Current Controller Optimum Design for Three-Phase Photovoltaic Grid-Connected Inverter

Dou Wei Xu Zhengguo Peng Yanchang Li Jing Xu Honghua
（Institute of Electrical Engineering , Chinese Academic of Science Beijing 100080 China）

Abstract Three-phase grid-connected voltage source inverter(VSI) is often used to feed high quality current into grid in photovoltaic(PV) power generation system. But many factors, such as switching dead-time effects and disturbance of grids etc, will deteriorate the current waveform, and a large number of harmonic will be fed into grid too. Owing to the conflict between stability and fast response, proportional-integral (PI) controller has limited capabilities to restrain harmonic disturbances and can not guarantee the output performance of grid-connected inverter, so a new control algorithm using compound controller constituted by repetitive controller(RC) and PI controller is proposed in this paper to overcome the shortcomings of PI controller in harmonic control. A dynamic model of grid-connected inverter in synchronous rotating frame(SRF) is derived and the compound current controller design is presented too. Theoretic analysis and experimental results on a 20kW prototype verify that the proposed current controller offers a high performance of current control.

Keywords: PV, grid-connected inverter, PI control, repetitive control

1 Introduction

As a new means of power generation, PV power generation systems are experiencing rapid growth. In this system, three-phase grid-connected pulse-width-modulation(PWM) VSI, shown in Fig.1 is usually necessary for purposes of power conversion and grid interfacing[1]. Usually, the inverter used in PV system was controlled to feed current into grid. Then the power quality fed into grids mainly depends on the output current of inverter. However, many factors contribute to the inverter output current distortions: switching dead-time effects[2], ripple of DC link voltage, disturbance of grids and so on.

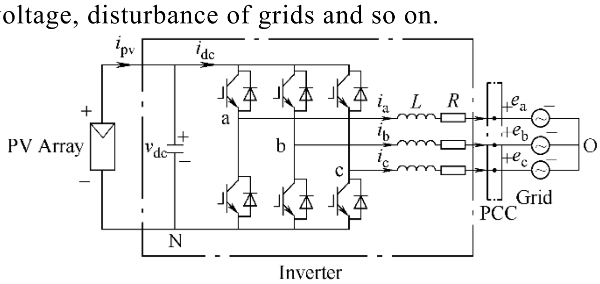


Fig.1 The topology of three-phase grid-connected PV power generation systems

In order to meet the requirement of high quality current, passive filter is a good method for eliminating harmonics. Passive filter can increase the harmonic impedance, so the harmonic components can be eliminate effectively. But passive filter have many disadvantages such as limited attenuation, slow dynamics, large size, and high cost.

Compared with passive filter, using control method is a better choice for eliminating the harmonic [3-4]. Through good design, excellent attenuation and fast dynamic response can be got. At the same time, using control method adds little cost too.

In order to improve steady tracking accuracy of grid-connected inverter, a compound current control scheme with PI and RC controller in parallel is proposed. The PI controller is used to ensure the dynamic response ability of inverter while the RC controller is used to eliminate harmonics in the inverter output current and improve the steady-state performance of the system. Theoretic analysis and experimental results on a 20kW prototype verified that the proposed current controller offers a high performance of current control.

Received June 20, 2008; received in revised form July 25, 2009.

2 System modeling

A typical topology of PV grid-connected power generation system is shown in Fig.1.

Where L is the inductance of filter and R is the equivalent series resistance (The inductance of the transmission line is lumped into L).

According to the basic principle of PWM for VSI, the voltage at the middle point of each leg (a, b, c) can be considered as a controllable voltage source, whose magnitude and frequency is determined by the control strategy. Therefore, the output current of grid-connected inverter is determined completely by the controllable PWM voltage, the voltage at the point of common coupling (PCC) as specified by grids, and the connection inductor.

Following the direction of voltage and current shown in Fig.1, we can get the differential equation of output current in stationary frame based on KVL theorem as follows

$$L\frac{\mathrm{d}i_k}{\mathrm{d}t}+Ri_k+e_{\mathrm{f}k}+V_{\mathrm{h}k}=V_{\mathrm{f}k} \quad k=\mathrm{a,b,c} \tag{1}$$

Where $V_{\mathrm{f}k}$ is the PWM fundamental positive sequence voltage; $e_{\mathrm{f}k}$ is the grid fundamental positive sequence voltage; i_k is the output current; $V_{\mathrm{h}k}$ is the harmonic voltage source which represents the harmonic voltage included in PWM voltage and grid voltage.

