Comparative Study of Maximum Power Point Tracking Algorithms Using an Experimental, Programmable, Maximum Power Point Tracking Test Bed

D. P. Hohm, M. E. Ropp
Electrical Engineering Department
South Dakota State University
Brookings, SD 57007-2220

ABSTRACT

Maximum Power Point Tracking (MPPT) is important in solar power systems because it reduces the solar array cost by decreasing the number of solar panels needed to obtain the desired output power. Several different MPPT methods have been proposed, but there has been no comprehensive experimental comparison between all the different algorithms and their overall Maximum Power Point (MPP) tracking efficiencies under varying conditions (i.e. illumination, temperature, and load). This paper provides such a comparison. Results are obtained using a microprocessor controlled MPPT powered by a 250W photovoltaic (PV) array and also a PV array simulator.

INTRODUCTION

One significant problem in PV systems is the probable mismatch between the operating characteristics of the load and the PV array.

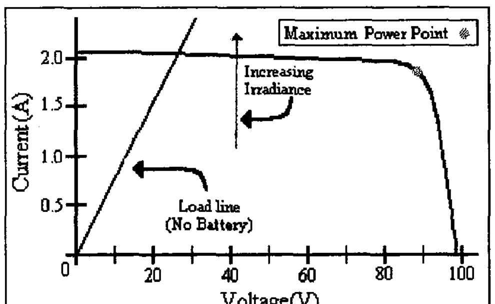

Figure 1.) PV Array Curve vs. Voltage

Shown in figure 1 is a plot of a typical I vs. V curve for a PV panel, with the X-axis representing voltage and the Y-axis representing current. When a PV array is directly connected to a load, the system's operating point will be at the intersection of the I-V curves of the PV array and load. Under most conditions, this operating point is not at the PV array's maximum power point (MPP), which can be clearly seen in figure 1. To overcome this problem, an MPPT can be used to maintain the PV array's operating point at the MPP. However, the location of the MPP in the I-V plane is not known *a priori*. It can be calculated using a model of the PV array and measurements of irradiance and array temperature, but making such measurements is usually too expensive for this application, and often the required parameters for the PV array model are not known adequately. Thus, the MPPT must continuously search for the MPP. Several MPPT search algorithms have been proposed that make use of different characteristics of solar panels and the location of the MPP. Unfortunately, it is difficult to compare the effectiveness of these methods because no comprehensive experimental comparison has been performed. Several papers have been written comparing different algorithms to the perturb and observe algorithm "P&O" (see the algorithm definition section for operating principal), but they have either been experimental comparisons between one algorithm and P&O, or they have been simulations using an un optimized form of P&O [1]. The purpose of this work is to obtain such an experimental comparison and to suggest which MPPT control algorithm is the most effective on the basis of MPPT efficiency, which is defined as

$$\eta_{MPPT} = \frac{\int_0^t P_{actual}(t)dt}{\int_0^t P_{\max}(t)dt} \qquad (1)$$

where P_{actual} is the actual power produced by the PV array under the control of the MPPT, and P_{max} is the true maximum power the array could produce under the given temperature and irradiance. Since temperature and irradiance are both functions of time, P_{actual} and P_{max} are also time varying. In this work, only MPPT algorithms that could feasibly be implemented in a low-cost MPPT were considered. Thus, Fuzzy Logic, DSP, Neural Network, and the use of pilot cells are beyond the scope of this project. The following MPPT algorithms have been chosen for further investigation:

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- Perturb and Observe (P&O)
- Incremental Conductance (INC)
- Constant Voltage (CV)
- Parasitic Capacitance (PC)

PROCEDURE

MPPT Test Bed

To facilitate the comparison of MPPT algorithms, a 250W, microprocessor-controlled MPPT was designed and built. Most MPPT's utilize either a step-up (Boost) or step-down (Buck) switched converter. The choice of converter is based on the desired output voltage from the MPPT. A buck converter was chosen here since the desired output voltage was less than the PV array operating voltage. The MPPT test bed is designed around the Motorola HC11 microprocessor. Shown in figure 2 is the block diagram of the MPPT. The measured load and array voltages and currents are fed into the voltage-conditioning block, which scales and offsets the voltages to the desired levels for the microprocessor. The microprocessor is programmed with the MPPT algorithm to be tested. The control signal calculated by the MPPT algorithm is sent to the control circuitry block, that generates the appropriate control signal for the DC-DC buck converter. A 250W variable power resistor was used as a load for the system. The battery consisted of four 12V deep cycle batteries connected in series to achieve the desired 48V at the output of the DC-DC converter.

