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# A Reliable Maximum Power Point Tracker for Photovoltaic Systems

***Abstract**. This paper presents a reliable maximum power point tracker (MPPT) for photovoltaic (PV) systems. This MPPT tracks the maximum power point of a PV module by calculating the optimum resistance of the PV module at certain solar radiation level, ambient temperature value and load impedance. The calculated resistance is used to calculate the optimum duty cycle of the DC-DC converter triggering signal using a developed relation. Based on results, the proposed MPPT has better efficiency (95%) than perturbation and observation (P&O) method (92 %). Moreover, the proposed method is faster than P&O method because there is no perturbation around the MPP during the tracking process.*

***Streszczenie.** W artykule zaprezentowano układ śledzący maksymalną pobieraną moc dla system fotovoltaicznego. Moc jest wyznaczana na podstawie optymalnej rezystancji przy danym nasłonecznieniu, temperaturze otoczenia i impedancji obciążenia. Zaproponowany system jest bardziej skuteczny niż metoda zakłóceń I obserwacji P&O. (**Skuteczny układ śledzenia maksymalnej mocy systemu fotowoltaicznego**)*

**Keywords:** MPPT, PV systems, DC-DC buck converter.
**Słowa kluczowe:** baterie słoneczne, śledzenie mocy.

## Introduction

Recently, the maximum power point tracking technology becomes very important for photovoltaic systems. Consequently, many developments have been done in this area until it reached the saturation phase. As a result, the interest of the authors when implementing this work has been focused on achieving a certain added value in the proposed system, which can be found in the accurateness, speed and low cost [1]. Thus, the developed algorithm presents the advantage of its simplicity and its high speed which also helps to improve photovoltaic system efficiency.

In general, to overcome the undesired effects on the output PV module's power because of load variation , a DC/DC converter can be inserted between the PV generator and the load (batteries and typical loads), which can control the seeking of the MPP, beside including the typical functions assigned to the controllers. These converters are normally named as maximum power point trackers (MPPTs). They consist of a topology and control circuit where there will be a MPP seeking algorithm. The input DC–DC converter is formed by the PV array and the output section of the batteries and load. The role of the MPPT is to ensure the operation of a PV generator at its MPP, extracting the maximum available power [1].

The methods of maximum power tracking developed up until now can be grouped by their control strategies used. Thus, two categories can be presented: direct and indirect methods. Direct methods include those methods that use PV voltage and/or current measurements. From those, and taking into account the variations of the PV generator operating points, the optimum operating point is obtained. These algorithms have the advantage of being independent from the a priori knowledge of the PV generator characteristics. Thus, the operating point is independent of isolation, temperature or degradation levels. The problems are undesirable errors which strongly affect tracker accuracy. The methods belonging to this group include the differentiation, feedback voltage (current), P&O, conductance incremental (C.I.), auto-oscillation as well as the fuzzy logic, among others. The indirect methods are based on the use of a database that includes parameters and data such as, for instance, curves typical of the PV generator for different irradiances and temperatures, or on the use of the mathematical functions obtained from empirical data to estimate the MPP. In most cases a prior evaluation of the PV generator is then required, or else it is based on the mathematical relationship obtained from empirical data, which does not meet all climatologic conditions. The following methods belong to this category (indirect methods): curve fitting, look-up table, open-voltage PV generator and short circuit PV generator [1].

The proposed method tracks the maximum power point by calculating the optimum duty cycle which investigates the optimum resistance. The optimum duty cycle calculation is based on load's equivalent impedance, theoretical optimum voltage and theoretical optimum current. A buck DC-DC converter triggered by a signal has the calculated duty cycle will be used in order to reach the optimum operating point.

## The mathematical model of the photovoltaic module

The equivalent electric diagram of a PV module is shown in Figure 1. The PV module's electric characteristics under solar radiation are given in terms of output current Ipv and voltage Vpv [2]:

(1) $$I_{PV} = I_L - I_o[\exp(\frac{V_{PV} + R_p I_{PV}}{V_T})] - \frac{V_{PV} + R_S I_{PV}}{R_P}$$

Io=NpIos corresponds to the reverse-saturation current of the solar array, with Ios the cell reverse saturation current. (VT=(NsnKBT)/q )is the thermal voltage, where Ns is the number of cells connected in series, KB the Boltzmann's constant, n the ideality factor, T the cell temperature, q the electron charge; Rs the series parasitic resistance of a solar array and Rp its shunt parasitic resistance. The load resistance is represented by RLoad. The PV array's short-circuit current Isc and open-circuit voltage Voc at solar intensity G and cell temperature T are given by [3]:

(2) $$I_{SC} = I_{SC}^{*}(\frac{G}{G^{*}}) + \alpha_1 (T - T^{*})$$

(3) $$V_{oc} = V_{oc}^{*} + \alpha_2 (T - T^{*}) - (I_{SC} - I_{SC}^{*}) R_S$$

Where Isc and Voc are the PV array short-circuit current and open-circuit voltage at the reference solar intensity G* and the reference solar cell temperature T*, and α1 and α2 are the solar cell temperature coefficients, respectively, for current and voltage. An ideal PV module is one for which Rs is zero and Rp is infinitely large. The output current and voltage are then

(4) $$I_{PV} = I_L - I_o[\exp(\frac{V_{PV}}{V_T}) - 1]$$

(5) $$V_{PV} = V_T \ln[\frac{I_L - I_{PV}}{I_o} + 1]$$

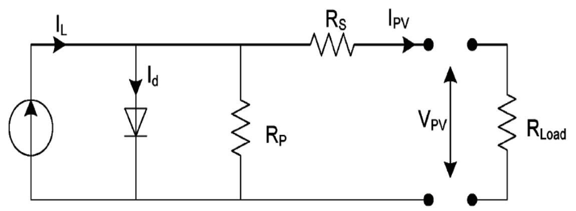


Fig. 1. Equivalent electric diagram of a solar module.

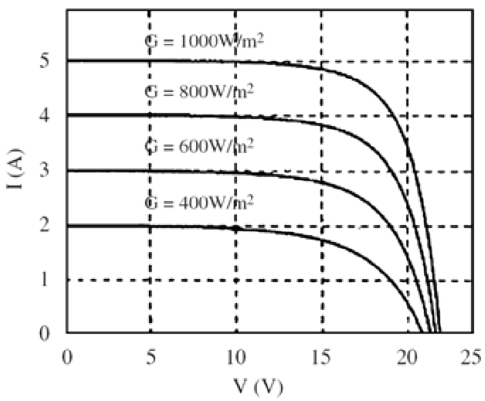


Fig. 2a Solar radiation influence on I-V characteristic curve at constant module temperature

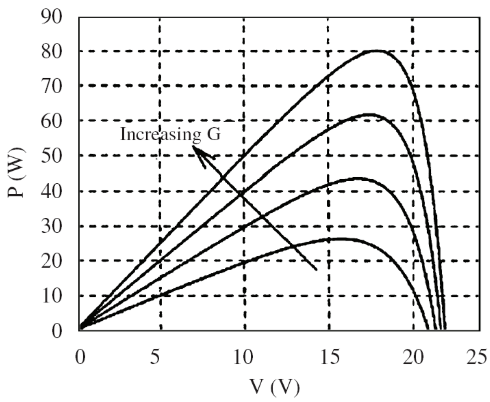


Fig. 2b Solar radiation influence on P-V characteristic curve at constant module temperature

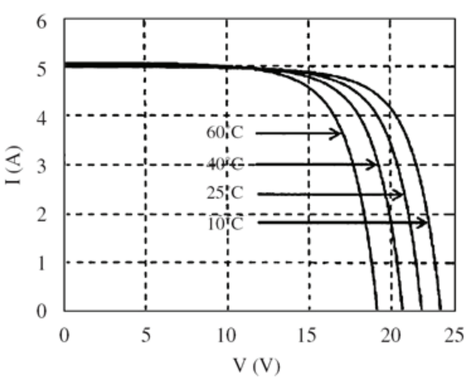


Fig. 3a Temperature influence on I-V characteristic curve at constant solar radiation

The PV module characteristic presents three important points: the short circuit current Isc, the open-circuit voltage Voc and the optimum power $P_{op}$ delivered by the PV module to an optimum load $R_{op}$ when the PV module operate at its MPP. Figures 2 and 3 give the current–voltage (I–V) and power–voltage (P–V) characteristics of a PV module for different values of solar radiation and temperature. The short circuit current is clearly proportional to the solar radiation (Figure 2(a &b)): more radiation, more current, and also more maximum output power. On other hand the temperature dependence is inverse (Figure 2(a &b)): an increase in temperature causes a reduction of the open-circuit voltage (when sufficiently high) and hence also of the maximum output power. Hence these opposite effects of the variations of solar radiation and temperature on the maximum output power make it important to track the MPP efficiently.

