A Modified Adaptive Hill Climbing MPPT Method for Photovoltaic Power Systems

Weidong Xiao
Department of Electrical and
Computer Engineering
The University of British Columbia
Vancouver, BC Canada
weidongx@ece.ubc.ca

William G. Dunford
Department of Electrical and
Computer Engineering
The University of British Columbia
Vancouver, BC Canada
wgd@ece.ubc.ca

***Abstract*—Maximum power point tracking (MPPT) must usually be integrated with photovoltaic (PV) power systems so that the photovoltaic arrays are able to deliver maximum available power. In this paper, a modified adaptive hill climbing (MAHC) MPPT method is introduced. It can be treated as an extension of the traditional hill climbing algorithm. The simulation and experimental results show that the proposed MPPT control can avoid tracking deviation and result in improved performance in both dynamic response and steady-state.**

***Index Terms* — Maximum power point tracking (MPPT), photovoltaic (PV) power system, maximum power point (MPP), digital signal processor (DSP), hill climbing algorithm (HC), modified adaptive hill climbing method (MAHC), switching mode DC/DC converter, switching duty cycle, and the incremental step of duty cycle**

I. INTRODUCTION

In most photovoltaic (PV) applications, maximum power point tracking (MPPT) is essential as there is a probable mismatch between the load characteristics and the maximum power points (MPPs) of the PV array, which changes with solar insolation and cell temperature.

A common MPPT topology is the so called power feedback method, which makes a measurement of the array power and uses it as the feedback variable. Three popular tracking methods based on power feedback are widely adopted in PV power systems. They are the perturbation and observation method (P&O) [1], the incremental conductance method (IncCond) [2] and the hill climbing method (HC) [3].

Both P&O and IncCond are based on the same technology by regulating the PV array's voltage to follow an optimal setpoint, which represents the voltage of maximum power operating point (V_{MPOP}). This point is continuously tracked and updated to satisfy a simple mathematical equation: $dP/dV = 0$, where P represents the PV module's output power and V represents the PV voltage. By investigating the *Power-Voltage* relationship of a typical PV module shown in Fig.1 and Fig.2, the maximum power points can always be tracked if we keep dP/dV equal to zero for any solar insolation or temperature, because all local maximum power points have the same mathematical attribute.

In most applications, PWM type DC/DC converters or DC/AC inverters are used as the power interface between the PV arrays and loads. The switching duty cycle is the control variable of these kinds of topologies. So another approach [3] to MPPT is based on the relationship of the PV array power and switching duty cycle. Fig.3 shows the hill-shaped *P-D* relationship curve, where *P* represents the PV array output power and *D* is the duty cycle of a switching mode DC/DC converter. Mathematically, the local maximum power points can be tracked if the dP/dD is forced to zero by the control. This kind of MPPT technology is also defined as the hill climbing method (HC) [4], which simplifies the system control structure to one control loop shown in Fig.4.

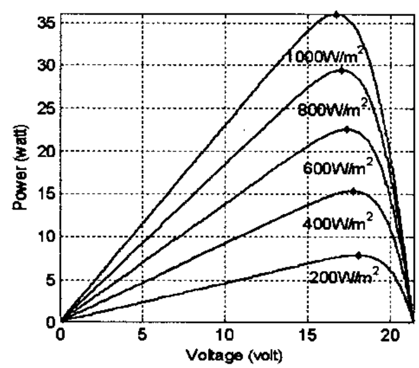

Fig. 1 Power-voltage characteristics of a photovoltaic module for different insolation levels at constant temperature (25°C)

The flowchart of the hill climbing (HC) method [3] is illustrated in Fig. 5.

"Slope" is a program variable with values either "1" or "-1", indicating the direction that must follow on the hill-

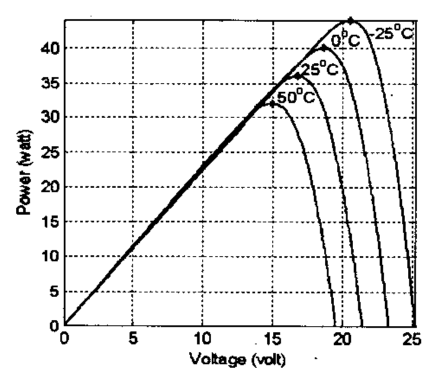

Fig. 2 Power-voltage characteristics of a photovoltaic module for different temperature levels at constant solar insolation (1000w/m²)

