Research on static reactive power generator based on asymmetric distribution network

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Abstract: Negative or zero sequence components are generated when the voltage is asymmetric or harmonic in distribution networks. Meanwhile, the decoupling process of traditional d_q transform is complex. To solve the above problems, firstly, the *T*/4 delay method (*T* is the period of grid voltage) is presented to separate positive and negative sequence components, which improves the stability of software phase-locked. Then, software phase-locked loop (SPLL) is designed to ensure the instantaneity of reactive current check. Besides, a double-loop control scheme combining proportional integral (PI) controller for DC voltage in outer loop and proportional resonance (PR) controller for AC current in inner loop without decoupling is designed by considering the characteristics of traditional PI and PR without static error regulation. It avoids the complicated decoupling process and improves the real-time performance of the system. Finally, both simulation and experimental results are given to verify the feasibility of design scheme in the static var generator (SVG) system by MATLAB/Simulink and experimental platform based on DSP28335.

Keywords: static reactive power generator; asymmetrical distribution network; PR controller; software phase-locked loop; SPLL.

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1 Introduction

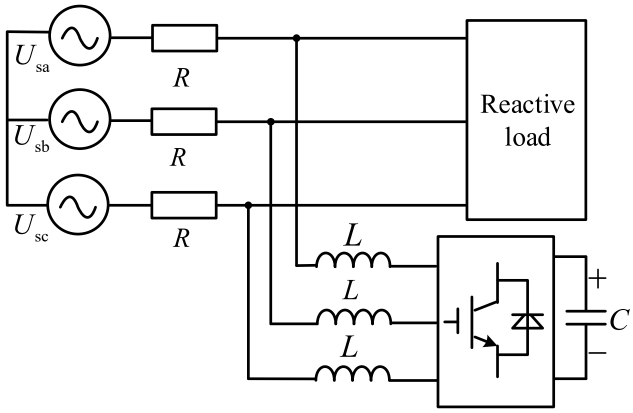
The presence of reactive power not only leads to voltage swing, low power factor and voltage instability in the distribution network, but also may lead asymmetry and flickering of power system voltage and other power quality problems. Reactive power compensation device can compensate in real time when reactive power is demand, so that it can achieve the control system flow and improve the transmission capacity of power transmission and transformation system to ensure safe and efficient operation of distribution network, and optimise the power quality in the distribution network (Zeng, 2005). Therefore, it is a hot research to improve the quality of power supply by compensating reactive power. The harmonic and reactive current detection methods are analysed (Lin et al., 2011). In Ji et al. (2011) the three-phase software phase-locked loop (SPLL) based on dq transform is designed. The method to select the DC energy storage capacity of the new synchronous compensator is researched (Ma et al., 2011). The voltage-directed vector control strategy of the stationary reactive power generator is analysed (Tian et al., 2014). With the application and development of power electronics, the current distribution voltage operates in asymmetric state or contains harmonics. When the distribution voltage is asymmetrical or contains harmonics, the negative sequence and the zero sequence component will be produced (Wang et al., 2013). If the positive sequence component cannot be separated well, the above transformation will not achieve the phase-lock. This paper focus on the negative and zero sequence components which is leaded by asymmetric or harmonics voltage in distribution network. A $T/4$ delay method is used to separate positive and negative sequence components, then SPLL is used to ensure the instantaneity of reactive current check. According to the relative merits of proportional integral (PI) control and the characteristics of proportional resonance (PR) controller without static error, we design a double closed loop control strategy which consists of a DC PI voltage outer loop and an AC PR current inner loop of without decoupling.

2 SVG system principle and mathematical model analysis

2.1 SVG system topology and its principle

Stationary reactive voltage generator (SVG) which parallels to the distribution grid can be equivalent to a controllable reactive power source. The system reactive voltage can automatically be compensated when the output current is controlled flexibly through the SVG. Based on the principle of the voltage-type converter, SVG is connected to the distribution network through the inductor, and then the output voltage and phase of inverter bridge AC is adjusted to absorb the required reactive power. Thus, the dynamic adjustment propose is achieved (Zhang and Zhang, 2013; Huang et al., 2012). The diagram of SVG system topology is shown in Figure 1.