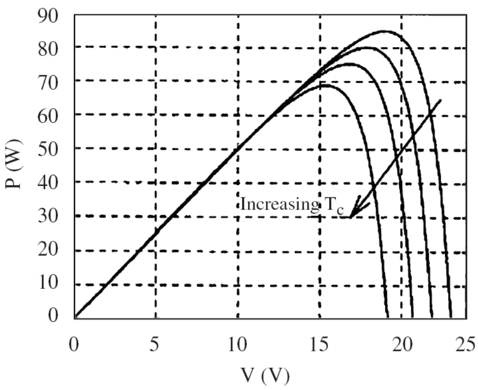


Fig. 3b Temperature influence on P-V characteristic curve at constant solar radiation

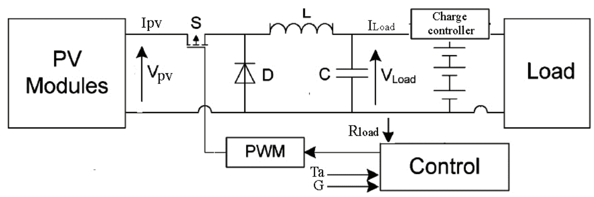


Fig. 4 Proposed PV system

## The proposed maximum power point tracker

Figure (4) shows the proposed PV system which is consisted of photovoltaic modules and loads (chargeable battery and normal load). A buck DC-DC converter controlled by a microcontroller has been installed between the photovoltaic modules and the loads to track the maximum power point. Moreover, the chargeable battery is controlled by a charge controller to protect the battery from being over charged or discharged by keep measuring the battery state of charge (SOC).

Based on [5], the relations between the input parameters (module's voltage (Vpv) and module's current ($I_{PV}$)) and the output parameters (load's voltage ($V_{Load}$) and load's current ($I_{Load}$)) of the buck converter are given as below:

(6) $$\frac{V_{load}}{V_{PV}} = D$$

(7) $$\frac{I_{PV}}{I_{Load}} = D$$

where (D) is the duty cycle of a triggering signal. From Figure (4), the resistance which has been seen by the PV modules can be described as:

(8) $$R_{seenbyPV=} \frac{V_{PV}}{I_{PV}}$$

Where the equivalent resistance of the load (the storage batteries and the load) also can be given by:

(9) $$R_{load} = \frac{V_{load}}{I_{load}}$$

Substituting equations (6) and (7) in equation (9) leads to:

(10) $$R_{load} = \frac{V_{PV} D^2}{I_{PV}}$$

Consequently, form equations (8) and (10):

(11) $$R_{seenbyPV} = \frac{R_{load}}{D^2}$$

where $R_{load}$ is the equivalent resistance of the load. However, to extract the maximum power point, $R_{seen\ by\ PV}$ must be equal to $R_{optimum}$ which can be given by:

(12) $$R_{optimum} = \frac{V_{optimum}}{I_{optimum}}$$

An important consideration in the tracking process is to determine the optimum power which is calculated from the optimum voltage, $V_{optimum}$ and current, $I_{optimum}$, given by:

(13) $V_{optimum} = K_V V_{OC}$

(14) $I_{optimum} = K_i I_{sc}$

where Kv and Ki are proportional factors with typical values of Kv in the range of 0.75- 0.85 and Ki in the range of 0.9-0.92. However, the calculated optimum voltage by equation 13 using a roughly value of $K_V$ is not accurate because of two reasons, firstly, Kv has no exact value and secondly, the optimum voltage is calculated in terms of the open circuit voltage only while the thermal voltage ($V_T$) is neglected. However, a new optimum voltage is proposed in [2] and it is given by,

(15) $$V_{optimum} = \frac{V_T[\exp(\frac{V_{oc}}{V_T}) - 1]}{(1 - \frac{1}{K_1})\exp(\frac{V_{oc}}{V_T}) - 1}$$

Meanwhile, to ensure maximum power point operation, the following equation should be investigated during operation:

(16) $R_{optimum} = R_{seen\ by\ PV}$

Therefore, combining equations (13, 15, and 19) gives

(17) $$\frac{R_{load}}{D_{optimum}} = \frac{V_{optimum}}{I_{optimum}}$$

Solving for $D_{optimum}$:

(18) $$D_{optimum} = \sqrt{\frac{R_{load} I_{optimum}}{V_{optimum}}}$$

Figure 5 shows the tracking algorithm. The tracking proccess starts by measuring solar radiation, ambinet tempreture and batteries' state of charge. open circuit voltage, short cicuit cuurent and intrnal resistance of the battries calculated based on the meaured values. Then, the optimum duty cycle is calculated using equation (18).