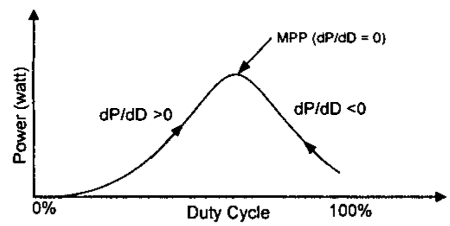

Fig. 3 *P-D* relationship curve with a switching mode converter as the interface between the PV array and load

shaped *P-D* curve in order to increase the output power. While "a" represents the increment step of duty cycle, which is a constant number between 0 and 1, and "*D*" and "*P*" represent the duty cycle value and power level respectively. The current power level *P(k)* is periodically compared to the value calculated in previous measurement *P(k-1)*. According to the result of the comparison, the sign of "*Slope*" is either complemented or remains unchanged. Then, the switching duty cycle *D(k)* is changed accordingly until the operating point oscillates around the maximum power point.

II. Features of the Hill Climbing MPPT Method

The advantage of the hill climbing MPPT method is its simplicity. The drawbacks will be analyzed in following paragraphs.

It was proved that the P&O MPPT control system sometimes deviates from the maximum operating point in case of rapidly changing atmospheric conditions, such as broken clouds [2]. This problem could happen with the adaptive hill climbing method as well. Simulation results (Fig.6) show that the hill climbing MPPT controller can occasionally make the system operating point far from the optimal point in case of rapidly changing insolation conditions. When a sudden increase or decrease in insolation dominates the change of PV output power shown in Fig.6, according to the HC tracking algorithm, the controller may be confused and lead the operating point in the wrong direction. This process continues until the sudden change in insolation slows down or stops.

Another disadvantage [4] is that this simple tracking method has difficulty in providing good performance in both dynamic and steady-state response because a constant

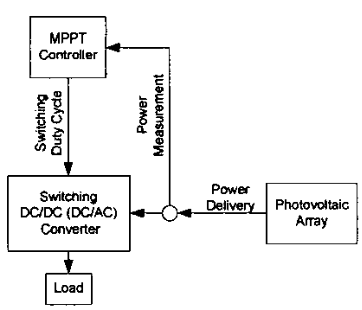

Fig. 4 The block diagram of the hill climbing MPPT control system

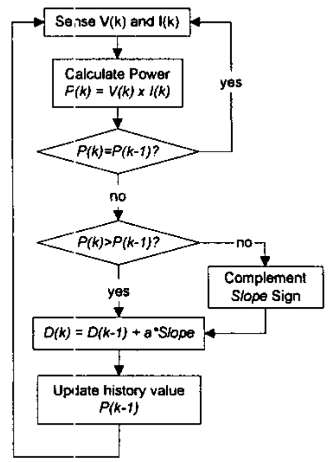

Fig. 5 The flowchart of the Hill Climbing MPPT control method

incremental step of duty cycle was adopted as the control parameter. If the incremental step of the duty cycle "a" is small, the tracking time is long and the system shows poor dynamic response. If a large duty cycle step is used, the output power fluctuations are large and the average power is significantly less than the maximum, resulting in energy waste.

These control problems may be reduced by making some modifications to this method. In the following sections, a modified tracking algorithm will be presented as an improvement to the HC tracking algorithm.

III. Performance Specification of MPPT-PV Control Systems

The following requirements are important for a successful MPPT-PV system design.

A. Stability

Stability is the most fundamental design requirement of a dynamic control system. In PV power systems, the switching mode converters are nonlinear systems and the output characteristics of solar array are also nonlinear. Therefore, stability is a critical factor to evaluate a PV-MPPT control systems dealing with non-linearity.

In MPPT control system, a high control bandwidth is desirable for the fast tracking requirement, but there are limitations. The actual system control bandwidth needs to be decided by parameter calculation and experimental results to make the system's response faithful and to sense the power change correctly. Otherwise, the maximum power point tracking may become unstable if the control system is operated at a wrong frequency.

B. Dynamic response

A good MPPT control algorithm needs to respond quickly to rapidly changing atmospheric conditions, i.e. array temperature and insolation, and track the maximum power points quickly.

