Control Strategy of Photovoltaic Grid Connected System Based on PI and QPR Double Closed Loop Control

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Abstract. The traditional proportional integral (PI) controller in photovoltaic three-phase inverter system has the problems of no static error tracking and poor resonance suppression effect. In order to improve the resonance suppression effect and current control effect of photovoltaic three-phase inverter system, a control strategy of photovoltaic three-phase inverter system based on PI and quasi proportional resonance (QPR) double closed-loop control is proposed. The control strategy and control block diagram based on PI and QPR double closed-loop control are designed to realize no static error tracking of incoming current, which has better waveform of incoming current and resonance suppression effect, and improves system stability. Finally, the effectiveness of the control strategy are verified by simulation.

1. Introduction

Energy shortage and environmental protection have gradually become the primary problems restricting global development, and the international community is paying more attention to the development of renewable energy. Solar energy as one of the most widely distributed, the highest reserves and no pollution clean energy will be focused on and utilized [1]. With the rapid development of P-V power generation mode, photovoltaic three-phase inverter system will be more and more widely used. As an important structure of the system, whether the inverter can be effectively controlled will affect the safe of the whole system[2].

At present, the control strategies of P-V three-phase inverter system mainly include PI control, PR control, QPR control, repetitive control and deadbeat control. Due to the advantages of fast response and high power factor, traditional PI control is widely used in P-V single-phase inverter system. However, in the photovoltaic three-phase inverter system[3], PI control needs to go through many complex coordinate transformations in the rotating coordinate system, and the control variables are coupled, so the calculation is very complex[4]. Therefore, PI control in photovoltaic three-phase inverter system has the problems of poor tracking performance, low
power factor and difficult to maintain system stability[5]. The quasi proportional resonance (QPR) control is widely used in three-phase inverter system because it can realize the regulation control in coordinate system and has the advantage of tracking performance. A joint control strategy of PI and PR is proposed, which can suppress the DC component of photovoltaic grid connected system, but can not suppress other subharmonic components, so its overall harmonic distortion rate is high. In reference [9-11], a quasi PR and PI composite control strategy for single-phase P-V grid connected system is proposed, and the system model simulation shows that the control strategy can obtain good sinusoidal current waveform and significantly improve the total harmonic rate. However, the application of the control strategy in three-phase system is not studied in this paper. Based on the above analysis, in order to improve the resonance suppression effect and current control effect of photovoltaic three-phase inverter system, this paper proposes a control strategy of photovoltaic three-phase inverter system based on PI and quasi PR double closed-loop control. The simulation results show that the proposed method has better tracking effect without static error. Compared with the traditional quasi PR control method in photovoltaic three-phase inverter system, the proposed method has better resonance suppression effect[6-8].

2. Topology of photovoltaic three phase inverter system

The topological of P-V three-phase inverter is shown in Figure 1. The main structure of the system is PV cell array, MPPT control module, inverter module, LCL filter module, common bus and power grid.

![Fig.1 Structure diagram of P-V three-phase inverter system](image)

$I_g$ is the grid current, $Z_g$ is the grid impedance, and $U_g$ is the grid voltage. LCL filter module is composed of inverter side inductor $L_1$, grid side inductor $L_2$ and filter capacitor $C_1$. LCL filter can obtain better high-frequency harmonic suppression effect with smaller inductance. Therefore, LCL filter is used in P-V cluster grid connected system. However, because LCL filter is a third-order system, the low damping characteristic at the resonant frequency is easy to cause resonance problems, so LCL filter usually contains an inherent resonance peak, which affects the stability of the system[10][11].

In Fig.1, the relationship between $I_g$ and $U_g$ of LCL three-phase inverter system is as follows:

$$
\frac{I_g(s)}{U_g(s)} = \frac{1}{s^2 L_1 L_2 C_1 + s(L_1 + L_2)}
$$

(1)

It can be obtained from equation (1): It can be seen from equation (1) that LCL filter has a resonant frequency

$$
f_{res} = \frac{1}{2\pi \sqrt{\frac{L_1 + L_2}{L_1 L_2 C_1}}}
$$

(2)

If the filter capacitance is ignored and $L = L_1 + L_2$, the following results can be obtained...
\[ \frac{I_e(s)}{U_i(s)} = \frac{1}{Ls} \]  

(3)

3. Control strategy of traditional photovoltaic three phase inverter

3.1. Analysis of PI, PR and quasi PR control principle

The traditional control strategy of single-phase inverter often adopts PI control

\[ G_{pl}(s) = K_p + \frac{K_i}{s} \]  

(4)

The gain function expression of PI controller at \( \omega_0 \) as follows:

\[ |G_{pl}(j\omega_0)| = \sqrt{k_p^2 + (k_i / \omega_0)^2} \]  

(5)

It can be seen from equation (5) that the gain of PI controller at \( \omega_0 \) is limited. The structure of PI controller is simple and easy to implement, but from equation (4), it can be seen that in three-phase system, PI controller needs coordinate transformation to change AC signal into DC signal in order to adjust without static error. Therefore, it is difficult for PI controller to realize zero static error control[12].

