Adaptive Proportional Complex Integral Control Strategy of Three-Phase Grid-connected PV Inverter

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Abstract. The performance of conventional controller of three-phase grid-connected inverters possibly deteriorate during grid frequency drift. In this paper, an frequency adaptive proportional complex integral (PCI) controller with frequency locking loop (FLL) was proposed, the FLL was utilized to adjust the resonant frequency of PCI automatically, and the zero current steady error was achieved by PCI controller. The validity of the proposed control scheme was demonstrated through results of simulation and experimental.

1. Introduction

As a connection between the distributed power generation system and the power grid, the grid-connected inverter is widely used in new energy related fields. Its control performance will affect the quality of power output directly to the new energy power generation system in [1].

In recent years, in the control of grid-connected current, inductor-capacitor-inductor (LCL) inverters have adopted a variety of control strategies, such as simple structure proportional-integral control, which uses high gain at the resonance point. Proportional resonance control to eliminate steady-state error, split-capacitance control method to reduce system order, deadbeat control and predictive control relying on accurate object mathematical models, and fuzzy control method based on fuzzy set theory in [2]-[4]. The above control strategies can achieve stable control of grid-connected inverters under grids, but for weak grid that means the grid voltage is prone to oscillation and distortion, and the grid frequency fluctuates greatly in [5]. In the situation, the grid-connected current controlled by the above control strategy cannot meet the grid-connected requirements.

This paper proposes an adaptive control strategy for three-phase grid-connected inverters. The three-phase system is transformed into a two-phase system for control. Proportional complex integral (PCI) controllers naturally exist in the frequency domain quantity $j\omega_{0h}$, which is easy to achieve high gain at specific frequencies, and it is easy to adjust the resonance frequency by frequency locking loop. The validity of the proposed control scheme was demonstrated through simulations and experimental.

2. Principle of Proportional Complex Integral Control

Proportional-resonant (PR) controller has infinite gain at the resonance frequency $\omega_{0PR}$, so it can achieve zero steady-state error control at $\omega_{0PR}$. At the same time, the proportional-complex-integral (PCI) controller also can achieve zero steady-state error control of the AC quantity, because the gain at a sp-
specific $\omega_0$ frequency is infinite. According to the references [6]-[8], the proposed proportional complex integral PCI controller as

$$G(s)=k_p + \frac{k_i}{s-j\omega_0} = k_p + \frac{k_i(s+j\omega_0)}{s^2+\omega_0^2} \quad (1)$$

Equation (1) shows that when the controlled object is a DC quantity, if $\omega_0=0$ is selected, the PCI controller is completely equivalent to the PI controller. When $s=j\omega_0$, the frequency response of the PCI controller is the same as that of the PR controller.

The control system contains the PCI controller is analyzed in Fig. 1. $D(s)$ is means the interference quantity in the PV inverter, $P(s)$ is the controlled object, and $G(s)$ is the PCI controller.

![Figure 1. Control system structure diagram](image)

According to Fig. 2, the input-output transfer function can be expressed as

$$C(s) = \frac{N(s)P(s)}{(s-j\omega_0)+N(s)P(s)} R(s) \bigg|_{s=j\omega_0} + \frac{(s-j\omega_0)P(s)}{(s-j\omega_0)+N(s)P(s)} D(s) \bigg|_{s=j\omega_0} = R(s) \quad (2)$$

Equation (2) shows that after introducing the complex factor $j$, the system $C(s)=R(s)$. It means that the proportional complex integral controller can realize the control of high performance photovoltaic grid-connected inverter and also have good robustness.

3. Adaptive PCI control strategy for three-phase grid-connected PV inverter

3.1. Structure of the PCI control strategy

Fig. 2 is the main circuit diagram of a typical three-phase photovoltaic grid-connected inverter. The prestage boost circuit can increase the photovoltaic array voltage $u_{PV}$. According to $u_{PV}$ and photovoltaic array output current $i_{PV}$ usually adopt the disturbance observation method described to achieve maximum power point tracking (MPPT) control. $C_d$ is the DC-side supporting capacitor, $L_1$, $L_2$, and $C$ are the equivalent inductance and capacitance of the grid-side LCL-type filter, and $L$ is the input inductance of the boost circuit. The output voltage of the three-phase inverter bridge is $u_{lin}$, the three-phase grid voltage is $u_{g}$, and the grid-connected current is $i_2$. The inverter bridge is formed by the switching tubes $S_1$-$S_6$, and bipolar sine modulation is used. In mathematical modeling, the inverter can be equivalent to the proportional link $K_{PWM}$. 