Through positive sequence synchronous rotating transformation, Eq. (1) can be expressed in SRF as follows

$$\begin{cases} L\dfrac{\mathrm{d}i_\mathrm{d}}{\mathrm{d}t}-\omega Li_\mathrm{q}+Ri_\mathrm{d}+e_\mathrm{d}+V_\mathrm{hd}=V_\mathrm{d} \\ L\dfrac{\mathrm{d}i_\mathrm{q}}{\mathrm{d}t}+\omega Li_\mathrm{d}+Ri_\mathrm{q}+e_\mathrm{q}+V_\mathrm{hq}=V_\mathrm{q} \end{cases} \tag{2}$$

Where ω is the fundamental angle frequency and subscript “d” and “q” denote the parameters of d-axis and q-axis in SRF.

After transformation, the fundamental positive sequence component in Eq. (2) such as $e_{\mathrm{f}k}$, $V_{\mathrm{f}k}$ will become dc quantity and the fundamental negative sequence or other harmonic components are still alternative variables with different angle frequency [5]. For example, the 5th, 7th harmonic components generated in AC side of inverter will become the 6th harmonic component.

According to Eq. (2), equivalent circuit of the system under d-q reference frame is shown in Fig.2.

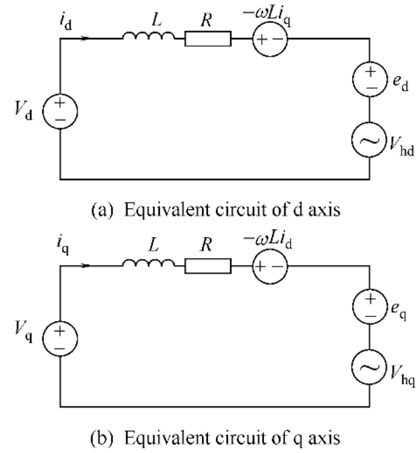


Fig.2 Equivalent circuit in d-q reference frame of inverter, filter, transformer and grid

3 Current control strategies

In order to feed current into grid, the current control strategy should be used. By far, the most commonly used algorithm in the industry is still PI control. Especially PI current controller in the SRF is an effective means of three-phase system in the current control of grid-connected VSI inverter, because the fundamental current is converted into dc quantity through synchronous rotating transformation and the bandwidth of PI controller in the case of dc input is infinite. So PI controller can achieve zero-steady-state tracking errors for fundamental current. However based on the above analysis, in the SRF, the feedback current of grid-connected inverter will include harmonic components which are a periodic disturbance for the inverter. Thus, the bandwidth of PI controller is not enough for tracking these fluctuations signals. In addition, if the gain of PI controller is too high for decreasing the tracking errors, it may result in the instability of system.

Before introducing the proposed current controller, a theoretical background of the internal model principle is presented here. Internal model principle, which states that perfecting tracking of any reference input or rejecting any periodic disturbance, in the steady state, can be accomplished if a generator of the reference input or the disturbance is included in the stable closed-loop system.

For each harmonic, we can insert its corresponding internal model into the control system. But this will add control complexity. Repetitive controller can solve this problem. The repetitive controller can be regarded as a simple learning control because the control input is calculated using the information of the error signal in the preceding periods. Repetitive controller offers a better alternative for current tracking, as it can deal with a very large number of harmonics simultaneous and even several disturbances at non-harmonic frequencies.

Unfortunately, the repetitive controller is known to have a low speed of response to dynamic variations of the operating conditions such as sudden changes in the load. For enhancing the dynamic response ability, a PI controller is plugged in parallel with the repetitive controller to form the compound controller. In this control scheme the PI controller plays an important role in improving an overshoot and a rise time response during severe perturbations and the RC controller responsible for good steady tracking accuracy.

The control system structure using compound controller is shown in Fig.3. In this control system, output current feedback cross decoupling is adapted too[6].

