# A Photovoltaic System with an Analog Maximum Power Point Tracking Technique for 97.3% High Effectiveness

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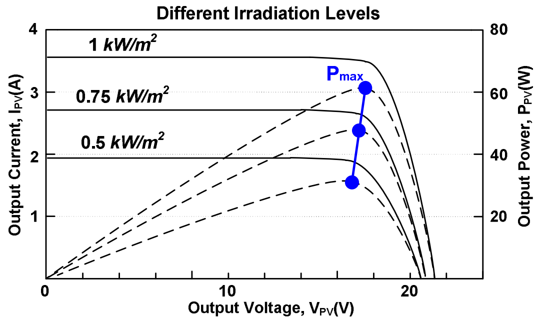
***Abstract*—A low cost analog MPPT technique is proposed in this paper for high power efficiency in photovoltaic systems. A wide-range current multiplier, which tracks the maximum power point (MPP) in the solar system, is implemented to detect the power slope condition of solar panels. Experiment results show the proposed technique can rapidly track the MPP with a high tracking effectiveness of 97.3%. Furthermore, the proposed system can supply a grid-connected inverter for providing AC power.**

## I. INTRODUCTION

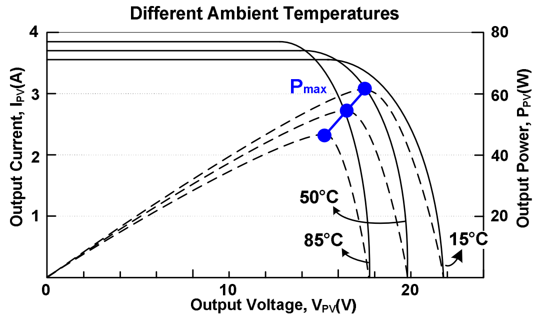
Recently, the global warming crisis has been drawing public attention to the topics concerning energy conservation and alternative energy all around the world. Several energy conservation methods, such as energy-recycling [1] [2] and energy-harvesting [3], have been proposed to reduce unnecessary energy waste on commercial appliances. Additionally, alternative energy, such as thermal energy [4], wind energy or solar energy is renewable and environmental friendly. Among all kinds of renewable energy, solar power, based on its ubiquitous characteristic and low maintenance cost, is definitely a reliable solution to solve the inevitable global warming crisis and to reduce greenhouse gas emission. The nonlinear physical characteristic of the photovoltaic (PV) panel, however, is a stumbling block toward highly efficient energy utilization.

Fig. 1 shows the characteristic curves of PV panels with respect to different irradiation levels and different ambient temperatures. The maximum available power provided by PV panels depends not only on the irradiation level but also the ambient temperature. In practice, both of these factors, irradiation level and ambient temperature, are hard to predict. Thus, contemporary PV product, such as PV inverter or solar charger, is usually accompanied with an MPPT technique to extract the most energy from PV panels. There exist a lot of MPPT algorithms to fulfill this requirement but all are implemented using highly costly devices, for example, microcontrollers and digital signal processors [5]. To cut the installation cost on PV systems, an analog MPPT circuit with low-cost feature and high tracking effectiveness is proposed in this paper. Furthermore, a boost DC-DC converter and a grid-connected PV inverter are utilized to convert the solar energy to the power grid for further use. The proposed PV system is shown in Fig. 2. The boost converter works in cooperation with the maximum power point tracking circuit to consistently track the MPP of solar panels. A full bridge inverter is incorporated to convert DC power to AC power.

Section II introduces the proposed maximum power point tracking algorithm to extract the most energy from solar panels. The circuit implementation is shown in Section III to demonstrate the proposed wide-range current multiplier used in the PV system. Measurement results shown in Section IV can prove the effectiveness of the proposed maximum power point tracking system. Finally, Section V draws conclusions to this paper.




(a)




(b)

Fig. 1. Characteristic curve of solar panel with respect to different conditions. (a) Different irradiation levels (b) Different ambient temperatures.

