Power Quality Control Method of Distributed Generation Based on Improved PI and Repetitive Control

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Abstract. In view of the similar structure between the distributed generation (DG) inverter and the active power filter (APF), it is of great significance to develop the DG inverters with harmonic suppression functions. The accurate tracking and rapid response to the phase and amplitude of the harmonic components is the guarantee of the effective use of the DG inverter to suppress the harmonic. In this paper, a harmonic suppression control method of DG inverter based on improved PI and repetitive control is proposed. This method can make the DG inverter output the active power of the fundamental wave by using the PI controller, and output the high precision harmonic current compensation by the repetitive controller. While considering the existence of a periodic delay in the repetitive controller, the feedforward control of harmonic components is added to speed up the dynamic response of harmonic suppression. Finally, the simulation results show that, compared with the traditional harmonic suppression method, the proposed control strategy can ensure the steady-state accuracy and dynamic response speed of the active output and harmonic suppression of the DG inverter while reducing the computational complexity.

1. Introduction

With the countries vigorously promoting the development of new energy, the scale of the DG grid connected inverter device is gradually expanding. Seriously harmonic problem of the grid is caused by the large use of power electronic equipment. In addition, the large use of non-linear load makes the harmonic problem in the distribution network more and more serious. If resonance is caused, it will endanger the power consumption safety of users [1-3]. In order to suppress harmonic, it is usually more economical to configure a passive filter for the line, but the passive filter can only suppress the harmonic current of the corresponding frequency. The more efficient method is to use active filter for dynamic compensation, but the cost is higher. In view of the similarity between the DG inverter and the APF in system structure, use and control method, it will be a future trend to study the multi-functional DG inverter with harmonic suppression function. As a kind of DC inverter, photovoltaic (PV) inverter is dormant for most of the time that its annual generation time is less than 2000 hours. Therefore, it can be completely used for harmonic suppression when there is no light, which has no impact on PV generation.

Many experts and scholars have done a lot of work in harmonic signal extraction and controller design. Only PI controller is used to track the harmonic signal of compensation in dq coordinate system, that cannot realize the racking of harmonic component without static difference at harmonic frequency.
due to the limitation of bandwidth of the PI controller. To solve the problem that of the single synchronous rotation coordinate transformation, the specified order harmonic current control strategy in the multi synchronous rotation coordinate system is proposed. Furthermore, some scholars have proposed using FFT to control the amplitude of the extracted harmonic component with PI in each coordinate, and then adding the control component through inverse transforming together to generate the total output current reference. However, the calculation amount of this method is large, and the number of specified order harmonics to be controlled should not be too much [4, 5]. In paper [6] and [7], a method combined repetitive control with PI control is introduced aiming at the problem of multi-frequency harmonic compensation. This method can effectively control the harmonic while reducing the amount of calculation, but there is a periodic delay in the control component of repetitive control.

Considering the above shortcomings, this paper proposes a harmonic suppression method of the DG inverter based on the improved PI and repetitive control that can realize the better active power generation and harmonic compensation function at the same time. Firstly, the repetitive controller of LCL inverter is modeled. The links of unified low-frequency gain, high-frequency resonance suppression and phase compensation are designed according to the characteristics of LCL filter. Then, considering that the repetitive controller has one period delay that cause poor dynamic response, the zero-phase error feedforward compensation method is used to add the harmonic component feedforward control in the PI and repetitive controller to improve the dynamic response speed of harmonic suppression [8]. Finally, the effectiveness of the proposed method is verified by analyzing the error tracking effect and output waveform change in simulation.

2. Design of LCL Repetitive Controller

The main circuit model of LCL grid connected inverter is shown in Figure 1.

![Figure 1. Circuit of LCL type PV inverter](image)

Where $i_1$ is the inverter-side current, $i_2$ is the grid-side current, $L_1$ is the inverter-side inductor, $C$ is the filter capacitor, $L_2$ is the grid-side inductor, $R_1$ is the parasitic resistance of inverter-side inductor, $R_C$ is the parasitic resistance of filter capacitor, $R_2$ is the parasitic resistance of grid-side inductor.

$$G(s) = \frac{R_C C s + 1}{L_1 L_2 C s^3 + (L_1 + L_2) R_C C s^2 + (L_1 + L_2) s}$$ (1)

The internal model of the repetitive controller in discrete domain is:

$$G_R = \frac{1}{1 - Q(z) z^{-N}}$$ (2)

$Q(z)$ is usually taken as 0.95 to weaken the integral effect. $N$ is the number of sampling points in a period. The bode diagram of $G_R$ shows that the internal mode gains are all 26dB at the fundamental and harmonic frequencies.
Although there are many orders of harmonics, they will appear in the same waveform in each period. The reference will be accumulated continuously when the error exists. When the error is controlled to zero, the internal model can still output the appropriate control reference so that it can ensure the control accuracy of the fundamental and harmonic in the steady state.

