A Novel Grid-Connected Current Control Method Based on Frequency Adaptive Proportional Resonance

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Abstract. In this paper, a novel quasi-proportional resonance (quasi-PR) controller for grid-connected current control is proposed. For the traditional quasi-PR controller, the performance decreases in cases when a large grid frequency deviation is going through. To solve the problem, a frequency adaptive structure is applied in the current control method to achieve online correction on the resonance frequency, so that a high control accuracy is maintained and the robustness of the control system is enhanced. The feasibility of the proposed method has been verified by experimental results.

1. Introduction
In recent years, with the development of new energy industries like energy storage and microgrid, the power electronic techniques of grid-connected control area are getting more and more applications [1, 2]. For different kinds of grid-connected power devices such as grid-connected inverters, active power filters (APF) and static var generators (SVG), the grid-connected current control is a key part of the control system, which has been receiving more and more attention and research [3-7].

There are some common methods of grid-connected current control for engineering applications such as hysteresis controller, proportional integral (PI) controller, and quasi-PR controller. Hysteresis controller and PI controller are good at robustness and easy for implementation, however when used for AC current control, the limitation of system bandwidth will lead to a large steady-state error [5, 8]. For quasi-PR controller, the control accuracy depends more on the local resonance bandwidth than the overall bandwidth of the controller, due to a high gain around the resonance frequency. When AC current is under control by quasi-PR controller, a lower steady-state error can be achieved compared to PI controller [9]. The smaller the resonance bandwidth, the closer the performance of quasi-PR controller to the ideal PR controller.

The high accuracy of quasi-PR controller is only achieved under the condition when the resonance frequency is consistent with the grid frequency. However, there is usually a certain range of deviation for the actual grid frequency, which makes some difficulties for quasi-PR controller with high frequency-selectivity when comes to digital implementation [8, 10]. The Tustin method is usually used for the discretization of quasi-PR controller, which causes an undesired deviation of the discretized resonance frequency [7, 11]. The actual deviation is strongly related to the computational accuracy of the chip in cases when the sampling frequency is high [11]. On the other hand, the resonance frequency discretized by the traditional Tustin method is acting as a constant and difficult to perform online correction [4, 6]. When the deviation of the grid frequency is large, the steady-state accuracy of the traditional quasi-PR controller will decrease rapidly.
To solve the problems above, a novel implementation method of quasi-PR controller for grid-connected current control is proposed in this paper. The resonant frequency of the novel quasi-PR controller is working as an independent variable so that frequency adaptation can be achieved combined with the phase-locked loop. A series of comparison experiments with traditional control methods are performed to verify the feasibility of the novel current control method.

2. Quasi-PR controller with traditional discretization method

The continuous transfer functions of PR controller and quasi-PR controller are given by

\[ G_{PR}(s) = K_p + K_r \frac{s}{s^2 + \omega_c^2} \]  
\[ G_{QPR}(s) = K_p + K_r \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \]

where \( K_p \) is the proportional factor, \( K_r \) is the resonance factor, \( \omega_c \) is the cut-off frequency and \( \omega_0 \) is the resonance frequency. The value of \( \omega_0 \) is equal to the grid fundamental frequency which is defined as 50Hz in this paper, when the grid-connected current is under controlled.

PR controller is capable of tracking sinusoidal signal with zero steady-state error theoretically, due to the infinite gain at the resonance frequency. However, when comes to digital implementation, the accuracy of the actual chip is limited, which results in a deviation of the resonance frequency after discretization. On the other hand, there is also a certain range of deviation for the actual grid frequency, which makes it difficult for a PR controller with high frequency-selectivity, to guarantee the actual performance.

For quasi-PR controller, a small damping term \( 2\omega_c s \) is added so that the gain of the controller at the resonance frequency reduces to a finite value \((K_p + K_r)\), and a resonance bandwidth of approximately \( 2\omega_c \) is obtained at the same time. The Bode diagram of quasi-PR controllers with different parameters is shown in Figure. 1. It can be summarized that the value of \( K_p \) adjusts the gain of the entire frequency band of the controller and the value of \( K_r \) only adjusts the gain around the resonance frequency, both of which are related to the steady-state accuracy and dynamic performance of the system. The value of \( \omega_c \) determines the resonance bandwidth of the controller. The smaller \( \omega_c \), the higher frequency-selectivity of the controller. Considering that the deviation of the actual grid frequency is normally within the range of \( \pm0.5\)Hz, the resonance bandwidth of the controller should be taken above 1Hz, that is, \( \omega_c \geq 3.14\)rad/s.