Figure 1 SVG topology construction

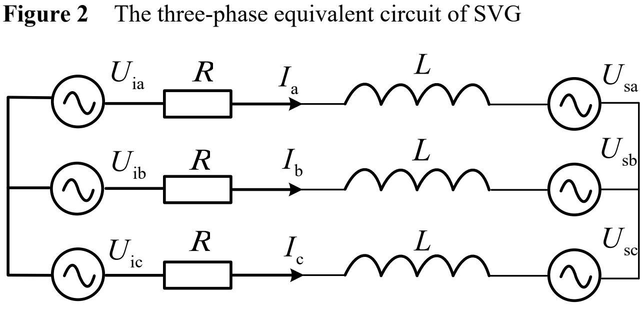


In Figure 1, SVG is divided into two parts, DC and AC side. AC side directly connects to the load side when it is working, and AC power is converted to DC energy storage on the DC side or to the required voltage and current by converter, then the voltage and current are transported to the distribution network system.

2.2 SVG mathematical model analysis

The three-phase equivalent circuit of SVG is shown in Figure 2. The outputs of SVG are U_{ia}, U_{ib}, U_{ic}, three-phase voltage of system are U_{sa}, U_{sb}, U_{sc}, the compensation currents of SVG are I_a, I_b, I_c. R is the equivalent resistance of the connected reactance of converter and the transformer and other devices. L is the equivalent value of the connected inductance and the transformer leakage.

Figure 2 The three-phase equivalent circuit of SVG



According to the rule of voltage, the time domain expression of SVG device under symmetric distribution is:

$$\begin{cases} L\dfrac{dI_a(t)}{dt} = mU_{dc}\sin(\omega t+\varphi) \\ \qquad -\sqrt{2}U_{sa}\sin\omega t - RI_a(t) \\ L\dfrac{dI_b(t)}{dt} = mU_{dc}\sin(\omega t+\varphi-2\pi/3) \\ \qquad -\sqrt{2}U_{sb}\sin(\omega t-2\pi/3) - RI_b(t) \\ L\dfrac{dI_c(t)}{dt} = mU_{dc}\sin(\omega t+\varphi+2\pi/3) \\ \qquad -\sqrt{2}U_{sc}\sin(\omega t+2\pi/3) - RI_c(t) \end{cases} \tag{1}$$

In equation (1), U_{dc} is the DC side voltage, m is the modulation index. According to energy conservation relationship, we can get the relationship between capacitance voltage U_{dc} and inverter bridge output voltage as:

$$CU_{dc}\frac{dU_{dc}}{dt} = -U_{Ia}(t)I_a(t) - U_{Ib}(t)I_b(t) - U_{Ic}(t)I_c(t) \tag{2}$$

From equations (1) and (2), we can get the model as:

$$\begin{cases} L\dfrac{dI_a(t)}{dt} = mU_{dc}\sin(\omega t+\varphi) \\ \qquad -\sqrt{2}U_{sa}\sin\omega t - RI_a(t) \\ L\dfrac{dI_b(t)}{dt} = mU_{dc}\sin(\omega t+\varphi-2\pi/3) \\ \qquad -\sqrt{2}U_{sb}\sin(\omega t-2\pi/3) - RI_b(t) \\ L\dfrac{dI_c(t)}{dt} = mU_{dc}\sin(\omega t+\varphi+2\pi/3) \\ \qquad -\sqrt{2}U_{sc}\sin(\omega t+2\pi/3) - RI_c(t) \\ \dfrac{dU_{dc}(t)}{dt} = -\dfrac{m}{C}[\sin(\omega t+\varphi)I_a(t) \\ \qquad +\sin(\omega t+\varphi-2\pi/3)I_b(t) \\ \qquad +\sin(\omega t+\varphi+2\pi/3)I_c(t)] \end{cases} \tag{3}$$

According to the instantaneous power theory, the expressions of SVG instantaneous active and reactive power are:

$$\begin{cases} p(t) = \dfrac{3}{2}\left[u_d(t)\cdot i_d(t) + u_q(t)\cdot i_q(t)\right] \\ q(t) = \dfrac{3}{2}\left[u_q(t)\cdot i_d(t) + u_d(t)\cdot i_q(t)\right] \end{cases} \tag{4}$$

From the equations (3) and (4), the output active and reactive powers of SVG are:

$$\begin{cases} p(t) = -3\sqrt{3}/2\, i_d(t) \\ q(t) = -3\sqrt{3}/2\, i_q(t) \end{cases} \tag{5}$$

From equation (5), output reactive power of SVG system is only proportional to the reactive current, which means that the key of control output reactive power in SVG is the detection and control of instantaneous reactive current.