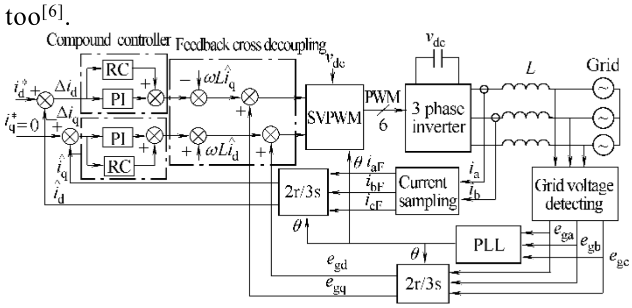


Fig.3 Block diagram of control system

For the compound controller, the PI controller and RC controller are complementary methods of error reduction and are directed toward different types of errors. Thus, they can be used simultaneously for best err-tracking. In addition, PI controller regulates the errors in switching time while repetitive controller does in a modulation period. The control of these two controllers can be decoupled in the time domain. So it is feasible to design each controller independently.

4 Controller design

Some important parameters of the grid-connected inverter are listed in Tab.

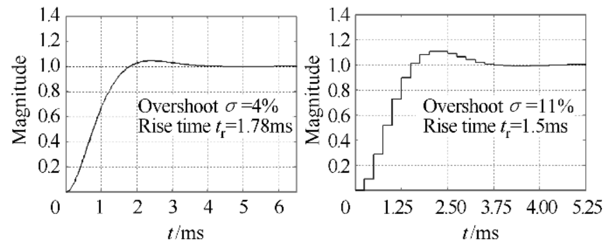
Tab. Parameters of the inverter

Parameters	Normal value
Output frequency f_o/Hz	50
Rated output power P_o/kW	20
Filter inductor L_f/μH	250
Equivalent series resistance R/Ω	0.4
Switching frequency f_{sw}/kHz	4
Sampling period T/μs	250
Dead-time t_D/μs	4.8

In Tab., the value of R comes from experiment.

4.1 PI controller design

From the block diagram of control system we can see that the controlled plant is a first-order system. So the current control closed-loop becomes a typical second-order system. For satisfying the requirement of dynamic response ability of the system, the parameter tuning method of PI controller proposed in Ref. [7] is used. Because a digital control is employed, the parameters of PI controller which was designed in the continuous domain should be modified to meet the requirement of system performance in the discrete domain[8-10]. The unit step response bode plot of current closed-loop transfer function is shown in Fig.4.



（a）The plot in continuous domain （b）The plot in the discrete domain

Fig.4 Step response of current closed-loop transfer function

From the Fig.4, we can see that the dynamic response of current control loop with PI compensation is fine.

4.2 Repetitive controller design

The repetitive controller consists of a repetitive signal generator (reference or disturbance signal internal model) and a compensator as shown in Fig.5.

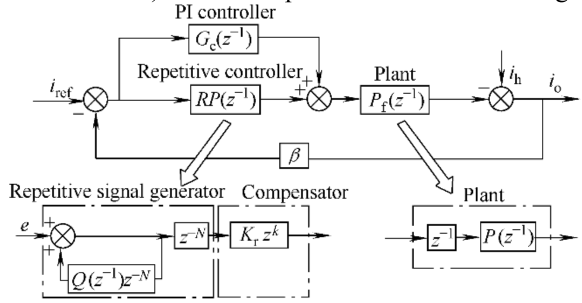


Fig.5 Block diagram of compound current controller

(in the d-q reference frame)

According to Fig.5, repetitive signal generator is a positive feedback part of a modulation period delay. No matter what the input signal is, the output of the signal generator is the accumulation of the input signal period by period. Even though the input decreases to zero, the signal generator will still repetitively produce the same control signal with those of last period constantly. Therefore, if the system is stable, it can be predicted that the periodic errors will be zero. In the repetitive signal generator, $Q(z^{-1})$ is an important element. It determines the steady tracking accuracy and the system stability. In this paper, we make it a constant 0.95.

Function of the compensator is to eliminate the resonant peak of the inverter and attenuate high-frequency gains according to controlled plant's ($P(z)$) characteristics. The design of the compensator determines the performance of repetitive controller. The compensator consists of a gain coefficient K_r and a stability compensator $S(z^{-1})$. A smaller K_r means enlarged stable margin, while a higher K_r brings faster error convergence and smaller steady-state error but decrease the stability of the system. Careful selecting of K_r is compromised between the convergent rate and relative stability of the repetitive control system. $S(z^{-1})$ is a stabilizing compensator. The compensator ensures exponential stability of the entire system. Detailed design of the compensator is carried out in Ref. [11]. In this paper time advance variable z^k is employed to realize phase cancellation of the controlled plant[12].