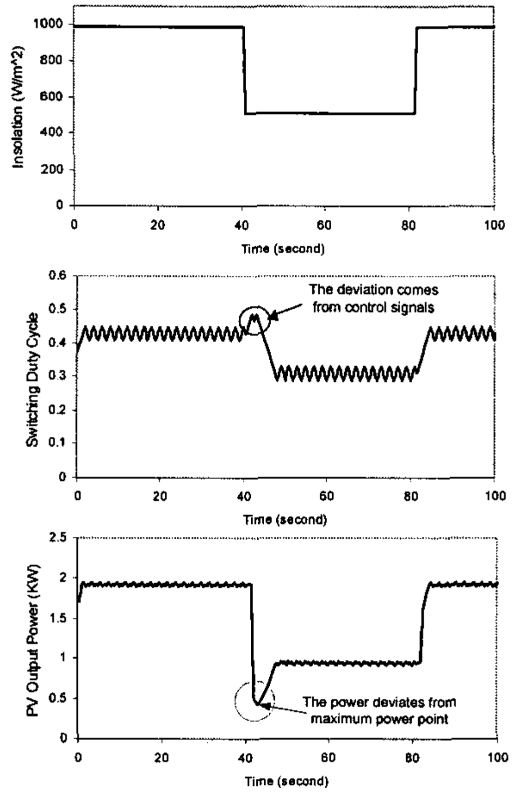

Fig. 6 Simulation results of the hill climbing MPPT system under sudden insolation change (Incremental step of duty cycle is set to 2%)

C. Steady state error

When the optimal operating point is found, it is ideal to keep the system operate exactly on this point statically. In an actual PV power system, this is impossible because of the active MPPT control algorithm and the continuous variation in insolation and temperature. Thus, a small output power fluctuation is preferred during the steady-state stage. The tracking accuracy is directly related to the efficiency of the PV power system.

D. Robustness to disturbances

MPPT control systems need an accurate and stable response under uncertain conditions. Sometimes, the disturbances of control systems from various sources can cause the MPPT system to become inefficient. One problem is that the PV modules manufactured by different technologies respond differently to the changes in solar insolation and cell temperature [5]. So it is important to design a MPPT control system robust to any kind of disturbances.

E. Efficient in a large power range

The ratio between the potential PV array power and the actually delivered power is an indication of how successful the MPPT-PV system is designed. The efficiency at low light level is a serious problem for many MPPT-PV system designs because many systems only work efficiently during nominal power delivery. In reality, the PV array output power varies over a large range according to the insolation variation during a one-day period. A successfully designed MPPT control system shall show good performance at different power levels.

IV. The Modified Adaptive Hill Climbing MPPT Method

A modified adaptive hill climbing (MAHC) MPPT control method is introduced, based on the previous research and detailed analysis of the characteristics of PV power systems. The modifications to the traditional hill climbing method include automatic parameter tuning and control mode switching.

A. Automatic parameter tuning

As discussed in [4], there is a tradeoff between dynamic response and steady state performance due to the selection of "a", the incremental step of switching duty cycle. Through analysis, it is ideal to make "a" large during transient stage and "a" small in steady state. In the proposed MAHC method, this problem is solved by the automatic tuning of parameter "a" on-line. The system control and tuning mechanism is shown in Fig. 7.

In the design, the automatic tuning topology was illustrated as a linear equation:

$$a(k) = M \frac{|\Delta P|}{a(k-1)}$$

where $\Delta P = P(k)-P(k-1)$, represents the change of power condition, $a(k-1)$ is the historic value of "$a(k)$" (always > 0), and M is a constant parameter.

When the power changes in a large range primarily due to environmental variation, this tuner will change the "a" to a large value to satisfy the fast response requirement during the transient stage. When the power change is small, the controller assumes that the system enters the steady-state

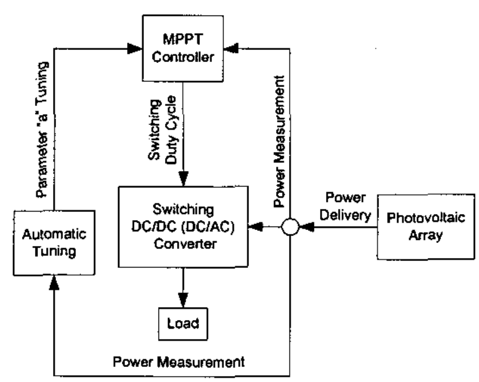

Fig. 7 The proposed control structure with automatic parameter tuning

stage and the value of "a" becomes small to keep control signal change smooth. With this tuning mechanism, both dynamic and steady-state requirements can be considered in the controller design, because the critical parameter is updated and adjusted adaptively.