The gain function expression of PR controller at \( \omega_0 \) as follows

\[ |G_{pr}(j\omega_0)| = \sqrt{k_p^2 + \left(\frac{2k_o\omega_0}{\omega_0^2 + \omega_0^2}\right)} \]  

(6)

It can be seen from equation (7) that the gain of PR controller at \( \omega_0 \) tends to infinity, so the controller can realize error free control and has strong anti-interference ability. But in practical application, PR controller is difficult to work at the ideal resonant frequency due to the problems of hardware equipment and control accuracy[13].

Finally, based on the PR controller, a quasi PR controller is proposed, which not only keeps the advantages of high gain of PR controller, but also has larger bandwidth, and can effectively reduce the influence of power grid frequency offset. The transfer function is as follows[14].

\[ G_{qpr}(s) = k_p + \frac{2k_o\omega_0s}{s^2 + 2\omega_0s + \omega_0^2} \]  

(8)

According to the transfer function expressions of the three, the Bode diagrams are drawn respectively, as shown in Fig 2. The characteristics of each controller are analyzed and compared.

| Table 1. Parameters of PI, PR and QPR controllers |
|-----------------------------------------------|
| Parameter | Numerical Value | Parameter | Numerical Value |
| \( k_p \) | 1 | \( k_i \) | 500 |
Fig. 2 Transfer function Bode diagram of PI, PR and QPR controllers

In Fig.2, the low-frequency gain of PI controller is larger than that of PR controller and quasi PR controller; at the \( \omega_0 \), the gain of PR controller is very high, which is easy to cause system instability. Relatively speaking, the gain of quasi PR controller is lower than that of PR controller, but it still maintains a higher gain as a whole; when it is higher than the \( f_\omega \), the gain difference between the three is very small. At the same time, it can be seen that the PR controller only has a large gain at the \( \omega_0 \), while the gain is almost zero at other frequencies. The bandwidth of the quasi PR controller is obviously larger than that of the PR controller. Therefore, the quasi PR controller still has a certain gain when the grid frequency is shifted, which can better realize the no static error regulation of AC signal. The control effect of quasi PR controller is better than PI and PR controller in three-phase photovoltaic grid connected system [15].

3.2. Parameter analysis of quasi PR controller
From the transfer function (8) of the quasi PR controller, it can be seen that the parameters \( K_p \), \( K_r \) and \( \omega_c \) affect the performance of the controller. Therefore, several groups of parameters can be selected to determine the influence of the control variables. The Bode diagram of transfer function of quasi PR controller with different parameters is shown in Fig 3.

Fig. 3 Transfer function Bode diagram of QPR controller with different parameters
It can be seen from the Fig.3 that when the control parameter $K_p$ increases and other parameters remain unchanged, the amplitude of low frequency and high frequency position of the quasi PR controller increases, and the corresponding phase margin also increases; when the control parameter $K_r$ increases and other parameters remain unchanged, the peak value of the quasi PR controller increases; when the control parameter increases, the bandwidth of the controller obviously increases, and the parameter affects the bandwidth of the controller greatly. According to the above analysis, a larger $K_r$ sum value can be selected according to the peak gain demand of the system, so that the system can obtain a larger peak gain and reduce the steady-state error at the fundamental frequency. At the same time, the system can obtain a larger bandwidth, which can better adapt to the changes of power grid frequency and ensure the stability of the system.

4. Double closed loop control strategy based on PI and quasi PR

The single loop control has the problems of slow response and unstable system. Therefore, the double closed-loop control strategy is composed of the inner current loop with inverter side current feedback and grid side current feedback, and the outer voltage loop with DC side voltage feed forward. In order to further reduce the total harmonic distortion of the incoming current and realize the system tracking without static error, PI control and quasi PR control are combined to form a composite control strategy. The double closed-loop control strategy based on PI and quasi PR is shown in Fig.4.

**Fig. 4** Double closed loop control strategy based on PI and QPR

According to the control strategy in Fig.4, the current inner loop control block diagram based on PI and quasi PR double closed loop control strategy can be deduced, as shown in Fig.5.
In the current inner loop control block diagram in Fig.5, KPWM is the gain of three-phase SPWM control module. In ideal case, the slight delay effect during sampling and switching is ignored. The KPWM value can be approximately expressed as follows:

\[ K_{PWM} = \frac{u_{ref}}{u_{abo}} = \frac{u_{dc}}{2} \]  

(9)

The current controller module GC(s) is replaced by a quasi PR controller, which can track AC signals without static error in static coordinate system. Its transfer function is shown in formula (4). According to the control block diagram in Fig.5, the open-loop transfer function of current inner loop control can be deduced as follows:

\[ G_{abo}(s) = \frac{G_{PR}(s)}{sL_2C_1(s+L_1)} = \frac{K_{PWM}}{s^2L_2C_1(s+L_1)} \] 