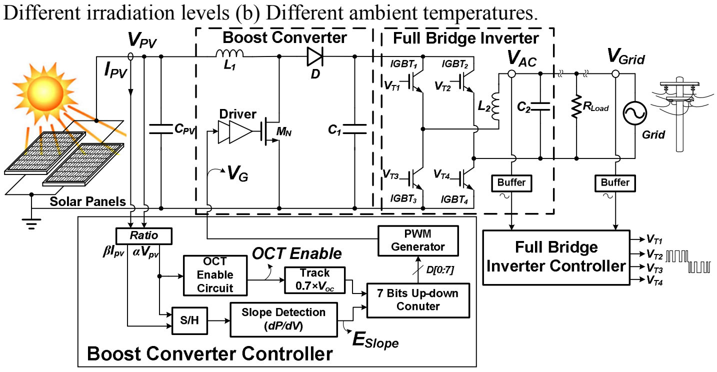



Fig. 2. The proposed grid-connected PV system.

## II. THE PROPOSED MPPT ALGORITHM

Fig. 3 demonstrates the concept of the proposed MPPT algorithm. Before the system turns on, the operating point of the PV system is located at the open-circuit voltage point, which is $V_{OC}$ in Fig. 3. Conventional MPPT algorithms, such as slope detection algorithms (e.g. perturbation/observation algorithm or hill-climbing algorithm) calculate the slope of the characteristic curve to determine the slope condition and to track the maximum power point. Nevertheless, a PV system adopting this algorithm takes a long time to track the operating point from $V_{OC}$ to *MPP* during the system power-on period, as depicted in Fig. 3. Other tracking algorithms, such as constant voltage algorithms, use a fixed ratio of maximum power voltage to open-circuit voltage, $V_{OC}$, to track the MPP. Theoretically, 0.7 fractions of open-circuit voltage $V_{OC}$ is close to the MPP [6]. Therefore, periodically disconnecting the solar panel and the power stage to measure the open-circuit voltage and multiplying it by 0.7 can detect the present maximum power point. The fraction factor, however, is greatly susceptible to environmental conditions, for instance, temperature and irradiation. In that sense, the MPP cannot be precisely tracked if the varying environmental conditions are taken into consideration. What's even worse is that consistent disconnection between PV panels and the power stage causes a power delivery drop during the sampling period and therefore low power efficiency of the PV system.

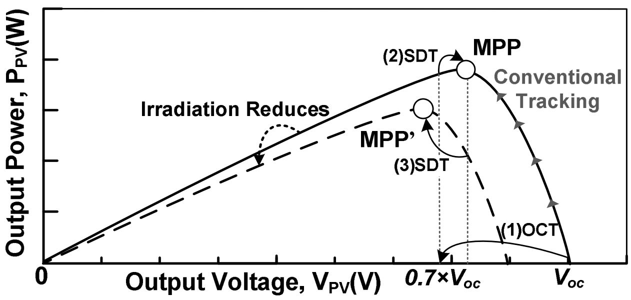



Fig. 3. Illustration of the proposed MPP tracking algorithm.

To raise both tracking speed and accuracy while maintaining high power efficiency, the open-circuit tracking (OCT) algorithm and the slope detection tracking (SDT) algorithm are both adopted to track the MPP. Disconnection between solar panels and the power stage only takes place once, during the system power-on period, to avoid degrading the power efficiency. Fig. 4 illustrates the timing diagram of the proposed tracking algorithm. $E_{slope}$ is a digital signal indicating the slope condition. A high value of $E_{slope}$ means the slope condition of the solar panel is positive, and vice versa. *OCT Enable* determines whether the OCT tracking algorithm is enabled or not. $V_G$ is the gate signal of the power NMOS in the boost converter. $I_{L1}$ shows the inductor current of the boost converter. The tracking procedure can be divided into the following sequences. (1) Before the system turns on, $V_{OC}$ is detected to set the PV panel voltage, $V_{PV}$, close enough to $0.7 \times V_{OC}$. During this period, the switching duty cycle of the boost converter is set to its maximum value in order to accelerate the tracking speed. (2) Thereafter, the SDT takes over the tracking procedure to continually track the MPP and make sure the power stage can receive the most energy from the solar panels. (3) If the environmental condition changes, say, the irradiation level reduces, the slope condition changes from positive to negative, according to the characteristic shown in Fig. 1. Then $E_{slope}$ transits from high to low. Because of the physical characteristic of solar panels, the voltage is inversely proportional to the current. As a result, SDT will increase the switching duty cycle, therefore increases the current of the solar panels, to pull down the voltage and ensure the system operate on the new maximum power point, that is *MPP'* in Fig. 3.