The traditional way of digital implementation of quasi-PR controller is to discretize the whole continuous transfer function (2) to z-domain. The Tustin (or trapezoidal) method is usually used to realize the transformation, as shown in equation (3), where \( T_s \) is the sampling period. In some cases when the sampling frequency is low, the Tustin with frequency pre-warping method is sometimes used, as shown in equation (4). This method takes the resonance frequency as a reference point to correct the mapping relationship between the continuous domain and the discrete domain, therefore the deviation of the resonance frequency caused by discretization is corrected.

\[ s = \frac{2}{T_s} \frac{z - 1}{z + 1} \]  
\[ s = \frac{\omega_0}{\tan(\frac{\omega_0 T_s}{2})} \frac{z - 1}{z + 1} \]

The Tustin method is simple to calculate and also easy for implementation, however since the resonance frequency \( \omega_0 \) has been transformed into several different coefficients of the final discretized expression, it is not easy to perform online correction. For this reason, in the case when the deviation of the actual grid frequency is large, the performance of quasi-PR controller will be adversely affected. The smaller the resonance bandwidth, the more serious the control accuracy reduction.
3. Novel quasi-PR controller with frequency adaptation

The novel frequency adaptive structure for quasi-PR controller is shown in Figure 2, where $\omega_{PLL}$ is the real-time estimated value of the grid frequency obtained by the phase-locked loop (PLL), while the definitions of $K_p$, $K_r$ and $\omega_c$ are consistent with the traditional quasi-PR controller. The resonant branch of the novel structure was first proposed in [12] in the form of a PLL algorithm called linear time invariant enhanced phase-looked loop (LTI-EPLL). In this paper, the novel structure will be analysed from the perspective of a controller, and will be implemented to grid-connected current control.

As shown in Figure 2, the controlled input is assumed to be a sinusoidal signal, given as $x = U\sin\theta$ in polar coordinates, where $U$ and $\theta$ are the amplitude and the phase-angle respectively. $x'$ is the output of the resonant branch, from which the waveform error signal $e$ is obtained by the feedback loop. $\omega'$ is the resonance frequency of the novel quasi-PR controller, which is directly added to the phase loop as a feedforward parameter, and can be obtained from outside the structure, like $\omega_{PLL}$ in Figure 2. After calculating the amplitude loop and the phase loop, the estimated amplitude $A$ and the estimated phase-angle $\phi$ are obtained successively, and finally the resonance output signal $x'$ is obtained in the form of polar coordinates, given by $x' = A\sin\phi$. The signal $A\cos\phi$ orthogonal to $x'$ is denoted as $-x_q'$, in addition. The differential equation of the resonant branch of the controller is given by

$$\begin{align*}
\dot{A} &= 2\omega e\sin\phi \\
\dot{\phi} &= \omega' + 2\omega\frac{e}{A}\cos\phi \\
e &= x - x'
\end{align*}$$

(5)

Take the derivative of $x' = A\sin\phi$ and $x_q' = -A\cos\phi$, respectively:

$$\begin{align*}
\dot{x}' &= \dot{A}\sin\phi + \dot{\phi}\cos\phi \\
\dot{x}_q' &= -A\cos\phi + \dot{\phi}A\sin\phi
\end{align*}$$

(6)

Substituting (5) into (6), the differential equations for the input and the output signal of the controller can be obtained, as shown in (7).

$$\begin{align*}
\dot{x}' &= 2\omega_x(x - x') - \omega'x_q' \\
\dot{x}_q' &= \omega'x'
\end{align*}$$

(7)

Using Laplace transform on (7), the transfer function of the resonant branch of the controller is given by

$$\frac{X'(s)}{X(s)} = \frac{2\omega_s}{s^2 + 2\omega_s + \omega'^2}$$

(8)
It can be seen that equation (8) shares the same form with the resonance term of equation (2). Therefore, the novel quasi-PR controller structure shown in Figure. 2 can replace the traditional one to perform grid-connected current control. Different from the traditional Tustin method, the resonance frequency $\omega'$ in the proposed structure is an independent variable, which can be adjusted online in many ways, such as using an additional grid frequency detection module. In grid-connected inverter systems, digital PLL techniques represented by the second-order generalized integrator phase-locked loop (SOGI-PLL) and the enhanced phase-locked loop (EPLL) [12] are generally used for grid voltage phase detection, which is capable of tracking the grid frequency meanwhile. Furthermore, the bandwidth setting of a PLL is usually much wider than that of a quasi-PR controller in order to achieve fast phase-locking and frequency-tracking. Therefore, when a large deviation of the grid frequency occurs, the new frequency value can be fast detected by the PLL, so that the resonance frequency of the proposed controller can be modified dynamically. The advantage of this method is that while maintaining narrow bandwidth characteristics, the frequency adaptability of quasi-PR controller is enhanced, thereby the steady-state error is reduced and the high control accuracy is guaranteed.

