Composite Control Strategy of Output Current of LCL Photovoltaic Grid-Connected Inverter

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Abstract. In order to further optimize the output current harmonic suppression effect of photovoltaic grid-connected inverters, a composite control strategy of LCL type photovoltaic grid-connected inverter output current is proposed. This strategy combines proportional complex integral (PCI) control and repetitive control (RC) in parallel, draws a composite control block diagram, introduces a transfer function, and designs PCI and RC control parameters. Prove that the compound control can reduce current harmonics, achieved the purpose of reducing the steady-state error of the fundamental frequency. And adopts a new PCI composite control strategy, which helps to save the cost of the control system. By building the MATLAB/Simulink simulation platform and establishing the PCI+RC composite control model of LCL photovoltaic grid-connected inverter, the comparison of the simulation results shows that compared with the PI+RC control strategy, the total harmonic distortion rate of the grid-connected current is reduced by 25.77 %, significantly improving the quality of grid-connected current.

1. Introduction
As an important form of renewable energy, photovoltaic power generation has the advantages of wide distribution, large reserves, environmental protection and safety [1-5]. As a key component of the photovoltaic grid-connected power generation system, the grid-connected inverter not only improves the grid-connected efficiency, but also needs to ensure that the Total Harmonic Distortion (THD) of the current input to the grid meets the relevant national standards [6]. The LCL type grid-connected inverter can filter out high-order harmonics and reduce the harmonic distortion rate of the grid-connected current, which has high research value [7-8]. The literature [9] shows that the traditional PI (Proportional Integral) control algorithm is simple and can fundamentally reduce system error. However, error-free adjustment cannot be achieved for AC signals, and PI control has weak ability to suppress various low-order current harmonics [10-11]. Requires additional harmonic compensation mechanism to optimize the quality of grid-connected current. Literature [15] proposed that the PCI (Proportional Complex Integral) control can theoretically completely eliminate the steady-state error, because the gain at the
fundamental frequency is infinite. Compared with the traditional PI control, PCI control eliminates the need for network-side software and phase-locked loop hardware systems, and improves control reliability [16-17]. Literature [13] proposes that RC control can periodically accumulate errors, so as to realize the system without static error tracking, so it is regarded as the first choice for composite inverter systems. Literature [14] introduces RC control to eliminate periodic load harmonics, forming a composite control system, which can reduce calculations and effectively control harmonics. RC control can well suppress the periodic disturbance signal in the system, and the steady-state performance is good, but the single RC control has poor dynamics and needs to be combined with other controls to achieve its control effect [12]. The traditional PI+RC control can be used to eliminate harmonics, but the literature [18] pointed out that the series or parallel connection of PI and RC control has current distortion, which leads to unsatisfactory control effect. Literature [19] uses RC control and PI control technology to suppress grid-connected harmonics to a certain extent, but the algorithm is more complex and stability needs to be improved. Literature [20] proposes to combine PCI+RC control to be applied to LC-type grid-connected inverters. After comparison, it is found that the steady state accuracy is higher than PI+RC control. Based on the above research, this paper combines PCI+RC control and applies it to LCL type.

Aiming at the problem of large grid-connected harmonics and steady-state errors of photovoltaic inverters, this paper proposes a PCI+RC control strategy for LCL photovoltaic grid-connected inverters to optimize output current quality. First, analyze the principles of PCI and RC, then design PCI parameters and add RC control principles. This method can not only eliminate AC steady-state errors, but also it can improve the accuracy of system control and ensure good current quality. Design the RC controller based on the actual parameters; finally, through the simulation experiment, compare before and after the compound control is added to prove the feasibility and effectiveness of PCI+RC control.

2. LCL type grid-connected inverter structure

Fig.1 shows the main circuit structure of the LCL grid-tie inverter. The filter is used to filter the grid-connected current to suppress high-frequency harmonics. \(U_{dc}\) is the DC voltage, \(U_C\) is capacitor voltage, \(e\) is the grid voltage, \(i_1\) is inverter current, \(i_2\) is grid current, \(i_C\) is displacement current, \(L_1\) is inverter side filter inductor, \(L_2\) is grid filter inductor, \(C\) is a filter capacitor, \(L_1\), \(L_2\) and \(C\) form an LCL filter, and \(r_1\) and \(r_2\) are line impedances.

