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A Control Strategy for Single-phase Grid-Connected Inverter with Power Quality Regulatory Function

Jin Jiapei*[1,a], Chen Tiantian[1], Luo Ling[1], Su Shaoze[2,b]
[1]Electric Power Research Institute of Shanghai Power Company, Shanghai, China
[2]School of Electrical Engineering and Information, Sichuan University, Chengdu, China
*Corresponding author, e-mail: gaoyun.scu.88.03@163.com[a], 513853116@qq.com[b]

Abstract

A single-phase grid-connected inverter system based on LCL filter is established, which combines the features of inverter and active power filter. A composite control strategy for grid-connected inverter with the function of implementing reactive power compensation and harmonic compensation in the grid-connected power generation is proposed. Firstly, grid-connected inverter system structure and model is analyzed. A quasi-Proportional Resonant control method to gain the control of grid-connected fundamental wave current containing reactive power compensation current as well as the control of harmonic compensation currents is put forward; then the calculation methods of composite control command current based on both second order generalized integrator-quadrature signal generator (SOGI-QSG) and instantaneous reactive power theory are given. Finally, the effectiveness of the control strategy proposed in this paper is verified by simulation.

Keywords*: single-phase grid-connected inverter, harmonic compensation, harmonic compensation, SOGI-QSG, quasi-PR controller*

1. Introduction

In recent years, the voltage source converter has been widely used in wind power, photovoltaic and other distributed generation systems and Active Power Filter (APF). The converter, as the interface of distributed generation systems and the grid, achieve the grid-connected generation of intermittent power source [1]. Inverter will generate harmonics, but this structure also enables a more flexible control of the distributed power. Converter control is divided into linear or non-linear voltage control and current control, and the latter is more widely used in the grid-connected inverter. The quite common current control includes PI control, proportional-resonant (PR) control, hysteresis control and repetitive control, etc [2-6].

Non-linear and impact load produce harmonic current and reactive current, and will bring great pressure to the public grid power quality. Due to its high cost and single function, APF is mainly used for industrial areas, and is seldom used for single-phase grid in residential areas. The building-integrated PV (BIPV) system installed in low voltage is connected to the grid by the inverter, which achieves the grid-connected generation nearby and endows with certain market prospects [7]. The photovoltaic inverter and the structure of the APF have similarities, so some literatures have proposed the control strategy that the grid-connected inverter provides active filter function [8-13]. When sunshine is adequate and the total power obtained by photovoltaic cell array are fed into the grid, harmonics and reactive power compensation are carried out by using the remaining capacity of the inverter; when at night or the sunshine is inadequate, the inverter fully works in the active filtering mode, which will improve the photovoltaic grid-connected system utilization.

Composite control for three-phase grid-connected inverter is mostly used in the two-phase rotating coordinate system [11]. Since only one-phase variable exists in single-phase grid-connected inverter, it is necessary to construct one “fictitious” or imaginary variable in which all frequencies are phase-shifted by 90 electrical degrees with respect to the original variable. In [8], a method of constructing the two-phase quadrature system without delay was proposed; however, it only can conduct grid-connected generation and reactive power compensation instead of providing harmonic compensation. In [9-10], the instantaneous reactive power theory was adopted to detect reactive and harmonic current, and then the PI control was used to

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realize the unified control of grid-connected inverter and the active filter, but the PI controller cannot achieve any static error tracking AC signals and the response is slow. Some literatures utilized the repetitive control strategy based on the Discrete Fourier transform to achieve the function of generates active power and harmonic compensation [11-12]. In [13], the deadbeat control was introduced to achieve the purpose of conducting active power as well as reactive power and harmonic compensation, but it aimed at the three-phase system, not apply to single-phase photovoltaic system.