3 Analysis of reactive current detection and phase-lock loop principle

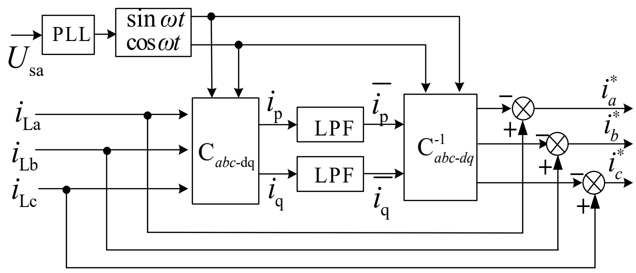
3.1 *i_p-i_q current vector transformation detection method*

The principle of i_p-i_q current vector transformation detection method is based on the instantaneous power theory, which is used to convert the instantaneous current vector which is detected by three-phase *abc* to active i_p and reactive i_q of the d_q rotation system without the intermediate conversion of $\alpha\beta$, the conversion is shown as follow.

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\omega t & \cos(\omega t-2\pi/3) & \cos(\omega t+2\pi/3) \\ \sin\omega t & \sin(\omega t-2\pi/3) & \sin(\omega t+2\pi/3) \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{6}$$

The principle is shown in Figure 3.

Figure 3 The i_p-i_q current vector transformation detection



After detecting current transforming by *abc-dq* coordinate, the *d* axis and the voltage have the same phase as the active axis, *q* axis and *d* axis are perpendicular as the reactive axis, where i_q is the reactive current component and i_p is the active current component, i_p and i_q are the corresponding DC current component respectively through the filter link. In this paper, the key which reactive power is compensated is accurate detection of reactive current. Therefore, in order to obtain command current, we only need to invert the DC component $\overline{i_p}$ of the reactive current i_q, and no longer to estimate the difference of current (Li, 2012).

3.2 *SPLL based on T/4 delay method*

When the distribution voltage is asymmetric or harmonic, it will produce negative sequence and zero sequence components. If the positive sequence components could not be separated well, it will not lead to a good phase-lock. Therefore, the *T*/4 delay separation method is used to separate the positive and negative sequence components under asymmetric voltage state accurately, and then achieve the phase-lock through the positive sequence component tracking. Therefore, the voltage distortion will be suppressed.

According to the principle of coordinate transformation, the zero sequence component obtaining by $\alpha\beta$ transformation is zero when the system voltage is asymmetric. Thus, the positive and negative sequence components in the $\alpha\beta$ coordinate system can be expressed as:

$$\begin{cases} U_{\alpha(t)} = U^{+}\cos(\omega t+\theta_1)+U^{-}\cos(-\omega t+\theta_2) \\ U_{\beta(t)} = U^{+}\sin(\omega t+\theta_1)+U^{-}\sin(-\omega t+\theta_2) \end{cases} \tag{7}$$

In equation (7), $U_\alpha(t)$ and $U_\beta(t)$ are the amplitude components of α and β axis at time axis, respectively. U^+ and U^- are amplitude of positive and negative sequence components.

