MPPT ALGORITHM EFFECTS ON THE PERFORMANCE OF A SMALL SCALE GRID-CONNECTED PV ARRAY SYSTEM

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Abstract

Currently, the direct conversion of solar energy into electricity is being accepted as an important form of power generation. This electricity generated by a process known as the photovoltaic effect, using photovoltaic (PV) system. The operating power of PV system depends on the sun's intensity, the ambient temperature and the PV system output voltage (PV load). The maximum power point tracking (MPPT) algorithms usually are used in PV system in order to make the system operate with maximum efficiency. Many of MPPT algorithms/techniques for PV system have been proposed vary in complexity, sensors required, convergence speed and dynamic response, cost, range of effectiveness, implementation hardware, popularity, and in other respects. In this paper, some most widely-used of MPPT algorithm will be reviewed and studied, in order to develop a PV model with MPPT algorithm, refer to an existing a small scale grid-connected PV array system at Szent István University (SIU). Simulation results of MPPT line characteristics, both for ASE-100 (polycrystalline technology) and DS-40 (amorphous silicon technology) modules, as main components of grid-connected PV array at Szent István University, will be shown, as a preliminary step to understand the voltage critical values of each module at different weather conditions.

Keywords: power generation, sun's intensity, ambient temperature, the maximum power point tracking, voltage critical values.

1. Introduction

Solar energy is one of the most promising renewable resources that can be used to produce electric energy through photovoltaic (PV) system, which convert directly the energy contained in photons of light into electrical energy. PV generation is becoming increasingly important as a renewable source since it offers many advantages such as incurring no fuel costs, not being polluting, requiring little maintenance, and emitting no noise, among others.

The amount of power generated by a PV system depends on the operating voltage of the system. The current-voltage-power (*I-V-P*) characteristic of PV systems is nonlinear and depending on atmospheric conditions, such as solar irradiation and temperature. In general, there is a unique point on the *I-V-P* curve, called the Maximum Power Point (MPP), at which the entire PV systems (array, converter, etc) operates with maximum efficiency and produces its maximum output power. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. Therefore Maximum Power Point Tracking (MPPT) techniques are needed to maintain the PV array's operating point at its MPP. Moreover, since the power efficiency of PV system available in the market still low, the PV systems must be ensured to operate always on the maximum power point (Lalili et al., 2011).

Currently, many of MPPT algorithms/methods have been developed and implemented. The methods vary in complexity, sensors required, convergence speed and dynamic response, cost, range of effectiveness, implementation hardware, popularity, and in other respects. They range from the almost obvious (but not necessarily ineffective) to the most creative (not necessarily most effective). In fact, so many methods have been developed that it has become difficult to adequately determine which method, newly proposed or existing, is most appropriate for a given PV system (Esram et al., 2007). However, the MPPT main mission generally is to adapt the operation point of the module, usually modifying its output voltage, in order to adapt the system to different irradiance conditions and also to temperature variations (Calavia et al., 2010).

Generally, PV system can be operated in three categories: stand-alone, grid-connected or hybrid modes. Currently, the grid-connected PV array system application is widely used in the worlds, and typically can be seen in Fig. 1. and composed of five main components as follow (Liu et al., 2004):

1) A PV array that converts solar energy to electric energy,
2) A DC-DC converter that converts low DC voltages produced by the PV arrays to a high DC voltage,
3) An inverter that converts the high DC voltage to a single-or three-phase AC voltage,
4) A digital controller that controls the converter operation with MPPT capability, and
5) A DC filter that absorbs voltage/current harmonics generated by the inverter.