**Simulation results**

To ensure the effectiveness of the proposed algorithm, a MATALB code for the proposed system in figure 4 has been developed. The modeled system consists of one PV module (200 Wp, 26.3 V, 7.61 A), (60 Ah/24 V) storage battery and load. Figure 6 shows the simulated load profile. The total consumption is 930 Wh where the peak of the load is 120 Watt. Figure 7 shows the simulated solar radiation profile. The peak solar radiation is 800 W/m$^2$ while the solar day long is about 12 hours.

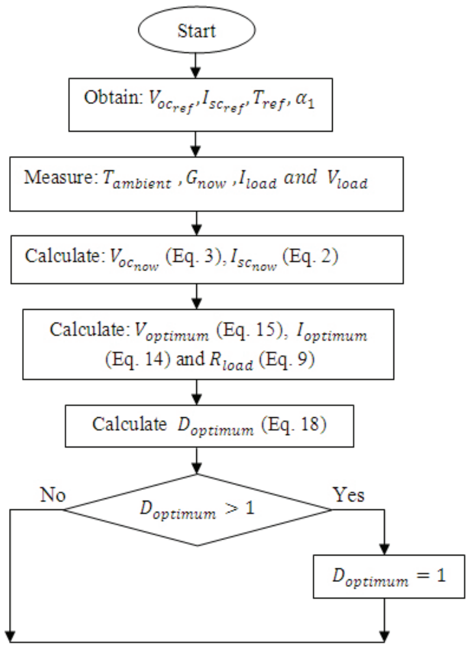


Fig. 5 Tracking algorithm

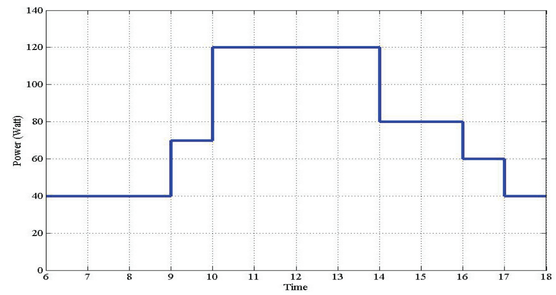


Fig. 6 Load profile

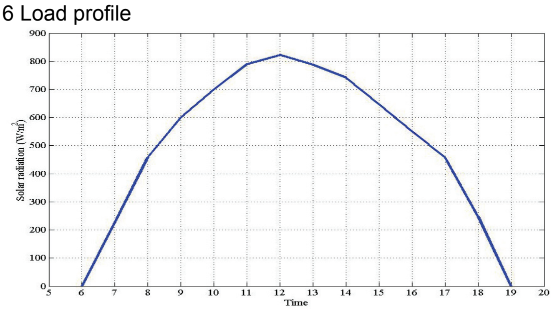


Fig 7. Solar radiation curve

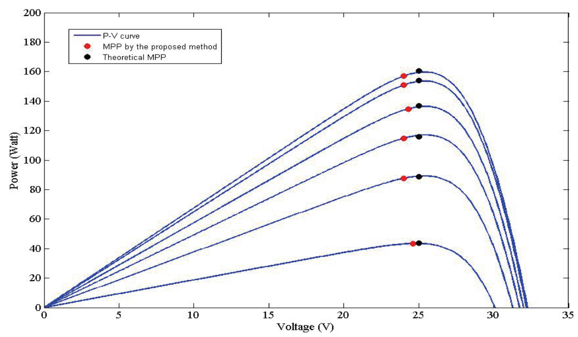


Fig. 8 MPP by the proposed method

Figure 8 shows the maximum power points which have been located by the proposed MPPT algorithm. The power point locations are close to the theoretical maximum power points. However, An MPPT efficiency can be defined as the power extracted divided on the theoretical maximum power

[1, 2]. Based on this definition, the average efficiency of the proposed method is 95 %.

For comparison purposes, the P&O method proposed in [2] has been taken as a bench mark in this research. Figure 9 shows the power extracted versus time at different load demands. From the figure, the extracted power by the proposed method is slightly higher than the P&O method proposed in [2]. In addition, Figure 10 shows the power extracted versus solar radiation. The power line is closer to the theoretical maximum power line than the proposed P&O method in [2].