B. Control Mode Switching

In some specific cases, it was shown that the traditional hill climbing method [1] could cause the operating point to deviate from the optimal point during the period of rapid insolation changes. This problem could be avoided by switching the control mode. The control algorithm can be demonstrated in flow chart format shown in Fig.8, where "*P*" and "*D*" represent the PV power level and the duty cycle value respectively.

The switching criterion is defined as $|\Delta P/a(k-1)|$, where $\Delta P = P(k)-P(k-1)$, represents the change of power condition, and $a(k-1)$ is the historic value of "$a(k)$". If the value of $|\Delta P/a(k-1)|$ is larger than the threshold "*e*", the controller understands that the power variation was mainly caused by the solar insolation, so the increment of duty cycle is set to the same direction as ΔP, the change of power condition. The perturbation direction is represented by "*Slope*" in the flow chart (Fig.8). If the value of $|\Delta P/a(k-1)|$ is small, the controller assumes that the system control is within the y stead state, or the large change on power is caused by the large step of "a" only. During this period, the ordinary HC method is adopted. In the MAHC control mechanism, there are two important tuning parameters, "*e*" and "*M*", which make the controller flexible to deal with different situations. The validity of the presented control and tuning mechanism are evaluated in simulation and experimental results, demonstrated in following paragraphs.

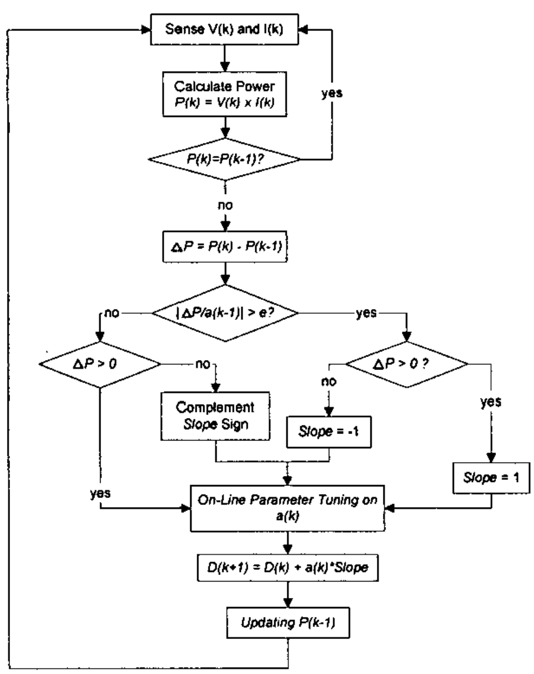

Fig. 8 Flowchart of the modified adaptive hill climbing MPPT control algorithm

V. SIMULATIONS AND EXPERIMENTAL EVALUATIONS

A simple MPPT-PV stand-alone power system was installed as a test bench shown in Fig.7. The power interface between the PV array and the load was a step-down switching mode DC/DC converter. A 16-bit fixed-point DSP (TMS320LF2407) acts as the controller, which was programmed with the MPPT control algorithm and automatic tuning mechanism. It is designed to verify the effectiveness of the proposed MPPT control algorithms.

A. Modeling and simulations

The photovoltaic cell is represented by a one-diode model [6], as shown in Fig. 9.

The model contains a current source *Iph*, one diode and series resistance *Rs*, which represents the resistance between the cells. The output current *I* is the difference between the photocurrent *Iph* and the normal diode current I_D:

$$I = I_{ph} - I_D = I_{ph} - I_0\left[e^{\frac{q(V+IR_s)}{mkT_c}} - 1\right]$$

The variable definitions used in the equation are described in Table I.

The step-down switching-mode DC/DC converter is modeled by the state-variables-averaging method [7].

The mathematical models of the proposed PV power system and maximum power point tracking algorithm are implemented and evaluated by using SIMULINK®, a model-based software package.