(10)

PI controller is used in the outer voltage loop. As can be seen from the control strategy in Fig.4, I_{dref} value is obtained through the voltage loop, and then fast tracking performance of the current loop can be considered as fast tracking I_{dref} value of the DC side current I_{in} value. At the same time, considering the influence between the inner and outer loops, as well as the dynamic and steady-state performance of the outer voltage loop, the cut-off frequency of the outer voltage loop should be far less than that of the inner current loop. Therefore, for the design of voltage outer loop, the dynamic process of current inner loop can be ignored, and I_{dref} = I_{in} is approximately considered. Thus, the voltage current relationship of the branch supporting capacitor C is obtained as follows:

\[ u_{dc} = \frac{1}{sC}i_e = \frac{1}{sC}(i_{dc} - i_m) \approx \frac{1}{sC}i_{dc} - \frac{1}{sC}I_{dref} \] 

(11)

The new USMC inverter stage adopts zero vector modulation. According to volt-second law and trigonometric sine theorem, the duty ratio of space vector is: The output current I_{dc} of PV array can be regarded as a disturbance, so the relationship between the output I_{dref} of PI controller and the DC voltage U_{dc} can be expressed as follows:

\[ \frac{u_{dc}}{I_{dref}} = -\frac{1}{sC} \] 

(12)

5. **Simulation verification and result analysis**

To verify the feasibility of the control strategy of PV grid connected system based on PI and quasi PR double closed-loop control, a system simulation model of multi-inverter grid connected system using the control strategy is built on the MATLAB / Simulink platform. The system simulation model is composed of a three-phase photovoltaic inverter system, and the tracking effect without
static error and resonance suppression effect of the control strategy are analyzed. The system simulation parameters are shown in Table 2.

| parameter | numerical value | parameter | numerical value |
|-----------|----------------|-----------|----------------|
| $U_s/V$   | 650            | $U_g/V$   | 380            |
| $L_1/mH$  | 0.48           | $L_2/mH$  | 0.16           |
| $C/\mu F$ | 110            | $L_g/mH$  | 0.08           |
| $K_d$     | 0.017          | Quasi PR  |                |
|           |                | controller| 0.006          |
| Quasi PR  |                | controller|                |
| $K_{r1}$  | 0.5            | $\omega C$ | 3.14          |
| PI controller |            | $K_p$     |                |
| $K_p$     | 0.6            | $k_i$     | 1              |
| $\omega_0$ |              |           |                |

**Fig. 6** Waveforms of voltage and current entering the network

Fig. 7 and Fig. 8 show the waveform and total harmonic distortion rate of grid current of photovoltaic three-phase inverter system with single PI control.

**Fig. 7** Network current waveform under PI control
Fig. 8 Total harmonic distortion rate of incoming current under PI

Fig. 9 and Fig. 10 show the current waveform and total harmonic distortion rate of photovoltaic three-phase inverter system with single quasi PR control.

Fig. 9 Network current waveform under QPR control

Fig. 10 Total harmonic distortion rate of incoming current under QPR control

Fig. 11 and Fig. 12 show the current waveform and total harmonic distortion rate under the control strategy of photovoltaic three-phase inverter system based on PI and quasi PR double closed-loop control.

Fig. 11 Network current waveform based on PI and QPR double closed loop control strategy
According to Fig.7, Fig.9 and Fig.11, it can be seen that the three-phase current waveform is smoother under the double closed-loop control strategy based on PI and quasi PR.According to the comparative analysis of Fig.8 and Fig.12, the total harmonic distortion rate of incoming current based on PI and quasi PR double closed-loop control strategy is 1.21% lower than that of single PI control strategy, and the 22nd harmonic is obviously suppressed. According to the comparative analysis of Fig.10 and Fig.12, the total harmonic distortion rate of incoming current under the double closed-loop control strategy based on PI and quasi PR is 0.98% lower than that under the single quasi PR control strategy. It is obvious that the resonance suppression effect is better and the current quality is better when the double closed-loop control strategy based on PI and quasi PR is adopted.

6. Conclusion
Based on the analysis of PI, PR and quasi PR controllers, this paper proposes a control strategy of photovoltaic three-phase inverter system based on PI and quasi PR double closed-loop control. Finally, the simulation results show that the proposed control strategy has better resonance suppression effect and current control effect than the traditional PI control strategy and quasi PR control strategy. The control strategy can achieve grid current tracking without static error, suppress the resonance of photovoltaic three-phase inverter system, improve the quality of grid current and maintain the stability of the system.

Acknowledgment
The National Natural Science Foundation of China (51977072); National Key Research and Development Plan (2018YFB0606005); Hunan Natural Science Foundation (2017J4024); Hunan Natural Science Foundation (2018J3128).

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