JPE 7-2-10

New MPPT Control Strategy for Two-Stage Grid-Connected Photovoltaic Power Conditioning System

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ABSTRACT

In this paper, a simple control method for two-stage utility grid-connected photovoltaic power conditioning systems (PCS) is proposed. This approach enables maximum power point (MPP) tracking control with post-stage inverter current information instead of calculating solar array power, which significantly simplifies the controller and the sensor. Furthermore, there is no feedback loop in the pre-stage converter to control the solar array voltage or current because the MPP tracker drives the converter switch duty cycle. This simple PCS control strategy can reduce the cost and size, and can be utilized with a low cost digital processor. For verification of the proposed control strategy, a 2.5kW two-stage photovoltaic grid-connected PCS hardware which consists of a boost converter cascaded with a single-phase inverter was built and tested.

Keywords: solar array power system, two-stage photovoltaic grid-connected power conditioning system, maximum power point tracker, digital control

1. Introduction

Concern for developing alternative energy systems has been increasing continuously. Among them, a solar energy system is one of the more important solutions because it produces electric power without inducing environmental pollution. Many studies on the reduction of development costs for solar energy systems have been completed.

A solar array has a nonlinear voltage-current (V-I) characteristic, and the operating condition of the maximum solar power delivered from the solar array varies according to solar illumination and array temperature. Thus, to effectively use solar power, a maximum power condition needs to be tracked by a maximum power point tracking (MPPT) control.

Numerous MPPT methods have been proposed for the enhancement of power efficiency [2-7]. Nevertheless, the perturbation and observation (P&O) method and incremental conductance (INC) method are widely used due to the ease of implementation [2, 5]. However, these approaches need sensors for solar array voltage and current and arithmetic operations in order to calculate the solar array power or conductance. Also, the inner loop controller for the MPPT control is required to stabilize the

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Manuscript received Jan. 24, 2007; revised March 9, 2007

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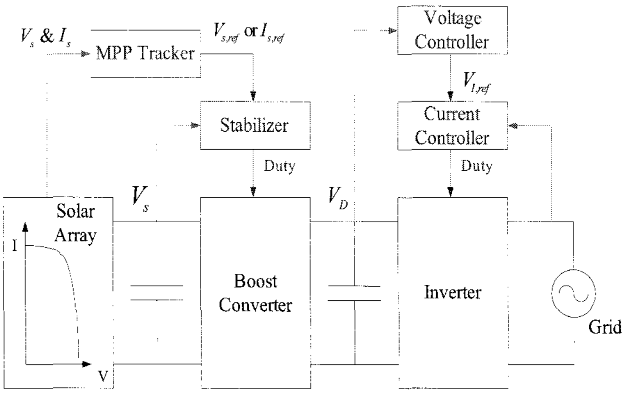
solar array operating point, such as the solar array voltage or current controller. In [4, 6], the converter output current sensing method is proposed. Even though the sensor and computations are reduced, the inner loop controller is still needed.

Unlike in conventional MPPT control methods, a simple MPPT method that is suitable for the two-stage power conditioning system (PCS) is proposed in this paper. The proposed method does not need to calculate power as in the conventional P&O method, and can detect the maximum power point to check the direction of the current peak reference value at the post inverter stage. Thus, this algorithm can remove the sensors for the MPPT control and can be simply realized by comparison in digital processors. In Section II, the proposed PCS control strategy is discussed for the simple MPPT control. Through the small signal model of the PCS, the design guideline of the MPP tracker is presented. In Section III, the implementation of the proposed method is performed. For the verification of the theoretical analysis, a 2.5kW two-stage PCS hardware which consists of a boost converter and a single phase inverter was made and tested using the solar array simulator. Conclusions of this paper are presented in Section IV.

