Comparative Study of Peak Power Tracking Techniques for Solar Storage System

Chihchiang Hua and Chihming Shen
Department of Electrical Engineering
National Yunlin University of Science & Technology

Abstract - As the power supplied by solar arrays depends upon the insolation, temperature and array voltage, it is necessary to control the operating points to draw the maximum power of the solar array. The object of this paper is to investigate the maximum power tracking algorithms which were often used to compare the tracking efficiencies for the system operating under different controls. A simple method which combines a discrete time control and a PI compensator is used to track the maximum power points (MPP's) of the solar array. The implementation of the proposed converter system was based on a digital signal processor (DSP). The experimental tests were carried out, the tracking efficiencies are confirmed by simulations and experimental results.

I. Introduction

In late years, the problem of energy crunch is more and more aggravating. Very much exploitation and research for new power energy are proceeded around the world. In particular, the solar energy attracts lots of attention. In recent years, The development of power semiconductor technology results in easier conversion between AC and DC. Therefore, the use of solar energy is emphasized increasingly and regarded as an important resource of power energy in next century.

Solar cells represent the fundamental power conversion unit of a photovoltaic system [1,2]. Crystalline silicon cell technology is well established. The modules have a long lifetime (20 years or more) and their best production efficiency is approaching 18%. Solar energy can be utilized in two ways: solar heating/cooling and solar electricity. Some appliances can be connected directly because they work on dc at the system voltage. Other appliances may need a voltage adaptor to adjust the voltage [5] or a power inverter to increase the voltage and change it to the ac forms[3].The application of solar arrays for residential or storage systems have been addressed in [4].Solar arrays were developed for power satellites in the space program [6]. In high power applications, parallel connected converters are often used to provide power [7].

As the power supplied by solar arrays depends upon the insolation, temperature and array voltage, it's necessary to draw the maximum power of the solar array. Some papers [5-9] had proposed different maximum power point tracking (MPPT) controls in the past years. A simple DSP-based MPPT algorithm that adjusts the solar array voltage with a discrete PI control to track the MPP for the converter system is used in this paper to achieve the maximum power transfer and high efficiency for the solar energy system. The tracking efficiencies are confirmed by simulations and experimental results.

II. Characteristics of solar arrays

The traditional I-V characteristics of a solar cell, when neglecting the internal shunt resistance, is given by the following equation [1]:

$$I_o = I_q - I_{sat}\left\{\exp\left[\frac{q}{AKT}\left(V_o + I_o R_s\right)\right] - 1\right\} \tag{1}$$

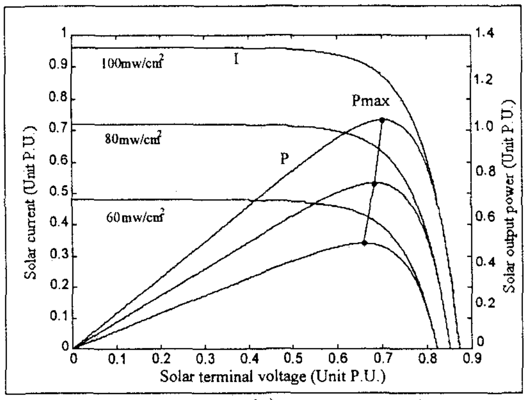
where I_q is the light generated current, I_{sat} is the reverse saturation current, q is the electronic charge, A is a dimensionless factor, K is the Boltzmann constant, T is the temperature in °K, R_s is the series resistance of the cell.

In literature, instead of the I-V characteristic given by Eq (1) the V-I characteristic which is given below is used in many cases:

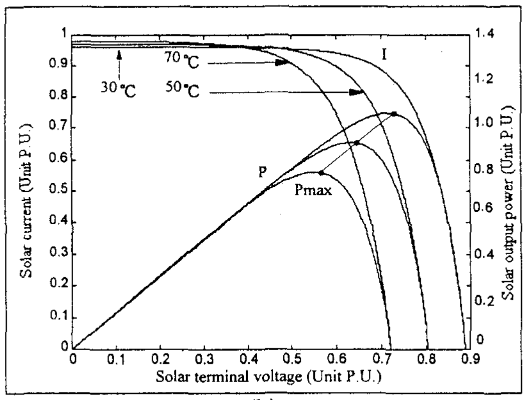
$$V_o = -I_o R_s + \frac{AKT}{q} \cdot In\left[\frac{I_q - I_o + I_{sat}}{I_{sat}}\right] \tag{2}$$

0-7803-4340-9/98/$10.00 © 1998 IEEE.