When $T/4$ circle delay, the positive sequence in the phase will lag $\pi/2$, and the negative sequence will lead $\pi/2$. The expression of the positive and negative sequence component corresponding to (t-T/4) moment is:

$$\begin{cases} U_{\alpha(t-T/4)} = U^{+}\cos(\omega t+\theta_1-\pi/2) \\ \qquad +U^{-}\cos(-\omega t+\theta_2+\pi/2) \\ \qquad = U^{+}\sin(\omega t+\theta_1)-U^{-}\sin(-\omega t+\theta_2) \\ U_{\beta(t-T/4)} = U^{+}\sin(\omega t+\theta_1-\pi/2) \\ \qquad +U^{-}\sin(-\omega t+\theta_2+\pi/2) \\ \qquad = U^{-}\cos(-\omega t+\theta_2)-U^{+}\cos(\omega t+\theta_1) \end{cases} \tag{8}$$

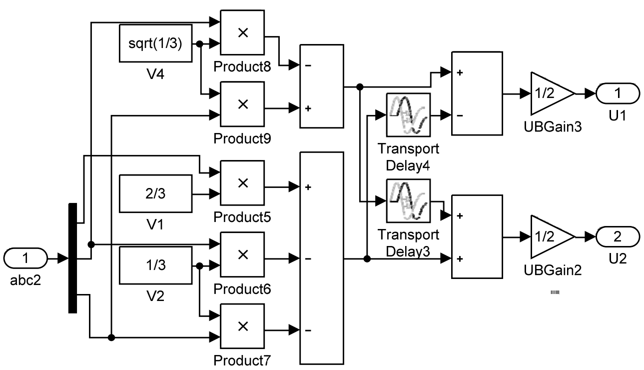
Through equations (7) and (8), we can get:

$$\begin{cases} U_{\alpha}^{+} = U^{+}\cos(\omega t+\theta_1) = \dfrac{1}{2}\left(U_{\alpha(t)}-U_{\beta(t-T/4)}\right) \\ U_{\beta}^{+} = U^{+}\sin(\omega t+\theta_1) = \dfrac{1}{2}\left(U_{\beta(t)}+U_{\alpha(t-T/4)}\right) \end{cases} \tag{9}$$

In equation (9), U_{α}^{+} and U_{β}^{+} are the value of positive sequence component on α and β axis.

According to the above-mentioned theory, the positive sequence and negative sequence voltage separation model based on $\alpha\beta$ transform is shown in Figure 4.

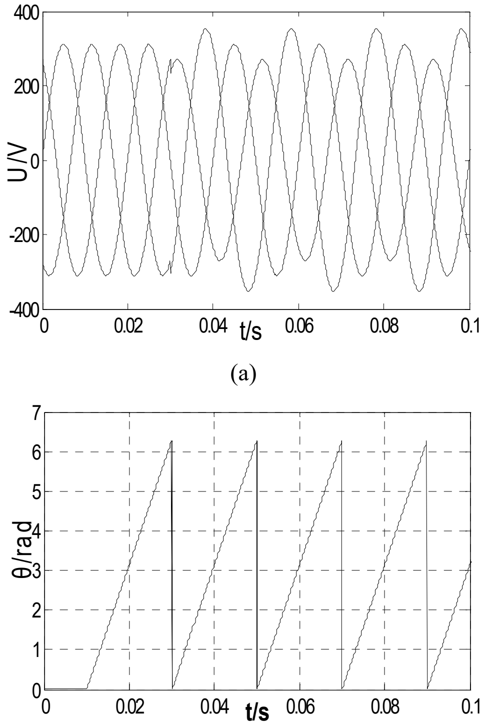
Figure 4 Separation algorithm simulation module



For the phase-lock under imbalance three-phase voltage, we can use MATLAB to simulate. When the fluctuated waveform of the voltages u_a and u_c are caused when there exist the imbalance in 0.02 s, and the simulation results are shown in Figure 5.

It is not difficult to find that the T/4 delay calculation method can separate the positive and negative sequence voltage components for the unbalanced or distortion condition of phase-lock matching network, meanwhile effectively suppressing the effect of negative sequence component of the unbalanced voltage to the phase.