In summary, for the realization of composite control of the single-phase inverter that generates active power and compensates the reactive power and current harmonics of local loads, two aspects of work are mainly included: on the one hand, choosing a suitable means for harmonic and reactive current detecting; on the other hand, choosing a fast and efficient current control strategy. In light of this, this paper proposed a composite control strategy based on a single-phase inverter LCL filter to implement the active filtering function in grid-connected process. First, the principle of second-order integrator quadrature signal generator (SOGI-QSG) to construct the orthometric two-phase signal and calculate the required compensation value of harmonic currents was exploited; and then the grid fundamental current containing reactive power compensation current was calculated through instantaneous reactive power theory, thus synthesizing the reference current of composite control with active, reactive power generation and harmonics compensation; Finally, the quasi- PR controller was adopted to achieve the zero steady-state error control of AC reference current. The simulation results verified the correctness of the proposed control strategy.

2.Grid-connected Inverter System Principle

2.1. System Structure

A single-phase grid-connected system structure studied in this paper is shown in Figure 1. DC source rated voltage is 420V, which is generally obtained by the PV array through the DC/DC boost. In order to reduce the harmonic content of grid current and the amount of inductance value, the inverter employs the LCL filter. For the purpose of inhibiting the instability phenomenon of the LCL filter, this paper introduced a passive damping method of cascading the damping resistance R_d with the filter capacitor C_f to improve system stability [14].

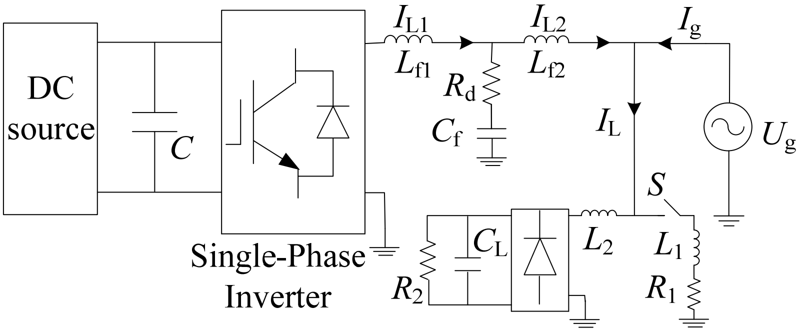


Figure 1. Schematic Diagram of grid-connected inverter

2.2. System Model and Control Strategy

According to the schematic diagram shown in Figure 1, the control model diagram shown in Figure 2 is built, wherein the reference current calculation process is shown in Figure 7. Due to the high switching frequency (10 kHz here), much higher than the grid frequency, the PWM is approximately replaced by the gain link K_{PWM} approximation, wherein $G(s)$ is the transfer function of the current controller.

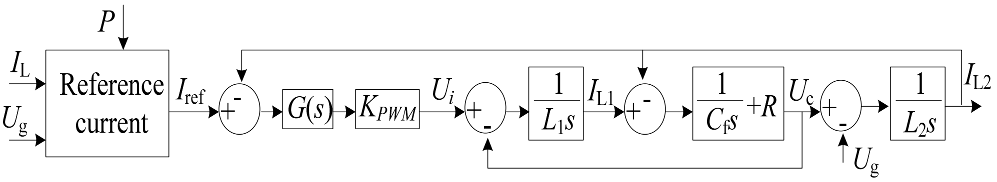


Figure 2. Control model of grid-connected inverter system

According to the control model in Figure 2, the grid-side current output by the inverter is:

$$I_{\text{L2}} = \frac{G(s)K_{\text{PWM}}}{G(s)K_{\text{PWM}} + D(s)} I_{\text{ref}} - \frac{L_1 C_{\text{f}} s^2 + R_{\text{d}} C_{\text{f}} s + 1}{G(s)K_{\text{PWM}} + D(s)} U_{\text{g}} \tag{1}$$

Where, $D(s) = \dfrac{L_1 L_2 C_{\text{f}} s^3 + R(L_1 + L_2) C_{\text{f}} s^2 + (L_1 + L_2)s}{C_{\text{f}} Rs + 1}$.

