Inverter Control Strategy Based on Improved Deadbeat Control and QPR Compound

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Abstract. In the process of photovoltaic power generation, it is particularly important to choose a suitable inverter control strategy. Aiming at problems such as the poor dynamic response of the traditional controller in the three-phase LCL grid-connected inverter, the current harmonic disturbance caused by the grid voltage distortion and the inability to achieve the optimal tracking of the AC quantity, this paper presented a method to control voltage by fuzzy PI, control current by discrete QPR and improved DBC. In the voltage outer loop, the fuzzy control principle was used to adjust the P and I parameters in real time, and its output was used as the reference value for the current inner loop. In the current inner loop, the repeated control improved deadbeat and discretized form of QPR were used for compound control. The simulation results show that the control strategy greatly improves the distortion of the grid-connected current, which can optimally track the AC volume, and makes the entire system have good stability and dynamic response capabilities.

1. Introduction

In recent years, with the gradual depletion of non-renewable resources such as oil, coal, and natural gas, photovoltaic power generation and wind power generation have received great attention from scholars and experts from all over the world, and they are in a core strategic position in the energy development of various countries [1]. In the process of photovoltaic power generation, the performance of the inverter will affect the stability of the grid current, so it is necessary to conduct a deeper research on the inverter technology [2]. Voltage source inverter has the advantages of simple design, fast response speed, and can freely reverse the voltage blocking ability during the on-off process, so it has been widely used in engineering practice [3-4]. In addition, according to the controlled object, it can be divided into two methods: voltage and current control. If the voltage control method is used for transmission, it is equivalent to the parallel operation of the inverter and the grid, and the grid can be equivalent to an infinite power source. In this case, the control system will have a slow response of the phase-locked loop and weakened anti-interference ability, which will lead to the power quality of the grid decline. Conversely, the current control method only needs to synchronize the output current of the inverter and the grid voltage, and meet the unit power factor to achieve efficient grid connection, so this method is often used in the industrial control process [5]. Currently, there are three types of filters, L, LC and LCL, in the inverter control process. Among them, the LCL type increases the capacitance road, and has a good suppression effect on high-order harmonics. Under the same inductance, the LCL type has better filtering performance than the other two, which greatly reduces the high-order harmonics of the grid-connected current [6].

At present, many scholars and experts at home and abroad pay special attention to the current control
of grid-connected inverters: Literature [7] pointed out that the hysteresis control has the advantages of simple principle and fast dynamic response, but the controller has higher requirements for filter parameter design, resulting in the grid-connected current is distorted. Literature [8] re-selected the LCL parameters of the inverter system, and at the same time added an integral link in the PR control, which reduced the harmonic content of the input current and made the grid-side current and the grid voltage the same frequency, but in its parameter design the resistance value of the middle capacitor road was too large, resulting in a large grid-connected loss. The PR controller in literature [9,10] can track each harmonic signal in real time, but its wide frequency tracking range will make the controller unable to eliminate the disturbance caused by low-frequency noise. Literature [11] proposed a PI and quasi-PR cooperative control inverter control strategy, which effectively suppressed the DC component injected into the grid, but the control effect on other sub-harmonics was not obvious. Literature [12] used deadbeat control (DBC) in the current loop and discrete reaching law design in the voltage outer loop, which significantly improved the stability of the system, but did not solve the existing delay problem. In [13], the current two-step correction algorithm was used to improve deadbeat control, which suppresses the current sampling error, but there was no quantitative design principle for the current correction algorithm. Literature [14] proposed a multi-inverter resonance method for resonant modal analysis, through different inverter combinations and changing the key parts of the system to control the resonance characteristics of the harmonics, but the parameters of the controller itself are difficult to tune. In the literature [15], RNN and improved particle swarm algorithm were used to adjust the system parameters online, and update them in real time, which can complete the optimal tracking of the communication volume. However, its control algorithm is too complicated and difficult to operate.