Because the gain of LCL filter at resonance frequency is infinite, it will cause repetitive controller instability at resonance frequency.

To ensure good stability and steady-state accuracy, it can insert a compensator between the repetitive controller and the control object in series to correct the amplitude and phase of the control object, so as to achieve rapid and accurate control and suppression of high-frequency resonance at low power frequency. LCL can be regarded as an integral link in the low frequency range so that it needs to be offset by a differential link. However, the ideal differential link does not exist, so this paper uses the differential link $D(s)$ correction with inertia, as shown in the formula (3), to make the gain of the system in the low-frequency range consistent.

$$D(s) = \frac{L_s}{\tau s + 1}$$  \hspace{1cm} (3)

Where $\tau = 1/\omega_0$, $\omega_0$ is the resonance frequency, which is determined by LCL parameters.

The resistance is usually added to the filter capacitor branch to suppress the resonance frequency and increase the stability of the system. The $R_C$ will cause power loss and reduce the attenuation rate of the high frequency band at the same time. Therefore, the $R_C$ should not be too large and the resonance peak is still large. In this paper, the resonance peak is suppressed by the notch filter $F_n(s)$ as shown in the formula (4) at the resonance frequency, and the gain in the low frequency band is not affected.

$$F_n(s) = \frac{s^2 + \omega_0^2}{s^2 + 2\xi\omega_0 + \omega_0^2}$$  \hspace{1cm} (4)

Where the damping ratio $\xi = 0.707$.

The notch filter can only suppress the resonance peak, but the gain of the high frequency band above the resonance frequency is still large. It is necessary to attenuate its amplitude to ensure the stability of the system so that the second-order low-pass filter (SOLPF) shown in the formula (5) is used to further reduce the high frequency gain.

$$F_2(s) = \frac{\omega_0^2}{s^2 + 2\xi\omega_0 + \omega_0^2}$$  \hspace{1cm} (5)

Finally, the phase lag of the system caused by differential link and filter link is compensated by k-beat lead link $z^k$.

To sum up, the compensator $S(z) = D(z)F_n(z)F_2(z)z^k$ is obtained by discretizing each link. The block diagram of repetitive control system can be drawn as shown in Figure 2. The amplitude and phase of $S(z)G(z)$ after correction are close to 0dB and 0° under 1kHz frequency as shown in Figure 3. The low frequency gain is consistent, phase offset is zero and the resonance frequency and the above gain are effectively suppressed in this system, which guarantees the high steady-state compensation accuracy so it can achieve the precise control of low-order harmonics.
3. Analysis of Improved Repetitive Control Structure

Although repetitive control can ensure that the output waveform can accurately track a given periodic reference signal, its dynamic corresponding speed is slow. There is a periodic delay for the error signal, which limits its application scenarios. Because PI controller can immediately produce correction effect on the detected error signal, so the reference [6] proposes "PI + repetitive control". The structure diagram of the composite control system is shown in Figure 4 and the transfer function is as follows.

$$C(s) = k_p + \frac{k_i}{s} + \frac{1}{1 - 0.95e^{Ts}}$$

(6)

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Due to the introduction of integral link in PI regulator, the fundamental component of power grid can be tracked quickly without static error in dq coordinate system. And the multi harmonic command can be tracked by repetitive control.

However, the response speed of the composite control system still needs to be improved. In the dynamic process, the output of the repetitive controller is not affected by the change of the harmonic reference signal in a period. The system is dominated by the PI controller. Although PI can track the fundamental component quickly without static difference, it has no ability to track the output harmonic
component which is used to suppress the grid harmonic. To solve the above problems, an improved PI and repetitive control based on zero-phase error tracking is proposed. The current inner loop control structure is shown in Figure 5 [7].

By adding feedforward of harmonic current component in repetitive control, the dynamic response speed of harmonic output is accelerated. Then, the control ability of the controller to harmonic signal in dq coordinate is further improved. Considering that there is a leading link in compensator $S(z)$, generally speaking, a separate leading link cannot be realized, so it is necessary to divide $S(z)$ into two parts, $z^k$ and $S'(z) = D(z)F_1(z)F_2(z)$. For the feedforward harmonic reference signal, there is still phase lag in the following notch filter and SOLPF. Therefore, phase compensation is needed to improve the control accuracy. In this paper, zero-phase error tracking is realized by using rotation coordinate transformation. The specific compensation method is shown in Figure 6.

\[ 2 / k f f \theta = 2 k \pi f_0 / f_s \]  

Where $f_s$ is the sampling frequency of the controller and $f_0$ is the system frequency 50Hz.