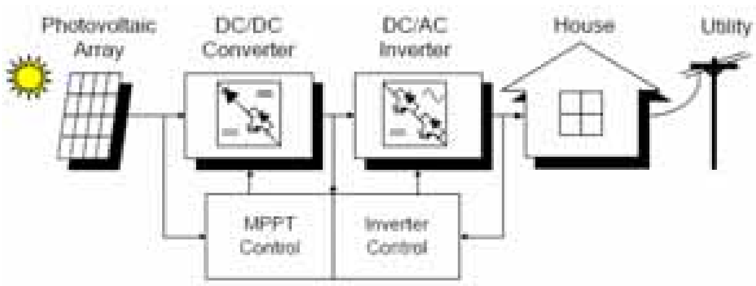


Fig. 1: A grid-connected PV power system block diagram

In the framework of the PV Enlargement project of EU, since October 8, 2005, a fixed frame 10 kWp grid-connected PV array system, has been installed at Szent István University (SIU), Gödöllő, Hungary, with the surface orientation of PV system is 30^o for tilt angle (β) and 5^o to East (or -5^o) for azimuth angle (γ), for South facing. The system was installed on the flat roof of SIU Dormitory building and is structured into 3 sub-systems. Sub-system 1 consists of 32 pieces of ASE-100 type modules (RWE Solar Gmbh) from polycrystalline PV technology, and sub-system 2 and 3 consists of 77 pieces of DS-40 type of modules (Dunasolar Ltd) from amorphous silicon PV technology, respectively. The total power of the system is 9.6 kWp with total PV surface area 150 m^2. Recently, performance analysis both energetic and exergetic has been performed theoretically, and it‘s found that efficiency energy and efficiency exergy for ASE-100 module are 15.72 % and 11.82 %, respectively and for DS-40 are 8.88 and 4.40, respectively. Meanwhile based on experiment it's found that actual efficiency for ASE-100 and DS-40 is 13% and 4%, respectively. Fig. 2 shows the schematic diagram of a 10 kWp grid-connected PV array at SIU, Gödöllő – Hungary (Seres et al., 2009).

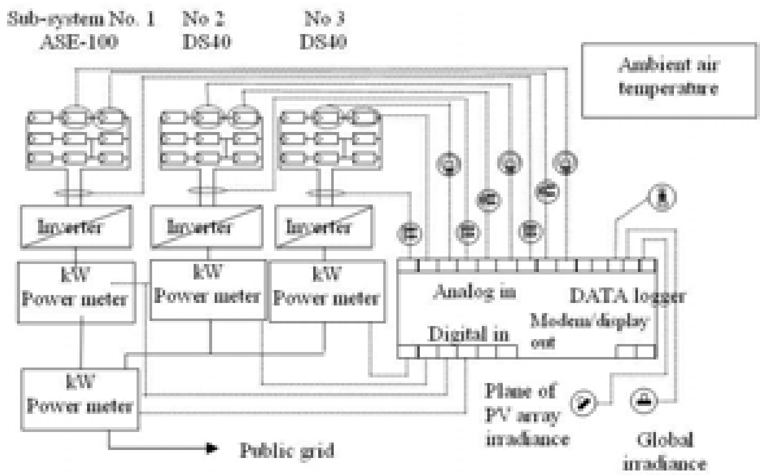


Fig. 2: The schematic diagrams of a 10 kWp grid-connected PV array at Szent István University, Gödöllő – Hungary.

In the present work, some of most widely-used of MPPT algorithm such as perturbation and observation algorithm, incremental conductance (fixed and variable-step algorithm), etc. will be reviewed and studied, in order to develop a PV model with MPPT algorithm, refer to an existing a small scale grid-connected PV array system at SIU. Simulation results of MPPT line characteristics by PVSOL 3.0 software packages, both for ASE-100 (polycrystalline technology) and DS-40 (amorphous silicon technology) modules (as main components of grid-connected PV array at SIU), will be shown as well, as a preliminary phase to understand the voltage critical values of each module at different weather conditions. As a further outcome, a PV model with appropriate MPPT algorithm and its effects on the performance parameter of PV array system at SIU will be developed, simulated and evaluated.

2. Mathematical model of PV system

2.1. Mathematical model of PV cell

The basic component of PV system is the PV cell (solar cell). The equivalent electric circuit diagram of PV cell is shown in Fig. 3, which consists of a photocurrent source, a diode, a parallel resistor expressing a leakage current and a series resistor describing internal resistance to the current flow.

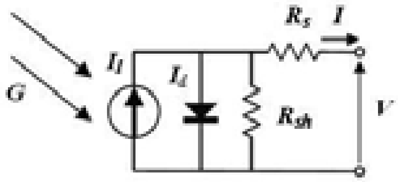


Fig. 3: General model of PV cell in a single diode model (five model parameter)

The PV cell's electric characteristics under solar radiation *G* is given in terms of PV cell output current *I* (A) and PV cell voltage *V* (V) and the basic equations describing *I-V* characteristics of the PV cell model are given in the sets equations as follow:

$$I = I_l - I_d - I_{sh}, \quad (1)$$

$$I_d = I_o\left[exp\left(\frac{V_d}{\frac{nkT_c}{q}}\right) - 1\right] = I_o\left[exp\left(\frac{V_d}{V_t}\right) - 1\right], \quad (2)$$

$$V_t = \frac{nkT_c}{q}, \quad (3)$$

$$V_{sh} = V_d, \quad (4)$$

$$V_d = V + IR_s, \quad (5)$$

$$I_{sh} = \frac{V_{sh}}{R_{sh}} = \frac{V_d}{R_{sh}}, \quad (6)$$

$$I_{sh} = \frac{V + IR_s}{R_{sh}}, \quad (7)$$

$$I = I_l - I_o\left[exp\left(\frac{V + IR_s}{\frac{nkT_c}{q}}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}. \quad (8)$$

where I_l is the light generated current (A), I_o is the diode saturation current (A), R_s is the cell series resistance (ohms), R_{sh} is the cell shunt resistance (ohms), V_d is the diode voltage (V), V_t is the thermal voltage (V), n is diode quality factor or an ideality factor (1 or 2), k is the Boltzmann's constant (= 1.381 x 10^{-23} J/K), T_c is the cell working temperature (K) and q is an electron charge (=1.602 x 10^{-19} C).