Figure 5 Simulation results of phase-locked loop under three-phase unbalanced voltage waveform, (a) three-phase unbalanced voltage waveform (b) phase output of phase-locked loop

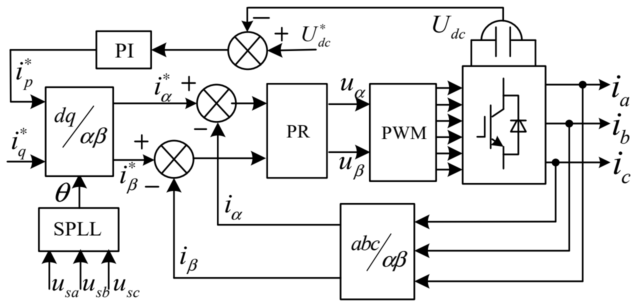


4 Control strategy and simulation of SVG based on PR regulator

In the rotating dq coordinate system, the variables of the d axis and the q axis are coupled to each other, so that the feedforward decoupling is required in the above-mentioned rotation vector indirect control method, where PI controller is used to realise real-time control of active and reactive current. In order to avoid the complex decoupling process, a new type of current inner loop control strategy based on the characteristics of the PR controller and the state equation of the SVG system with the complete decoupling in the $\alpha\beta$ coordinate system is proposed, that is, the current PR control strategy based on the $\alpha\beta$ stationary coordinate is considered for the inner loop without static tracking (Liu et al., 2012). The strategy is shown in Figure 6.

In the control structure shown in Figure 6, the active current i_p^* is regulated by using PI adjustment in the voltage outer loop on DC side through real-time feedback U_{dc} and reference value U_{dc}^*, while collecting distribution network voltages u_{sa}, u_{sb} and u_{sc}, and getting the synchronous phase angle θ via SPLL phase-lock. Then, we can get the command values i_α^* and i_β^* of $\alpha\beta$ by using dq reverse transform with active current i_p^* and reactive current i_q^*. At last, the SVG system produces real-time feedback currents i_a, i_b, i_c and gets the AC currents i_α and i_β in two-phase stationary coordinate system $\alpha\beta$. Also, they are subtracted by the reference values i_α^* and i_β^*, respectively, and adjusted by PR current controller without static in the inner loop.

Figure 6 SVG based on PR control



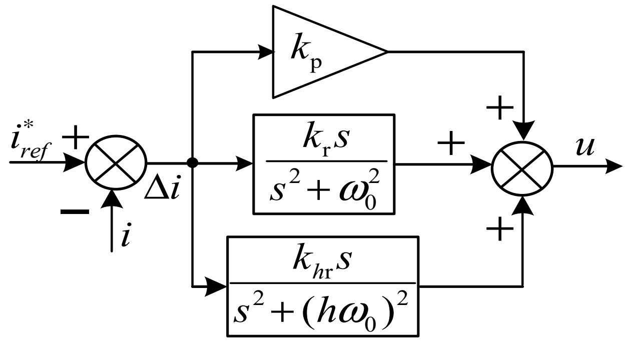
Since the PR controller can adjust the AC signal for a particular frequency without a static difference, the resonant frequency of the controller can be settled to a specific harmonic value to complete the no-function adjustment of the specified sub-harmonic current. Change ω_0 to $h\omega_0$ in the literature (Wu and Sheng, 2013), we can get the following expression based on harmonic compensation.

$$G_h(s) = \frac{2k_{hr}s}{s^2 + (h\omega_0)^2} \tag{10}$$

Because the harmonic compensation only has a response to the nearby value of $h\omega_0$, h times harmonic can be compensated by the fundamental current control. The corresponding harmonic compensation control structure is shown in the Figure 7.

Based on the analysis, it can be seen that simple PI control is adopted to ensure the reliability of the system in the control strategy. The PR control in current inner loop can adjust the AC signal in the coordinate system, and it is easy to realise the low harmonic compensation, and improve the dynamic stability of the SVG control system and compensate the quality of the output power.

Figure 7 Harmonic compensation-based control structure



The SVG simulation system model based on PR adjustment control is shown in Figure 8. In the structure, we can get the reference values i_α^* and i_β^* of $\alpha\beta$ by using dq reverse transform with active current and reactive current. Then, the AC currents i_α and i_β in two-phase stationary coordinate system $\alpha\beta$ are subtracted by the reference values i_α^* and i_β^* respectively, and adjusted in the inner PR current control loop without static tracking. Finally, the corresponding comparison signal is obtained by Clark inverse transformation.

The waveforms of voltage and current based on distribution network is compensated by SVG with PR adjustment, which is shown in Figure 9. The waveform of voltage on DC side is shown in Figure 10. Harmonic analysis of current after compensation is shown in Figure 11.