![Figure 1. LCL three-phase grid-connected inverter topology](image)

From figure 1,
where 

\[
\begin{align*}
U(t) - L_1 \frac{di_1(t)}{dt} - r_{L1}(t) &= U_{c1}(t) \\
U_{c1}(t) - L_2 \frac{di_2(t)}{dt} - r_{L2}(t) &= U_{c2}(t) \\
i_c(t) + i_2(t) &= i(t) \\
i_c(t) &= C \frac{dU_c(t)}{dt}
\end{align*}
\]

Obtain the open-loop transfer function between the output current of the LCL filter and the output voltage between the bridge arms by formula (1):

\[
P(s) = \frac{I_d(s)}{U(s)} = \frac{1}{As^3 + Bs^2 + Cs + D}
\]

In (1):

\[
A = L_1 L_2 C \\
B = L_1 r_2 C + L_2 r_2 C + L_1 + L_2 \\
C = L_1 + L_2 + r_2 C \\
D = r_1 + r_2
\]

In the grid-tie current control of the LCL filter, the current control on the inverter side is more stable, so the inverter-side current control is often used to realize the grid-connected current control, as shown in picture 2.

From Fig. 2, the characteristic equation of the closed-loop transfer function of the grid-tie current can be obtained:

\[
D(s) = G(s) K_{PWM} H (1 + L s^3) \\
+ L_1 L_2 C s^3 + L_1 s + L_2 s
\]

3. PCI+RC control strategy

3.1. PCI control strategy

Although traditional PI control has good dynamic performance, it cannot achieve tracking without static error. The PI control method uses rotating d-q coordinates for current tracking. Fig. 3 is diagram of PI control structure of rotating coordinate system.

From Fig. 3, it can be seen from Fig. 3:
The open-loop GPI(s) + the same controller K has obtained the same controller K. The GPI(s) = KP + KI/S, where KI is the integral coefficient and KP is the proportional coefficient.

Equation (4) is obtained after Laplace transform:

\[
\begin{bmatrix}
U_e(t) \\
U_p(t)
\end{bmatrix} = T_{2\pi/2r} \begin{bmatrix}
G_P(s) \\
G_I(s)
\end{bmatrix} T_{2\pi/2r}^{-1} \begin{bmatrix}
e(t) \\
e_p(t)
\end{bmatrix}
\]

(4)

\(e(t), e_p(t)\) is the output error amount, \(U_e(t), U_p(t)\) is the output amount, \(T_{2\pi/2r}\) is the coordinate transformation matrix, and GPI(s) is the PI controller transfer function. GPI(s) = KP + KI/S, where KI is the integral coefficient and KP is the proportional coefficient.

The transfer function of the PCI controller is:

\[G_{PCI}(s) = KP + \frac{KI}{s - j\omega_0}\]

(6)

It can be seen that PI is a special control of PCI. Substituting the transfer functions of GPI(s) and GPCI(s) into (3):

\[D_P(s) = K_{11}KPWMH + K_{12}KPWMHs + \]
\[(L_1 + L_2 + K_{11}KPWMH L_2 C)s^2 + \]
\[K_{11}KPWMH L_2 C^3 + L_1 L_2 C^4\]

(7)

\[D_{PCI}(s) = K_{11}KPWMH + K_{12}KPWMHs + \]
\[(L_1 + L_2 + K_{12}KPWMH L_2 C)s^2 + \]
\[K_{12}KPWMH L_2 C^3 + L_1 L_2 C^4 - \]
\[jK_{11}KPWMH \omega_0 + (L_1 + L_2)\omega_0s + \]
\[K_{11}KPWMH L_2 C\omega_0^2 + L_1 L_2 C\omega_0^3\]

(8)

In (7) and (8) feature equations, it can be seen that the real part of PI and PCI controller are the same, and PCI control has one more imaginary part. It shows that the two have the same response speed, but the PCI transient process will oscillate.