Equation (1) was used in computer simulations to obtain the output characteristics of a solar cell as shown in Fig. 1. From these figures, it is observed that the output characteristics of a solar cell is non-linear and vitally affected by the solar radiation, temperature and load condition. Each curve has a maximum power point (Pmax), which is the optimal operation point for the efficient use of the solar array.



(a)



(b)

Fig. 1 Output characteristics of a solar array
(a) Insolation characteristics
(b) Temperature characteristics

III. MPPT control approach

As the power supplied by the solar array depends upon the insolation, temperature and array voltage, an important consideration in the design of efficient solar array systems is to track maximum power point correctly. The purpose of the MPPT is to move the array operating voltage close to the MPP under changing atmospheric conditions.

A. Control algorithm

Many methods for tracking maximum power point had been proposed [5-11]. So far, two algorithms often used to achieve the MPPT are: 1. Perturbation and observation (P&O) method; 2. Incremental conductance (IncCond) method.

1. Perturbation and observation method

The perturbation and observation method has been widely used because of its simple feedback structure and fewer measured parameters. The peak power tracker operates by periodically incrementing or decrementing the solar array voltage. If a given perturbation leads to an increase (decrease) in array power, the subsequent perturbation is made in the same (opposite) direction. In this manner, the peak power tracker continuously hunts or seek the peak power conditions.

2. Incremental conductance method

The solar array terminal voltage can be adjusted relative to the MPP voltage by measuring the incremental and instantaneous array conductance (dI/dV and I/V, respectively). Although the incremental conductance method offers good performance under rapidly changing atmospheric conditions, four sensors are required to perform the computations. The drawback is that sensor devices require more conversion time thus result in a large amount of power loss.

B. Control variable

Two different control variables are often chosen to achieve the maximum power control.

1. Voltage-Feedback Control

The solar array terminal voltage is used as the control variable for the system. It keeps the array operating close to its maximum power point by regulating the array's voltage and matches the voltage of the array to a desired voltage. It has the following drawbacks:

1. The effects of the insolation and temperature of the solar array are neglected.
2. It cannot be widely applied to battery energy storage systems.

Therefore, this control is only suitable for use under constant insolation condictions, such as a satellite system, because it cannot automatically track the maximum power point of the array when variations in insolation and temperature occur.

2 . Power-Feedback Control

Maximum power control is achieved by forcing the derivative (dP/dV) to be equal to zero under power feedback control. A general approach to power feedback control is to measure and maximize the power at the load terminal. This has an advantage of unnecessarily knowing the solar array characteristics. However, this method maximizes power to the load not power from the solar array. Although a converter with MPPT offers high efficiency over a wide range of operating points, but for a bad converter, the full power may not be delivered to the load due to power loss. Therefore, the design of a high performance converter is a very important issue.

IV. Configuration of the solar system

The power circuit of the proposed solar energy storage system is shown in Fig. 2 The system consists of a non-linear current source as the power source, a DC/DC converter power stage circuit as the power processing unit, a battery set as the load and a control circuit based on a DSP.

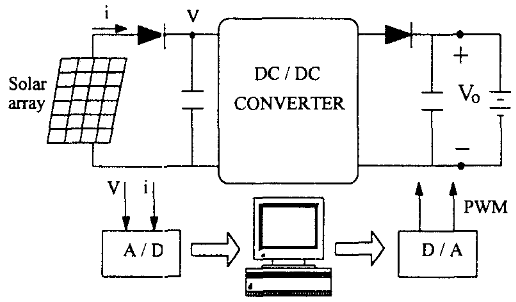


Fig. 2 The solar energy storage system circuit

A. DC/DC converter

Fig. 3 shows the circuit of the buck converter, whose output voltage (battery voltage) is less than or equal to the input voltage V_{in} (solar array voltage). The switch S operates at a at high frequency to produce a chopped output voltage. This converter is suitable for use when the array voltage is high and the battery voltage is low. The power flow is controlled by adjusting the on/off duty cycle of the switching. The average output voltage is given by :