The simulations were configured under exactly the same conditions to compare the performances between the

TABLE I
PARAMETER DEFINITIONS OF THE MODEL OF PHOTOVOLTAIC CELL

Symbols	*Description*
m	It is the idealizing factor
k	It represents the Boltzmann's constant
Tc	It is the absolute temperature of the cell
q	It represents the electronic charge
V	It is the voltage imposed across the cell
I_o	It represents the dark saturation current, which is strongly depending on temperature

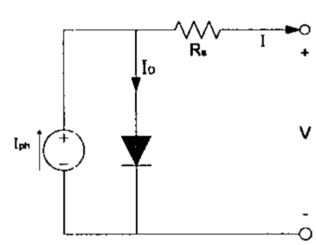

Fig. 9 The model of a single photovoltaic cell

MAHC and the ordinary hill climbing (HC) method. Fig.10 shows the simulated waveforms of insolation, switching duty cycle and PV output power of the MAHC control system. The results illustrate that each maximum power point was determined quickly and tracked accurately by this proposed tracking algorithm.

The improved performance of MAHC control over HC tracking method can be demonstrated in the comparison table. In Table II, the tracking times and the average power levels of steady-state are shown and compared under sudden change in solar irradiation. The MAHC shows better overall performance than HC on both dynamic response and steady state at two different simulated power levels.

B. Experimental results

To compare the control performances between the hill climbing (HC) method and the proposed algorithm (MAHC), indoor PV testing using artificial light was performed. Indoor testing has the advantage that a reproducible insolation level can be used. Therefore, this is a fair method to compare system performance because all MPPT control methods can be tested under the same (or very similar) operating conditions. The insolation can also be controlled to different levels by switching on/off the artificial lights.

One experiment was designed to test system step response by keeping insolation level constant. The experimental tracking performance controlled by the MAHC control algorithm is illustrated in Fig.11, where the adaptation of incremental step can be clearly seen.

During the first 23.5 seconds of tracking period, the voltage of two photovoltaic panels connected in series drops quickly to a level of about 30V, where it stabilizes, and the output power level was tracked and maximized to about 5.71W, which is 98.45% of the peak power point 5.80W. The plot also presents the details of PV voltage variation, which has a continuous oscillation of the operating point around the voltage of maximum operating point (V_{MPOP}). This continuous oscillation is fundamental to this kind of active tracking algorithm.

The values of 100% rise time that represents the speed of response of a control system and the steady-state error were

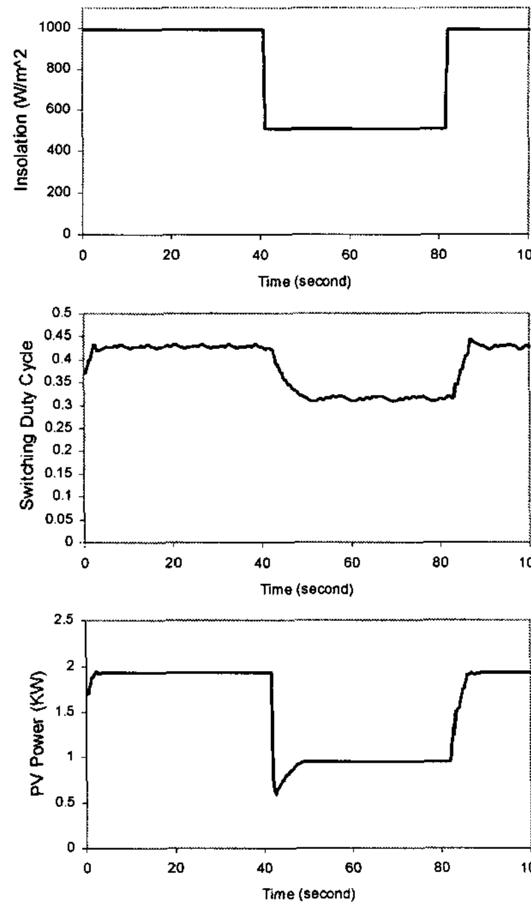

Fig. 10 Simulation results of sudden insolation change with the MAHC tracking

summarized in Table III. It is noticed that HC controller with small incremental step of duty cycle demonstrates very good steady state performance but poor dynamic response. The MAHC control shows not only smaller steady state error than the HC when the incremental step of duty cycle was set to 1.2% (a = 1.2%), but also the tracking speed is 5 seconds faster. These results show the system controlled by