Figure 2. Main circuit diagram of a typical three-phase photovoltaic grid-connected inverter

Fig. 2 establishes a simplified three-phase grid-connected inverter current control model. The proportional-complex-integral (PCI) control can achieve zero steady-state error control with FLL during grid frequency drift. LCL type grid-connected inverter has resonance phenomenon. The methods of eliminating resonance are divided into active damping and passive damping. In this paper, the active damping is chosen, it means that the feedback of capacitance current is used.

Three-phase grid-connected inverter frequency-adaptive PCI control principle: Firstly, the error signal is obtained by the difference between the three-phase grid-connected currents \( i_{2a}, i_{2b}, i_{2c} \) collected by the sensor and the grid-connected current reference value, and then the error signal is transformed by coordinates. The proportional-complex-integral PCI controller gets a modulation signal, generates 6 PWM waves and sends them to the inverter. This paper proposes to obtain the grid frequency information \( \omega \) in real time through a frequency-locked loop (FLL), and then feed it back into the PCI controller \( \omega_0 \), so that the PCI controller can change the resonance point according to the real-time grid frequency to achieve zero steady-state error. Compared with the new resonant control strategy, the PCI controller in this paper is superior in both control performance and controller implementation.

3.2. FLL-SOGI

In grid-connected inverters, a phase-locked loop (PLL) is often used to obtain grid information in [9]. For the second-order generalized integrator (SOGI) when the frequency of the weak grid fluctuates, the set resonance frequency and the actual grid frequency will cause tracking errors in the output signal amplitude and phase. In this paper, a frequency-locked loop is used to implement the frequency-adaptive function of the second-order generalized integrator, build a frequency-locked loop (FLL-SOGI) based on the second-order generalized integrator shown in Fig. 3.
The frequency-locked loop uses the product of the grid component $U_{ga}$ and the error signal $ε$ to define the frequency error variable $ε_f$. By adjusting the resonance frequency $ω$ of the second-order generalized integrator, the frequency error variable $ε_f$ is controlled according to the actual frequency of the grid. It achieves the purpose of frequency locked.

3.3. The Realization and Parameter Design of PCI Controller

The PCI controller is implemented by a stationary two-phase $αβ$ coordinate system, as shown in Fig. 4.

Using a bilinear transformation discrete PCI controller, the discrete equation of the PCI controller is obtained as:

$$m_α(k) = m_α(k-1) + \frac{kT}{2} [x_α(k) - \frac{ω_0}{k_i} m_β(k)] + \frac{kT}{2} k_i x_α(k-1) - \frac{ω_0}{k_i} m_β(k-1)$$

(3)
In the formula (3)-(6), $\omega_0$ is updated by the $\omega$ output by the frequency-locked loop to ensure that the PCI controller can realize the frequency-free tracking when the frequency of the power grid changes, and zero steady-state error control of the grid-connected current reduces the harmonic content.

Because PCI was developed by the PI controller, the parameters are simply set according to the design idea of PI, that is, $k_p$ mostly controls the dynamic performance, and $k_i$ is main responsible for the steady-state performance. Firstly, the proportionality coefficient $k_p$ is designed. In order to ensure a fast response speed of the system and avoid amplification noise, the system bandwidth range is set to be 10 times higher than the fundamental frequency and 1/5 lower than the switching frequency. The LCL parameters were set to $L_1=3\text{mH}$, $L_2=1.1\text{mH}$, $C=4.7\mu\text{F}$. To ensure that the system bandwidth falls within 500-1000 Hz, the PCI controller gains were set to $k_p=10$, $k_i=600$.