In view of the reference current I_{ref} containing not only the fundamental signal but also the harmonic current signal, the conventional PI control cannot achieve the no-steady-state error tracking on the AC signal. For the effective control of the fundamental component and the restraint of harmonic component, the current controller in this paper uses the Quasi-Proportional Resonant (PR) with good tracking results to AC signal.

Quasi-PR controller consists of the proportional regulator and the resonant regulator. It has a high gain at the resonant frequency while the gain is very small at the non-resonant, with the ability of anti-grid voltage disturbances [15-17]. The controller transfer function of the quasi-PR is:

$$G_{\text{PR}}(s) = k_{\text{p}} + \frac{2\omega_{\text{c}} k_{\text{r}} s}{s_2 + 2\omega_{\text{c}} s + \omega_0^2} \tag{2}$$

The above k_p and k_r are respectively the scale factor and resonant coefficient of quasi-PR controller; ω_0 is the resonance frequency; and ω_c is the cut-off frequency. When $s=j\omega_0$, the resonant gain reaches the maximum k_r.

In addition to quasi-PR fundamental current control, the use of non-ideal resonant controller to compensate for the low-order harmonics (3th, 5th, 7th, 9th harmonic content is the most in distribution network). The transfer function of non-ideal resonant controller is

$$HC(s) = \sum_{h=3,5,7,9} \frac{2\omega_{\text{c}} k_{hr} s}{s_2 + 2\omega_{\text{c}} s + \omega_h^2} \tag{3}$$

The above h is the harmonic number, k_{hr} as a resonance coefficient, and ω_h as harmonic frequency. $HC(s)$, the harmonic compensation, does not affect the dynamic characteristics of the fundamental quasi- PR control. It is only responsive to the signal in the vicinity of the resonance frequency, so harmonic compensation term can be superimposed on the quasi -PR controller.

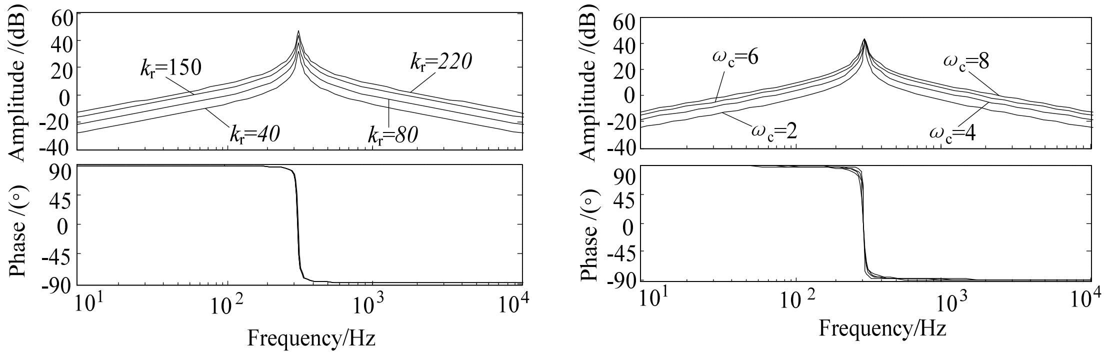
For quasi-PR controller, the adjustment k_P can adjust controller bandwidth [17]; the resonant controller can only be achieved by adjusting the k_{hr} with ω_c to the regulation of the harmonic signal. As for the fundamental signal, taking $k_P=0$, when ω_c is 5 rad / s and k_r changes, and k_r is 120 , ω_c changes, the Bode diagram of quasi-PR controller is shown in Figure 3.

As seen from Figure 3, k_r only affects the controller gain (achieving the amplitude-frequency curve to pan up or down), without affecting the controller bandwidth; ω_c not only affect the controller gain, but also affect the controller bandwidth. With the increasing of ω_c, bandwidth increases. ω_c in engineering practice generally takes 5-10 rad/s [17], and the fundamental controller ω_c in this paper as 3.2 rad / s, the harmonic controller ω_c as 5 rad / s. By the reasonable adjustment of k_p, k_r and k_{hr} , the differential regulation of the fundamental and harmonic without static can be achieved.