4. Current control system based on the novel quasi-PR controller

4.1. Grid-connected current control model

The simplified single-phase equivalent model of all kinds of grid-connected inverter devices is shown in Figure. 3, where $U_{dc}$ is the DC bus voltage, $U_g$ is the AC grid voltage and $I_g$ is the grid-connected current. The L-type filter is chosen to be the current filter in this paper, where $L$ is the filtering inductance and $R$ is the equivalent resistance of the coil. First, the grid voltage $U_g$ is sampled by sensor. After the PLL calculation, the estimated phase-angle and estimated frequency of the grid are obtained so that the reference current $I_{ref}$ can be calculated according to the power value and power factor required. Then the current error signal is obtained by comparing $I_{ref}$ and $I_g$, and received by the novel quasi-PR controller which leads to the PWM drive signal.

The transfer function block diagram of the current control system above is shown in Figure. 4. Considering that the switching frequency of the system is usually much higher than the grid fundamental frequency, the switching delay is ignored and the inverter bridge is regarded as a proportional component $K_{pwm}$. The novel quasi-PR controller is represented by $G_{QPR}(s)$ and the feedforward branch of $U_g$ is used to compensate the disturbance from the grid voltage.

4.2. Parameter tuning

Taking a grid-connected inverter of 2.2KW as an example, the parameter tuning method of the proposed controller is introduced. The relevant system parameters are shown in Table 1. In engineering applications, the frequency-domain method is commonly used for tuning [13], which is
suitable for investigating and comparing the steady-state accuracy of different controllers, by choosing the appropriate phase margin $\gamma$ and the crossing frequency $\omega_p$.

Table 1. System parameters required for analysis.

| Parameter / Unit | Value |
|------------------|-------|
| Grid-connected Power P / KW | 2.2 (220V/10A) |
| $K_{pwm}$ | 22 |
| Sampling frequency $f$ / Hz | 5k~20k |
| Filtering inductance $L$ / mH | 8 |
| Coil resistance $R$ / $\Omega$ | 1 |

The open-loop transfer function of the system is given by equation (9). As mentioned above, the parameter $\omega_r$ of a quasi-PR controller should be greater than 3.14rad/s if frequency adaptation is not considered. For the novel quasi-PR controller, a smaller bandwidth is allowed to be set when the frequency adaptation feature is introduced. Considering the subsequent comparative analysis between the proposed controller and the traditional one, the parameter $\omega_r$ is set to be 3.14rad/s in this paper. In addition, the resonance frequency $\omega^\prime$ should be regarded as the grid fundamental frequency 50Hz during parameter tuning process.

$$\frac{I_g(s)}{I_{ref}(s)} = \frac{K_{pwm}G_{gpg}(s)}{Ls + R} = \frac{K_{pwm}[K_p s^2 + (K_p + K_r)2\omega_r s + K_p\omega_r^2]}{Ls^3 + (2\omega_r L + R)s^2 + (\omega_r^2 L + 2\omega_r R)s + \omega^2 R}$$  \hspace{1cm} (9)

$$\begin{vmatrix}
I_g(j\omega_p) \\
I_{ref}(j\omega_p)
\end{vmatrix} = 1 \begin{vmatrix}
I_g(j\omega_p) \\
I_{ref}(j\omega_p)
\end{vmatrix} = -180^\circ + \gamma$$  \hspace{1cm} (10)

In engineering applications, the phase margin $\gamma$ is usually set within the range from 30° to 60°. The crossing frequency $\omega_p$ does not exceed 1/2 of the sampling frequency, usually taking within the range from 1/10 to 1/5. In order to verify the applicability of the propose controller at low sampling frequency, and to facilitate the subsequent experimental comparison, two indicator groups are used for parameter tuning in this paper. Group A is corresponding to the system with low sampling frequency (5kHz), which takes $\gamma = 60^\circ$, $\omega_p = 500Hz$; Group B is corresponding to the system with high sampling frequency (10kHz), which takes $\gamma = 60^\circ$, $\omega_p = 1kHz$. Substituting two indicator groups into equation (10) respectively, the parameter $K_p$ and $K_r$ can be obtained, as shown in Table 2. The tuning results of the traditional PI controller under the same indicators are also given in Table 2, where $K_{p,PI}$ is the proportional factor and $K_{i,PI}$ is the integral factor.