According the parameters shown in Tab., the transfer function of the plant can be described as Eq. (3)

$$P_f(z^{-1}) = \frac{0.8242z^{-1}}{1-0.6703z^{-1}} \tag{3}$$

For this plant, z^{-1} has almost the same phase shift below the cut-off frequency. The phase cancellation effect can be shown in Fig.6.

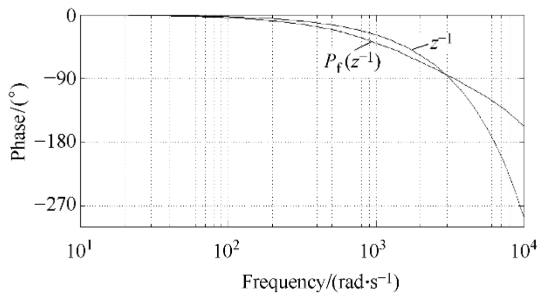


Fig.6 Phase cancellation using time advance variable

5 Experimental result

To verify the effectiveness of the proposed controller a 20kW laboratory grid-connected inverter prototype is developed. Two kinds of experiment using different current control strategy are carried out in the prototype.

5.1 Output current waveforms with PI controller

Fig.7 shows the output current waveforms and its frequency spectrum analysis with only PI controller. This figure indicates that the lower order harmonic components, mainly 5th and 7th harmonic, are high. The total harmonic distortion (THD) is about 5%.

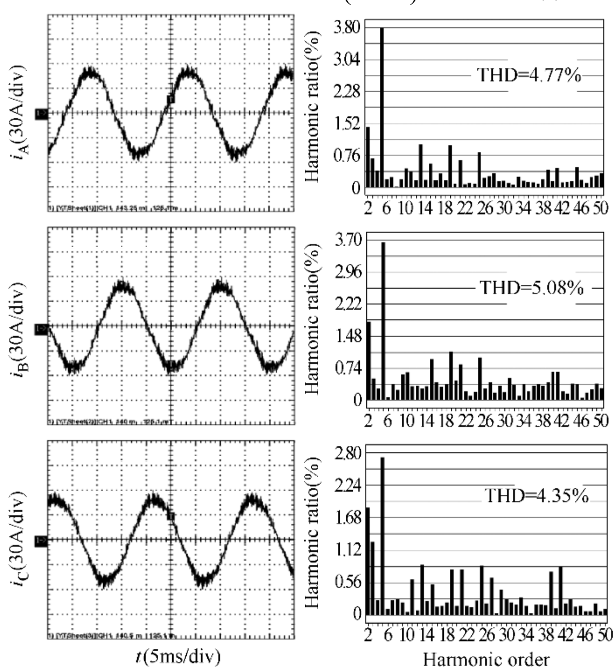
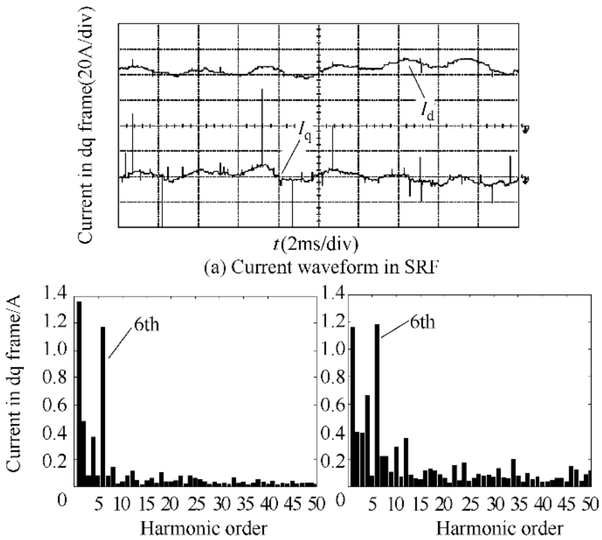


Fig.7 Output current and its frequency spectrum of using PI control

The current and harmonic analysis in SRF are also shown in Fig.8. It can be learned from this figure, that except the dc quantity, there are ac component in the current and the dominate order of harmonic current becomes 6th which is accordance with the theoretical analysis.