The transfer function of the current controller in this paper is

$$G(s)=G_{PR}(s)+HC(s) \tag{4}$$

The Control model of current is shown in Figure 4.



(a)Bode of PR controller when k_r changes (b)Bode of PR controller when ω_c changes

Figure 3. Bode of PR controller in variable parameters

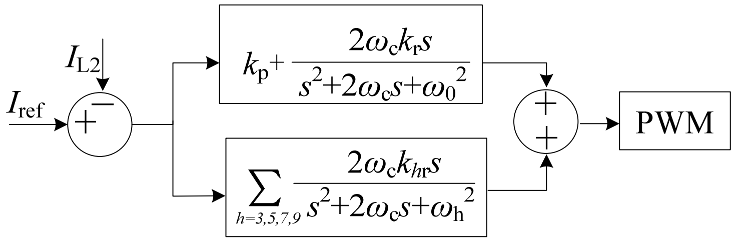


Figure 4. Control model of current generalized

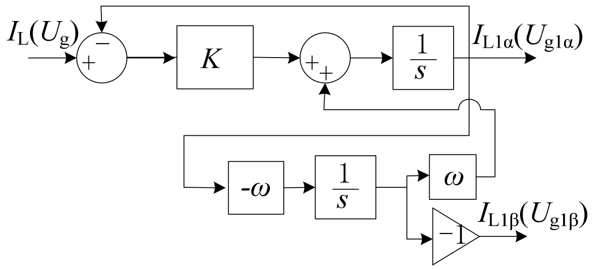


Figure 5. Second order integrator-quadrature signal generator

3. Composite Control Current Command

3.1. Harmonic Reference Current Calculation

This paper mainly exploited the point of common coupling PCC voltage U_g and nonlinear load current I_L to calculate the harmonic compensation reference current. A method of the generalized second integrator -based adaptive filtering to achieve the 90° phase angle offset and harmonic filtering was proposed in [18]. In this paper, a similar approach was applied to the single-phase system to constitute a quadrature signal generator based on second-order generalized integrator (SOGI-QSG), so the separation of the fundamental signal in the coordinates of the two-phase stationary coordinate system was achieved to implement the harmonic detection and its block diagram is shown in Figure 5.

Figure 5 shows that PCC voltage fundamental wave component（$U_{g1\alpha}$、$U_{g1\beta}$） and the fundamental wave component of the load current（$I_{L1\alpha}$、$I_{L1\beta}$） under the two-phase stationary coordinate system can be obtained by SOGI-QSG, and the transfer function of SOGI-QSG is

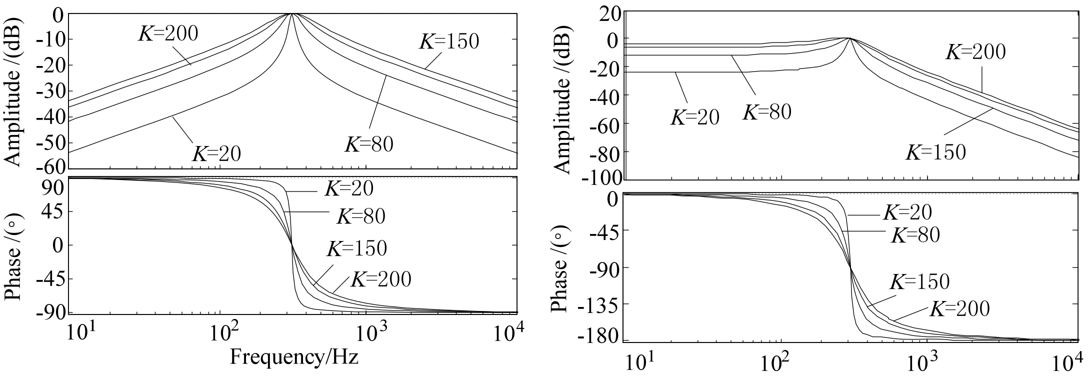
$$H_1(s)=\frac{I_{\mathrm{L1\alpha}}(s)}{I_{\mathrm{L}}(s)}=\frac{U_{\mathrm{g1\alpha}}(s)}{U_{\mathrm{g}}(s)}=\frac{Ks}{s^2+Ks+\omega^2} \tag{5}$$

