Improved active damping control strategy and closed-loop parameter design for LCL grid-connected inverter

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Abstract: In this paper, an active damping control strategy based on capacitance and voltage feedback is proposed to solve the resonance problem of three-phase LCL inverter grid-connected system. To solve the problem that the parameters of active damping control strategy are complicated and need to be adjusted repeatedly, a parameter design method is proposed in this paper, which is simple to implement and does not need to be adjusted repeatedly. Finally, the effectiveness of the control strategy and parameter design method is verified by experiments.

1. Introduction
With the rapid development of distributed generation technology, energy storage technology and micro energy generation technology represented by renewable energy, grid connection of new energy generation is gradually becoming a research hotspot. In the grid-connected system of renewable energy generation, LCL grid-connected inverter plays an important role as the interface device that between the distributed generation and the power grid. However, the LCL filter circuit is a third-order system, which is easy to cause the resonance problem of the system. Around this problem, there are a lot of literatures. It includes that closed-loop control method based on single current\textsuperscript{[1-2]}, active damping method for additional digital filters in the forward path\textsuperscript{[3-4]}, feedback control method based on model order reduction\textsuperscript{[5-6]}, and active damping control strategy based on feedback of additional variables\textsuperscript{[7]}. The single-current closed-loop control method is dependent on system parameters, and its robustness is poor when the parameters are disturbed\textsuperscript{[1]}. The active damping method of the forward path additional digital filter depends on the filter parameters, and it is difficult to give consideration to both bandwidth and amplitude phase margin\textsuperscript{[2]}. The feedback control method based on model order reduction requires the accurate allocation of the pole zero\textsuperscript{[4]}. Reference\textsuperscript{[8]} studies the situation that the equivalent resistance of the network side changes under the feedback control scheme of voltage and current variables at different positions. Capacitor voltage is selected as the feedback variable, but the capacitor voltage feedback coefficient contains a differential link, which is difficult to achieve. Reference\textsuperscript{[9]} proposes a cooperative control strategy method based on the mathematical model...
research of three-phase LCL grid-connected inverter, but the control strategy parameters adopted by the pole-zero assignment method are too complex.

Therefore, an active damping control strategy based on capacitive voltage feedback is proposed in this paper. In this strategy, a first-order high-pass filter is used to replace the capacitive voltage differential feedback. Aiming at the problem that the parameter design of control strategy is complex and needs to be adjusted repeatedly, this paper proposes a parameter design method which is simple to implement and does not need to be adjusted repeatedly.

2. Design of New Active Damping Control Strategy of Capacitor Voltage Feedback And Parameters of Inner Loop

2.1. A Novel Capacitive Voltage Feedback Active Damping Control Strategy

The traditional capacitive voltage feedback active damping control strategy contains the capacitive voltage feedback link, which is very sensitive to the high frequency input and will amplify the high frequency signal, making it difficult for the system to achieve [8]. Therefore, this link needs to be adjusted. Based on the fitting of second-order differential feedback, references [10] proposed a scheme of current feedback to the network based on additional phase shift link of high-pass filter. References [6] proposed a method of replacing PCC point voltage differential feedback link with \( H_r(s) \) of first-order high-pass filter.

Therefore, this paper proposes to replace the capacitance voltage differential feedback with the first-order high-pass filter to optimize and adjust the capacitance voltage feedback, so as to avoid the stability problem caused by the voltage feedforward of the power grid.

The transfer function of the first-order high-pass filtering link is:

\[
H_r(s) = \frac{K_r s}{s + \omega_c}
\]

Where \( K_r \) is the feedback coefficient of high-pass filtering, and \( \omega_c \) is the cutoff angular frequency of high-pass filtering.

The improved active damping control block diagram of capacitor voltage feedback is shown below:

![Block diagram of new capacitor voltage feedback active damping control](image)

In Figure 1, inductor \( L_1 \), capacitor \( C \) and network-side inductor \( L_2 \) constitute the LCL filter. \( G_i(s) \) is the transfer function of PI controller, \( U_c \) is the capacitor voltage, \( i_2 \) is the grid-connected current, \( e_g \) is the grid voltage, and \( L_{gi} \) is the grid internal resistance. In this case, the open-loop transfer function of the system is:

\[
G_i(s) = \frac{G_i(s) K_c}{s L C (L_2 + L_p) (s^2 + \omega_c^2) + H_r(s) K_c s (L_2 + L_p)}
\]

\[
\omega_r = \sqrt{\frac{L_1 + L_2 + L_p}{L C (L_2 + L_p)}}
\]

In formula (3), \( \omega_r \) is the resonance angular frequency of the system.
2.2. New Active Damping Control Strategy And Closed-loop Parameter Design For LCL Grid-connected Inverter

According to equation (2), the damping effect of the system is affected by the transfer function $H_r(s)$, $G_i(s)$ and the parameter $K_c$. The equivalent amplification link $K_c$ of the main circuit of the grid-connected inverter is a constant, which can be ignored. Therefore, it is necessary to explore the influence of high-pass filter feedback coefficient $K_r$, high-pass filter feedback link cutoff angular frequency $f_c$ and PI controller transfer function $G_i(s)$ on the damping of the system. The loop gain bode diagram of the system at different cutoff angular frequencies, $\omega_c$, is drawn as shown in FIG. 2(a).

