Research on an improved control strategy of photovoltaic grid-connected inverter

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Abstract. Grid-connected inverter is the core device of photovoltaic grid-connected power generation system. Its performance directly affects the quality of power grid. The control structure of the single-stage full bridge inverter is analyzed. The performance of the proportional resonant control algorithm and the PI control algorithm are compared in the paper. Based on the repetition, the feed-forward control is added to the control strategy of the grid-connected inverter. An improved proportional resonance control algorithm is proposed, which is applied to the current loop control of the inverter. The simulation results show that the control strategy can make the output current of the system the same as the frequency and phase of the grid current. There is no static error, and the output is not affected by the disturbance of the power grid.

1. Introduction

Solar energy has attracted worldwide attention because of the advantages of clean, pollution-free and renewable energy. Photovoltaic (Photovoltaic, PV) power generation can save energy, reduce emissions and reduce energy consumption. It is currently recognized as one of the new energy models. As the main interface equipment between PV array and power grid, the control technology of PV grid-connected inverter has become one of the hotspots of current research. As the key technology, the current control strategy has been developed greatly. The following principles are applied to the selection of current control strategies in grid-connected inverters [1-3]: First, the steady-state error of the actual current and the reference current can be minimized in a wider frequency range. Second, the switching frequency of the power switch tube is fixed to reduce switching losses. Third, the harmonic distortion rate is as small as possible. Forth, the control algorithm is easy to implement by the digital signal processor. In addition, it is hoped that these objectives can be achieved without knowing the specific circuit component parameters or load information, or with low accuracy of information. That is to say, the algorithm is required to have a wide range of adaptability to unknown parameters or loads, and is robust to incorrect parameter estimation.

The traditional control methods include proportional integration (proportion integration, PI) control, proportional resonance control, triangular wave comparison control, hysteresis control and predictive current control[4]. The method of the triangle wave comparison control uses the proportional integral regulator to track the target current, which is mature and has a long application time, but it can not eliminate the steady-state error between the target current and the actual current. Hysteresis control
method is simple and has good robustness, but the current ripple is large, and the unfixed switching frequency results in high loss. The PI controller is simple in design and easy in engineering implementation. There are steady-state errors (including amplitude and phase errors) in tracking periodic signals. Proportional resonant controller can realize zero steady-state error tracking of periodic signal at resonant frequency, which is very dependent on the accuracy of component parameters, and when the fundamental frequency does not match the PR resonant frequency due to the frequency fluctuation of the power grid, the control effect of the system is poor, even the control fails. [4]. An improved quasi-PR control method is proposed in order to solve this problem in [5-6]. The tracking of fundamental signal can be guaranteed by increasing the width of frequency selection. However, when multiple harmonics appears in the system, a corresponding number of PR controllers should be added, which is not conducive to the flexible control of the system. In this paper, an improved proportional resonant control is proposed, which is applied to the internal loop control of inverter with short adjustment time. The method can well suppress influence of frequency offset and there is basically no static error [7-8].

2. Improvement of three loop control algorithm
In single-stage inverter control, three closed-loop control strategy based on P and PI control is mostly used in inverter control algorithms which includes MPPT power outer ring, DC bus voltage control loop, grid connected current control inner loop [9-10]. PI control is adopted in the voltage outer loop of grid-connected inverter to balance the input and output energy of inverter by stabilizing the DC voltage. The inner loop of the current is controlled by PI, and the amplitude of the given value of the current inner loop is obtained by the output of the voltage outer loop PI controller. The reference signal $i_{ref}$ of the output current is obtained by the product of the $\sin \theta$ and the current given $i_{ref}$ by detecting the phase angle of the grid voltage with the phase-locked loop. The PI controller is commonly used in the voltage inner loop. The control accuracy and dynamic characteristics of the above control methods need to be improved due to the poor dynamic characteristics of MPPT outer loop and the static error of PI control.

The three-loop control strategy is improved, and the power feedback is added to the MPPT outer loop to improve its dynamic performance. The current inner loop adopts proportional resonant control to remove static error. Its control structure is shown in figure 1.

![Figure 1. Improved structure block of three loop control strategy.](image-url)
The output power of the inverter is as follows:

$$P = U_m \cos(\omega t) \ast I_m \cos(\omega t) = U_m \ast I_m \ast \frac{(1 + \cos(2\omega t))}{2} \quad (1)$$

$U_m$: peak voltage of power network, V;
$I_m$: grid current peak value, A;

It is known that the inverter has a power disturbance, which is 2 times fundamental frequency for the DC bus voltage from the formula (1). Because the MPPT lags behind larger and the output voltage is unstable, which increases the difficulty of system control[11-12]. The output power of the PV array as the feedforward is added to the current inner loop in the power feedforward algorithm. The control block diagram is shown in Figure 2. The current loop with input power information can improve the response speed when the input power changes, so that the dynamic response performance of the system is better. The given value of grid-connected current is obtained by adding two parts: the current reference value $I_d$ obtained by voltage control link and the reference current $I_{ref}$ calculated by power feedforward link. $I_{ref}$ is obtained from the power calculation formula including PV output power $P_{dc}$ and the effective of grid-connected voltage $U_{GV}$[9-10].