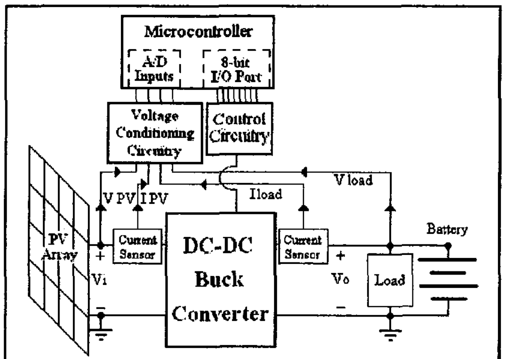

Figure 2.) Block Diagram of the Maximum Power Point Tracker

The PV Simulator and PV Array

MPPT algorithms were first compared using the MPPT test bed powered by the Agilent Technologies HP4350B Solar Array Simulator (SAS). This simulator has a maximum current, voltage, and power of 4.0 A, 100V, and 250 W respectively. The simulator was programmed by entering the I_{SC}, I_{MP}, V_{MP}, and V_{OC} values of the actual PV array that was to be used later. To obtain real-world results, the algorithms were also tested using an actual PV array. The array is comprised of five series-connected ASE Americas ASE-50-AL 50 W solar modules. Each module has the following characteristics at 1 sun and 25 C° shown in Table 1.

TABLE 1. Module Characteristics

I_{SC} (A)	I_{MP} (A)	V_{MP} (V)	V_{OC} (V)
3.2	2.9	17.2	20.0

Testing

To simulate real world irradiance and temperature conditions I_{SC}, I_{MP}, V_{MP}, and V_{OC} were varied to approximately simulate different cloud transients. Shown in figure 3 is the power curve used to simulate actual operating conditions. Each algorithm was tested four times using this power curve. The MPPT efficiency was then calculated using equation 1 over the entire simulation.

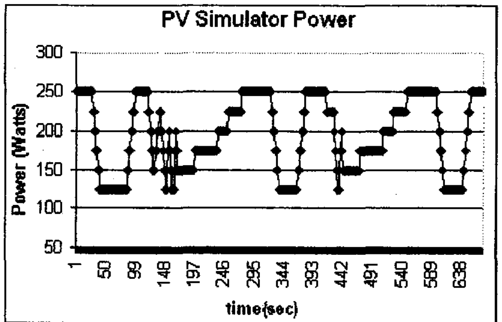

Figure 3.) Power Curve for the PV Simulator

All of the algorithms were tested on one day by rotating the algorithms used in the MPPT every 20 minutes. This was done to keep the atmospheric conditions as equal as possible between each algorithm. To determine the maximum amount of power available from the sun, a pyranometer and a thermistor were used to measure solar irradiance (W/m^2) and PV array temperature (°C) respectively. These values were used in a PV array model given by equations 2-4 [2] to determine the actual maximum power available at that sampling instance. The power flowing into the MPPT was also measured and using equation 1, the MPPT efficiency of the algorithm was found.

$$I_{OS} = I_{OR}\left(\frac{T}{T_R}\right)^3 \exp\left[\frac{qE_{Go}}{BK}\left(\frac{1}{T_R}-\frac{1}{T}\right)\right] \quad (2)$$

$$I_L = \left[I_{SC} + K_1\left(T_C - 28\right)\right] * \frac{Rad}{1000} \quad (3)$$

$$I = n_P I_L - n_P I_{OS}\left[\exp\left(\frac{\frac{V\cdot q}{A\cdot T\cdot K}}{n_S}\right)-1\right] \quad (4)$$

ALGORITHM DEFINITIONS

Perturb and Observe

The most commonly used MPPT algorithm is Perturb And Observe (P&O), due to its ease of implementation in its basic form [1]. Figure 4 shows the P vs. V curve of a PV array, which has a global maximum at the MPP. Thus, if the operating voltage of the PV array is perturbed in a given direction and dP/dV > 0, it is known that the perturbation moved the array's operating point toward the MPP. The P&O algorithm would then continue to perturb the PV array voltage in the same direction. If dP/dV < 0, then the change in operating point moved the PV array away from the MPP, and the P&O algorithm reverses the direction of the perturbation. A problem with P&O is that it oscillates around the MPP in steady state operation. It also can track in the wrong direction, away from the MPP, under rapidly increasing or decreasing irradiance levels [3].