$$\frac{V_o}{V_{in}} = \frac{t_{on}}{T} = D \tag{3}$$

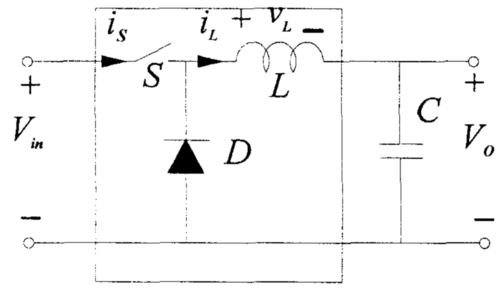


Fig. 3 The buck converter

If the solar energy system provides power to a load, the system often operates away from the maximum power point of the solar array. Fig. 4 shows the I-V characteristics of the solar array and the load, together with constant power curves ($P = VI = const$) . It is seen that the delivered output power, which is represented by the operating point 1, is significantly smaller than the maximum output power, which is represented by point 2. In order to ensure a maximum power transfer, DC/DC converters areuseed to adjust the voltage at the load to the value of $V_R = \sqrt{P_m \cdot R}$, where R is the equivalent resistance of the load.

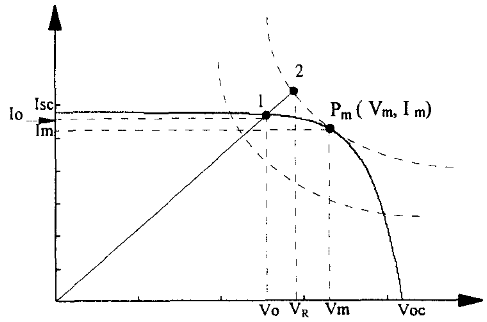


Fig. 4 The operation of the MPPT

B. System control discretization

The block diagram of the MPPT control is shown in Fig. 5 The proposed control consists of two loops, the maximum power point tracking loop is used to set a corresponding V_{ref} to the charger input, the voltage regulating loop is used to regulate the solar array output voltage according to V_{ref}, which is set in the MPPT loop. The functions of the two loops are performed by a DSP-based controller. The controller senses the solar array current and voltage to calculate the solar array output power, power slope and V_{ref} for maximum power control.

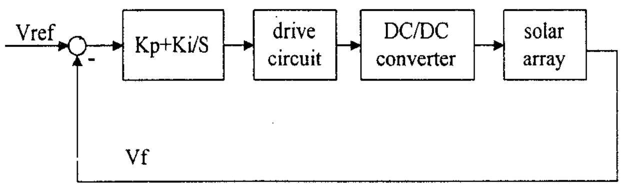


Fig. 5 Block diagram of the control loop

The algorithm can be expressed as the following equation :

$$V_{ref}(k+1) = V_{ref}(k) \pm C \tag{4}$$

C is the amount of disturbance and the sign of C is determined by the power slope. In the voltage loop, the PI compensator is used to make the system stable. Therefore, the discretization of the compensator transfer function is required for system implementation. The transfer function of a traditional compensator is

$$\frac{Y(S)}{U(S)} = K_P + \frac{K_I}{S} \tag{5}$$

where K_P is the proportional gain, and K_I is the integral gain.

Rearranging equation (5) in finite-difference form gives

$$\frac{Y(n+1)-Y(n)}{T} = K_I U(n) + K_P\left[\frac{U(n+1)-U(n)}{T}\right] \tag{6}$$

where T is the sampling time .

Taking the Z-transform of equation (9) yields

$$\frac{Y(Z)}{U(Z)} = .K_P + \frac{K_I T}{Z-1} \tag{7}$$

Equation (7) can be expressed in state variable form as

$$X(n+1) = AX(n) + BU(n) \tag{8}$$
$$Y(n) = CX(n) + DU(n) \tag{9}$$

where A=1 , B=$K_I T$, C=1 , D=K_P, and $X(n)$ is the state variable .

Fig. 6 shows the block diagram of the compensator for digital implementation .

