JAVA Journal of Electrical and Electronics Engineering
Volume 13, Number 1, April 2015

Power/Current-based MPPT Scheme for PV Modules Operated on Wide Ambient Temperature Range

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***Abstract*—Photovoltaic (PV) modules have non-linear characteristics described by their voltage-current relationship. At an optimum operating point of voltage and current, a PV module delivers its maximum power. The maximum power of a PV module depends on the irradiance level of sunlight and the module temperature. This paper demonstrates, through simulation and experimental verification, a method to extract maximum output power from a PV module at any irradiance level and wide range of temperature. The proposed maximum power point tracker (MPPT) is based on the power-current characteristics of a PV module. To eliminate the deviation of MPPT operation due to temperature variation, temperature compensation is added. This method yields a faster response and does not require short-circuit current or open-circuit voltage information of the module as required in constant current or voltage MPPT schemes. As the result, higher efficiency is obtained because there is no power interruption while searching the optimum point. Experimental results confirm the validity of the mathematical model and simulation of the proposed technique.**

Keywords—Photovoltaic systems; maximum power point tracker; maximum power line; temperature compensation

I. INTRODUCTION

The mismatch between power generated by a photovoltaic (PV) module and load demand leads to non-maximum power operation of the module, resulting in low conversion efficiency. Since the generated power depends on irradiance from the sun, the load impedance should be adjusted so that the operating point of the PV module (current and voltage) produces maximum power operation. In order to achieve maximum power operation, a dc/dc or dc/ac converter is inserted between the module and the load [1]. The converter duty cycle is then controlled by the maximum power command from the MPPT circuit that commonly employs a PWM technique.

Many methods have been proposed to achieve optimum operation of a PV module. The common classification of tracking methods are perturbation and observation [2], look-up table [3], constant voltage or current [4-6]. Most methods are suitable for digital or microcomputer implementation. Constant current method is a method based on the linear relationship between the short circuit current (I_{sc}) and the optimum operating current (I_{opt}) of a PV module. A constant k_i is used to obtain optimum operating current as I_{opt}□□□k_i□□□I_{sc}. A similar approach called a constant voltage method uses the relationship between the open circuit voltage (V_{oc}) and optimum operating voltage (V_{opt}) of a PV module. Optimum operating voltage is obtained by $V_{opt} = k_v$ □ V_{oc}, where k_v is a constant. Implementation of the methods above requires the PV module's output terminal to be shortened or opened yielding I_{sc} or V_{oc} respectively (power cannot be extracted during this period). Thus, these techniques will contribute to a loss of energy during MPPT operation. A comparison of a few MPPT methods with constant voltage MPPT has been reported [7].

Another different approach is known as the maximum power line technique [8]. This technique is based on the maximum power and current (P-I) characteristics of a PV module, which shows a linear correlation between maximum power P_{max} and the optimal operating current I_{opt} of a module at any irradiance level. The advantage of this method is that it does not require short-circuit current or open-circuit voltage information of the module as required using the constant current or voltage MPPT technique. Consequently, there is no power interruption while searching for the optimum point, which would reduce energy loss.

Implementations of a constant voltage, constant current and maximum power line method will yield a fast response and reasonable maximum power operation at any irradiance level. However, the fluctuation of the PV module temperature causes maximum power deviation in the methods above because they only consider irradiance fluctuation. The worst occurs when MPPT fails under some extreme circumstance, i.e. low irradiance level and high temperature in the PV module.

In order to overcome the maximum power deviation due to temperature fluctuation, [9] used information from the PV module temperature to obtain optimum voltage for voltage-based MPPT. Another method proposed uses a combination of the hill-climbing method and constant current MPPT. This technique overcomes a collapse of linearity between power and optimum current when the temperature changes at a high irradiance state [10]. Both techniques were implemented in a digital-based system using mathematical equations and conditional decision algorithms.

This paper proposes a simple implementation of P-I based MPPT which considers the effect of temperature fluctuation on the PV module. In the implementation, the designed MPPT performs it operation without imposing open-circuit or short-circuit at the PV module output terminal such in constant current or constant voltage technique. As the result, there is no power interruption and consequently increasing energy captured from PV modules.