## III. THE PROPOSED CIRCUIT OF THE MPPT CONTROLLER

The proposed slope detection circuit, shown in Fig. 5, detects the slope condition at the operating point, that is, determines *dP/dV* as a positive value or a negative one. $E_{slope}$ indicates the slope information for the 7-bits up-down counter, which increases or decreases the duty cycle of the boost converter. As mentioned in Section II, the voltage and current of solar panels are inversely proportional to each other. When the slope is positive, $E_{slope}$ is high to decrease the duty cycle of the converter and thus increases the operating voltage. On the other hand, a low value indicates the slope is negative. Then the duty cycle increases to decrease the operating voltage. The slope equation according to the power-voltage curve can be written as:

$$\frac{\partial P}{\partial V} = \frac{\partial\left(V_{PV} \cdot I_{PV}\right)}{\partial V_{PV}} = I_{PV1} - V_{PV1} \times \left(\frac{I_{PV1} - I_{PV2}}{V_{PV2} - V_{PV1}}\right)$$

$$= I_{PV1} - V_{PV1} \times \frac{\Delta I_{PV}}{\Delta V_{PV}} = I_{PV1} - k \cdot I_{Vpv1} \cdot \Delta I_{PV} \qquad (1)$$

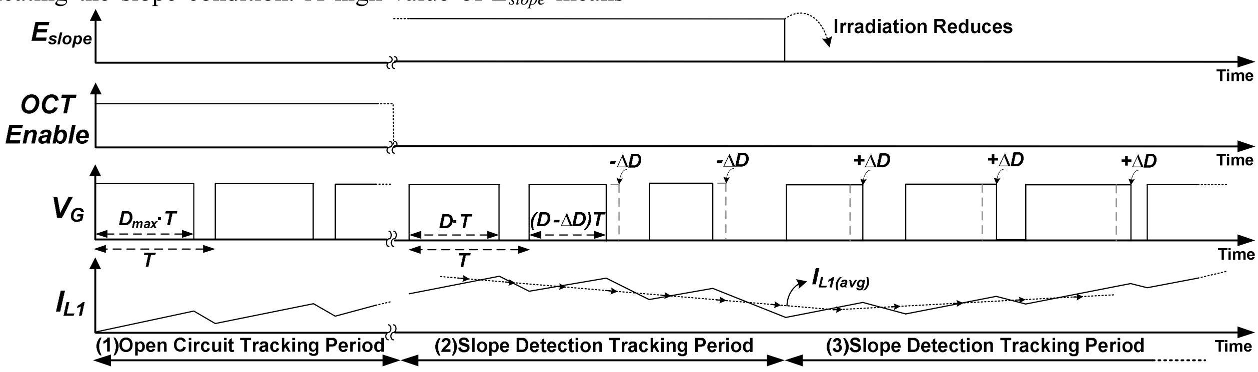



Fig. 4. The timing diagram of the proposed MPP tracking algorithm.

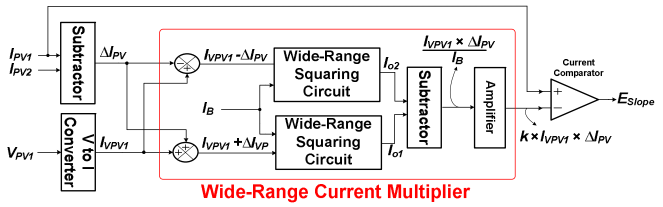


Fig. 5. The proposed slope detection circuit.