$$H_2(s)=\frac{I_{\mathrm{L1\beta}}(s)}{I_{\mathrm{L}}(s)}=\frac{U_{\mathrm{g1\beta}}(s)}{U_{\mathrm{g}}(s)}=\frac{K\omega}{s^2+Ks+\omega^2} \tag{6}$$

Under the steady-state condition, the formulas (5) and (6) have the following relationship in the frequency domain.

$$\angle H_1(\mathrm{j}\omega)=\angle H_2(\mathrm{j}\omega)+\frac{\pi}{2} \tag{7}$$

From the foregoing, if taking ω as fundamental angular frequency, the fundamental component of the two-phase stationary coordinate system can be isolated. They are equal in magnitude, phase mutual difference is 90°. SOGI-QSG achieved its goals mainly through internal model principle-based adaptive filtering, with anti-jamming capability. Therefore, even in the case of the load or the grid voltage distortion, the fundamental current voltage can still be well isolated. When taking a different coefficient K, the Bode diagram of formula (5) and (6) are shown in Figure 6. As seen from Figure 6, the smaller the adaptive coefficient K and the bandwidth are, the better the filtering effect is, but the slower the response is. In the application process, the appropriate coefficient K can be selected as required.



(a)Bode plots of $H_1(s)$

(b)Bode plots of $H_2(s)$

Figure 6. Bode of H1(s) and H2(s) in variable parameters

The fundamental current in the load current can be isolated by the method in Figure. 5, so the harmonic current I_{Lh} in need of compensation is

$$I_{\mathrm{Lh}}=I_{\mathrm{L}}-I_{\mathrm{L1\alpha}} \tag{8}$$

3.2. Grid-Connection Reference Current Calculation

The fundamental voltage of the PCC, the load fundamental current and harmonic current under the two-phase stationary coordinate system is calculated through Figure 5 and the formula (8). According to the instantaneous reactive power theory, the required reactive power by load is

$$Q_{\mathrm{L}} = I_{\mathrm{L1\alpha}}U_{\mathrm{g1\alpha}} - I_{\mathrm{L1\beta}}U_{\mathrm{g1\beta}} \tag{9}$$

The required reactive power by load can be calculated in terms of the detected load current and voltage. For the inverter output power, there is

$$\begin{cases} P^* = I_{1\alpha}U_{\mathrm{g1\alpha}} + I_{1\beta}U_{\mathrm{g1\beta}} \\ Q^* = I_{1\alpha}U_{\mathrm{g1\beta}} - I_{1\beta}U_{\mathrm{g1\alpha}} \end{cases} \tag{10}$$

The above $I_{1\alpha}$ and $I_{1\beta}$ are the fundamental component of the inverter output current under the two-phase stationary coordinate system. Typically, the grid-connected inverter output reactive power is almost zero in order to maintain a high power factor operation. To compensate the load reactive power, the reactive power of the load calculated by the formula (9) acts as a reference value of the inverter output reactive power, set $Q^*=Q_{\mathrm{L}}$. According to (10), there is

$$\begin{bmatrix} I_{1\alpha}{}^* \\ I_{1\beta}{}^* \end{bmatrix} = \frac{1}{U_{\mathrm{g1\alpha}}{}^2 + U_{\mathrm{g1\beta}}{}^2} \begin{bmatrix} U_{\mathrm{g1\alpha}} & U_{\mathrm{g1\beta}} \\ U_{\mathrm{g1\beta}} & -U_{\mathrm{g1\alpha}} \end{bmatrix} \begin{bmatrix} P^* \\ Q^* \end{bmatrix} \tag{11}$$

Where in, P^* is the inverter output active power. If Previous level inverter DC source is the photovoltaic array, P^* can be achieved by the maximum power point tracking (MPPT) algorithm [11]. According to the method of formula (11) to calculate the fundamental reference current, all the power issued by the PV array can be fed to the grid.