For an ideal solar cell, there is no series loss and no leakage to ground, i.e., $R_s = 0$ and $R_{sh} = \infty$. With this assumption, the equation (8) can be rewritten as:

$$I = I_l - I_o \left[exp \frac{V}{\left(\frac{nkT_c}{q} \right)} - 1 \right]. \tag{9}$$

Equations (8) and (9) can be used in computer simulation to obtain the output characteristics of PV cell, as shown in Fig. 4. This curve clearly shows that the output characteristics of a PV cell are non-linear and are crucially influenced by solar radiation G, operating cell temperature T_c and load condition R. Each curve has a maximum power point (MPP), at which the solar array operates most efficiently (Air Jiang et al., 2005).

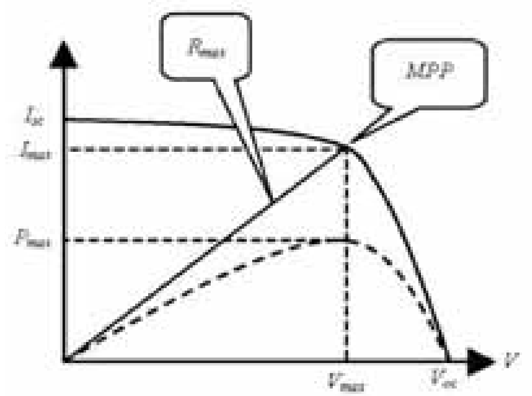


Fig. 4: I-V-P characteristic of PV cell

The PV system characteristic present three important points: the short circuit current I_{sc}, the open circuit voltage V_{oc} and the optimum power P_{max} delivered by PV system to an optimum load R_{op} (or R_{max}) when the PV system operate at their MPP. Short circuit current (I_{sc}) is the maximum current, at $V = 0$. In the ideal condition, if $V = 0$, $I_{sc} = I_L$. Open circuit voltage (V_{oc}) is the maximum voltage, at $I = 0$.

The power curves on Fig. 4 show that the optimum power point corresponds to a load connected to the PV system that varies with the ambient conditions of irradiation and temperature. In practice this variable optimal load will be achieved through the use of a variable duty cycle (d) of the control part of MPPT converter, which controls directly the operating voltage which corresponds to this optimal load.

2.2. Mathematical model of PV module/panel/array

PV cells are grouped together in order to form PV modules/panel/array, which are combined in series and parallel to provide the desired output power. When the number of the cells in series is N_s and the number of cells in parallel is N_p, the relationship between the output current and voltage is given by:

$$I_{l,tot} = N_p I_l , \tag{10}$$

$$I_{o,tot} = N_p I_o , \tag{11}$$

$$n_{tot} = N_s n , \tag{12}$$

$$R_{s,tot} = \frac{N_s}{N_p} R_s , \tag{13}$$

$$I = N_p I_l - N_p I_o \left[exp\left(\frac{\left(V + I \frac{N_s}{N_p} R_s \right)}{N_s \left(\frac{nkT_c}{q} \right)} \right) - 1 \right] - \frac{V + I \frac{N_s}{N_p} R_s}{R_{sh}}, \qquad (14)$$

$$I = N_p I_l - N_p I_o \left[exp\left(\frac{\left(\frac{V}{N_s} + \frac{IR_s}{N_p} \right)}{\left(\frac{nkT_c}{q} \right)} \right) - 1 \right] - \frac{\frac{N_p}{N_s} V + IR_s}{R_{sh}}. \qquad (15)$$

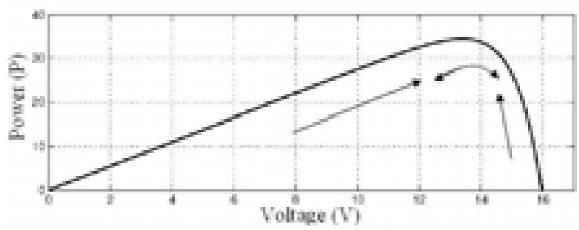
For ideal condition R_s very small ($R_s = 0$) and R_{sh} very large ($R_{sh} = 0$)

$$I = N_p I_l - N_p I_o \left[exp\left(\frac{\left(\frac{V}{N_s} \right)}{\left(\frac{nkT_c}{q} \right)} \right) - 1 \right]. \qquad (16)$$

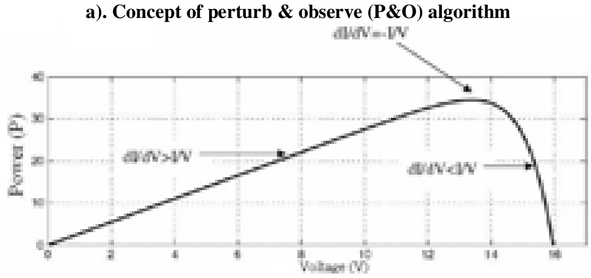
Equation (8) – (9) is applied for single PV cell and equation (15) - (16) is applied for module/panel/array. The complete behaviour of a single diode model PV cells is described by five model parameters (I_l, n, I_o, R_s, R_{sh}) which are representative of a physical PV cell/module.