The u is the voltage waveform of power grid and the i is the compensated current waveform.

It is not difficult to see that the SVG compensation with PR regulator responds faster. The DC voltage is basically raised to 700 V at 0.03 s, the distribution voltage has the same phase as the current. The power factor is close to 1, and the THD value after the current compensation has reduced to 0.94%.

Figure 8 Simulation model of reference current detection based on PR

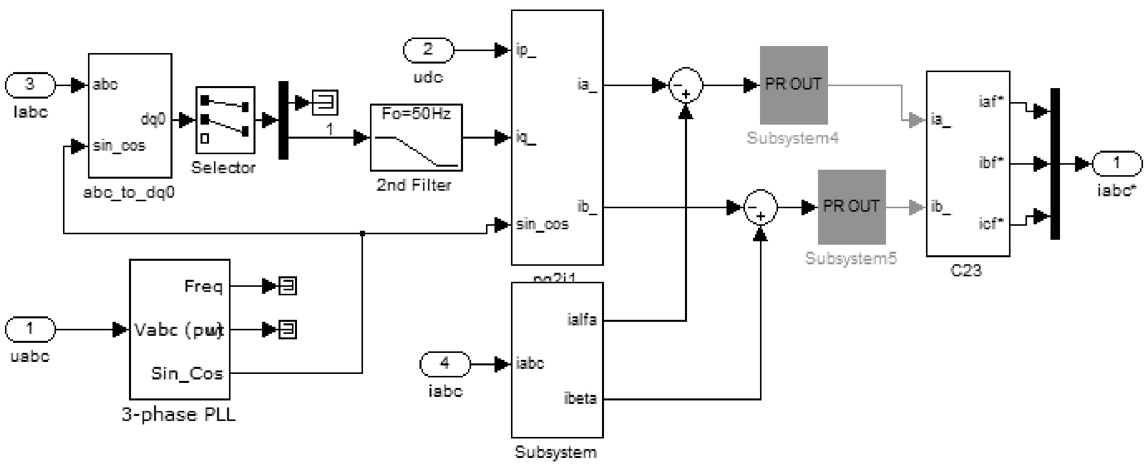


Figure 9 Distribution network-based voltage and current after compensation

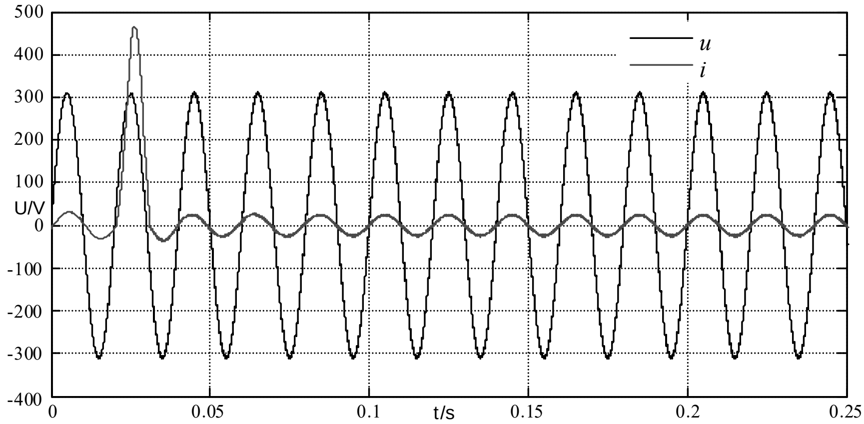


Figure 10 Output waveform of voltage on DC side

