side, and the system parameters. For the same system, the current harmonic content on the grid side is approximately the same (THD < 5%). When \(1+jwR_1C \approx 1\), the power consumed by the damping resistor \(R_1\) is basically proportional to the resistance of the resistor itself. Figure 12 is a graph showing the variation of the damping resistance loss with time when active + passive damping and passive damping are used. It can be seen from the figure that the resistive loss using passive damping is three times that of the active + passive damping resistor, which is consistent with the above analysis, thus verifying the correctness of the above analysis.

![Figure 12. the power loss of damping resistor](image)
6. Conclusion
In the LCL type grid-connected inverter, in order to suppress the LCL resonance peak and reduce the system loss, the active damping form of the capacitive current feedback is generally adopted. Due to the existence of the digital control delay, the active damping is used to make the inverter appear. The negative damping characteristic, which will cause the grid-connected inverter to have poor robustness to the grid impedance.

In order to improve the robustness of the inverter to the grid impedance, this paper proposes an active + passive damping method. The method ensures the system phase margin while minimizing system loss and improving the high-frequency filtering characteristics of the filter. On this basis, various methods are compared and analyzed, and the active + passive damping method is considered to be the best.

References
[1] Yang Shenchun, Xiang Kelin, Zhou Benduo. Current Situation and Prospect of Solar Thermal Power Generation Industry in China [J]. SINO-GLOBAL ENERGY 2017, 15 (6): 19-23.
[2] Huerta J M E, Castello J, Fischer J R, et al. A Synchronous Reference Frame Robust Predictive Current Control for Three-Phase Grid-Connected Inverters [J]. IEEE Transactions on Industrial Electronics, 2010, 57 (3): 954-962.
[3] Midtsund T, Suul J A, Undeland T. Evaluation of current controller performance and stability for voltage source converters connected to a weak grid [C]// IEEE International Symposium on Power Electronics for Distributed Generation Systems. IEEE, 2010:382-388.
[4] Lindgren M, Svensson J. Control of a voltage-source converter connected to the grid through an LCL-filter-application to active filtering [C]// Power Electronics Specialists Conference, 1998. Pesc 98 Record. IEEE. IEEE, 2002:229-235 vol.1.
[5] ang S, Lei Q, Peng F Z, et al. A Robust Control Scheme for Grid-Connected Voltage-Source Inverters [J]. IEEE Transactions on Industrial Electronics, 2010, 58 (1): 202-212.
[6] Peña-Alzola R, Liserre M, Blaabjerg F, et al. Analysis of the Passive Damping Losses in LCL-Filter-Based Grid Converters [J]. IEEE Transactions on Power Electronics, 2012, 28 (6): 2642-2646.
[7] Bao C, Ruan X, Wang X, et al. Step-by-Step Controller Design for LCL-Type Grid-Connected Inverter with Capacitor–Current-Feedback Active-Damping [J]. IEEE Transactions on Power Electronics, 2013, 29 (3): 1239-1253.
[8] Xie Xiaorong, Liu Huakun, He Jingbo, Liu Hui, Liu Wei. On New Oscillation Issues of Power Systems [J]. Proceedings of the CSEE, 2018, 38 (10).
[9] Wang Yi, Liu Shu, Liu Jianzheng, Mei Hongming, Chen Li. Resonance Mechanism Analysis of the Power System Involving Distributed Grid-connected Inverters [J]. Proceedings of the CSEE, 2018 (09): 2693-2706+2839.
[10] Zhao Rende, Zhao Qiang, Li Fang, Wang Ping. Impact of Damping Resistance on Grid Inverter with LCL-filter [J]. Proceedings of the CSU-EPSA. 2009, 21 (6): 112-116.