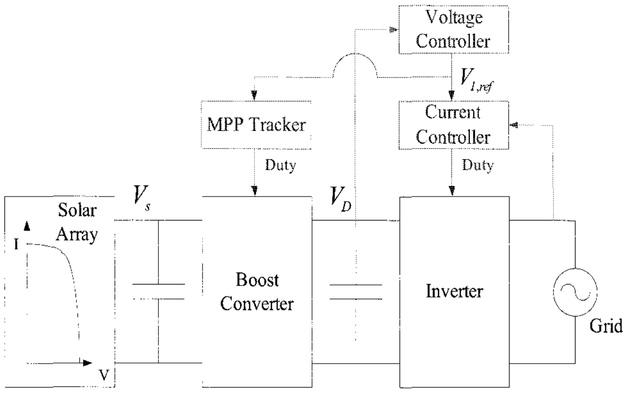
2. The Proposed PCS Control Strategy

Recently, in grid-connected solar array systems, two stage PCS schemes have been developed without the bulky 60Hz step-up transformer. These schemes have the advantages of low inverter current, reduced filter size, and small overall size and hence can be integrated into one module. The conventional two stage PCS is shown in Fig. 1. The operating principle of the conventional PCS control scheme, as shown in Fig. 1 (a), is that the boost converter controls the solar array operating point, and the post single phase inverter controls the DC-link capacitor voltage and controls the output current to be in-phase with the grid voltage for the high power factor. Therefore, the boost converter performs the MPPT control by regulating the solar array voltage or current to the reference value generated by the MPP tracker. The MPP tracker algorithm usually involves mathematical operations to calculate the maximum power point of the solar array.

The proposed PCS control method is shown in Fig. 1 (b). The inverter stage is the same as the conventional PCS control scheme. However, the boost converter controls the solar array operating point by the switch duty command from the MPP tracker. The MPP tracker of this approach uses the inverter current reference, which is proportional to the solar array output power for the MPPT. The proposed control scheme is quite simple because it performs the MPPT control without a mathematical operation for the calculation of the solar array maximum power point and in addition the boost converter does not need a feedback control circuit. Also, there is no sensor for the MPPT control such as the solar array voltage/current or the converter output current. This simple operation principle offers cost competitiveness and compactness of size.



(a) The conventional PCS control scheme



(b) The proposed simple PCS control scheme

Fig. 1 The two stage control scheme of the grid connected power conditioning system

2.1 The operation principle of proposed MPPT control scheme

The MPPT control method in two stage PCS schemes is presented with the following assumptions: the DC link voltage regulation control speed is much faster than the MPPT loop, and the efficiency of the boost converter is almost constant throughout the operating point. Fig. 2 shows the proposed two stage PCS control schematic. As in a conventional scheme, the inverter has the voltage loop to regulate the input DC link voltage and the current loop to control the output current to be in-phase with the line voltage for the high power factor. By maintaining the DC link voltage constant, the output of the voltage loop, $V_{I,ref}$, determines the output current amplitude, and thus controls the level of power processed by the PCS.

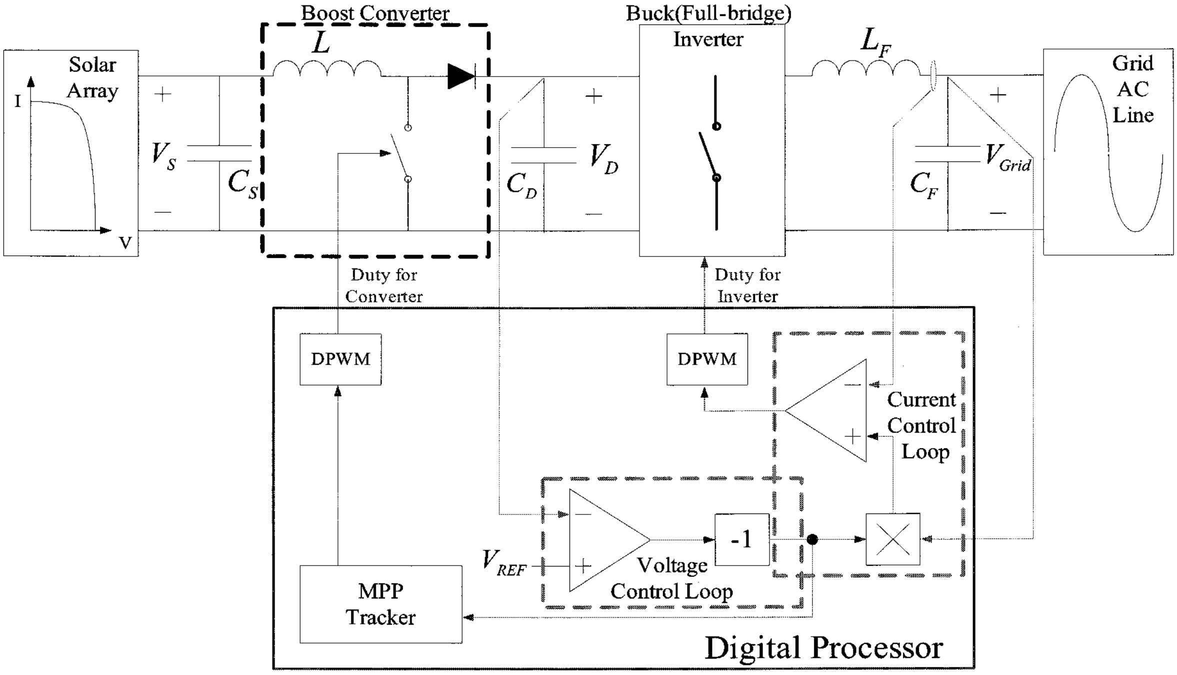
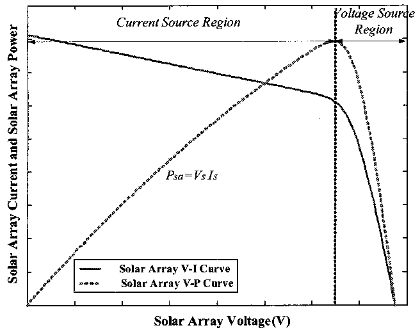