### 4. Simulation and experimental results

In order to verify the feasibility and practicability of this theory, a MATLAB/Simulink simulation model was constructed, in which the S-Function module was used to implement the program based on the adaptive PCI control algorithm. At the same time, a 1.5kW prototype experimental platform was built. The control chip is the DSP TMS320F28335 of the American TI company, and the sampling frequency is set to 10kHz.

#### 4.1. Simulation

Fig. 5 is the simulation results of the three-phase PCI control strategy at the grid frequency of 50Hz. Fig. 5(a) is the transient waveform of the PCI control strategy. At 0.35s, changing the current from 10 A to 5A, the current waveform reaches 5A after a period of 0.02s stably. At 0.5s, the current waveform can also reach 10A stably after a period of 0.02s. The Fig. 5 shows that the adaptive PCI has good steady-state performance at the fundamental frequency, and quickly follows a given change under dynamic conditions.
Figure 5. simulation results. (a) step change in $i_2$ from 5 A to 10 A and 10A to 5 A. (b) simulation results under frequency drift. (c) FFT analysis result of $i_2$ by PR controller (1.93%). (d) FFT analysis result of $i_2$ by PCI controller (0.6%)
Fig. 5(b) is the transient waveform of the PCI control strategy at frequency drift. At 0.3s, changing the current given frequency from 50 Hz to 40 Hz, the current waveform is stable after 2.5 cycles 0.05s. At 0.52s, the current given frequency is changed again to 60 Hz, and the current waveform can reach 5 A at 0.7s, and the system is stable. The figure shows that the control strategy is robust to the grid frequency drift. To verify the control performance of the PCI control strategy and PR control strategy in response to minor changes in the frequency of the operating grid. Adding tiny grid frequency fluctuations in the simulation, using FFT analysis to compare the harmonic content of the grid circuit under PR and PCI control. Fig. 5(c) and Fig. 5(d) show that the connected current THD value under PCI control is lower, the harmonic suppression ability is strong, and the steady-state performance is good.

4.2. experimental results

The AC side 100V grid voltage is connected to the isolation transformer through the grid and then connected to the voltage regulator, and the DC side voltage 180V is provided by the DC regulated power supply instead of the new energy generation.

Fig. 6 proves that the strategy can make corresponding adjustments under the frequency change of the grid to stabilize the current waveform, because there will be no serious grid frequency drift phenomenon under the working conditions and the power grid itself has 49.8-50.2Hz fluctuation, which will increase the harmonic content of the output current. The strategy is proved to be effective by comparing the current harmonic content simulation with the experimental results under PR control in the prototype experiment. As shown in Fig. 6(a) the grid-connected current under PR control, the measured THD value is 3.7%, whereas under PCI control, since the PCI control strategy can track the grid frequency change and suppress the current harmonics caused by the grid frequency fluctuation, Fig. 6(d) shows 2.1%, demonstrating that the PCI strategy can provide excellent steady-state performance.
Figure 6. Experimental results. (a) Experimental result by PR. (b) THD of $i_2$ by PR controller (3.7%). (c) Experimental result by PCI. (d) THD of $i_2$ by PCI controller (2.1%). (e) Step change in $i_2$ from 5 to 10A. (f) Step change in $i_2$ from 10 to 5A.
The A-phase PCI transient waveform is measured by a two-way oscilloscope, as shown in Fig. 6 (e) and Fig. 6(f), setting the current given zero-crossing change. the figure shows that the current waveform under PCI control has better dynamic performance.

5. Organization of the Text
This paper is organized as follows. Section II describes the principle of proportional complex Integral controller. The structure and the system analysis of the PCI control strategy in Section III. Section IV covers the simulation results and the experimental results. The organization of the text in Section V. finally, The conclusions are drawn in Section VI.

6. Conclusion
This article proposes a PCI control strategy that adapts to grid frequency drift and still maintains high output performance in three-phase grid-connected PV inverter:
1) Compared with PI and PR controllers, PCI controllers have better control performance when tracking a given amount of AC.
2) This control strategy can effectively suppress the grid harmonics under working conditions, and achieve zero steady-state error control of AC quantities in aβ stationary coordinates.
Simulation and experiments prove that the PCI control strategy is valid.

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