![Figure 2. Power feedforward control block diagram.](image)

### 3. Improved proportional resonant inverter current control algorithm

#### 3.1. Current inner loop control

The inverter controlled by SPWM can be equivalent to a proportional link. The current inner loop control frame is shown in figure 3.

$U_{net}$: power grid voltage, V;
$I_{ac}$: grid current, I;
$L$: grid connected filter inductor, H;
$R_L$: equivalent resistance of inductors, Ω;
$I_{ref}$: current value of grid connected system, I.

![Figure 3. Current loop control block diagram.](image)
The output current of inverter is taken as the state variable, and the formula (2) is as follows.

\[ L \frac{dI_{net}}{dt} = U_a - U_{net} - I_{net}R_L \]  

(2)

\( U_a \) : the voltage at both ends of \( U_A \) and \( U_B \).

It can be obtained formula (3) from (2) by Laplace transform.

\[ I_{net}(s) = \frac{1}{Ls + R_L} (U_a(s) - U_{net}(s)) \]  

(3)

According to the system model of figure 3, the output current transfer function of single-stage single-phase grid connected inverter can be promoted as formula (4).

\[ I_{net} = \frac{K_{PWM}G_c(s)}{sL + R + K_{PWM}G_c(s)} I_{ref} - \frac{1}{sL + R + K_{PWM}G_c(s)} U_{net} \]  

(4)

The transfer function of the PI controller is as formula (5).

\[ G_{PI}(s) = K_p + \frac{K_I}{s} \]  

(5)

The amplitude of the PI controller can be obtained by bringing the fundamental frequency \( \omega_0 \) to formula (5).

\[ A(\omega_0) = \sqrt{K_p^2 + \left(\frac{K_I}{\omega_0}\right)^2} \]  

(6)

The first item in formula (4) is as follows.

\[ 0 < \frac{1}{1 + \frac{Ls + R}{G_{PI}(s)K_{PWM}}} \]

Therefore, \( I_{net} \) is smaller than \( I_{ref} \) and the system has steady-state error. In addition, the second formula (7) was established.

\[ \frac{1}{Ls + R + G_{PI}(s)K_{PWM}} \neq 0 \]  

(7)

Therefore, the output of grid connected current \( I_{net} \) is bound to be affected by the grid voltage. The anti-interference capability of the system is poor. Although feedforward compensation can be used to offset the influence of grid voltage on \( I_{net} \), the feedforward compensation coefficient has an offset of about 5%, which can not remove the disturbance of the power-grid completely. So an improved proportional resonant control algorithm is used to overcome the above problems.

3.2. Proportional resonant control algorithm

The S-domain model of trigonometric function signal in the open-loop transfer function of the system is required according to the internal model theorem if the reference signal is to be controlled without static error in a single-phase grid-connected inverter controller. Trigonometric function signals have two forms, sin and cos, so the corresponding S domain models have the following two forms correspondingly.

\[ G_1(s) = \frac{s}{s^2 + \omega_0^2} \quad G_2(s) = \frac{\omega_0}{s^2 + \omega_0^2} \]  

(8)

\( G_1(s) \) and \( G_2(s) \) have infinite open-loop gain near the grid voltage angular frequency \( \omega_0 \) and can track and control the signal without static error whose angular frequency is \( \omega_0 \). However, the phase angle of \( G_1(s) \) varies from 90°~90°, it is more advantageous to the system. The phase angle of \( G_2(s) \) varies from 0°~180°, which will cause turbulence due to insufficient phase margin in the system. After adding the proportional term, the transfer function of the proportional resonant control can be obtained.

\[ G_3(s) = K_p + \frac{K_I}{s^2 + \omega_0^2} \]  

(9)
The amplitude frequency characteristics of the proportional resonant controller can be obtained by substituting the fundamental frequency frequency $\omega_0$ to the proportional resonant transmission function.

$K_p$: Proportional term coefficient;
$K_r$: Coefficient of resonance term.

$$A_{PR}(\omega_0) = \sqrt{K_p^2 + \left(\frac{2K_r\omega_0}{-\omega_0^2 + \omega_r^2}\right)^2} \quad (10)$$

It can be seen that APR ($\omega$) tends to infinity, so it can be considered that

$$\frac{1}{1 + \frac{\omega}{\omega_r}} = 1 \quad (11)$$

There is no steady-state error in the system, and no static error tracking can be achieved. The second approximations in formula (4) are zero. The proportional resonant controller can greatly reduce the influence of grid voltage disturbance. However, the gain outside the fundamental frequency is very small. When the frequency of the grid is offset, it can not effectively suppress the generation of harmonics.