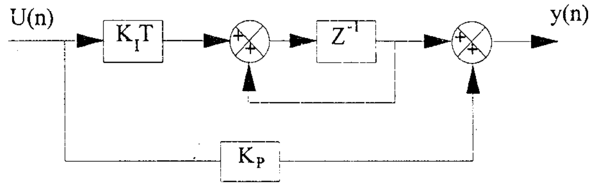


Fig. 6 Implementation of the digital compensator

V. Simulations and experimental results

In this paper, different maximum power point tracking techniques (P&O, IncCond, Voltage-feedback) and direct method were investigated and compared using measured results. Owing to the algorithms of the P&O method and power-feedback control are similar, power-feedback control was not considered in this paper. The implementation of the MPPT controls was based on a DSP controller.

Fig. 7~10 show the measured wave forms under changing atmospheric conditions. Fig. 7(a) ~ Fig. 10(a) show the results under slowly changing atmospheric conditions. Fig. 7(b) ~ Fig. 10(b) show the results under rapidly changing atmospheric conditions. The measured insolation values were used to find the theoretical maximum array power values, which were compared with the measured maximum array power values. It is obviously observed that the system with direct method (without MPPT) has a large amount of power loss. The system with P&O or IncCond method shows excellent performance under changing atmospheric conditions. And further, in this paper tracking efficiency η was used to evaluate tracking performance for different MPPT. The tracking efficiency η is defined as:

$$\eta = \frac{\int_{t_1}^{t_2} P dt}{\int_{t_1}^{t_2} P_{max} dt} \tag{10}$$

where t_1 is start-up time of the system and t_2 is close-down time of the system, P is the array output power, and P_{max} is the theoretical maximum array power.

It has been shown that the P&O and IncCond methods successfully followed the rapidly solar insolation changes and tracking efficiencies are above 80%. The efficiency with voltage feedback control is about 75% under slowly changing conditions, and only about 65% under rapidly changing conditions. However, the direct method has significant power loss without MPPT and the efficiency is below 30%. The efficiency comparison for different MPPT techniques is shown in Table 1.

VI. Conclusion

The purpose of the MPPT is to adjust the solar operating voltage close to the MPP under changing atmospheric conditions. In this paper, different MPPT techniques were investigated and compared. A simple method which combines a discrete time control and a PI compensator is used to track the MPP's of the solar array. The proposed converter system based on a DSP was constructed and the experimental tests were carried out, the tracking efficiency was confirmed by simulations and experimental results.

Acknowledgement

This research is sponsored by National Science Council under the contract NSC 86-2213-E-224-014.

Reference

[1] T.Markvart, "Solar Electricity", John Willy & Sons, 1994.

[2] S.Roberts, "Solar Electricity", Prentice Hall, 1991.

[3] F. Harashima and H. Inaba, "Microprocessor-Controlled SIT Inverter for Solar Energy System", IEEE Trans. on Industrial Electronics, vol. IE-34, no. 1, pp50~55, Feb. 1985.

[4] B.K.Bose, P.M.Szczesny and R.L.Steigerwald, "Microcomputer Control of a Resi-dential Photovoltaic Power Condictioning System", IEEE Trans. on Industry Applications, vol. IA-21,no. 5, pp1182~1191, Sep. 1985.

[5] Z. Salameh, F.Dagher and W.A.Lynch, "Step-Down Maximum Power Point Tracker for Photovoltaic System", Solar Energy, vol. 46, no. 1, pp.278~282, 1991.

[6] S.J. Kim, J.R. Lee and B. H. Cho, "Large Signal Analysis of Space craft Power Systems" IEEE PESC, pp.2873~2880, 1989.