II. PV Module Characteristics and Maximum Power Line

Fig. 1 shows the well known single diode equivalent circuit model of a photovoltaic cell [11, 12]. Omitting the parallel resistance R_p, the mathematical expression of the photovoltaic cell is given by:

$$I = I_s - I_o\left[e^{\left(\frac{V+IR_s}{V_T}\right)} - 1\right] \tag{1}$$

I cell terminal current V cell terminal voltage

I_S photo current R_s series resistance of cell

V_T thermal voltage I_o reverse saturation current

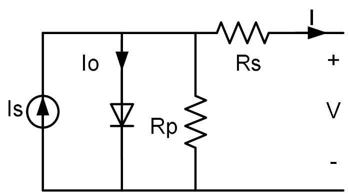


Fig. 1. Photovoltaic cell in single diode model

In this paper, a crystalline-silicon 60 Watt PV module is used for simulation and experiments. Typical P-I characteristic of PV module under different irradiance levels in Fig. 2 has an optimum point (I_{opt},P_{max}) at which the module generates maximum power.

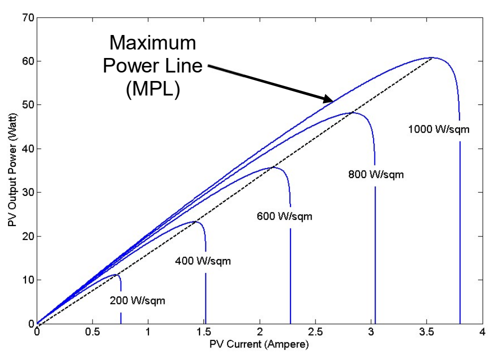


Fig. 2. P-I characteristic of PV module under various irradiance levels at 25□C.

Rearranging (1) in term of PV module terminal voltage:

$$V = V_T \ln\left(\frac{I_s + I_o - I}{I_o}\right) - IR_s \tag{2}$$

Multiplying (2) with terminal current will yield a PV module output power as:

$$P = VI = IV_T \ln\left(\frac{I_s + I_o - I}{I_o}\right) - I^2 R_s \tag{3}$$

In order to obtain the maximum value of P, (3) is differentiated as follows:

$$\frac{\partial P}{\partial I} = \frac{\partial}{\partial I}\left[IV_T \ln\left(\frac{I_s + I_o - I}{I_o}\right)\right] - \frac{\partial}{\partial I}(I^2 R_s)$$

$$= V_T \ln\left(\frac{I_s + I_o - I}{I_o}\right) - \frac{V_T I}{I_s + I_o - I} - 2IR_s \tag{4}$$

Solving (4) for $\partial P / \partial I = 0$ and substituting the result to (3) on any certain irradiance level yields $P = P_{max}$ and explicitly leads us to an optimum operating current of PV module $I = I_{opt}$. A 6th order polynomial regression for points of (I_{opt},P_{max}) is applied to investigate the correlation between P_{max} and I_{opt} at an irradiance level from 100 W/m^2 to 1000 W/m^2 (at a PV module temperature of 25□C). The polynomial regression yields:

$$P_{max} = 0.0172 I_{opt}^6 - 0.2083 I_{opt}^5 + 1.0038 I_{opt}^4 - 2.5034 I_{opt}^3 + 3.6402 I_{opt}^2 + 14.2399 I_{opt} - 0.0605 \tag{5}$$

1. In comparison, a 1st order regression is also applied to simplify (5) obtaining a common straight-line equation $y = mx+C$. The linear regression yields:

$$P_{max} = 17.2672\, I_{opt} - 0.8177 \tag{6}$$

Table 1 shows the calculated maximum power (P_{max}) while employing a 6th order polynomial regression and linear regression. The linear regression has an average error of 0.95 % from the exact value, while a polynomial has 0.04%.

Table 1. Comparison of maximum power line (MPL) using polynomial regression.

Irradiance	Theoretical P_{max} from MSX-60 model	1st order regression		6th order regression	
(W/m2)	(Watt)	Pmax (Watt)	Error (%)	Pmax (Watt)	Error (%)
100	5.303	5.251	0.99	5.311	0.15
200	11.136	11.360	2.01	11.125	0.10
300	17.139	17.473	1.95	17.141	0.01
400	23.240	23.591	1.51	23.247	0.03
500	29.404	29.713	1.05	29.406	0.01
600	35.613	35.830	0.61	35.606	0.02
700	41.856	41.948	0.22	41.849	0.02
800	48.126	48.094	0.07	48.144	0.04
900	54.416	54.195	0.41	54.406	0.02
1000	60.723	60.320	0.66	60.725	0.00

Note: P_{max} is calculated at 25 °C.