![Bode Diagrams](image)

(a) under different $\omega_c$  
(b) under different $K_r$

Figure 2. System loop gain bode diagram under different $\omega_c$ and different $K_r$

Can be analyzed from the figure, when $\omega_c = 1.5 \omega_r$, the system damping effect, the phase angle of the margin and amplitude margin are better.

When $\omega_c = 1.5 \omega_r$, the loop gain bode graph of the system with different high-pass filter feedback coefficients $K_r$ is drawn as shown in FIG. 2(b). As can be seen from FIG. 2(b), when $K_r = 1$, this control strategy has the worst damping effect on the system, but the maximum amplitude margin. As $K_r$ decreases, the damping effect of the system increases, the amplitude margin decreases, and the phase angle margin increases. When $K_r$ is less than or equal to 0.05, the system becomes unstable.

2.3. Design method of PI parameter of PI controller

The transfer function $G_i(s)$ of PI controller is:

$$G_i(s) = K_p + \frac{K_i}{s}$$

(4)

When the loop gain cut-off frequency is lower than or equal to, the capacitive reactance of the filter capacitor is much higher than the inductive reactance of the grid side. It can be considered that the filter capacitor branch is open, and the LCL filter is simplified to a single L filter with the sensitivity of $(L_1+L_2)$.

According to equation (2), the approximate loop gain of the system is:

$$T(s) = \frac{G_i(s)K_r}{3L_1+3L_2s+H_r(s)K_c}$$

(5)

In formula 5: $L_p = L_1 + L_2 + L_{gi}$, $L_{2g} = L_1 + L_{gi}$

According to literature[11], $G_i(s)$ can be approximately replaced by $K_p$ when analyzing the amplitudes and frequency characteristics of the system at the gain cutoff frequency $f_c$ of the loop above or equal to, so formula (5) becomes:
Since at the loop gain cut-off frequency $f_c$, the gain amplitude of the system loop is 1, i.e.

$$T_i(f2\pi f_c) = 1$$

Then, according to equation (13):

$$K_p = \frac{2\pi f_c L_p + 2\pi f_c L_c}{2\pi f_c + \omega_0} K_c$$

According to equation (7), $K_p$ determines the cutoff frequency $f_c$ of the system.

The larger $K_p$ is, the higher the cutoff frequency $f_c$ of the system is, the faster the dynamic response speed of the system is, and the higher the low-frequency gain is.

According to the steady-state error requirement of the grid-connected current, the minimum amplitude of the loop gain at the fundamental frequency of the system is obtained.

Then according to the cut-off frequency $f_c$, amplitude gain $T_{fo}$ and phase margin PM requirements of the system, the value range of $K_i$ is calculated.

According to equations (8), the maximum and minimum values of PI parameter $K_i$ can be determined.

3. Design Example

According to the above principles, an experimental prototype of three-phase grid-connected inverter with DSP (Digital Signal Processor) TMS320F28335 as the control core and LCL filter based on capacitor voltage feedback control is built in the laboratory. According to the experimental parameters, the experimental voltage and current waveforms are obtained as shown in the following figure.

Figure 3(a) shows the waveforms of grid-side voltage $U_g$ and grid-connected current $i_2$ when the fundamental wave of grid-connected current is set as the effective value of 27.27a. It can be seen from figure 3(a) that when the grid-connected current has a high sinusoidal degree, the harmonic content is low. Figure 3(c) is the spectrum analysis diagram of grid-connected current, in which the total harmonic distortion rate of grid-connected current is 1.24%, which proves that the control strategy and parameter design method proposed in this paper are effective.

Figure 3(b) shows the dynamic response waveform of single-phase grid-connected current when it jumps between half-load and full-load. The overshoot of grid-connected current is 14%, and the dynamic adjustment time is 2 ms.
4. Conclusion
In this paper, the first-order high-pass filter element is used to replace the capacitance voltage differential feedback element, and the capacitance voltage feedback element is optimized and adjusted. Based on the new LCL-type grid-connected inverter control strategy proposed in this paper, the influence of the closed-loop parameters of the three-phase LCL grid-connected inverter on the system performance is analyzed.

In this paper, a closed-loop parameter design method based on system phase margin, amplitude margin and system damping effect is proposed. Closed-loop parameters that meet the requirements can be obtained simply with a simple implementation method. A prototype of 6kW three-phase LCL grid-connected inverter is built. The experimental results prove that the parameter design method and control strategy in this paper can effectively damp the resonant peak of the system, and the system has strong robustness and good dynamic response performance.

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