The gain of the PCI controller at the fundamental frequency is:

\[|G_{PCI}(j\omega_0)| = \sqrt{K_P^2 + (j \frac{K_I}{\omega - \omega_0})^2}\]

(9)

When \(\omega = \omega_0\), the PCI controller transfer function adds an open-loop pole in the complex frequency domain. At this frequency, the gain approaches infinity. PCI control has better dynamics and stability, and PCI control can achieve system zero steady state error control. It can achieve zero steady-state error of fundamental current, but has limited harmonic current capability. The dynamic response speed of RC control is slow, and there is a period of delay to the error signal, but it can ensure that the output waveform accurately tracks the given periodic reference signal.

### 3.2. RC control strategy

The principle of RC control is an internal model principle, which can reduce the influence of dead zone and periodic disturbance of the grid voltage. In Fig. 4, the RC control diagram: I(z) is the current error, K(z) is RC control internal model, Q(z)Z^N is discrete domain transfer function of the RC control link, P(z) is discrete control object, and ig is grid-side output current.
Figure 4. Diagram of repetitive control system

From Fig. 4, RC control transfer function:

\[ G_{RC}(z) = \frac{Z^{-N}C(z)}{1 - Q(z)Z^{-N}} \]  

(10)

\( Z^N \) is the extension link, \( N \) is the number of sampling points of the fundamental wave period. The rated frequency in this article is 50Hz, and the switching frequency and sampling frequency are both 10kHz. Then the number of cycle sampling points is \( N=200 \), considering that the inverter calculation delay time is about 2 period, so the delay link is \( Z^{198} \). In this paper \( Q(z)=0.95 \), better control efficiency and accuracy can be obtained. The compensator \( C(z)=K_zZ^6S(z) \), \( K_r \) is the gain of the RC controller, \( Z^6 \) leads the compensation link, and \( S(z) \) is the low-pass filter. When \( C(z)P(z)=1 \), \( C(z) \) is an ideal compensator.

Simplify (2) the open-loop transfer function and substitute the parameters into:

\[ P(s) = \frac{1}{(L_1+L_2+r_f r_i C)s + r_f + r_i} \approx \frac{1}{6 \times 10^3 + 0.04} \]  

(11)

The compensator obtained from the above formula is:

\[ C(s) = \frac{60s + 400}{s - 0.333} \]  

(12)

\[ C(z) = \frac{40.01z + 39.99}{z - 0.333} \]  

(13)

3.3. PCI+RC control strategy design

The mathematical model is established according to Fig. 5. \( K \) is the inverter equivalent gain, and \( K_{PWM} \) is the pulse width modulation equivalent gain.

Figure 5. Control diagram of grid-tie system

Knowing formula (6) the transfer function of PCI controller, transfer function of the grid-tie system is obtained:

\[ G(s) = \frac{G_{IC}(s)K_{PWM}K}{L_1L_2C^2 + K_{PWM}KL_2C^2 + L_2L + L_2S + G_{IC}(s)K_{PWM}K} \]  

(14)

After simplification:
In (15):

\[
G(s) = \frac{a_0s + a_1}{b_0s^4 + b_3s^3 + b_2s^2 + b_1s + b_0}
\]

(15)

\[a_0 = K_{PWM}K_PK]\]

\[a_1 = K_{PWM}K_I - j\omega_0K_{PWM}K_PK]\]

\[b_0 = L_1L_2CS^4\]

\[b_1 = K_{PWM}KL_2C - j\omega_0L_1L_2C\]

\[b_2 = L_1 + L_2 - j\omega_0K_{PWM}KL_2C\]

\[b_3 = K_{PWM}K_IC - j\omega_0(L_1 + L_2)\]

\[b_4 = K_{PWM}KK_J - j\omega_0K_{PWM}K_PKK_J\]

\[L_1=5mH, L_2=1mH, C=2.2uF, \omega_0=\frac{2\pi f_0}{\omega}, K=K_{PWM}=1.\] The effective range of \(K_P\) and \(K_I\) is obtained:

\[0<K_P<1.99, \ 0<K_I<1200.\] Take \(K_P=1, K_I=500,\) and substitute (10) to get the bode diagram of PCI controller as shown in Fig. 6.