TABLE II
TRACKING PERFORMANCE COMPARISON BETWEEN MAHC AND ORDINARY HILL CLIMBING METHOD

MPPT Algorithms (The "a" represents the incremental step of duty cycle)	*Tracking Time (seconds)*		*Averaged Power Level during Steady State Period (watt)*	
	Insolation changes from 990W/m² to 510W/m²	*Insolation changes from 510W/m² to 990W/m²*	*Insolation Ga = 990W/m²*	*Insolation Ga = 510W/m²*
HC ("a" =1.5%)	6	4.5	1920.60	941.28
HC ("a" =1.0%)	7	7	1926.47	950.82
HC ("a" =0.8%)	8.5	8.5	1926.45	949.81
HC ("a" =0.6%)	10	11	1929.45	955.19
HC ("a" =0.4%)	16.5	13	1931.35	955.85
MAHC (adaptive "a")	8	8.5	1931.57	956.66

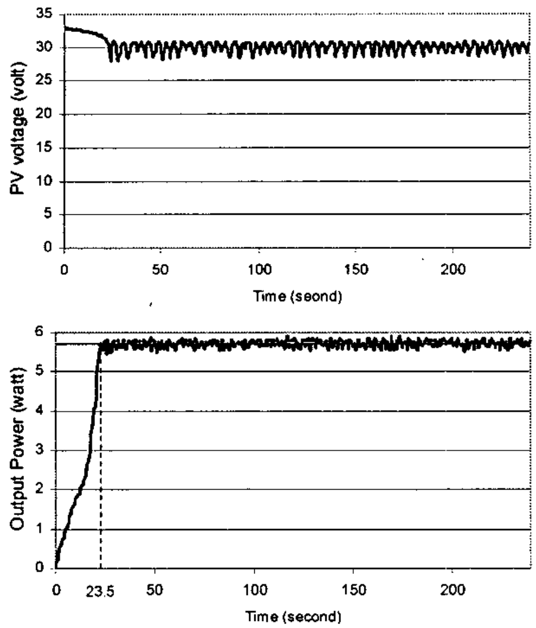

Fig. 11 Experimental waveforms of PV voltage and output power by using the artificial lights as the power source with MAHC control

the modified adaptive hill climbing control algorithm can provide better steady-state performance than the traditional HC algorithm without loss of dynamic response.

Fig. 12 illustrates the waveforms of the PV voltage and output power during the controlled tracking period to show the dynamic tracking performance with MAHC control algorithm. The power variation was caused by insolation changed by switching on/off an artificial lamp. As shown in Fig.12, the MAHC controller can always detect the deviations from the local optimal operating point and adjust the control variables to re-capture the new maximum power points at the two different insolation levels. The recorded tracking time was used to compare the dynamic responses of different control algorithms.

The validity of the proposed MAHC controller was finally examined in natural solar insolation for 10 minutes. The weather condition during the test period is partially cloudy with 19°C in temperature. Fig.13 illustrates the change of PV voltage and the output power curve during 10-minute tracking period. It can be noticed that the PV voltage was kept almost constant due to a relatively steady temperature condition. The output power varied in a small range because of the minor insolation change.

VI. CONCLUSION

A modified MPPT algorithm, namely the modified adaptive hill climbing method (MAHC) was presented in this paper. The automatic parameter tuning was implemented to satisfy the requirements of good dynamic

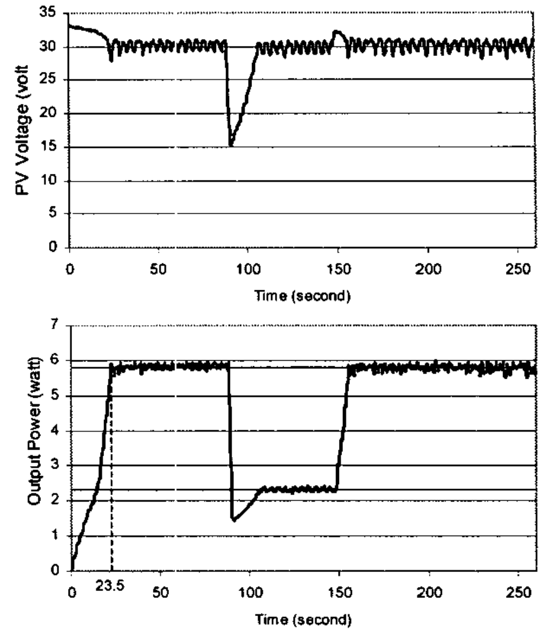

Fig. 12 Experimental waveforms of the PV voltage and output power by using artificial lights as the power source with MAHC control

and steady-state performances. The control mode switching was designed to avoid the tracking deviation. The improved tracking performance of this suggested method was verified through computer simulations and experimental tests. By comparing the simulation results shown in Table II, the MAHC control not only shows smaller steady state error