According to the sample/hold circuit used to sense the voltage and current of the solar panels, $V_{PV1}$ and $I_{PV1}$ represent the present voltage and current of solar panels, respectively. $V_{PV2}$ and $I_{PV2}$ are the previous ones. When the current of solar panels is sampled at a fixed voltage difference, the slope equation can be rewritten as $I_{PV1}$-$k$×($I_{VPV1}$×$\Delta I_{PV}$), which is realized by the slope detection circuit. Here, $k$ denotes the gain of the current multiplier and $I_{VPV1}$ is the converted current of $V_{PV1}$ by the voltage-to-current converter. The denominator in (1) is eliminated deliberately by the conversion ratio of voltage-to-current converter to improve the accuracy of the slope detection circuit. The MPP occurs at the slope transition point, where the slope changes from either positive to negative or negative to positive. Comparing the current $I_{PV1}$ and $k$×($I_{VPV1}$×$\Delta I_{PV}$), therefore, can determine the slope condition of the solar panels, which is implemented by the current comparator in Fig. 5.

Since the voltage and current range of the solar panels are very wide, typical current multipliers cannot meet the need in this application. The proposed wide-range squaring circuit in the current multiplier is composed of a large current (LI) processor and a small current (SI) processor. This wide-range squaring circuit serves the purpose of extending the allowable current range of the current multiplier. The current comparator in Fig. 6 decides whether the input current, $I_{VPV1}$+$\Delta I_{PV}$, is larger or smaller than the reference current, $I_{ref}$. When ($I_{VPV1}$+$\Delta I_{PV}$) is larger than $I_{ref}$, the LI processor is activated and ($I_{VPV1}$+$\Delta I_{PV}$) flows into the drain of $M_{HI3}$. After that, the current mirror produces current 2×($I_{VPV1}$+$\Delta I_{PV}$) flowing out from the source of $M_{HI3}$. By KVL theorem, the summation of $V_{GS,MHI1}$ and $V_{GS,MHI3}$ is equal to that of $V_{GS,MHI2}$ and $V_{GS,MHI4}$ as expressed in (2).

$$V_{GS,MHI1} + V_{GS,MHI3} = V_{GS,MHI2} + V_{GS,MHI4} \tag{2}$$

Based on the squaring principle of MOSFET, the following equation can be derived from (2).

$$\sqrt{I_{MHI1}} + \sqrt{I_{MHI3}} = \sqrt{I_{MHI2}} + \sqrt{I_{MHI4}} \tag{3}$$

$$I_{MHI3} = I_{o1} + \left(I_{VPV1} + \Delta I_{PV}\right) \tag{4}$$

$$I_{MHI1} = I_{o1} - \left(I_{VPV1} + \Delta I_{PV}\right) \tag{5}$$

$$I_{MHI2} = I_{MHI4} = I_B \tag{6}$$

$I_B$ is the bias current in the squaring circuit. Substituting (4)-(6) into (3), (7) can be derived.

$$I_{o1} = {\left(I_{VPV1} + \Delta I_{PV}\right)^2}\Big/{4I_B} + I_B \tag{7}$$

Similarly, another identical wide-range squaring circuit can derive $I_{o2}$ in Fig. 5, as shown in (8).

$$I_{o2} = {\left(I_{VPV1} - \Delta I_{PV}\right)^2}\Big/{4I_B} + I_B \tag{8}$$

After subtracting $I_{o2}$ from $I_{o1}$, $k$×($I_{VPV1}$×$\Delta I_{PV}$) can be obtained by amplifying the current ($I_{VPV1}$×$\Delta I_{PV}$)/$I_B$. $E_{slope}$ is generated in the end to adjust the duty cycle of the boost converter. Accordingly, the operating voltage of the solar panels is ensured to locate at MPP.