3. Maximum power point tracking (MPPT) algorithms

Many maximum power point tracking (MPPT) algorithms have been proposed and developed in the literature, such as perturbation and observation (P&O) algorithm, the incremental conductance (IC) algorithm (see in Fig. 5), constant voltage and current algorithm, parasitic capacity algorithm, model based algorithm and intelligent-based algorithms (included the artificial neural network technique and the fuzzy logic control technique). Among them, the "perturbation and observation" and the "incremental conductance" algorithms are probably the most extensively used in commercial MPPT system. However, there is no clear agreement on which algorithm is the best (Air Jiang et al., 2005, Faranda et al., 2008 and Enrique et al., 2010)



a). Concept of perturb & observe (P&O) algorithm



a). Concept of incremental conductance (IC) algorithm

Fig. 5: Most widely used of MPPT algorithms principle operation for PV system

A very short description of the most usual of MPPT algorithms are presented below.

3.1. Perturbation and observation algorithm of MPPT (P&O MPPT)

The Perturbation and Observation algorithm of MPPT is probably the most frequently used in practice, mainly due to its simplicity and easy implementation. P&O MPPT has been used to track the MPP by continuously changing the operating voltage point of PV system. In this method, small increasing (incrementing) or decreasing (decrementing) on the PV operating voltage will be applied and refers to that the PV power output at the present and the previous perturbation cycle is compared it.

The main concept of this algorithm is to push the system to operate at the direction which the output power obtained from the PV system increases. Following equation describes the change of power which defines the strategy of the P&O technique.

$$\Delta P = P_k - P_{k-1}\,. \tag{17}$$

Generally, P&O MPPT operation is briefly explained as follows: assume that the PV system (module/panel/array) operates at a given point, which is outside the MPP. The PV system operational voltage is perturbed by a small ΔV, and then the change in the power (ΔP) is measured. If $\Delta P > 0$, the operation point has approached to the MPP and therefore, the next perturbation must take place in the same direction as the previous one (same algebraic sign). If, on the contrary, $\Delta P < 0$, the system has moved away from the MPP and, consequently, the next perturbation must be performed in the opposite direction or opposed algebraic sign **(Tafticht et al., 2008, Enrique et al., 2010 and Chin et al., 2011).** Detail illustration for various cases can be seen in Fig.6.

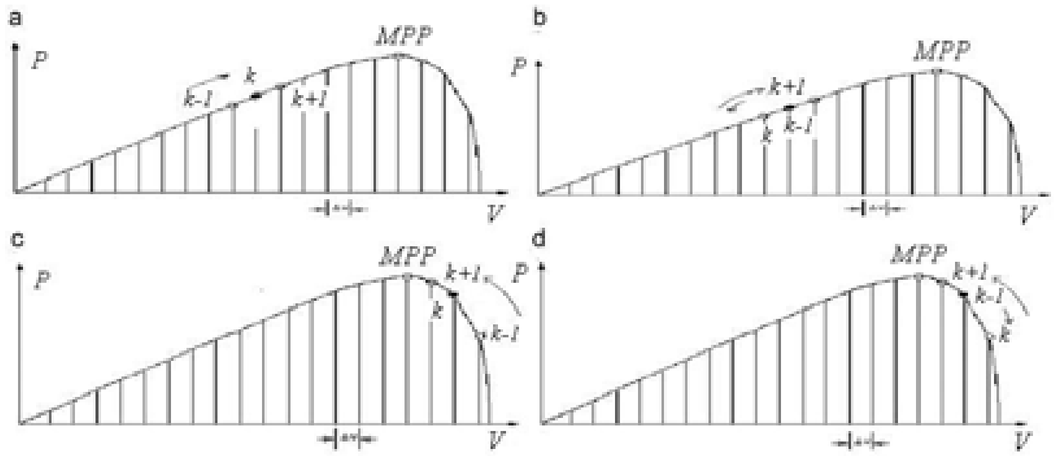


Fig. 6: Four cases of displacement of the operating point

Based on Fig.6, MPP search control analysis for above four cases can be summarized in Table 1.