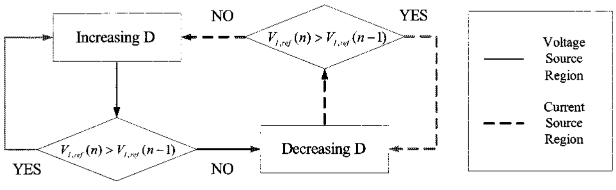
Fig. 2 The proposed prototype experimental hardware schematic

For the constant DC link voltage, the input current of the inverter is directly proportional to the solar array output power. Thus, using $V_{I,ref}$, the MPP can be tracked without calculating the solar array power. Also, the boost converter can stabilize the solar array operating point by the switch duty command from the MPP tracker. The proposed method is quite simple because it performs MPPT control without calculating any operations and the boost converter does not need a feedback control circuit.

Fig. 3 shows the flowchart of the MPPT algorithm. Initially, the duty ratio of the boost converter is arbitrarily set to a specified value. Then information of the output current of the boost converter (which is the input current of the inverter) is detected by the control voltage, $V_{I,ref}$, which is fed to the MPP tracker block.



(a) The output characteristic of the solar array



(b) The flowchart of proposed MPPT algorithm

Fig. 3 The proposed MPPT control algorithm

The MPPT compares the current value of $V_{I,ref}$ with the previous sampled value to determine the next duty ratio, as shown in the flowchart. In the voltage source region of the solar array V-I curve, the inverter current increases when the duty ratio increases, but in the current source region, the inverter current reduces when the duty ratio increases. Therefore, if the inverter current amplitude (which is proportional to the $V_{I,ref}$) increases when the duty ratio increases, the MPP tracker increases the duty ratio until the inverter current amplitude decreases. If the inverter current amplitude decreases when the duty ratio increases, the MPP tracker reduces the duty ratio. In this way, the MPPT control is achieved by changing the duty ratio with respect to an increasing direction of the inverter current.

2.2 The analysis and design of MPPT tracker

The MPPT algorithm in the flowchart can easily be implemented in comparison to use of a digital processor. The amount of the gain in the duty ratio, M, and the sampling frequency, $T_{s,mppt}$, determine the dynamic response of the MPP tracker, such as speed, accuracy and stability.

In order to design the feedback controller and loop stability, small signal modeling and analysis of the MPP tracker is performed. Fig. 4 shows the small signal equivalent model for the proposed two stage PCS control scheme. The inverter stage can be assumed to be the voltage controlled current source because the current control loop bandwidth is much faster than the voltage control loop and the MPPT control loop bandwidth. Using the un-terminated modeling of the converter stage with a solar array and an inverter stage, the transfer functions from duty to diode current, I_d, and from diode current to inverter current, I_c, can be obtained as follows [8];

$$G_{id\_C} = \frac{\hat{i}_d}{\hat{d}} = \frac{D'V_D}{R}\frac{\left(1+ s/w_{z1}\right)}{1+ s/Q_c w_{oc} + s^2/w_{oc}} - I_L \tag{1}$$

where $w_{z1} = \dfrac{1}{C_S R}$, $w_{oc} = \dfrac{1}{\sqrt{LC_S}}$, $Q_c = \dfrac{1}{w_{oc}}\dfrac{1}{C_s r_{cS} + L/R}$

$$G_{ii\_I} = \frac{\hat{i}_c}{\hat{i}_d} = \frac{\left(1+ s/w_{vz}\right)\left(1+ s/w_{z2}\right)}{1+ s/Q_i w_{oi} + s^2/w_{oi}^2}, \tag{2}$$