Using computer-based programming to implement (5) is an easy task [13]. In contrast, it would be very difficult to develop such high order polynomial equation in an analogue circuit. Considering simplicity at a practical stage, this paper prefers to use (6) rather than (5). Also the average error of linear regression is less than 1%, which is reasonably omitted in practical. Equation in (6) represents a straight line that crosses the y-axis at negative 0.8177, which is small enough and reasonable to be neglected as well. Hence, (6) becomes:

$$P_{max} = 17.2672 I_{opt} \quad \text{or} \quad I_{opt} = \frac{1}{17.2672} P_{max} \tag{7}$$

Thus (7) can generally be written in the different form of a straight line equation as:

$$I_{opt} = \frac{1}{m} P_{max} = K.P_{max} \tag{8}$$

Equation in (8) represents a straight-line equation with a slope of $1/m$ and crosses the origin of the P-I plane, where m is a constant and can be calculated from the MPL in Fig. 2. By sensing module voltage V_{pv} and current I_{pv}, a simple MPPT circuit can be implemented using a gain element *K;* single quadrant multiplier; and an error amplifier network. Fig. 3 shows the diagram of MPPT based on MPL of P-I characteristic of PV module.

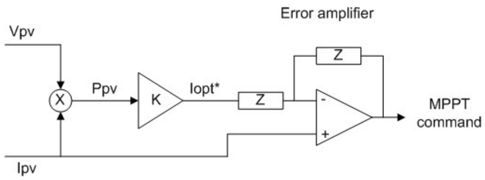


Fig. 3. Constant gain P-I based MPPT diagram.

Error amplifier in Fig. 3 regulates the operating current I_{pv} into a reference value I_{opt}*. The reference value I_{opt}* is obtained by scaling P_{pv} by factor of *K*. The advantage of this implementation compared with a constant voltage or current method is that there is no disconnecting or shortening of the PV module output to obtain V_{oc} or I_{sc}. As a result, there is no power interruption or loss while locating the maximum power. Another advantage is that the control circuit implementation is much simpler because it does not need an extra triggering circuit to control switch device (such in constant-current or constant voltage technique).

III. Temperature Compensation

Temperature increase in a PV module under sunlight exposure reduces the maximum output power and consequently changes the optimum operating point. Fig. 4 shows the effect of temperature on the MPL slope of PV module. For example in Fig. 4, the value of slope m varies from 0.0575 to 0.0730 for a temperature fluctuation range of 20°C to 70°C. In practice, the gain element *K* in Fig. 3 can only have one preset value to a certain PV module temperature. Gain element *K* will give an incorrect reference value I_{opt}* when the module temperature is fluctuating. As the result, constant gain MPPT fails to locate a new maximum power point. This is the main drawback of the usage of constant gain in MPL technique. Therefore this paper aims to find a solution that minimizes the drawback.

The easiest way to cover all slope values of the maximum power lines in Fig.4 is to find the average value of $1/m$ and apply this average value as a constant gain element. This technique leads to either deviation or even failure of constant gain MPPT in locating the maximum power at a low irradiance level and high PV module temperature.

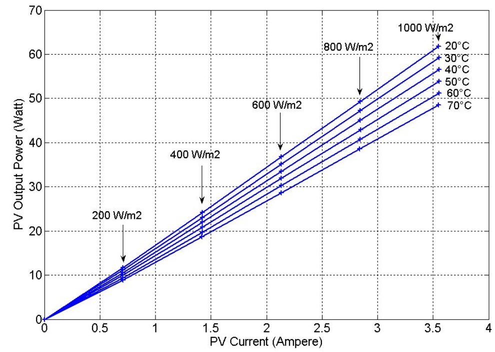


Fig. 4. Maximum power lines under various temperatures and irradiance levels.

As seen in Fig. 4, the increase of a PV module temperature yields a lower slope for maximum power line m. While the value of $1/m$ is implemented in gain element *K*, the value of *K* increases along with the PV module's temperature. To obtain a gain that depends on the temperature, a temperature sensor should be added to provide PV module temperature information. This technique is shown in Fig. 5, where the sensor produces a higher gain while the PV module temperature increases and vice versa.