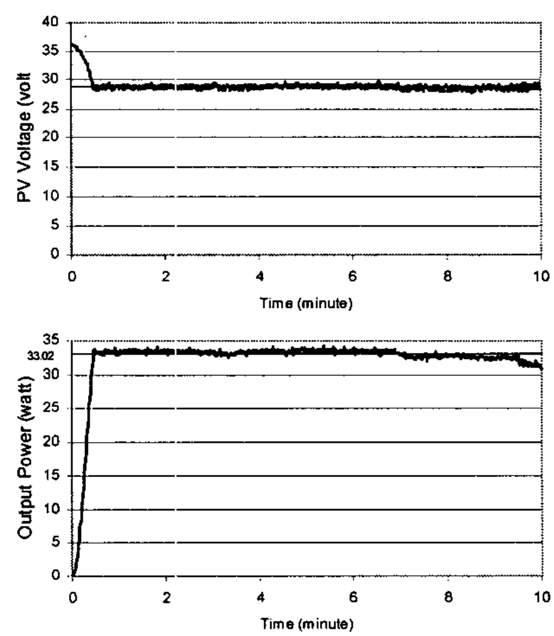

Fig. 13 Experimental waveforms of the PV voltage and output power by using natural sunlight as the power source with MAHC control

than the AHC when the incremental step of duty cycle was set to 0.4%, but also makes the tracking speed 34.62% faster. By comparing the experimental performances, shown in Table III, the MAHC control shows better steady state performance than the AHC when the incremental step of duty cycle was equal to 1.2%, and the tracking speed is 17.5% faster. It is shown that the proposed MAHC MPPT control method exhibits better overall performance than the HC algorithm in both transient and steady-state response.

TABLE III
COMPARISON OF THE PERFORMANCE OF STEP RESPONSE

Control Algorithm	*Steady State Error (watt)*	*100% Rise Time (second)*
AHC (a = 0.8%)	0.05	39.5
AHC (a = 1.2%)	0.10	28.5
AHC (a = 1.6%)	0.19	20.5
AHC (a = 2%)	0.27	16.5
MAHC	0.09	23.5

REFERENCES

[1] C. Hua, J. Lin, and C. Shen, "Implementation of a DSP-controlled photovoltaic system with peak power tracking", *IEEE Trans. Industrial Electronics*, vol. 45, pp. 99 –107, Feb. 1998

[2] K.H. Hussein, I. Muta, T. Hoshino, and M. Osakada, "Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions", in *IEE Proc. Generation, Transmission and Distribution*, vol. 142, pp.59 –64, Jan. 1995

[3] E. Koutroulis and K. Kalaitzakis, "Development of a Microcontroller-Based Photovoltaic Maximum Power Point Tracking Control System", *IEEE Trans. Power Electronics*, vol. 16, pp.46-54, Jan. 2001

[4] T. Senjyu and K. Uezato, "Maximum power point tracker using fuzzy control for photovoltaic arrays", in 1994 *Proc. the IEEE Int. Conf. Industrial Technology*, pp. 143 –147

[5] E.E. van Dyk, A.R. Gxasheka, and E.L. Meyer, "Monitoring current-voltage characteristics of photovoltaic modules", in *Conf. Rec. 2002 IEEE Photovoltaic Specialists Conf.*, pp.1516 –1519

[6] A.D. Hansen, P. Sorensen, L.H. Hansen and H. Bindner, "Models for a stand-alone PV system", Riso National Lab., Roskilde, Tech. Rep. Risø-R-1219(EN)/SEC-R-12, Dec. 2000

[7] R. D. Middlebrook, and S. Cuk, "A general unified approach to modeling switching-converter power stages", in Conf. *Rec.1976 IEEE Power Electronics Specialists Conf.*, pp. 18-34