![Bode Diagram](image-url)

**Figure 6.** Bode diagram of PCI controller

The complex integral \(\int \frac{K_I}{s^2 + j\omega_0s}\) of the PCI controller is a first-order integrator, which can achieve infinite gain at a certain frequency domain point with almost no attenuation, and compensates for harmonics.

Apply the above PCI control and RC control to the system. PCI control can speed up the response speed, quickly adjust the tracking error, RC control can track without static error, reduce the output waveform distortion rate, so these two controls are combined. The composite control block diagram based on PCI control and RC control in Fig.7.

![Composite Control Block Diagram](image-url)

**Figure 7.** Composite control block diagram

The transfer function of PCI+RC control is as follows:
\[
\phi(Z) = \frac{i_Z}{i_{\text{ref}}} = \frac{[PCI(Z)+G_c(Z)]P(Z)}{1+[PCI(Z)+G_c(Z)]P(Z)H(Z)} \nonumber \\
= \frac{PCI(Z)P(Z)+G_c(Z)P(Z)}{1+PCI(Z)P(Z)H(Z)+G_c(Z)P(Z)H(Z)} \tag{16}
\]

Parallel the PCI controller and the RC controller to affect the output of the system. There is a big disturbance in the system, the tracking error increases, the PCI controller plays a role in regulation, and the output of the RC controller does not change until the system reaches a new steady state. When the system is in a steady state, the PCI control is not effective, and the RC control is used to control the required operation of the system.

4. Simulation analysis
Build a model on Matlab/Simulink simulation software to verify the feasibility of PCI+RC compound strategy, and compare it with the PI+RC control model. The system parameters in Tab. 1.

| Table 1. System simulation model parameters |
|--------------------------------------------|
| Related parameter                        | Value |
| DC side bus voltage \(U_{dc}/V\)          | 520    |
| Grid voltage effective value \(e_g/V\)    | 220    |
| switching frequency \(f_s/kHz\)           | 10     |
| Grid voltage frequency \(f/Hz\)           | 50     |
| Inductance at inverter side \(L_1/mH\)    | 5      |
| Grid side inductance \(L_2/mH\)           | 1      |
| Filter capacitance \(C/uF\)               | 2.2    |

The PI+RC control waveform is shown in Fig. 8, and the composite control waveform is shown in Fig. 9. After 0.3s, the current waveform begins to stabilize. After comparing the two composite control waveforms, the PCI+RC composite control is used in Fig. 9. The three-phase grid-tie current waveform is better, which can effectively suppress the grid-tie current harmonics.

\[\text{Figure 8. PI+ repetitively controlled grid-connected current}\]

\[\text{Figure 9. PCI+ repetitively controlled grid-connected current}\]
As shown in Figure 10, the THD value of the grid-tie current controlled by PI+RC is 3.88%, and the THD value corresponding to the PCI+RC control is 1.00%. After the compound control is added, the total harmonic distortion rate of the grid-tie current is reduced by 2.88%. The latter has higher steady-state waveform quality, meets the grid-tie standard, reduces harmonic pollution to grid when grid-connected inverter is operating in a steady state. The improved compound control proposed in this paper can well suppress the current harmonics, which proves the feasibility and superiority of the PCI+RC control strategy.

5. Conclusion
The purpose is to reduce the grid-tie current harmonics. The PCI+RC control strategy of the LCL photovoltaic grid-tie inverter is studied. Combining PCI control can eliminate errors and RC control has good steady-state performance. The control compound is applied to the LCL type photovoltaic inverter system and suppresses the harmonics. Through the comparison of simulation results, the AC-side grid-tie current THD value of the grid-tie inverter system using compound control is significantly reduced, has a lower harmonic distortion rate, and quality of steady-state current waveform is better. The example verification shows that PCI+RC strategy can effectively reduce harmonics and improve the steady-state accuracy of the grid-connected current. This proves that the PCI+RC composite control strategy proposed in this paper has better performance when directly controlling AC variables. The feasibility is better.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (51977072); National Key Research and Development Plan (2018YFB0606005); Hunan Natural Science Foundation (2017JJ4024); Hunan Natural Science Foundation (2018JJ3128);

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