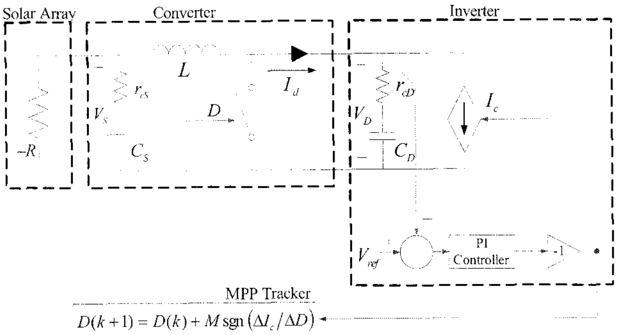


Fig. 4 The small signal equivalent model of the proposed control scheme

where $w_{vz} = \dfrac{K_I}{K_P}$, $w_{vi} = K_I$, $w_{z2} = \dfrac{1}{C_D r_{cD}}$,

$$w_{oi} = \frac{1}{\sqrt{C_D/w_{vi} + 1/w_{vz}w_{z2}}}, \quad Q_i = \frac{1}{w_{oi}}\frac{1}{1/w_{vz} + 1/w_{z2}}$$

where K_I, K_P are the proportional and integral gain of the voltage loop PI controller at the inverter stage.

Through the proposed algorithm, the MPP tracker can be represented as an integrator including sampling time.

$$G_{mppt} = \frac{\hat{d}}{\hat{i}_c} = \frac{w_{mppt}}{s} \quad \text{where } w_{mppt} = \frac{M}{T_{s,mppt}} \tag{3}$$

From (1) – (3), the overall MPPT loop gain can be derived as follows;

$$T_{mppt} = G_{id\_C} G_{ii\_I} G_{mppt} \tag{4}$$

The stability conditions of the overall system are as follows [7]:

- The sampling frequency of the MPPT loop is less than the resonant frequency of the converter stage.
- The bandwidth of the MPPT loop is less than the voltage loop bandwidth of the inverter stage.
- The DC gain of the MPPT loop at the resonant frequency of the converter stage is less than 0dB.

If the MPPT loop satisfies the above conditions, the overall system is stable. For the design, if the gain of the MPP tracker, w_{mppt}, is set by w_{piv}/N (w_{piv} is bandwidth of the voltage control loop at the inverter stage), the interaction between the inverter voltage control loop and the MPPT control loop can be grasped. In this case, the

N represents the decoupling rate between the two loops. With the sampling frequency of the MPPT loop, the amount of the gain in the duty ratio, M in w_{mppt}, also affects the performance of the proposed control method. A large M increases the deviation from the maximum power point, despite the fast peak power tracking speed, and a small M produces the opposite results.

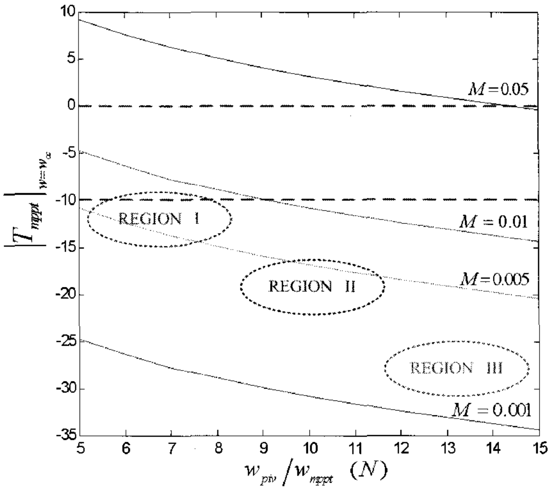


Fig. 5 The design guideline of the proposed MPP tracker

Fig. 5 shows that the design guideline can be constructed with M, w_{mppt} and the gain of the MPPT loop at the resonant frequency of the converter stage, which satisfies the stable conditions. As stated above, the stable region for the DC gain of the MPPT loop at the resonant frequency of converter stage is less than 0dB. Allowing some margin, say 10dB, to compensate a modeling simplification error, can be set at the boundary line. In Region I, the MPPT loop speed is fast and the error between MPP and the operating point is small. However, this MPPT loop has a fragile stability at the transient state because of a low N value. In Region III, the MPPT loop is slow, but is stable and the error from the MPP is very small. Because of the slow speed, this MPPT loop is insensitive to environmental variation. Thus, the MPPT loop in Region II, which has a medium speed and a small error from the MPP, is the optimal design scenario.