In view of the above problems, this paper proposes a method to control the voltage with fuzzy PI, control the current with QPR in the form of discretization and improved DBC together. It used fuzzy PI control to adjust the $P$ and $I$ parameters in real time to achieve the purpose of controlling the DC side voltage. At the same time, DBC and QPR improved by the repeated principle were used to jointly control the current, and the discretization form of QPR was derived. The improved DBC of the repeated principle suppresses the harmonic distortion of the grid-connected current and reduces the high-order harmonics in the grid-connected current. Discrete QPR solves the impact of the control accuracy problem on the system, and can complete the optimal tracking of the communication volume, so that the entire system maintains good stability.

2. LCL Three-phase grid-connected Inverter Structure

2.1. Topology structure of inverter main circuit

The main circuit structure of three-phase LCL grid-connected inverter as shown Figure 1, which is composed of inverter circuit composed of switch tubes and LCL filter. In Figure 1, three-phase inverter bridge composed of switch tube $Q_1$-$Q_6$, $L_1$, $L_2$ and $L_3$ is the filter inductance on the inverter side; $L_g$, $L_f$ and $L_h$ is the filter inductance on the grid side; $C_1$, $C_2$ and $C_3$ is the filter capacitor, and the connection mode of the filter capacitors is star; $U_{dc}$ is the DC side voltage; $u_{ga}$, $u_{gb}$ and $u_{gc}$ is the three-phase grid voltage; $u_a$, $u_b$ and $u_c$ is the inverter output voltage; $i_{1,abc}$ is inductor current at inverter side; $i_{g,abc}$ is grid-connected current; $C_{dc}$ is the DC side capacitance.
2.2. Mathematical model of control system
In the three-phase LCL grid-connected inverter system, phase a is selected for analysis, and the rest phases can be obtained by phase a reasoning. Assuming that $L_1$, $C_1$ and $L_g$ are ideal devices, ignoring the influence of parasitic resistance, the mathematical model of the whole system can be obtained by Kirchhoff’s law.

\[
\begin{align*}
    u_a(t) &= L_1 \frac{di_{ia}(t)}{dt} + u_s(t) \\
    u_s(t) &= u_{ga}(t) + L_g \frac{di_{ga}(t)}{dt} \\
    i_{ia}(t) &= i_{ga}(t) + C_1 \frac{du_s(t)}{dt} 
\end{align*}
\]  

(1)

$u_a(t)$ is the inverter output voltage, $u_s(t)$ is the filter capacitor voltage, $i_{ia}(t)$ is the inverter side inductor current, and $i_{ga}(t)$ is the grid-connected current. The function of inverter is to modulate the voltage signal, so as to control the grid-connected current, make the grid voltage and grid-connected current in the same frequency state, and expect good power quality to be connected to the grid.

The above formula is in the form of single-phase time domain state, and the formula (1) is transformed from time domain state to complex frequency domain state. With the inverter voltage $u_a$ as input and the grid current $i_{ga}$ as output, the transfer function of the filter is obtained as follows:

\[
\begin{align*}
    i_{ga}(s) &= \frac{1}{C_1L_1L_g s^3 + \left(L_1 + L_g\right) s} u_a(s) - \frac{1 + C_3L_s^2}{C_3L_1L_g s^3 + \left(L_1 + L_g\right) s} u_{ga}(s) \\
    G(s) &= \frac{i_{ga}(s)}{u_a(s)} = \frac{1}{\left(L_1 + L_g\right) s + C_3L_1L_g s^3} 
\end{align*}
\]  

(2)

3. Inverter voltage outer loop control strategy

3.1. Traditional PI control
The PI controller has a long history of development, and it has occupied an important position in the field of automatic control and industrial production by virtue of its good performance and simple control. When we are not clear enough about the internal structure and control parameters of the controller, or the accurate system parameters cannot be obtained, the PI controller is most suitable.
To put it simply, the proportional link is to control the deviation signal of the system, but in this case the system will have a certain steady-state error. The role of the integral link is to introduce an integral term into the controller to eliminate errors and make the system enter a stable operation state. The mathematical model is as follows:

\[
G_{pi}(s) = \frac{U(s)}{E(s)} = k_p \left(1 + \frac{1}{Ts} \right) = k_p + \frac{k_i}{s}
\]