4. Analysis of Simulation Results

In order to verify the above analysis, three control models of photovoltaic inverter with harmonic suppression function, which are PI controller (type I), PI + repetitive controller (type II) and improved PI + repetitive control (type III), are simulated and compared in Matlab/Simulink.

The simulation conditions are set as follows: the effective voltage of the power grid is 220V, the voltage frequency of the power grid is 50Hz, and the rated power of the PV array is 8kW at the DC side. The sampling frequency and switching frequency of the system are 20kHz. The parameters of $L_1$, $C$, $L_2$, $R_C$ in the filter are 0.74mH, 6.6μF, 55μH and 0.5Ω respectively. The grid side is connected with 5Ω three-phase symmetrical load and three-phase uncontrollable rectifier with 30Ω and 2mH nonlinear load.
According to the above parameters, the resonance frequency $\omega_0$ is $5.44 \times 10^4$ rad/s, so the parameters of each part of the compensator can be obtained. Because $S(z)$ lags two beats that means $k=2$, so $\theta_k$ can be calculated.

During the simulation, the three-phase symmetrical load is always connected. Firstly, the MPPT process of PV array is not the focus of this paper and will not be reflected. The nonlinear load is connected at 0.2s, and the harmonic current signal is extracted by the harmonic and reactive current detection method based on the instantaneous reactive power theory described in reference [9]. At 0.3s, the harmonic compensation control is added. According to the simulation of three control models, the output current waveform of phase A of power grid is shown in Figure 7.

It can be seen from Figure 7 that the current waveforms of the three controllers are similar. In the first cycle [0.3s, 0.32s] after the harmonic compensation is added, the PV grid connected inverters under the control of type I and type II are unable to quickly track the change of current signal, while the type III controller added the feedforward harmonic current signal can compensate the harmonic current and recovers the output current of the grid into a sine wave quickly when the pulse current waveform generated by the nonlinear load arrives. After three periods, the repetitive control in the type II and type III controllers gradually tracks the harmonic reference signal so the current waveform tends to be the same. Because only PI controller is included in type I controller, the output current is not improved gradually, and it is still greatly affected by pulse current.

![Figure 7](image_url)

**Figure 7.** A phase output current waveform of grid

The waveform of current error on d-axis and q-axis is shown in Figure 8. From figure 8(a), it can be seen that the signal error reaches 19.5A in an instant after the harmonic signal is added.

It can be seen from figure 8(b) that in the first period after the harmonic signal is added, the q-axis current error of type III controller can be adjusted relatively quickly. It will start to decrease when it reaches 4.525A and fluctuate within the range of [-1.557A, 4.525A] that is closer to the 0 coordinate than others. However, the q-axis current error of type I and type II controllers began to decrease at 5.621A and fluctuated in the range of [-0.366A, 5.915A]. When it is stable, the q-axis current error of type I controller is about [-0.706A, 4.167A], the q-axis current error of type II controller is about [-0.642A, 1.27A], the q-axis current error of type III controller is about [-0.42A, 1.186A]. Therefore, the control ability of type III controller to q-axis current is further enhanced when it is stable.
Figure 8. d-axis and q-axis current error waveform

Figure 9 shows the results of the 1st, 2nd and 10th period Fourier transform of the grid current after the harmonic current compensation is added. It can be seen from Fig. 9 (a) and (b) that the content of 5th, 7th, 11th, 13th, 17th and 19th harmonics decreases obviously and rapidly when using type III controller. It can be seen from Figure 9 (c) that the compensation effect of type II and type III repetitive controllers is similar to that of type I and the compensation ability is significantly improved compared with that of type I after the compensation is stable. The specific THD changes are as follows: THD before compensation is 10.8% and THD under three controllers after compensation is reduced to 3.61%, 1.61%, 1.71% respectively when stable.

Figure 9. Harmonic content after compensation

5. Conclusion
In terms of design, since the main design purpose of DG inverter is active power generation, the inverter can only be used for harmonic suppression when there is surplus capacity. In order to realize the better active power generation and harmonic compensation function of the DG inverter at the same time, this paper takes the inverter controller as the research object and proposes a harmonic suppression control method of the DG inverter based on the improved PI and repetitive control. The following conclusions are obtained by simulation.

1) The 5th, 7th, 11th, 13th, 17th and 19th harmonic currents can be suppressed with less calculation when the repetitive controller is added, which can be applied to the grid connected inverter of DG with harmonic suppression function.

2) The improved PI and repetitive controller can effectively improve the dynamic response speed of harmonic suppression, accelerate the tracking speed of the controller to the harmonic reference signal and reduce the deviation between the actual output current and the reference current signal.
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