Tab. 1: Summary of control action for various operating points

Case	ΔV	ΔP	$\frac{\Delta P}{\Delta V}$	Tracking direction	d: Duty cycle control action
a	+	+	+	Good direction	Increase: $d(k) = d(k-1) + \Delta d$
b	-	-	+	Bad direction	Increase: $d(k) = d(k-1) + 2\Delta d$
c	-	+	-	Good direction	Decrease: $d(k) = d(k-1) - \Delta d$
d	+	-	-	Bad direction	Decrease: $d(k) = d(k-1) - 2\Delta d$

The PO works well when the irradiance change slowly but it presents drawbacks such as slow response speed, oscillation around the MPP in steady state, and even tracking in wrong way under rapidly changing atmospheric condition.

To establish the quality of a given MPPT system (and to be able to compare it with other systems), it is necessary to define the tracking efficiency (η) , given by :

$$\eta_{MPPT} = \frac{\int_0^t P_{inst}(t)dt}{\int_0^t P_{max}(t)dt}. \quad (18)$$

where, for radiation and temperature conditions in the given time period, $P_{inst}(t)$ is the instantaneous power supplied by the MPPT system controlled PV system, and $P_{max}(t)$ is the actual MPP power.

3.2. Incremental conductance algorithm of MPPT (IC MPPT)

The incremental conductance algorithm consists in studying the slope of the PV system power – voltage curve.

Comparative study shows that incremental inductance algorithm tracks fast the MPPT under rapid changing atmospheric conditions. The incremental conductance algorithm is based on the fact that the derivative of the PV output power with respect to output voltage is zero at the MPP, positive on the left of MPP and negative on the right of the MPP (Calavia et al., 2010 and Lalili et al., 2011).

$$\frac{dP}{dV} = 0 \text{, at MPP,} \quad (19)$$

$$\frac{dP}{dV} > 0 \text{, left of MPP,} \quad (20)$$

$$\frac{dP}{dV} < 0 \text{, right of MPP.} \quad (21)$$

Derivating the output power $P = VI$ with respect to output voltage:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV}, \quad (22)$$

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} \approx \frac{\Delta I}{\Delta V} = -\frac{I}{V}. \quad (23)$$

$\frac{\Delta I}{\Delta V}$ represents the incremental conductance, and $\frac{I}{V}$ represents the instantaneous conductance. The MPP can be tracked by comparing $\frac{I}{V}$ to $\frac{\Delta I}{\Delta V}$ as follows:

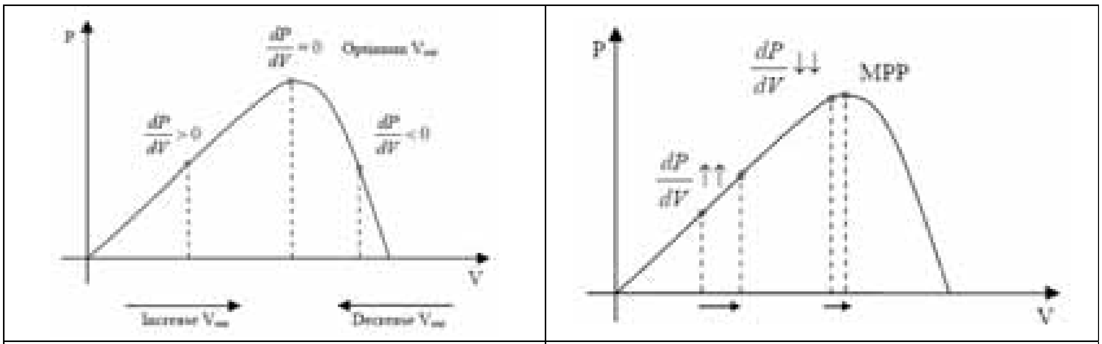
$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \text{, at MPP,} \quad (24)$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V} \text{, left of MPP,} \quad (25)$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V} \text{, right of MPP,} \quad (26)$$

The input of MPPT controller are the voltage and current of the PV array, and its output is the reference voltage used for the PMW (pulse width modulation) control of the dc-dc or dc-ac converter connected to the

PV array. When atmospheric conditions changes, the MPPT controller increments or decrements the reference voltage by a predefined iteration step in order to reach the new MPP (Fig. 7).