The formula (11) shows that just through the simple arithmetic the method described herein can get grid-connected current the fundamental reference value containing reactive power compensation current. Because of the single-phase system in this paper, beta axis voltage current generated in the SOGI method is just designed for the calculation of the reference current. So in the calculation of controller input reference current, $I_{1\beta}{}^*$ is ignored.

The required compensation for harmonic currents in the formula (8) is obtained, and grid-connected fundamental reference current which containing the reactive power compensation capability is obtained (11). Therefore, as known by (8) and (11), the reference current of composite control that generates active power and compensates the reactive power and current harmonics of local loads described in this paper is:

$$I_{\mathrm{ref}} = I_{1\alpha}{}^* + I_{\mathrm{Lh}} \tag{12}$$

The method to gain the composite control reference current is shown in Figure 7.

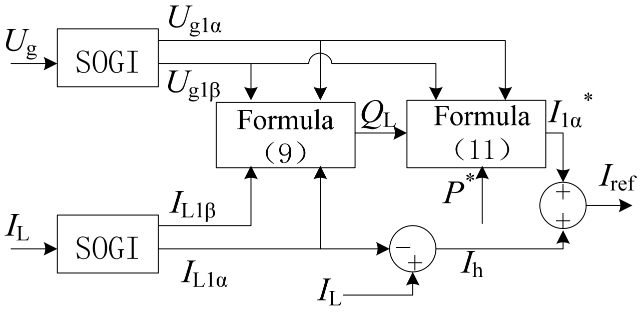


Figure 7. Reference current calculation structure diagram

4.Simulation Study

To verify the effectiveness of the proposed control strategy, the model shown in Figure 1 is built by using Matlab/Simulink software to simulate. The main parameters of the electrical components in Figure 1 are shown in Table 1.

Table 1. System parameters

Parameters	Value	Parameters	Value
Udc /V	420	Ug /V	220
C/μF	2200	R1/Ω	25
Lf1 /mH	1	L1 /mH	50
Lf2 /mH	0.22	R2 /Ω	50
Cf /μF	6.8	L2 /mH	900
Rd /Ω	1.7	CL /μF	1000

To verify the proposed composite control strategy, the respective simulations of the grid and reactive power compensation composite control as well as the grid and harmonic compensation composite control are carried out. In order to facilitate the observation of the waveform, the voltage waveforms below are scaled down to 50V.

1) The simulation waveforms of the reactive power compensation are shown in Figure 8.

As seen from Figure 8, due to the load containing reactive load, the load power factor is low. Through the reactive power compensation of the inverter, the power factor is improved significantly. Before 0.7s, the inverter output active power is greater than the load required for the active power, and it not only can meet the load demand, but also make the remaining active power fed to the grid. So in the power outage as a result of a grid fault, the inverter can also provide power for critical loads to achieve the uninterrupted operation of the load. After 0.7s, as the inverter output power reduces, the load not only consumes all the inverter output active power, but also absorbs a part of the active power from the grid.