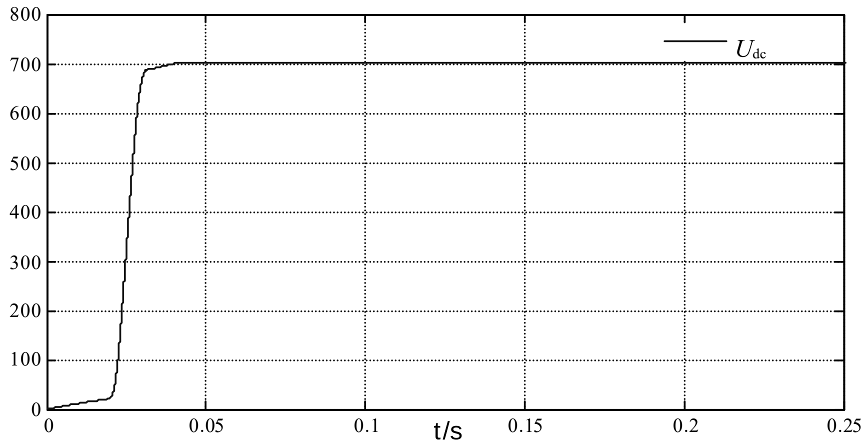
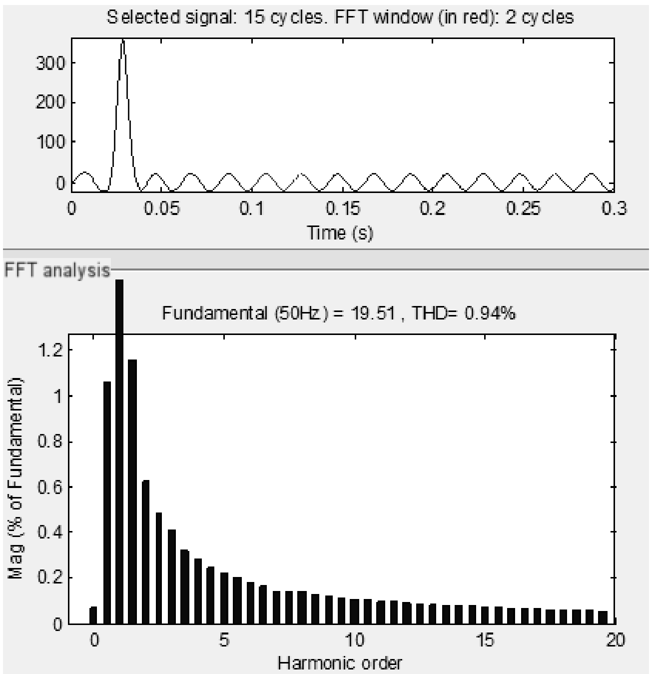


Figure 11 Harmonic analysis of current waveform after compensation

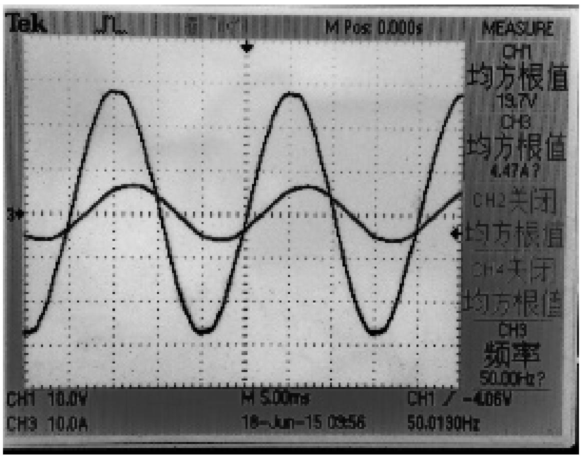


5 Implementation of SVG system

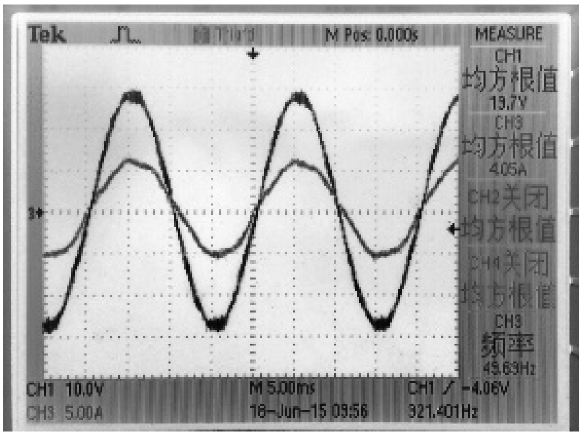
A SVG prototype is built, and the software programs and tested system are prepared. For safety reasons, the prototype is connected to the grid through a 36/200 V transformer in this paper, where the maximum compensation current of the prototype is 5A, DC side capacitor is 1,100 μF, he connection reactance value is 3mH. The whole prototype is shown in Figure12.