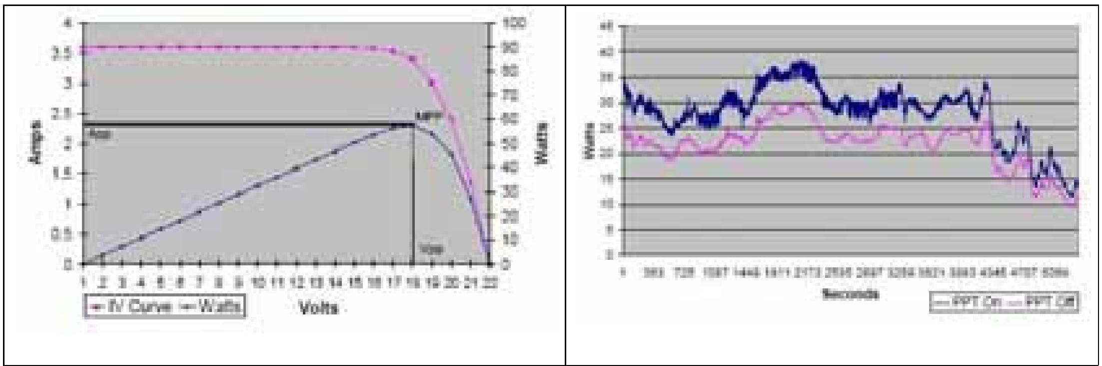


a). Operation of the fixed step IC algorithm | b). Operation of the variable step IC algorithm

Fig. 7: Type of IC algorithm and its principle operation

3.2. Some of comparative study of algorithm of MPPT

Figs. 8-10 show an illustration of comparative study between PV system with and without MPPT and also between P&O and IC algorithms.



Sample of IV curve with MPP of PV system | Sample of power measurement of PV system

Fig. 8: Effect of an MPPPT algorithm on a specified of PV (Arduino Peak Power Tracker Solar Charger, http://www.cutedigi.com)

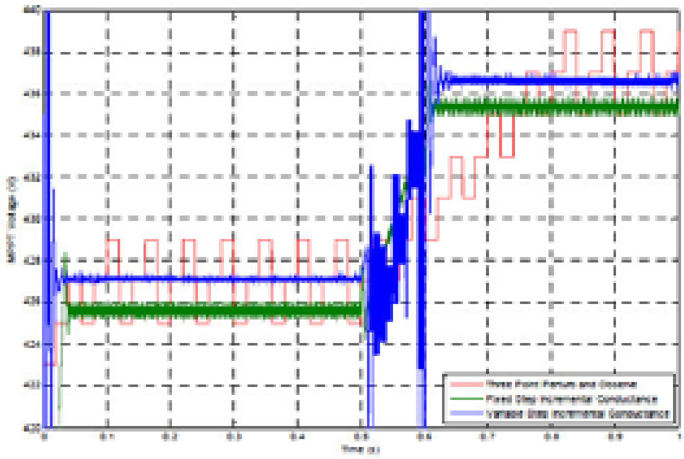


Fig. 9: Performance comparison of two types MPPT algorithms (Calavia et al., 2010)

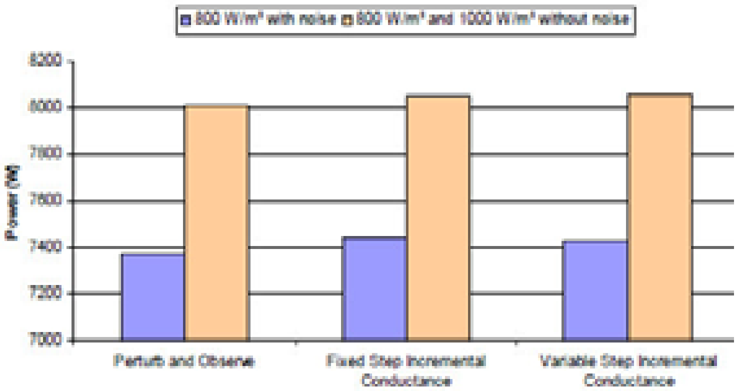


Fig. 10: Generated power comparison for the three MPPT algorithms in the two analyzed scenarios (Calavia et al., 2010)

4. An Initial evaluation of MPPT on the existing system at Szent István University

A two different of PV technologies i.e. polycrystalline silicon and amorphous silicon, as a main component of fixed frame a 10 kWp grid-connected PV array system at SIU, shown in Fig. 11 (Farkas et al., 2005).

(a) ASE-100 Polycrystalline silicon **(b) DS-40 Amorphous silicon**

Fig. 11: Different of PV module technology at SIU

The first step to evaluation a PV array performance is to calculate *I-V-P* characteristics (included to find MPPT locations) of a PV module, as a smallest component in PV array, respect to changes on environmental parameters. PV*SOL 3.0 software packages is used to simulate the *I-P-V* characteristics. Some model parameters are required for modelling is taken from Table 2 (Seres et al., 2009)

Table 2: Electrical and others parameters of ASE-100 and DS-40 module specifications.