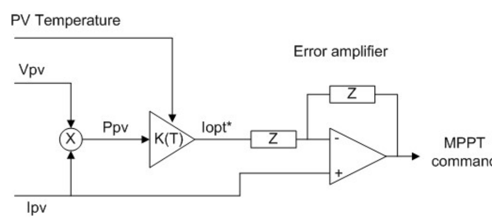
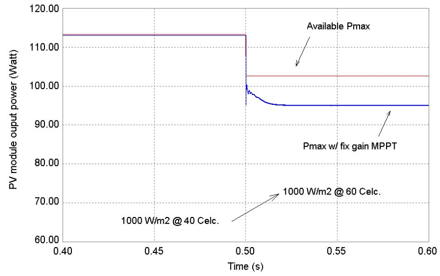


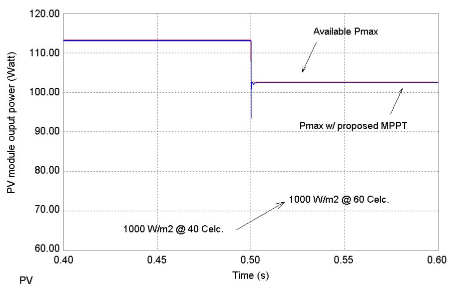
Fig. 5. Modified P-I based MPPT using temperature dependent gain $K(T)$

IV. Simulation Results

The simulation consists of two MSX-60 modules [14] in series connection, buck converter, constant gain and proposed MPPT circuit, and a resistive load. The first simulation is purposed to verify the effectiveness of the proposed MPPT transient response when the PV module temperature is fluctuating. Simulation results in Fig. 6 show the transient response of MPPT when the temperature changes from 40°C to 60°C at an irradiance level of 1000 W/m^2. In simulation, constant gain MPPT (Fig. 6a) cannot achieve maximum power operation properly. In contrast, MPPT with temperature dependent gain (Fig. 6b) provides maximum power operation consistently because the gain element has the ability to follow the temperature change of a PV module.



(a)



(b)

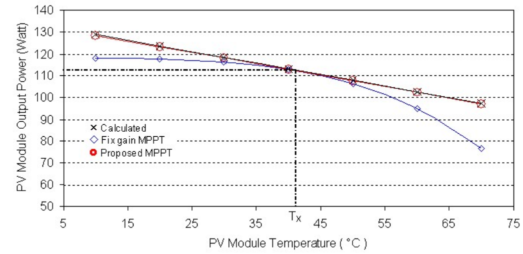
Fig. 6. Transient response due to temperature change of fix gain (a) and compensated (b) MPPT.

Fig. 7 illustrates the results of the simulation to evaluate the steady state performance for a wide temperature range. It shows the performance of MPPT in the temperature variation of 10°C to 70°C when the module is exposed to a high level irradiance of 1000 W/m^2 (Fig. 7a). It was found that at a certain module temperature, T_x, the constant gain MPPT gives the same performance as the proposed compensated MPPT. At this temperature, the value of gain K in Fig. 3 is the same as the value of $K(T)$ in Fig. 5. Therefore both MPPT schemes can extract the same amount of power from the PV modules.

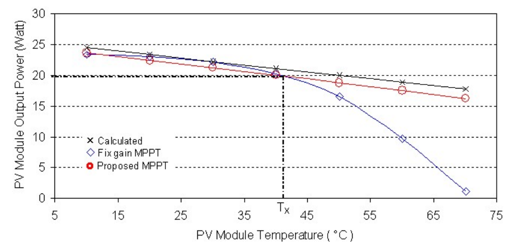
Simulation results show the consistency of the proposed MPPT technique in tracking the optimum operating point. At a high irradiance level, the average deviation in locating the maximum power of the proposed scheme is 0.25% as shown in Fig. 7a. It may be noted that the constant gain MPPT has an average deviation of 6.5%. A similar response is also obtained (Fig. 7b) when the module is exposed to a lower irradiance level of 200 W/m^2. At the lower irradiance level the deviation in both MPPTs (fix and compensated gain) increase mostly at high temperatures. However, the proposed MPPT scheme consistently delivers a better result in achieving the optimum operating point.

Table 2. Steady state performance of MPPT under tempreature fluctuation

Module temperature (°C)	Error at 1000 W/m2		Error at 200 W/m3	
	Fix gain MPPT	Proposed MPPT	Fix gain MPPT	Proposed MPPT
10	8.53%	0.27%	4.58%	3.49%
20	4.92%	0.26%	1.39%	3.94%
30	1.88%	0.25%	0.30%	4.65%
40	0.28%	0.25%	4.06%	5.36%
50	1.52%	0.23%	17.54%	6.11%
60	7.51%	0.22%	48.73%	7.17%
70	21.25%	0.20%	93.77%	8.34%



(a)



(b)

Fig. 7. Steady state performance of MPPT at irradiance level of (a) 1000 W/m^2 and (b) 200 W/m^2.