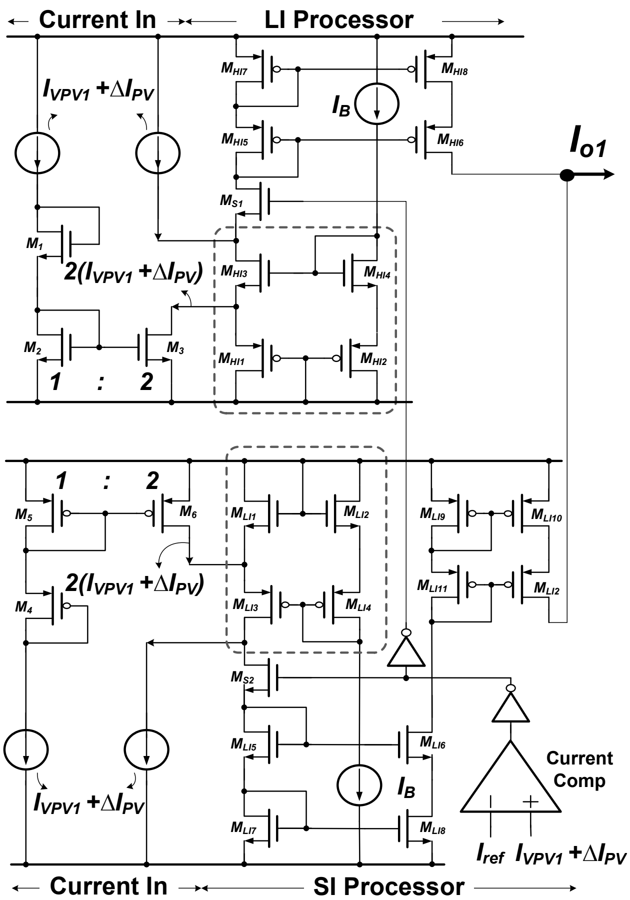


Fig. 6. The proposed wide-range squaring circuit.

## IV. EXPERIMENT RESULTS

Fig. 7 shows the maximum power point tracking effectiveness based on the proposed tracking algorithm and circuit. The tracking effectiveness is higher than 97.3% in the available power range from 100W to 300W at ambient temperature of 28 Celsius degree. Fig. 8 shows the experiment prototype and the chip photo of the controller for the boost converter. The chip was fabricated by the 0.25μm BCD 40V 1P4M process.

According to Fig. 9, at the time the system turns on, the OCT technique is enabled to adjust the operating voltage close to 0.7×$V_{OC}$. During this period, the duty cycle is set to its maximum value to enhance the tracking speed. After that, the SDT technique takes over the tracking procedure to keep tracking the MPP. When the slope detection circuit detects the present slope condition as being positive ($E_{slope}$ is high), the duty cycle decreases, as shown in Fig. 9, to reduce the inductor current and therefore increase the operating voltage toward the MPP. Fig. 10 shows the duty cycle transition when the detected slope condition changes from negative to positive. The control signal, $V_G$, to the power NMOS ($M_N$)

gradually changes from the large duty cycle to the small duty cycle. On the contrary, $V_G$ changes from the small duty cycle to the large duty cycle when the detected slope condition transits from positive to negative as shown in Fig. 11. Fig. 12 shows the waveforms at the output of the DC-AC inverter when the grid-connected PV system is activated. TABLE I summarizes the measurement results.

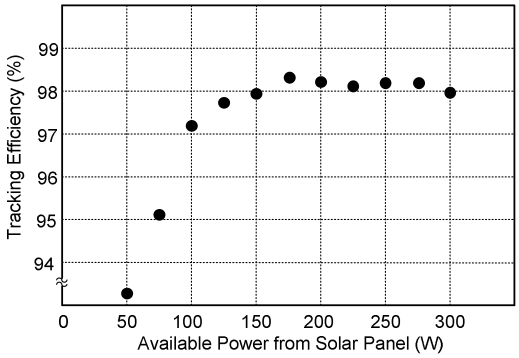



Fig. 7. Tracking effectiveness of the proposed algorithm and circuit.

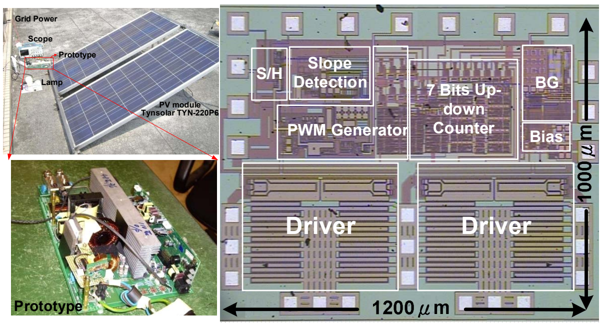



Fig. 8. Experiment prototype and chip photo.