Module parameters Electrical Module *	Sub-system 1 ASE-100	Sub-system 2 DS-40	Sub-system 2 DS-40
Typical peak power (W)	105	40	40
Voltage at peak power (V)	35	44.8	44.8
Current at peak power (A)	3	0.8	0.8
Short circuit current (A)	3.3	1.15	1.15
Open circuit voltage (A)	42.6	62.2	62.2
Temp. coefficient of open circuit voltage (%/^{o}C)	-0.38	-0.2797	-0.2797
Temp. coefficient of short circuit current (%/^{o}C)	0.10	0.0897	0.0897
Approximate effect of temp. On power (%/^{o}C)	-0.47	-0.190	-0.190
Nominal operating cell temperature/NOCT (^{o}C)	45	50	50
Others			

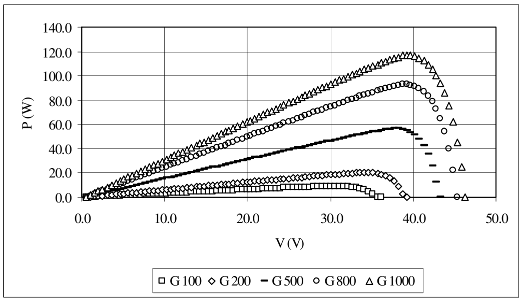
Active surface area (m^2)	0.83	0.79	0.79
Specific heat capacity (J/kg.K)	920	920	920
Absorption coefficient (%)	70	70	70
Weight (kg)	8.5	13.5	13.5
Array			
No. of modules in series (per string)	16	7	7
No. of strings in parallel (per inverter)	2	11	11
Total module area (m^2)	27	61	61

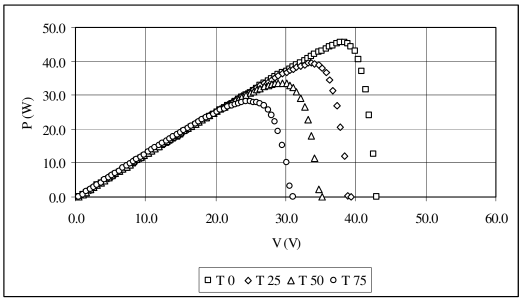
* Under Standard Test Conditions (G = 1000 W/m^2, AM = 1.5 and Tc = 25°C).

5. Results and discussions

In Figs. 12-13, the MPP ideal conditions of ASE-100 and DS-40 modules arre to be presented.

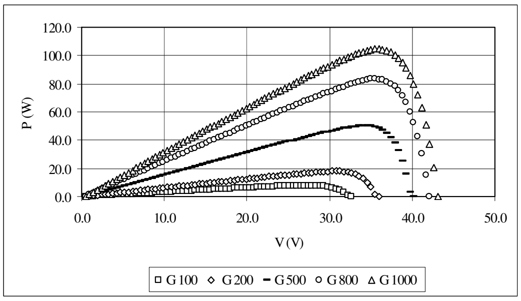
5.1. MPP Ideal condition of ASE-100 module (Variation of MPP location with change conditions)

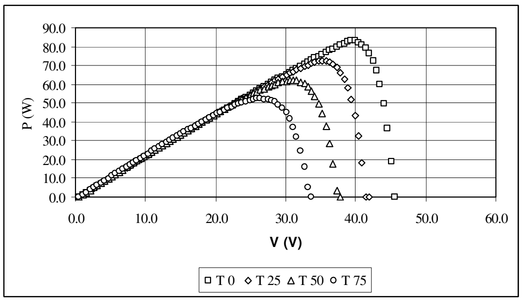




T = 5°C

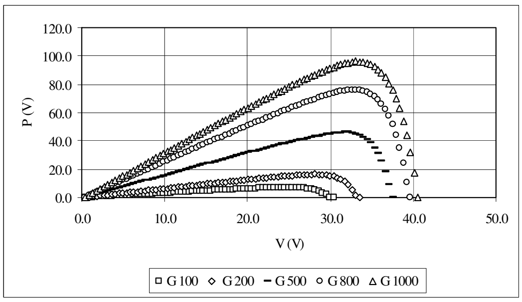
G = 400 W/m^2

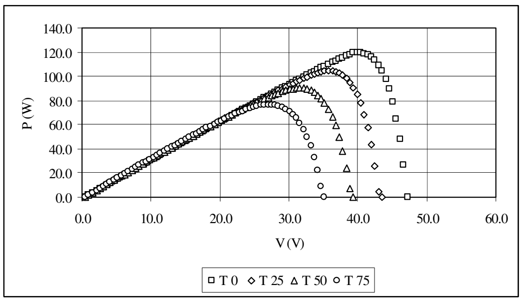




T = 25°C

G = 700 W/m^2





T = 40°C

G = 1000 W/m^2

Fig. 12: Ideal MPPT line characteristic for various *G* and *T* of ASE-100 module

Based on Fig. 12, it's clear that the output power of a PV module is influenced by solar radiation incident on the system and cell and ambient temperatures. As solar irradiance increases, the short circuit current, maximum power, and conversion efficiency increases. It is proven that as temperature increases the open circuit voltage decreases, which leads to the reduction of maximum power.