Table 2 summarizes the performance of MPPT depicted in simulation results. It is shown in table that the proposed technique is better in locating the maximum power in the wide range operating condition of temperature and irradiance. The worst is that constant gain MPPT might fail under low level irradiance and high temperature conditions. Such conditions could emerge at fine weather with partly cloudy skies, where the irradiance level varies dynamically while the temperature changes slowly.

V. Experimental Results

A prototype of the proposed MPPT was built to verify the simulation with experimental results. The MPPT is designed to control a buck converter to extract maximum power from PV modules. The system consists of a two MSX-60 PV modules (in series), buck converter, resistive load and PWM controller equipped with the proposed MPPT. All circuits use analogue components such as op-amp for gain implementation, analogue multiplier to obtain power value, and voltage mode PWM chip to generate a triggering signal for MOSFET [15]. Temperature-dependent gain is implemented using an NTC thermistor [16] and op-amp. NTC is located on the back side of the PV module to obtain the module temperature. A constant gain MPPT was also built to verify the performance of the proposed MPPT where the NTC is replaced by a carbon resistor.

Fig. 8 and Fig. 9 show the experimental results of proposed MPPT compared to constant gain MPPT. The field tests were conducted for two consecutive days with one minute logging interval time. Curves shown in Fig. 8 were obtained during fine and clear weather. In comparison, curves in Fig. 9 were measured during fine weather with partly cloudy skies. All data shown was recorded between 5:00 to 19:00 o'clock. Information regarding temperature fluctuation is represented by ambient temperature. The actual temperature of PV module surface is higher than the ambient temperature by 20°C approximately.

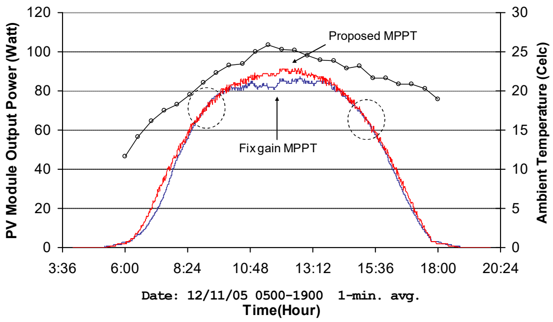


Fig. 8. Output power of PV module under fine and clear skies.

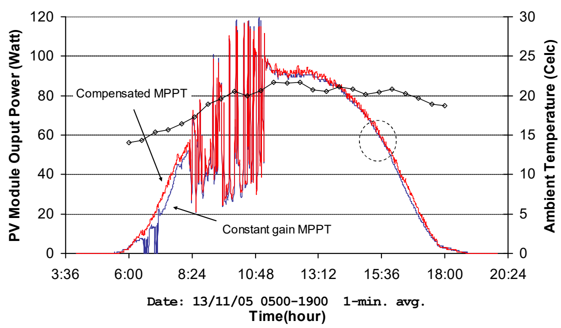


Fig. 9. Output power of PV under fine weather with partly cloudy skies.

The circles marked in Fig. 8 and Fig. 9 denote the circumstances where constant gain MPPT delivers the same performance when compared with the compensated MPPT. At these points, experimental results confirm the simulation results (denoted by T_x in Fig. 7). Comparison of extracted energy from the PV module using the proposed MPPT and constant gain MPPT is summarized in Table 3. It is obvious that the buck converter equipped with the proposed MPPT captured a higher amount of energy. Energy captured using the proposed MPPT in two cumulative days is 4.28% higher than that which the constant gain MPPT achieved.

Table 3. Extracted energy during field test.

Date	Extracted Energy: Constant gain MPPT	Extracted Energy: Compensated MPPT	Weather
12/11/2005	716 Wh	685 Wh	Fine, clear
13/11/2005	669 Wh	643 Wh	Fine, partly cloudy

VI. CONCLUSION

This paper presented the drawback of a constant gain P-I based MPPT scheme for a PV module where the maximum power operation deviates because of temperature variation. It was shown that compensation using a temperature gain dependent element can improve MPPT performance. Simulation results show an improved response for the proposed MPPT scheme at low and higher irradiance levels, at a temperature range between 10°C to 70°C. A prototype of the proposed MPPT was built using low cost analogue circuits to verify the fast response and high performance in locating maximum power. Field test results show a significant improvement of the proposed MPPT scheme, which can extract about 4% more energy from a PV module than the constant gain MPPT.

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