Meanwhile, the gain of the controller at the fundamental frequency:

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

In formula (4), \(\omega_0 = 2\pi f \approx 314\), it can be seen that the gain of controller at power frequency is not infinite, and there is a certain error, which leads to the failure of timely adjustment when the controller is disturbed by the system, and the anti-interference ability is weak.

### 3.2. Fuzzy-PI controller

In view of the above problems, this paper uses fuzzy control to deal with P and I parameters, taking \(e\) and \(e_c\) as inputs and \(k_p\) and \(k_i\) as outputs of fuzzy reasoning. By fuzzy processing the sum, the parameters of P and I are adjusted online, so that the system is always in the optimal state, and the influence of voltage fluctuation on DC side is suppressed. The principle of fuzzy self-tuning PI control is shown in the figure.

![Fuzzy-PI control block diagram](image)

In Figure 2, the parameter \(k_p\) can make the system respond quickly, but if \(k_p\) is larger, overshoot will occur, which will affect the stability. The function of parameter \(k_i\) is to eliminate the static error of the system. The larger or smaller will have different impacts on the system, so the appropriate value should be taken.

### 4. Current Inner Loop Strategy of Inverter

#### 4.1. Resonance suppression based on improved deadbeat control

**4.1.1. Traditional deadbeat control principle.** The deadbeat control (DBC) has the characteristics of small steady-state error and quick response to system disturbance, which has been widely used in industrial control. The three-phase grid-connected inverter obtained by formula (1) can be obtained by \textit{clark} transformation:

\[
\begin{align*}
    u_a &= L_i \frac{di_{al}}{dt} + L_g \frac{di_{ga}}{dt} + u_{ga} \\
    u_r &= L_i \frac{di_{rl}}{dt} + L_g \frac{di_{gr}}{dt} + u_{gr}
\end{align*}
\]

It can be obtained by discretizing it:
\[
\begin{align*}
    u_a(n) &= u_{gaa}(n) + L_g \frac{i_{gaa}(n+1) - i_{gaa}(n)}{T_s} + L_i \frac{i_{ias}(n+1) - i_{ias}(n)}{T_s} \\
    u_\beta(n) &= u_{g\beta}(n) + L_g \frac{i_{g\beta}(n+1) - i_{g\beta}(n)}{T_s} + L_i \frac{i_{i\beta}(n+1) - i_{i\beta}(n)}{T_s}
\end{align*}
\]

(6)

It can be seen from formula (9) that the influence of deadbeat control accuracy mainly includes current sampling error, inductance deviation and sampling period. Firstly, the reference current is preprocessed, and the current value at time \(n+1\) is obtained as follows:

\[
\begin{align*}
    i_{ias}(n+1) &= i_{ias}(n) \\
    i_{i\beta}(n+1) &= i_{i\beta}(n)
\end{align*}
\]

(7)

The deadbeat current control transfer function is derived as follows:

\[
\begin{align*}
    u_a(n) &= u_{gaa}(n) + L_g \frac{i_{gaa}^*(n) - i_{gaa}(n)}{T_s} + L_i \frac{i_{ias}(n) - i_{ias}(n)}{T_s} \\
    u_\beta(n) &= u_{g\beta}(n) + L_g \frac{i_{g\beta}^*(n) - i_{g\beta}(n)}{T_s} + L_i \frac{i_{i\beta}(n) - i_{i\beta}(n)}{T_s}
\end{align*}
\]

(8)

From the analysis of formula (8), it can be seen that the voltage \(u_a(n)\), \(u_\beta(n)\) and the accuracy of the grid-side current are all affected by the output reference current at time \(n+1\). The accuracy of the controller is also closely related to the inductance of the filter. The inductance of the filter is affected by the switching frequency of the device, the actual temperature, and the amplitude of the voltage and current. When the actual inductance value in the circuit is larger than the model inductance value, it will cause system instability. At the same time, taking into account the suppression of system resonance, higher requirements for the accuracy of the controller need to be put forward.