5.2. MPP Ideal condition of DS-40 module

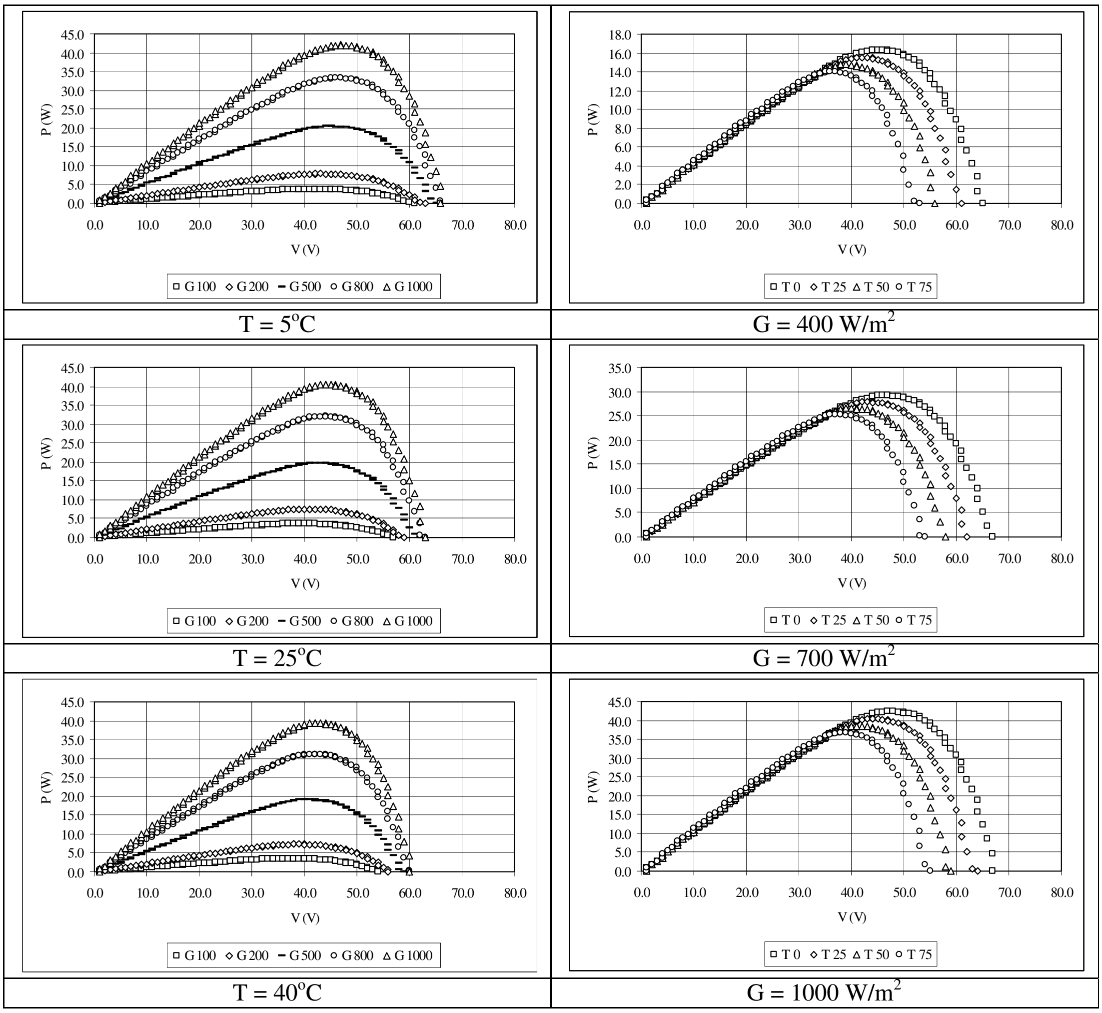


Fig. 13: Ideal MPPT line characteristic for various *G* and *T* of DS-40 module

5.3. Discussions

At predetermine condition (G and T_c or T_a), the power of the PV system has only single maximum point. Peak Power of the module changes with the change in temperature. Peak power of the module changes with the change in isolation level. Based on above figures, it is need to track the peak power in order to maximize the utilizations of the solar module/array. Methods of obtaining Peak Power can be achieved:

1. Though Manual tracking is possible but is waste of time.
2. Automatic tracking is a better choice.
3. MPPT Algorithms are used for Automatic Peak Power tracking.

6. Conclusion

An initial study to evaluate effect of MPPT algorithm on a small scale grid-connected PV array system has been elaborated, in order to develop a grid-connected PV system model and appropriate MPPT algorithm, refers to an existing installation at Szent István University.

The MPPT line characteristics of module (as a component of an existing grid-connected PV array system) are situated around critical value. In further study, effect of MPPT algorithm on the performance of PV module will be evaluated, respond to fluctuation of environment conditions.

Acknowlegements

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