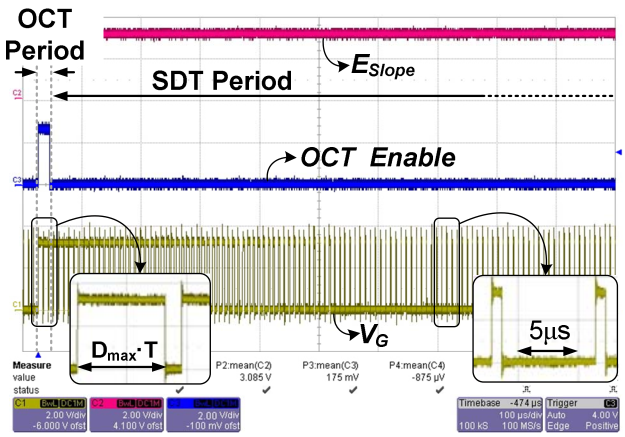



Fig. 9. Waveforms of the PV system during the system power-on period.

TABLE I

| | |
|---|---|
| **Fabrication Process** | 0.25μm BCD 40V 1P4M |
| **Chip area** | 4.22mm$^2$ |
| **Inductor** | $L_1$=5mH, $L_2$=5mH |
| **Capacitor** | $C_1$=150μF, $C_2$=5μF |
| **Switching frequency** | 120kHz |
| **Nominal AC output voltage** | 112V |
| **Power factor** | 0.998 |
| **Tracking effectiveness** | >97.3% (@$P_{PV}$=100W~300W) |
| **Overall efficiency** | 88.97% |
| **THD of current multiplier** | 1.02% (@$I_{in}$=30μA, 100kHz) |
| **Operation range of current multiplier** | 0μA~60μA |

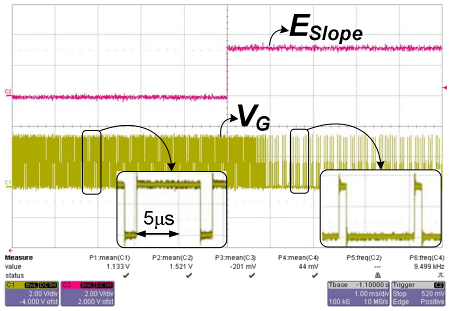



Fig. 10. The waveform of $V_G$ when $E_{slope}$ changes from low to high.

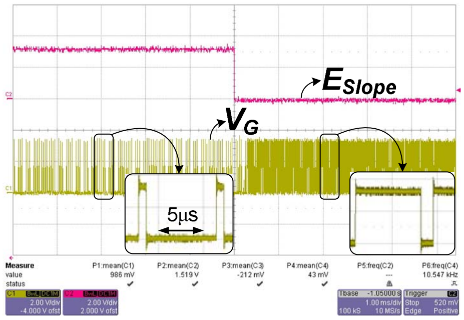



Fig. 11. The waveform of $V_G$ when $E_{slope}$ changes from high to low.

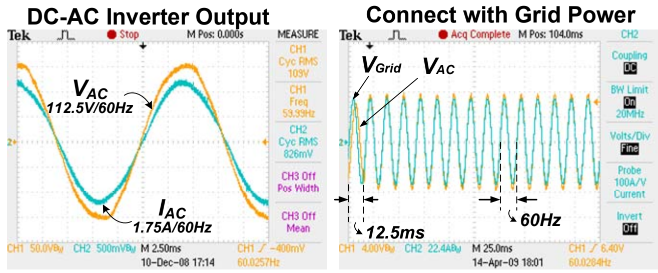



Fig. 12. Output voltage and current of the gird-connected inverter.

## V. CONCLUSIONS

The proposed maximum power point tracking algorithm can not only achieve fast tracking speed but maintain high tracking efficiency in the solar electricity system. A wide-range current multiplier circuit is implemented to meet the requirement of the tracking circuit. Experiment results verify the proposed MPPT algorithm and demonstrate the PV system can also convert solar energy into grid electricity.

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