3. Experimental Verification

The hardware prototype of the two stage solar power PCS for experimental verification is shown in Fig. 6, and the main parameters are summarized in Table. 1.

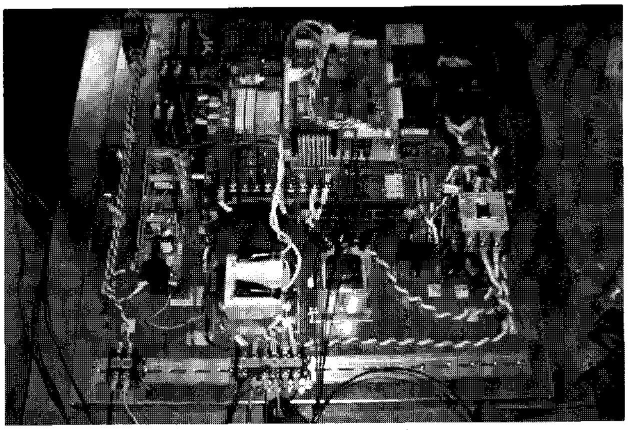


Fig. 6 The prototype two stage power conditioning system

Table 1 System parameters of the implemented power conditioning system

Parameter	Value
C_S	4700 $[\mu F]$
L	1 $[mH]$
C_D	4700 $[\mu F]$
L_F	3 $[mH]$
C_F	5 $[\mu F]$
F_{sw}	10 $[kHz]$

A solar array simulator from the NF Company (15kW, 600V/30A) is used. A grid connected type full bridge inverter is used for the PCS. A filter capacitor, C_F in Fig. 2, attenuates the 120Hz AC ripple component from the grid connected inverter.

Fig. 7 shows the inverter output current, which is in-phase with the grid voltage, showing a good power factor. Fig. 8 shows the relation between the inverter current and the solar array power, as well as the designed MPPT loop tracking speed and performance. Fig. 9 is the experimental result when the illumination level is changed from 100% to 50% with a 10% incremental value. The experimental result obtained when the illumination level is stepped up is shown in Fig. 10. These figures show that when the duty ratio increases in the voltage source region, or decreases in the current source region, the inverter current increases and the solar array power also increases. Finally, Fig. 11 shows the closed MPPT loop performance around the MPP.

4. Conclusions

A simple control method for the two stage grid connected photovoltaic power conditioning system is proposed in this paper. This approach enables maximum power point tracking control with post-stage inverter current information instead of calculating the solar array power, which significantly simplifies the controller and sensor. Furthermore, there is no feedback control loop in the pre-stage converter to stabilize the solar array operating point, because the MPP tracker directly drives the converter switch duty cycle. This simple PCS control strategy can reduce cost and size, and can be easily utilized with a digital processor. For verification of the proposed control strategy, a 2.5kW two stage photovoltaic grid connected PCS hardware which consists of a boost converter cascaded with a single phase inverter was built and tested.

Acknowledgment

This study is partly supported by the Korea Institute of Energy Research.