4.1.2. Deadbeat control based on repetitive control. In order to improve the resonance suppression capability of DBC, a repetitive control dead-beat control (RCDBC) method based on repetitive control is proposed. The repetitive controller is embedded in the current inner loop, and the repetitive controller suppresses the current harmonics and DC signals to improve the anti-disturbance ability of the system and quality of grid-connected current.

The discrete form of repetitive control is \(G_r(z) = z^{-N}(1 - z^{-N}) = 1/z^N - 1\), take \(N = f_m/f_0\), where \(f_0\) is the fundamental frequency and \(f_m\) is the sampling frequency. In order to maintain the stability of the system, the repetitive controller is redesigned by adding a low-pass filter \(Q(z)\) and adding \(S(z)\) as a compensator. The RCDBC control structure diagram is shown in Figure 3.

\[
\begin{align*}
    i_{ias}(n+1) &= i_{ias}(n) \\
    i_{i\beta}(n+1) &= i_{i\beta}(n)
\end{align*}
\]

Figure 3. Equivalent diagram of RCDBC control

In Figure 3, the transfer function of the compensator in discrete form is:

\[
S(z) = k_c z^k C(z)
\]

(9)

Therefore, the expression \(G_M\) of the repletion principle after discrete transformation in \(z\) domain:

\[
G_M = k_c z^k C(z) \frac{z^{-N}}{1 - z^{-N} Q(z)}
\]

(10)
Ignoring the delay process in the modulation link, the expression $k(z)$ of the current loop is:

$$k(z)=1\frac{1-z^{-N}Q(z)}{1-z^{-N}Q(z)[1-k'_{r}z^{k}C(z)G_{p}(z)]}$$

(11)

Type in, $k'_{r}=k_{r}L_{4}L_{g}/T_{s}$. If you want to keep the system running efficiently, you must ensure that the root of $k(z)$ denominator $\{1-z^{-N}Q(z)[1-k'_{r}z^{k}C(z)G_{p}(z)]=0\}$ is inside the unit circle, so there are the following requirements:

$$\left|1-k'_{r}z^{k}C(z)G_{p}(z)\right| = \left|\frac{1}{z^{-N}Q(z)}\right| < \left|\frac{1}{Q(z)}\right|$$

(12)

In the formula, $k'_{r}$ is mainly controlled by gain $k_{r}$, which determines the response speed and stability of the controller, so the greater the selectivity of $k_{r}$ value, the better the system. $Q(z)$ controls the optional range of $k_{r}$. In order to make the system run more stably, $Q(z)$ is selected as:

$$Q(z) = \sum_{i=0}^{r}z^{i}a_{i} + \sum_{i=1}^{r}z^{-i}a_{i}$$

$$2\sum_{i=1}^{r}a_{i} + a_{0}$$

(13)

In which $a_{i}$ and $a_{0}$ are weighted values. In order to simplify the calculation process and consider the complexity of multi-order form, the first-order form is chosen in this paper. In formula (12), the smaller the value of $1/Q(z)$, the larger the selectable range of $k_{r}$, and vice versa. Therefore, the first-order low-pass filter $Q(z)$ is:

$$Q(z) = \frac{z+z^{-1}+2}{4}$$

(14)

4.2. Improved deadbeat control and QPR composite controller

4.2.1. QPR controller. At present, the tracking control of current signal mainly includes PI, PR and QPR. In this article, the output signal of the inverter is a low-to-medium frequency current. Although the current loop is easy to implement using PI control, it is difficult to optimally track the AC signal. Compared with PI control, the PR controller introduces two closed-loop poles in the complex frequency domain. Resonance occurs at the system resonant frequency to obtain gain. Under ideal conditions, optimal tracking can be achieved. Its transfer function is:

$$G_{PR}(s) = k_{p} + \frac{2k_{r}s}{s^{2}+w_{0}^{2}}$$

(15)