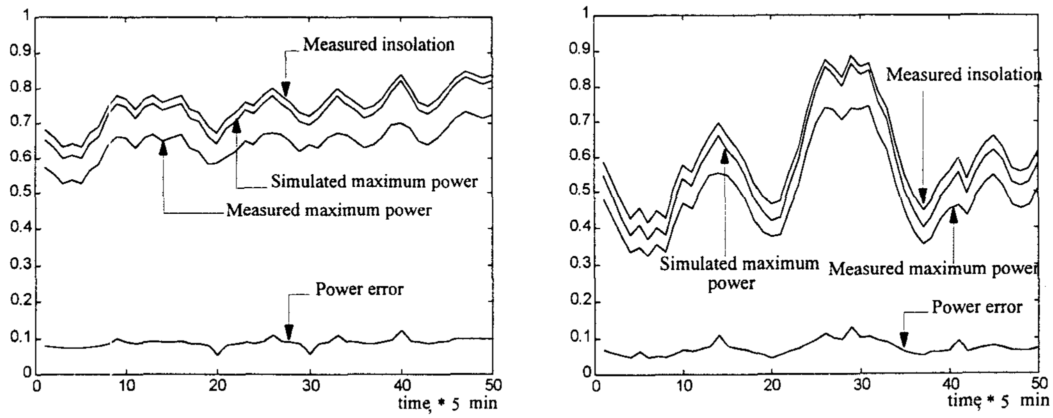
[7] K.Siri, T.-F.Wu and C.Q.Lee, "Maximum Power Tracking in Parallel Connect-ed Converter System", IELEC'91, pp.128~133, 1991.

[8] C.R.Sullivan and M.J.Powers, "A High-Efficiency Maximum Power Point Tracking for Photovoltaic Arrays in a Solar-Power Race Vehicle", IEEE PESC'93, pp.574~580, 1993.

[9] K.Siri, V.A.Caliskan, and C.Q.Lee, "Peak Power Tracking in Parallel Connected Converters", PESC'92, pp1401~1406, 1992.

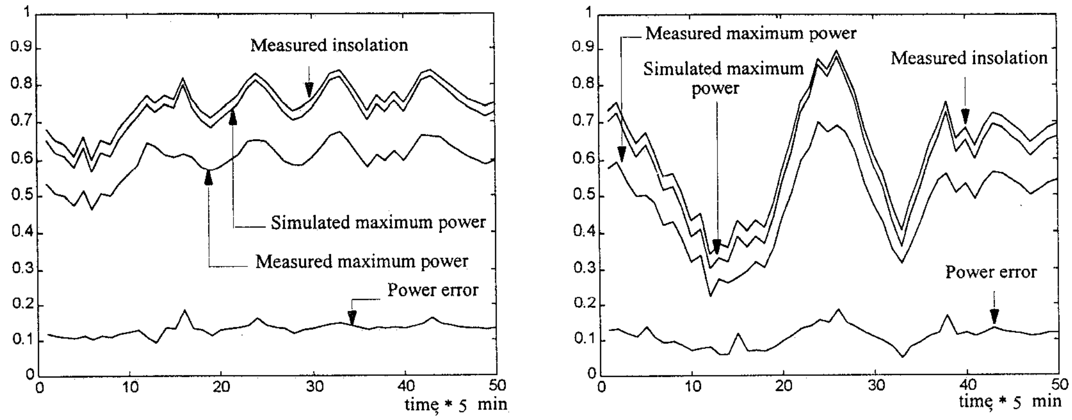
[10] S.M. Alqhuwainem, "Matching of a dc motor to a photovoltaic generator using a step-up converter with a current-locked loop", IEEE Trans. on Energy Conversion, vol. 9, no. 1, March 1994.

[11] K.H. Hussein and G.Zhao, "Maximum Photovolatic Power Tracking :An Algorithm for Rapidly Changing Atmospheric Conditions", IEE Proc.-G, vol. 142, no.1, Jan. 1995.