3.3. Improved proportional resonant control algorithm

Due to the limitation of analog system component precision and digital system precision, the proportional resonance controller is difficult to realize. The gain outside the fundamental frequency is very small. When the grid frequency offsets, the harmonics generated by the grid can not be effectively suppressed in formula (8). Therefore, on the basis of proportional resonance, an improved proportional resonant controller is adopted. It has high gain of proportional resonant controller, and can realize zero steady-state error basically. At the same time, it can effectively reduce the influence of grid frequency offset on the output grid-connected current of inverter. The transfer function of the improved proportional resonant controller is as follows.

$$G_A(s) = K_p + \frac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (12)$$

$\omega_c$: cut-off frequency

The Bode diagram of the controller is shown in Figure 4. It has a large gain at the fundamental frequency and an infinite phase margin, so it can achieve zero steady-state error and has a good steady-state margin and transient performance. The adjustable parameters of the control system are $K_p$, $\omega_c$ and $K_r$, the appropriate regulator can be obtained by adjusting these 3 parameters in practical application. The choice of $K_p$ can improve the dynamic characteristics of the system, but the value can not be too large, otherwise it will cause output overshoot. The value of $\omega_c$ affects the bandwidth of the controller and the gain near the $\omega_0$. $K_r$ is used to improve the gain characteristics of fundamental frequency and its vicinity frequency.

![Bode Diagram](image)

**Figure 4.** Bode diagram of improved proportional resonance control.
4. Experiment simulation and analysis
Substituting $K_p=0,s=j\omega$ into formula (9), the result is

\[ G_d(\omega) = \frac{2K_r\omega^2\omega j\omega}{\omega^2+2\omega^2 j\omega+\omega^2} = \frac{K_r}{1+j(\omega^2-\omega_0^2)/2\omega_0\omega} \]  

(13)

According to bandwidth definition, as $|G_d(\omega)| = K_r / \sqrt{2}$, the bandwidth is the difference between the two solutions. As $\frac{\omega^2 - \omega_0^2}{2\omega_0\omega} = 1$, the bandwidth of the quasi resonant controller is calculated to be $\omega_0 / \pi$ Hz. According to the requirement of power quality in China, the range of frequency deviation is $\pm 0.5$Hz $\sim -0.5$Hz, so $\omega_0 / \pi = 1$Hz, $\omega_0 = 3.14$rad/s, $K_p=0.25$, $K_r=100$. In PI controller, there are $K_p=0.25$, $K_r=0.5$. The MATLAB/Simulink simulation results are shown in figures 5 and 6.

![Figure 5](image1.png)

**Figure 5.** The waveform diagram of PI control in power grid voltage disturbance.

![Figure 6](image2.png)

**Figure 6.** Improved proportional resonant control waveform for grid voltage disturbance.
As can be seen from figure 5 and figure 6, when the grid voltage is continuously disturbed, the inverter output current under PI control will be affected by the grid disturbance. The output not only has a spike, but also it is easy to mutate. It can be seen that the PI control algorithm is susceptible to grid voltage disturbance, and the phase difference between grid current and grid voltage is obvious. The power factor is small. The inverter under the improved proportional resonance control is still sinusoidal when the grid is disturbed. The grid connected current can accurately track the grid voltage and has no phase difference basically, so it is not easy to be disturbed by the grid voltage.

5. Conclusions
Feedforward control is added to the control strategy of single-stage grid-connected inverter. The advantages of improved proportional resonance control and PI control are discussed. The improved proportional resonance control based on MATLAB / Simulink simulation has no static error. Its output current is not affected by the grid disturbance, and will not cause "pollution" to the grid, so as to ensure the operation of the whole grid-connected control.

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References
[1] Zhu Weifeng, Dou Wei 2009 J. Renewable energy. 2 52
[2] Hu H, Harb S, Kutkut N 2010 IEEE Energy Conversion Congress and Exposition(ECCE) 3235
[3] Ji Y H, Jung D Y, Kim J H 2010 International Power Electronics Conference (IPEC) 2924
[4] ZHANG Xing, CAO Ren-xian 2010 Photovoltaic grid connected generation and its inverter control[M] Beijing: Machinery Industry Press
[5] ZHAO Qinlin, GUO Xiaojian, WU Weiyang 2007 J. Journal of Chinese Electrical Engineering Science 27 16
[6] DENG Yuen, LI Shaping, LIU Guifying 2015 J Electric Power Science and Engineering 31 10
[7] LI Zebin, LUO An, TIAN Yuan 2014 Power System Technolog 38 10
[8] ZHANG Yan, ZHAO Yishu, YU Mi 2009 J Power Electronics 43 5
[9] JIA Yaoqin, ZHU M inglin, FENG Yong 2014 J. Transactions of China Electrotechnical Society 29 6
[10] Liu Yushan, Ge Baoming, Abu-Rub H 2014 J. IEEE Transactions on Industrial Informatics 10 1
[11] Liu Z J, Li J T J 2007 IEEE Transactions on Magnetics 43 10
[12] SHEN Ke, WANG Jianze, GAO Zhi -qiang 2010 J. IEEE Power &Energy Society 2010 1