Although the PR controller can complete the tracking of the AC signal, there is a certain degree of non-linearity in the grid load, which will produce phased fluctuations, and the gain will be significantly reduced when the power frequency is not 50Hz. Due to the accuracy of the control system, the PR controller cannot make real-time corrections along with the grid frequency deviation, resulting in a decrease in its ability to suppress harmonics. Therefore, the QPR controller used in this article can still optimally track the AC quantity, while eliminating the steady-state error of the fundamental current and suppressing the grid-connected current harmonics. The transfer function is:

$$G_{QPR}(s) = k_{p} + \frac{2k_{r}w_{c}s}{s^{2}+2w_{c}s+w_{0}^{2}}$$

(16)

In formula (16), $w_{c}$ is the cut-off frequency. The control schematic diagram is shown in Figure 4
Figure 4. QPR control schematic diagram

Because the precision of the whole control system is limited, it is difficult to achieve the ideal effect of QPR control, so Tustin transform and zero-order keeper method are usually to discretize it. In this paper, Tustin transform is used to discretize QPR controller:

$$s = \frac{2(1-z^{-1})}{T(1+Z^{-1})}$$

Further, the transfer function of QPR is obtained as follows:

$$G_{QPR}(z) = \frac{-4k_p w_T z^{-2} + 4k_p w_T}{(4 - 4w_O T + w_O^2 T^2)z^{-1} + w_O^2 T^2 + 4w_O T + 4 + k_p}$$

The formula (18) is simplified, and the $z^{-1}$ term, $z^{-2}$ term and constant term are expressed by a, b, c, d and e. Respectively, which can be obtained:

$$\begin{aligned}
q_1 &= \frac{2T^2 w_0^2 - 8}{4 + 4Tw_c + T^2w_0^2} \\
q_2 &= \frac{4 - 4Tw_c + T^2w_0^2}{4 + 4Tw_c + T^2w_0^2} \\
m_0 &= \frac{4k_p Tw_c + 4k_p + 4k_p Tw_c + k_p T^2 w_0^2}{4Tw_c + 4 + T^2w_0^2} \\
m_1 &= \frac{2k_p T^2 w_0^2 - 8k_p}{4Tw_c + 4 + T^2w_0^2} \\
m_2 &= \frac{k_p T^2 w_0^2 - 4k_p Tw_c - 4k_p Tw_c + 4k_p}{4 + 4Tw_c + T^2w_0^2}
\end{aligned}$$

The QPR controller transfer function with simplified parameters can be obtained from formulas (18) and (19):

$$G_{QPR}(z) = \frac{m_0 + mz^{-1} + m_z z^{-2}}{1 + q_1 z^{-1} + q_2 z^{-2}}$$

The difference equation of QPR controller is derived:

$$i_{qpr}(k) = m_0 e(k) + m_1 e(k-1) + m_2 e(k-2) - q_1 i_{qpr}(k-1) - q_2 i_{qpr}(k-2)$$

Among them, $e(k)$ is the current error signal, and $i_{qpr}(k)$ is the controller output signal. The QPR is processed by Tustin transform, and its frequency range is converted from $-\infty < w_0 < +\infty$ in the continuous domain to $-\frac{\pi}{T} < W < +\frac{\pi}{T}$ in the discrete domain, which effectively solves the impact of
the control accuracy problem on the system.