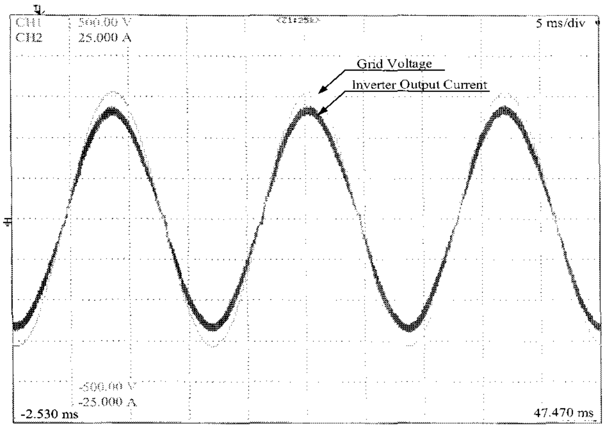


Fig. 7 The experimental results of the inverter output current and grid voltage

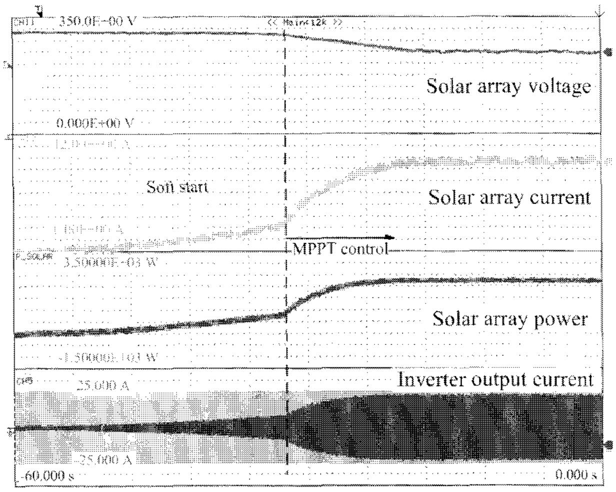


Fig. 8 The performance of the proposed MPP tracker

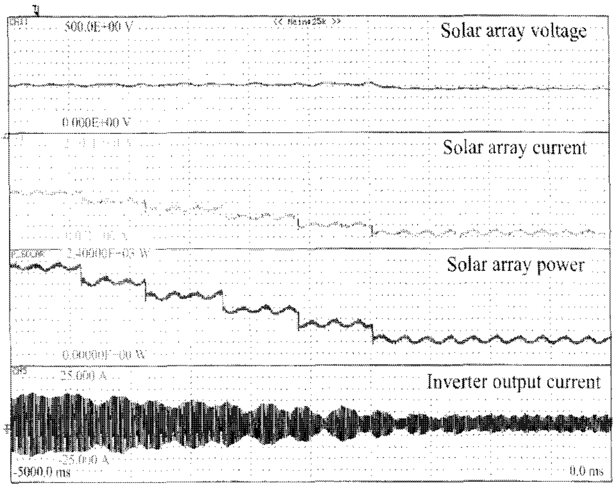


Fig. 9 The transient response at the illumination step-down

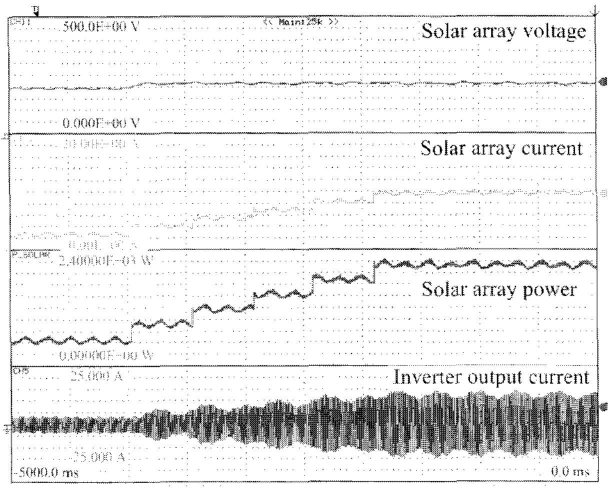


Fig. 10 The transient response at the illumination step-up

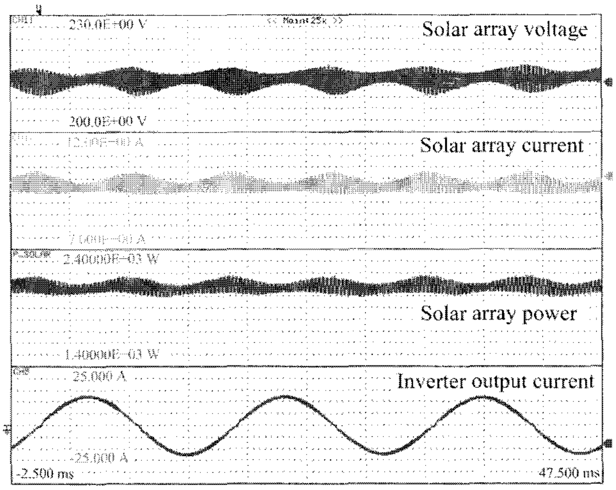


Fig. 11 The enlarged waveforms around the MPP

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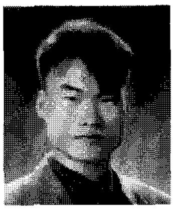

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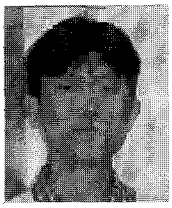

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