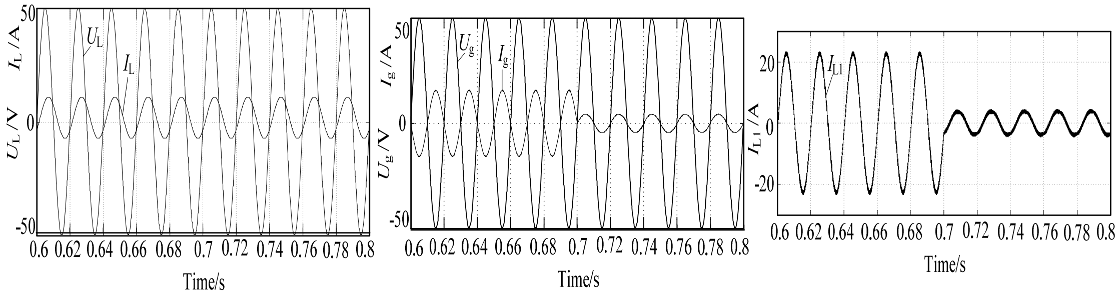
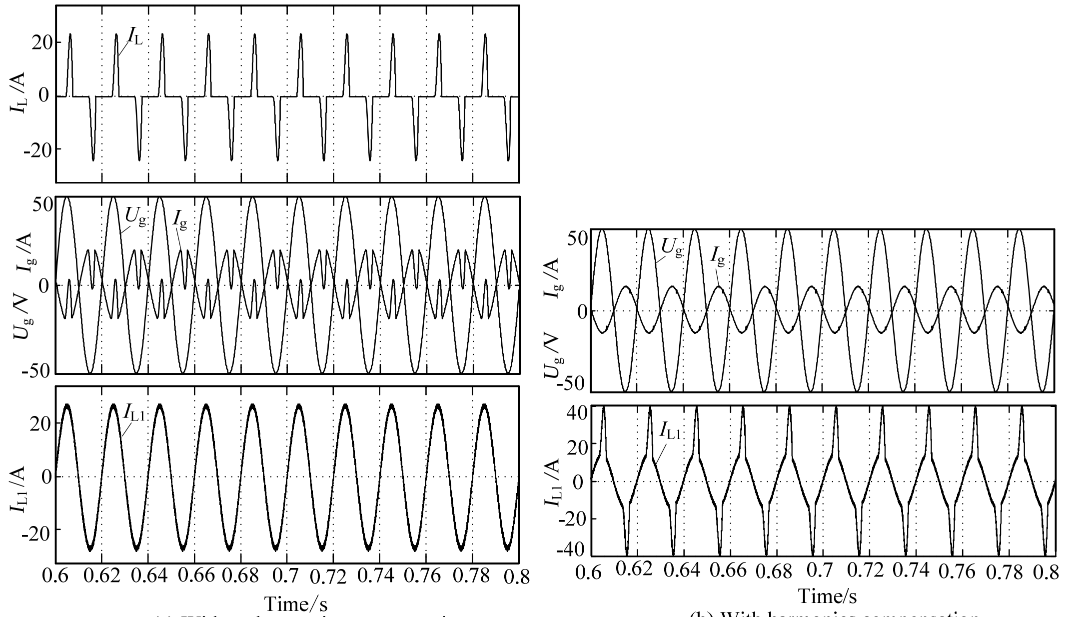


Figure 8. Reactive compensation rendering diagram

2) The simulation waveforms of harmonic compensation are shown in Figure 9.

As seen from Figure 9 (a), due to the presence of non-linear loads, the load current consists of mass harmonics. The grid current will come to the severe distortion without the harmonic compensation. Through the Fourier analysis, the total harmonic distortion (THD) of the grid current reaches 69%, of which the most harmonic content of 3th, 5th, 7th and 9th are the most. Compared with Figure 9 (b), by the means of the proposed control strategy, the current containing harmonic issued by the inverter is offset with the harmonic in the load, the grid current THD declines to 1.83%, and the power quality is significantly improved.



(a) Without harmonics compensation (b) With harmonics compensation

Figure 9. Harmonic compensation rendering diagram

5. Conclusion

1) The structure of the distributed power single-phase grid-connected inverter at the end of the grid is similar to that of APF, playing the same similar function as the active filter through the reasonable control.
2) The method based on SOGI-QSG to isolate the fundamental component and harmonic component of the load current was proposed. Combining the instantaneous reactive power theory, the fundamental reference of the grid-connected generation and reactive power compensation was deduced, together with the isolated harmonic currents to constitute the compound control reference current.
3) Adopting the quasi-PR current controller carrying the resonant controller, the rapid control for the fundamental component as well as the effective compensation for harmonic currents are achieved.

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