4.2.2. **RCDBC-QPR composite controller.** This text uses RCDBC and QPR to take compound control of the electric current. Among them, RCDBC suppresses harmonic interference, and QPR optimally tracks the current signal to improve current quality and system stability. The structure diagram of the composite controller is as follows:

![Block diagram of structure of RCDBC-QPR](image)

**5. Analysis of simulation results**

In order to verify the practicability of the proposed method, a 35KW photovoltaic grid-connected inverter system model is established in Matlab/Simulink.

| Parameter name               | Value | Unit    |
|------------------------------|-------|---------|
| Rated grid phase voltage     | 220   | \( u_g/v \) |
| Grid frequency               | 50    | \( f/Hz \) |
| DC side voltage              | 800   | \( U_{dc}/v \) |
| DC side capacitance          | 4700  | \( C_{dc}/\mu F \) |
| Inverter side inductance     | 3.75  | \( L_a/mH \) |
| Filter capacitor             | 1     | \( C/\mu F \) |
| Net side inductance          | 0.44  | \( L_g/mH \) |
| Switching frequency          | 5     | \( f_s/kHz \) |

In this paper, the PI-QPR and the new RCDBC-QPR control are simulated and compared, in which the initial parameters of PI are \( k_p = 0.5 \), \( k_i = 2 \); the QPR initial parameter \( k_p = 4 \), \( k_r = 100 \), \( w_c = 5 \). The simulation results are shown in figure 6 and 7.

![System voltage and output current waveform controlled by PI-QPR](image)
Figure 7. System voltage and output current waveforms under two control strategies

Through the analysis of Figure 6 and 7, because the PI parameters cannot be adjusted in real time following the changes of the system, the system voltage fluctuates periodically. At the same time, harmonic spikes appear, making it difficult for QPR to accurately track the grid-connected current. The new inverter compound control strategy proposed in this paper controls the dynamic response and stability of the system, and at the same time reduces the resonance peak value of the grid-connected current. The comparison shows that the grid voltage amplitude fluctuation of the new composite control is reduced, and the current waveform is closer to a sine wave, and the problem of harmonic current spikes is solved, which greatly improves the dynamic response and stability of the entire control system.

Figure 8. FFT analysis diagram of output current waveform of PI-QPR and RCDBC-QPR

According to the analysis of Figure 8, although the system grid-connected current THD under the traditional PI-QPR control strategy is 4.07%, which meets the international grid-connected current standard of THD<5%, the grid-connected current still has harmonic disturbances. Resonance spikes appear, causing distortion of the grid-connected current. In the new control strategy proposed in this paper, the parameters of the PI controller are adjusted in real time through the fuzzy principle, which solves the problem that the P and I parameters are difficult to determine. At the same time, the repeated principle is used to control the deadbeat control to suppress the harmonic disturbance in the grid, reduce the distortion of the grid-connected current, and improve the anti-disturbance ability and power quality of the system, and then use the discretized QPR controller to track the current in real time. The results show that the output current THD of the new RCDBC-QPR composite control strategy is only 1.84%, which is 2.23% lower than that of the traditional controller. It conforms to the international IEEE 1547 standard for current requirements and can achieve better current grid connection.

To further verify the dynamic response performance of the proposed new RCDBC-QPR composite control, the reference value of grid-connected current is suddenly reduced from 80A to 60A and then
suddenly increased to 80A. The current waveform is shown in figure 9.

![Figure 9. Dynamic performance waveform of new RCDBC-QPR compound control](image)

Through the analysis of Figure 9, it can be found that when the current is suddenly increased and suddenly decreased at 0.3 s, the grid-connected current waveform can re-enter a stable state in a short period of time, and quickly eliminate the impact of current fluctuations caused by disturbances. It is verified that the new RCDBC-QPR control strategy has a faster dynamic response speed.

6. Conclusion

In view of the poor dynamic response of the traditional controller in the photovoltaic grid-connected system, the harmonic disturbance of grid-connected current and the difficulty in solving the optimal tracking of grid-connected current, this paper proposed fuzzy PI control voltage, discretized QPR and improved the DBC method of common control of current. The simulation results show that the new RCDBC-QPR control strategy proposed in this paper can greatly improve the stability and dynamic response of the system, complete the optimal tracking of the current signal, greatly improve the suppression of resonance, and achieve good power quality grid connection.

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