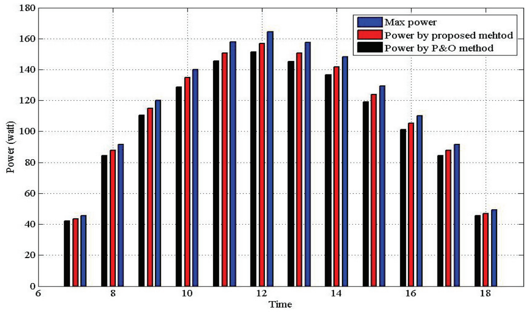


Fig. 9. Power generation at different load demands

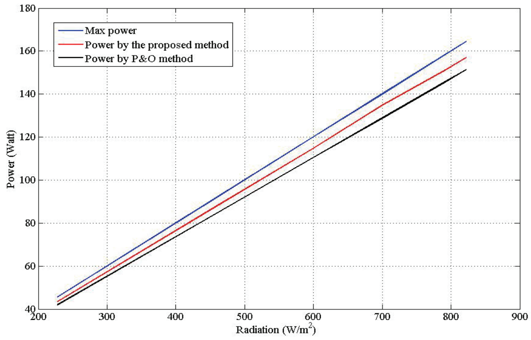


Fig. 10. Power extracted by the proposed method

Finally, Figure 11 shows the efficiency of the proposed method compared with the efficiency of the proposed P&O method in [2]. The efficiency of the proposed method (95%) is higher than the P&O efficiency (92%)

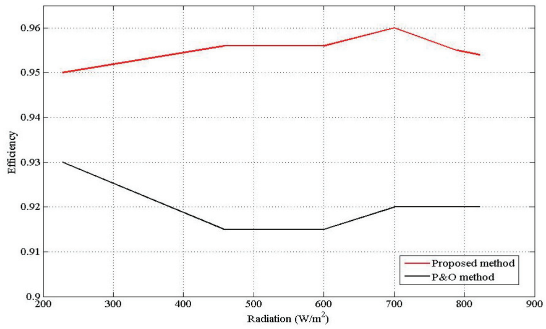


Fig. 11. Tracking efficiency

## Experiment results

The proposed system was tested using an existed hybrid PV/wind system at the “Solar Park” of Solar energy research institute (SERI)\ University Kebangsaan Malaysia (UKM). The hybrid system is consisted of 240 Watt PV system and 60 Watt wind turbine. The PV system is consisted of 4 PV modules each one is a 60 Wp PV module. These PV modules charge 12V/78Ah battery, while, the battery supplies the loads through a 400 watt inverter. This hybrid system supplies lighting loads and one ventilation unit where both together are 50 Watt total power. However, the PV system is being operated without MPPT , thus, a comparison of the PV system performance with and without MPPT has been done in order to test the impact of the proposed MPPT.

The existed PV system is designed to charge the battery completely in one solar day (11 hours). Therefore, to do the test, the testing PV system is supposed to charge the battery until being fully charged then at night time the battery is discharged by the loads for 12 hours and so on. This test was done for 6 days, 3 days without MPPT while 3 days with MPPT.

Table 1. PV system performance

| without MPPT | | | | |
|---|---|---|---|---|
| Day | PSH | Initial SOC | Final SOC | charging hours |
| 1 | 5.1 | 45% | 95.2% | 11 hours |
| 2 | 4.6 | 41% | 80.9% | 11 hours |
| 3 | 5.2 | 50% | 99.5 % | 10.6 hours |
| with MPPT | | | | |
| 4 | 5.7 | 50% | 99.4% | 8.6 hours |
| 5 | 5.3 | 48% | 99.9% | 9.7 hours |
| 6 | 5.1 | 43% | 99.6% | 11 hours |

Table 1 shows the comparison of the PV system performance with and without MPPT. From the table, the time which is needed to fully charge the battery in the case of the PV system with MPPT is less than the charging time needed to fully charge the battery in the case of the PV system without MPPT. Moreover, the battery state of charge in the case of the PV system with MPPT reached almost 100% in all the testing days while the battery state of charge in the PV system which has been operated without MPPT did not reach 100% in all the testing days. This to say the PV system with MPPT generated more energy, therefore, its efficiency is higher that the PV system without MPPT.

## Conclusion

A reliable maximum power point tracker for photovoltaic systems has been proposed. The new MPP controller tracks the MPP using the equivalent impedance of a load. Simulation results show that the tracking efficiency of the proposed method is 95% as an average value which is higher than P&O method which is 92% based on [4]. Moreover, the response of the proposed tracker is faster than P&O method because there is no perturbation around the operation point. Such proposed controller increases the efficiency and the reliability of a photovoltaic system.

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