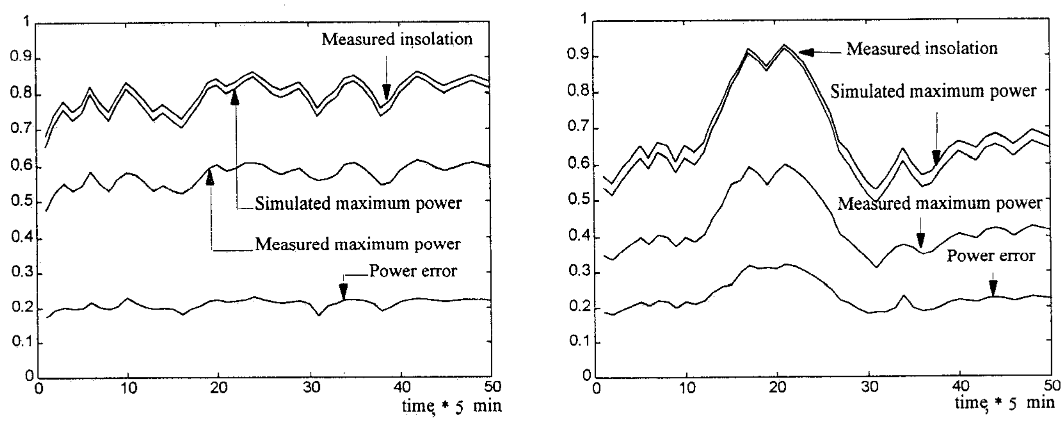
(a) (b)

Fig. 7 The tracking wave forms with IncCond method. (a)Slowly changing ($65 \sim 85 mw/cm^2$). (b) Rapidly changing ($42 \sim 88 mw/cm^2$).



(a) (b)

Fig. 8 The tracking wave forms with P&O method. (a) Slowly changing ($60 \sim 83\,mw/cm^2$). (b) Rapidly changing ($35 \sim 87\,mw/cm^2$).



(a) (b)

Fig. 9 The tracking wave forms with voltage-feedback control. (a) Slowly changing ($68 \sim 86\,mw/cm^2$). (b) Rapidly changing ($55 \sim 90\,mw/cm^2$).

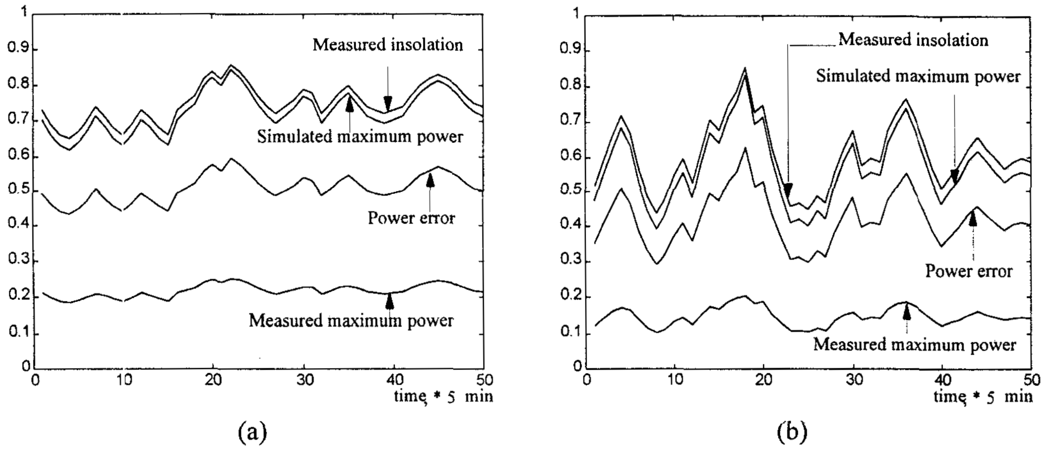


Fig. 10 The wave forms with direct method. (a) Slowly changing ($65 \sim 86 mw/cm^2$). (b) Rapidly changing ($44 \sim 85 mw/cm^2$).

Table.1 The efficiency comparison for different MPPT techniques

Algorithm	Insolation	η
IncCond method	Slowly ($65 mw/cm^2 \sim 85 mw/cm^2$)	0.88
	Rapidly ($42 mw/cm^2 \sim 88 mw/cm^2$)	0.86
P&O method	Slowly ($60 mw/cm^2 \sim 84 mw/cm^2$)	0.85
	Rapidly ($35 mw/cm^2 \sim 87 mw/cm^2$)	0.82
Voltage-feedback control	Slowly ($68 mw/cm^2 \sim 86 mw/cm^2$)	0.73
	Rapidly ($55 mw/cm^2 \sim 90 mw/cm^2$)	0.65
Direct method	Slowly ($65 mw/cm^2 \sim 86 mw/cm^2$)	0.30
	Rapidly ($44 mw/cm^2 \sim 85 mw/cm^2$)	0.26