Table 2. Parameter tuning results.

| Indicator group | A | B |
|-----------------|---|---|
| Sampling frequency | 5kHz or more | 10kHz or more |
| Novel quasi-PR and traditional quasi-PR | $K_p = 0.966, K_r = 302$ | $K_p = 1.955, K_r = 1176$ |
| PI | $K_{p,PI} = 0.966, K_{i,PI} = 1918$ | $K_{p,PI} = 1.954, K_{i,PI} = 7424$ |
Based on the tuning results above, the open-loop Bode diagram of the PI control system and the quasi-PR control system is shown in Figure 5. It can be seen that the stability margin and the high-frequency gain of quasi-PR controller are consistent with those of PI controller under the same indicators. Quasi-PR controller sacrifices a certain dynamic performance at low frequency, in exchange for a high gain around the resonance frequency, for which the high steady-state accuracy of the system at low sampling frequency is maintained.

5. Experimental results

To verify the feasibility of the novel quasi-PR controller, a single-phase grid-connected inverter prototype of 2.2KW is built, based on the model in Figure 3 and the system parameters in Table 1. Comparison tests among the novel quasi-PR controller, the traditional Tustin quasi-PR controller and PI controller are performed using the parameters in Table 2. The DC-side of the prototype is powered by a 400V DC regulated power supply, while the AC-side is connected to a programmable AC power supply of Chroma series as a simulation for power grid. A floating-point DSP is used for digital control and generation of bipolar PWM signals, with the model TMS320F28335.

The grid-connected test results of PI controller and the novel quasi-PR controller with parameters of Group A at the sampling frequency of 5kHz, are shown in Figure 6, where $e_i$ is the error signal of the grid-connected current, equal to $(I_{ref} - I_g)$. It can be observed that there is considerable periodic fluctuation of the current steady-state error of PI controller with a peak value of about 0.8A; while the
steady-state error of the novel quasi-PR controller is about 0.3A, with no fluctuation observed. Increase the sampling frequency to 10kHz and repeat the same test with parameters of Group B, the results are shown in Figure. 7. Figure. 7 shows that at a higher sampling frequency of 10kHz, the steady-state performance of the novel quasi-PR controller still maintains certain advantages compared to PI controller. The steady-state error of PI controller is about 0.3A while the novel controller is about 0.2A. In summary, the current tracking accuracy of the novel quasi-PR controller is better than that of PI controller under the two indicators groups, with much more advantages in low sampling frequency situations.

In order to verify the frequency adaptive ability of the novel quasi-PR controller, the prototype system is tested under the condition where the grid frequency abrupt change is going through. The grid frequency is set to jump from 50Hz to 55Hz at the moment of 0.2s by the programmable AC power supply. The comparison test results between the traditional Tustin quasi-PR controller and the novel controller are shown in Figure. 8. It can be observed that before the frequency abrupt change occurs, there is no obvious difference between the Tustin quasi-PR controller and the novel one. The steady-state error of both controllers is about 0.3A and the resonance frequency of both is 50Hz. When the frequency abrupt change occurs, the steady-state error of the Tustin quasi-PR controller increases to about 0.4A and a certain periodic fluctuation is observed, as because the resonance frequency is unable to follow the change of the grid frequency. For the novel quasi-PR controller, the resonance frequency can be adjusted by the grid frequency estimated value $\omega_{PLL}$ obtained from the PLL. Therefore, the steady-state error of the novel system is maintained at about 0.3A after a dynamic state of about 60ms. In summary, with frequency adaptation, the robustness and the control accuracy of the novel quasi-PR controller are better than that of the traditional one when the grid frequency deviation is going through.

6. Conclusion
A novel quasi-PR controller implementation method for grid-connected current control is proposed in this paper. With model analysis and comparison experiments based on a single-phase grid-connected current control system, the following outcomes are reached:

- The steady-state error of the proposed controller is smaller than that of the traditional PI controller, with more advantages in system with low sampling frequency.
- When the grid frequency deviation is negligible, the proposed controller has the same transfer function model as the traditional quasi-PR controller, and with no obvious difference in control performance.
- The proposed controller is frequency adaptive, for which a high control accuracy is maintained when a large grid frequency deviation is going through.
7. References

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