5.2 Output current waveforms with compound controller

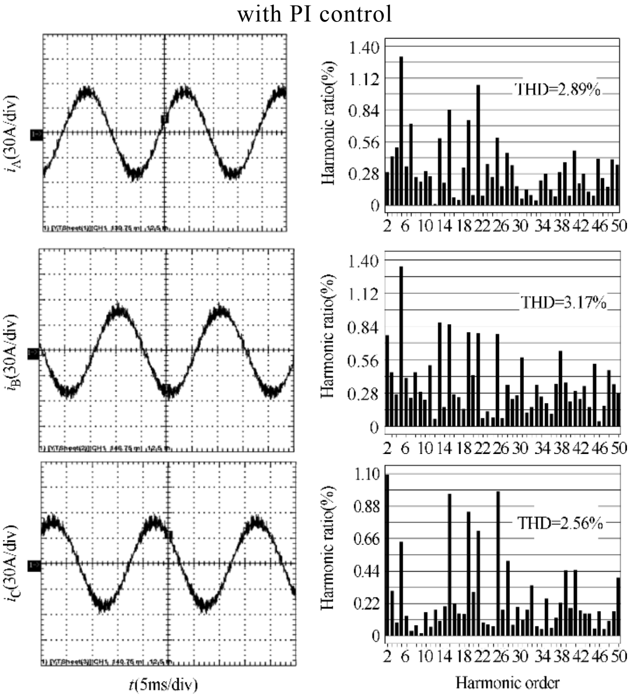
Fig.9 shows the current waveforms with the proposed compound current controller and the frequency spectrum of each current is also shown in the same figure. Compared with the results shown in Fig.7, the current THD of each phase has been reduced largely. The 5th and 7th harmonic component was suppressed effectively. The current in SRF which is shown in Fig.10 becomes almost dc quantity.



(a) Current waveform in SRF

(b) Frequency domain rms of I_d　(c) Frequency domain rms of I_q

Fig.8 Output current in SRF and its frequency spectrum with PI control



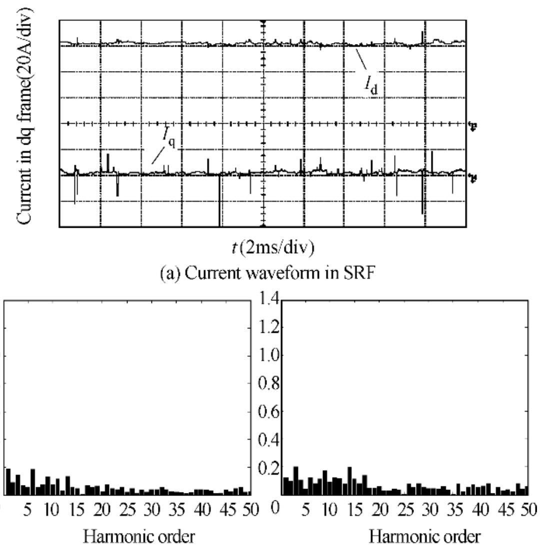
(a) Output current　(b) Output current harmonics

Fig.9 Output current and its frequency spectrum of using compound control

From the above results, we can see that using compound control strategy can improve the steady state performance effectively.

5.3 Dynamic response waveform with PI controller and with compound controller

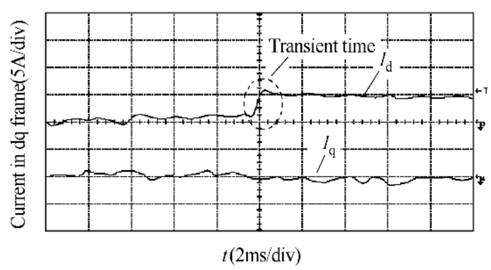
In order to compare the dynamic response performance of each control strategy, we also give some dynamic waveforms when the step reference signal is applied to the control system, shown in Fig.11. From this figure we can see that the dynamic response characteristic of compound controller is almost the same with those of PI controller. This means that compound controller can improve the steady state performance of the system but without deteriorate the system's dynamic response.