The compensation performance of the A phase is analysed as follows. Only the inductive reactive load exists, the distribution voltage waveform and output current are shown in Figure 12(a). It shows that the voltage leads the current and the power factor is 0.765. The corresponding voltage and current after SVG system compensation are shown in Figure 12(b). The distribution voltage waveform and current nearly have the same phase, and the power factor reached 0.996. The harmonic analysis after compensation is shown in Figure 12(c). It can be seen that the platform can achieve reactive power compensation function, the current waveform THD value after compensation is 4.33%.

Figure 12 Waveform analysis diagram for inductive reactive load, (a) voltage and current waveform before compensation (b) voltage and current waveform after compensation (c) harmonic analysis of current waveform after compensation



(a)

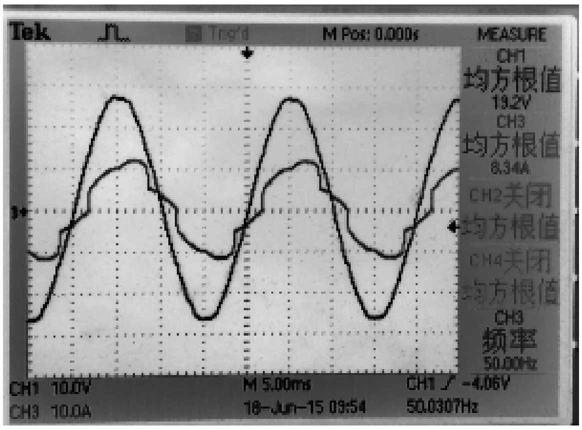


(b)

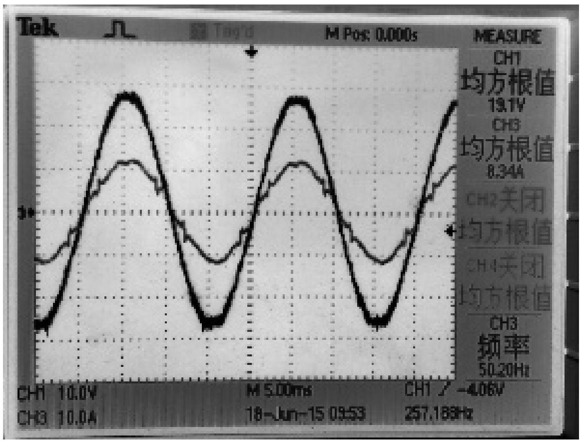
(c)

When there exist the system harmonics and reactive power, the distribution voltage and output current are shown in Figure 13(a). At this time, the power factor is 0.83. Voltage and current after SVG system compensation are shown in Figure 13(b), and power factor is 0.986. The harmonic analysis after compensation is shown in Figure 13(c). We can see that the experimental platform can achieve reactive power and harmonic compensation at the same time, the current waveform THD value after compensation is 5.53%.

Figure 13 Compensation waveform of both harmonic and reactive power existed, (a) voltage and current waveform before compensation (b) voltage and current waveform after compensation (c) harmonic analysis of current waveform after compensation



(a)



(b)

(c)

6 Conclusions

In this paper, the topology of SVG system is established and its model are analysed in order to improve the dynamic compensation performance of static reactive power generator. From the aspects of reactive current detection and controller design, the control strategy of SVG system, simulation verification and prototype realisation are presented. The theory of reactive current detection is analysed and the current vector detection method based on i_p-i_q transform is proposed to improve the real-time accuracy of reactive current detection. Combining with the advantages and disadvantages of traditional PI control system and the characteristics of PR controller without accurate adjustment, a double closed-loop control strategy consisting of PI controller for DC voltage in outer loop and PR controller for AC current in internal loop is designed to improve the dynamic stability of SVG system. Finally, we use MATLAB/Simulink software to simulate the SVG system, and carry out the experiment by utilising the experimental platform based on DSP28335 which is the control core. The results show that the designed SVG system can respond quickly to the system reactive power change, and the ideal real-time dynamic compensation effect is obtained.

Acknowledgements

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