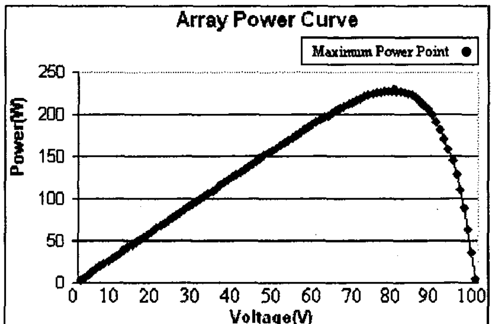

Figure 4.) Power vs. Voltage Curve

There are several variations of the basic P&O that have been designed to minimize these drawbacks. These include using an average of several samples of the array power and dynamically adjusting the magnitude of the perturbation of the PV operating point.

Incremental Conductance

The incremental conductance algorithm seeks to overcome the limitations of the P&O algorithm by using the PV array's incremental conductance to compute the sign of dP/dV without a perturbation [3]. It does this using an expression derived from the condition that, at the MPP, dP/dV = 0. Beginning with this condition, it is possible to show that, at the MPP dI/dV = -I/V [3]. Thus, incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationship between dI/dV and -I/V [3]. This relationship is derived from the fact that dP/dV is negative when the MPPT is to the right of the MPP and positive when it is to the left of the MPP. This algorithm has advantages over perturb and observe in that it can determine when the MPPT has reached the MPP, where perturb and observe oscillates around the MPP. Also, incremental conductance can track rapidly increasing and decreasing irradiance conditions with higher accuracy than perturb and observe. One disadvantage of this algorithm is the increased complexity when compared to perturb and observe. This increases computational time, and slows down the sampling frequency of the array voltage and current.

Parasitic Capacitance

The parasitic capacitance method is a refinement of the incremental conductance method that takes into account the parasitic capacitances of the solar cells in the PV array [4]. Parasitic capacitance uses the switching ripple of the MPPT to perturb the array. To account for the parasitic capacitance, the average ripple in the array power and voltage, generated by the switching frequency, are measured using a series of filters and multipliers and then used to calculate the array conductance [3]. The incremental conductance algorithm is then used to determine the direction to move the operating point of the MPPT. One disadvantage of this algorithm is that the parasitic capacitance in each module is very small, and will only come into play in large PV arrays where several module strings are connected in parallel. Also, the DC-DC converter has a sizable input capacitor used filter out small ripple in the array power. This capacitor may mask the overall effects of the parasitic capacitance of the PV array.

Constant Voltage

This algorithm makes use of the fact that the MPP voltage changes only slightly with varying irradiances, as depicted in figure 5. The ratio of V_{MP}/V_{OC} depends on the solar cell parameters, but a commonly used value is 76% [5]. In this algorithm, the MPPT momentarily sets the PV array current to zero to allow a measurement of the array's open circuit voltage. The array's operating voltage is then set to 76% of this measured value. This operating point is maintained for a set amount of time, and then the cycle is repeated. A problem with this algorithm is available energy is wasted when the load is disconnected from the PV array, also the MPP is not always located at 76% of the array's open circuit voltage.

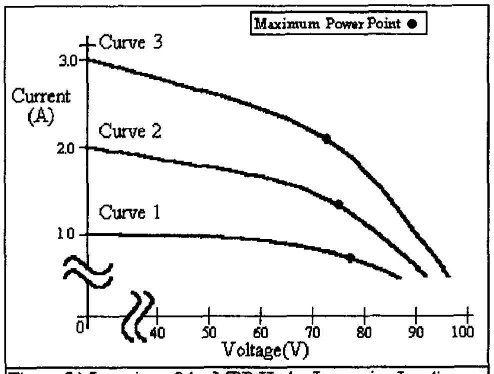

Figure 5.) Location of the MPP Under Increasing Irradiances

RESULTS AND ANALYSIS

The average MPPT efficiencies determined in this study are summarized in Table 2. The equations used to calculate the maximum power available for the PV array give are slightly inaccurate for MPP values under 80W. From this the array results have a margin of error of ±0.3%. The higher efficiencies of the MPPT ability when using the simulator are due to the discrete values of power vs. time curve used to drive the simulator (see figure 3).

Table 2. Overall MPPT Efficiencies

	P&O	INC	CV
Array	96.5%	98.2%	88.1%
Simulator	97.2%	98.5%	92.7%

Future work includes refining the PV array equation to encompass all power values attainable by the PV array. Also the parasitic capacitance algorithm will be implemented and tested using the previously described procedure. The version of perturb and observe used in this paper utilized an average of two samples of voltage and current. Other optimization techniques such as varying the step size of the duty cycle will be explored.

CONCLUSION

Preliminary results indicate that perturb and observe compares favorably with incremental conductance and constant voltage. Although incremental conductance is able to provide marginally better performance, the increased complexity of the algorithm will require more expensive hardware, and therefore may have an advantage over perturb and observe only in large PV arrays.

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