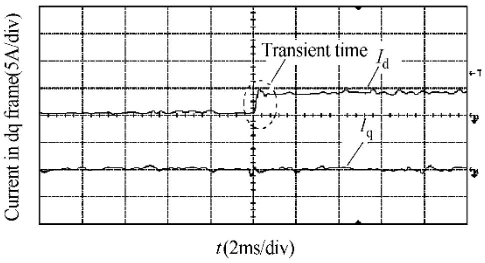
(a) Current waveform in SRF

(b) Frequency domain rms of I_d　(b) Frequency domain rms of I_q

Fig.10 Output current in SRF and its frequency spectrum with compound control



(a) Current control with PI controller



(b) Current control with compound controller

Fig.11 Dynamic response characteristic of current control system

6 Conclusions

The proposed control strategy combines a RC controller with a PI controller. The RC controller is used to improve the steady state performance of system and the PI controller is used to ensure the dynamic response ability of inverter. Based on theoretic analysis, a 20kW inverter prototype is developed to verify the feasibility of this control scheme. The experimental results show that the proposed current controller is capable of eliminating the harmonic current disturbance and improving the waveform quality of current fed into grid. In addition, the control system using compound controller has a good dynamic response too.

Reference

[1] Beck Y, Bishara B, Medini D. Connecting an alternative energy source to the power grid by a DSP controlled DC/AC inverter [C]. Power Engineering Society Inaugural Conference and Exposition in Africa, 2005: 120-124.

[2] Victor M, Cardenas G, Sergio Horta M, et al. Elimination of dead-time effects in three phase inverters [C]. IEEE CIEP Conf. Rec., 1996:258-262.

[3] Garcia Cerrada A, Roncero Sanchez P, et al. Detailed analysis of closed-loop control of output-voltage harmonics in voltage-source inverters [J]. IEE Proc. Electr. Power Appl., 2004, 151(6): 734-743.

[4] Duan Shanxu, Sun Zhaohui, et al. A compensation strategy for dead-time effect of SPWM inverters based on repetitive control[J]. Transactions of China Electrotechnical Society, 2004, 19(2): 52-57.

[5] Kong Xuejun, Wang Jingjiang, et al. The control scheme of three-phase voltage-source inverter output waveform based on internal model theory [J]. Proceedings of the CSEE, 2003, 23(7): 67-70.

[6] Wei Xueliang, Dai Ke, et al. Performance analysis and improvement of output current controller for three-phase shunt active power filter [C]. IEEE Industrial Electronics, IECON, 2006: 1757-1762.

[7] George Ellis. Control system design guide: using your computer to develop and diagnose feedback controllers [M]. San Diego: Academic Press, 1991.

[8] Burup U, Prasad P N,et al.A new space-vector-based control method for UPS systems powering nonlinear and unbalanced loads [J]. IEEE Transactions on Industry Applications, 2001, 37(6): 1864-1870.

[9] Zeng Qingrong, Chang Liuchen. Development of an SVPWM-based predictive current controller for three-phase grid-connected VSI [C]. IEEE IAS Conf., 2005: 2395-2400.

[10] Li M, Xing Y. Digital voltage regulation with flux balance control for sine wave inverters[C]. IEEE APEC Conf. Rec., 2004:1311-1314.

[11] Zhang K, Kang Y. Direct repetitive control of SPWM inverter for UPS purpose [J]. IEEE Transactions on Power Electronics, 2003, 1(3): 784-792.

[12] Harold L Broberg, Richard G Molyet. A new approach to phase cancellation in repetitive control[C]. IEEE IAS Conf. Rec., 1994: 1766-1770.

Brief notes: Dou Wei male, born in 1977, PhD degree, his research interests are in power electronics and control technique in PV power generation systems.Xu Zhengguo male, born in 1974, PhD degree, his research interests are in power electronics and control technique in PV power generation systems.

三相光伏并网逆变器电流控制器优化设计

窦伟 徐正国 彭燕昌 李晶 许洪华

（中国科学院电工研究所 北京 100080）

摘要 在光伏发电系统中，并网逆变器通常用来将高质量的电能馈入电网。但是由于死区

控制、电网扰动等因素的影响，逆变器馈入电网的电流中含有大量谐波成分。由于带宽的限制，单纯的比例积分控制器不能有效地抑制谐波。因此本文提出了一种由比例积分控制器（PI）和重复控制器（RC）并联构成的复合控制器以提高系统的谐波电流抑制能力。本文建立了同步旋转坐标系下的逆变器动态模型并给出了控制器设计方法。理论分析以及一台 20kW 逆变器样机的实验结果证明了所提控制策略的可行性。

关键词：光伏 并网逆变器 PI 控制 重复控制

中图分类号： TM615；TM644