Comparative study of maximum power point tracking methods for photovoltaic system

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Abstract: Maximum Power Point Tracking (MPPT) is one of the important part of photovoltaic system, which the output power and efficiency of photovoltaic system. A comparative study between Perturb and Observe (P&O) based on PID controller and incremental conductance (IC) base on PID controller verified in this paper. To verify the response of the MPPT methods under changing solar irradiance and temperature a simulation have been established by MATLAB/Simulink. Experimental study was established to test the response of both algorithms to solar radiation changes, also to compare between to the two algorithms.

Key words: Photovoltaic system, MPPT algorithm, incremental conductance, perturbs and observe PID controller

1. Introduction

Solar power generation is considered as a natural energy source that is more useful, as it is pollution free, maintenance free, distributed over the earth, fast technological progress and continuous cost reduction. Also, of all advantages of PV generation, the main technical difficulties are small conversion efficiency of electric power generation, the initial cost for its implementation is still considered high and the output power is influenced by irradiance and ambient temperature, also there are another parameters affect the maximum power as nature of the load, the technology of the PV cells and the shadowing of the panels from various sources [1]. To overcome these problems, we should track the maximum power point of PV cell's output power, thus improving the efficiency and reducing the cost [1].

Various maximum power point tracking (MPPT) algorithms such as Constant Voltage (CV) method, Perturb and Observe (P&O) method, Incremental Conductance (IC) method, Fractional Open-Circuit Voltage method, Fractional Short-Circuit Current method, Current Sweep method, Ripple correlation control method, Fuzzy Logic method, and Artificial Neural Network method, DC-Link Capacitor Droop Control method, Load Current or Load Voltage Maximization method, dP/dV or dP/dI Feedback Control method, have been proposed in literature [2]-[3]. These algorithms are differing from each other in terms of number of sensors used, complexity in algorithm and cost to implement the algorithm [2].

The P&O method has been widely used for its simple and easy control algorithm and less measured parameters, but The P&O method has a great oscillation around MPP which lead to amount of power loss special for large scale application [4]. Another method is incremental conductance method which minimizes the oscillation about the MPP.

This paper is organized as follows. Section (2) discuses modelling and characteristics of PV module. Section (3), discuses Perturb and observe method and incremental conductance method. Simulation study is reported in section (4). Experimental study is reported in section (5). Finally, conclusions are summarized in Section (6).

2. Modeling PV module

The photovoltaic cell is a p-n semiconductor junction, which convert light to electricity. The characteristic of PV cell (I-V and P-V) is a nonlinear due to change in weather condition (temperature and irradiance). PV module is composed of many PV cells. Different models of PV cell have been discussed [5].

a- Mathematical modeling of PV module

The equivalent circuit of PV cell is a photovoltaic current in parallel with a diode, shunt resistor (R_{sh}) and series resistance Rs, as shown in fig.1.

By applying Kirchhoff current law, the output current of PV cell will obtain by the equation:

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

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V + R_s.I)}{AKT_c}\right) - 1\right] - \frac{V + R_s.I}{R_{sh}} \quad (2)$$

Where I_{ph} light generated current or photocurrent (A), V represents the output PV voltage of PV cell, I_o is the saturation current, q is the electrical charge $(1.6x10^{-19}C)$, A is the p-n junction quality factor which depends on PV cell technology, k is the Boltzmann constant$(1.38x10^{-23}J/K)$, and T_c is the temperature (in Kelvin's).

The output current of PV module containing N_s cells in series is:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V + R_s.I)}{N_s.A.K.T_c}\right) - 1\right] - \frac{V + R_s.I}{R_{sh}} \quad (3)$$

The photocurrent depends on both irradiance and temperature:

$$I_{ph} = \frac{G}{G_{ref}}\left(I_{sc,ref} + \mu_{sc}.\Delta T\right) \quad (4)$$

Where G is irradiance (W/m²), G_{ref} irradiance at STC=1000 W/m², $\Delta T = T_c - T_{c.ref}$ (Kelvin), $T_{c.ref}$ cell temperature at STC in Kelvin, μ_{sc} coefficient temperature of short circuit current (A/K).

The reverse saturation current I_0 varies with temperature according to the following equation:

$$I_0 = I_{0,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 exp\left[\left(\frac{q\varepsilon_G}{A.K}\right)\left(\frac{1}{T_{c.ref}} - \frac{1}{T_c}\right)\right] \quad (5)$$

$$I_{0.ref} = I_{sc,ref} exp\left(\frac{-qV_{oc,ref}}{AKT_c}\right) \quad (6)$$

Substituting by equation (6) in equation (5) we can get the following equation:

$$I_0 = I_{sc,ref} exp\left(\frac{-qV_{oc,ref}}{AKT_c}\right)\left(\frac{T_c}{T_{c,ref}}\right)^3 exp\left[\left(\frac{q\varepsilon_G}{A.K}\right)\left(\frac{1}{T_{c.ref}} - \frac{1}{T_c}\right)\right] \quad (7)$$

Where $\boldsymbol{\varepsilon_G}$ is material band gap energy (eV), equal to 1.12 eV for silicon [5].

Substituting by equations (4) and (5) in equation (3), then implemented in MATLAB/Simulink using the electric characteristic listed in Table 1.

Table 1: electric characteristic of PV module at STC (irradiance 1000 W/m², temperature 25°C)

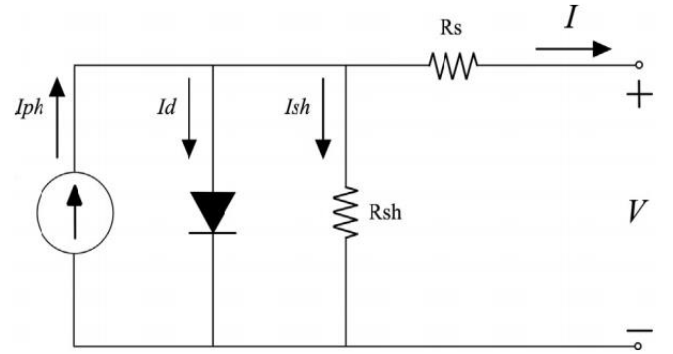| parameter	value
Maximum power (P_{mp})	49 W
Voltage at MPP (V_{mp})	17 V
Current at MPP (I_{mp})	2.88 A
Short circuit current ($I_{sc,ref}$)	3.11 A
Open circuit voltage ($v_{oc,ref}$)	21.8 V
Number of cell's in series (N_s)	36
coefficient temperature of Isc(μ_{sc})	$1.3 * 10^{-3}K°$

Fig. 1. Equivalent circuit of PV cell

b- **Characteristic of PV module**

The characteristics of PV module are shown in Fig. **2**, Fig. 3, Fig.4 and Fig.5. The curves show clearly the nonlinear characteristic due to changing weather condition. If the irradiance is increased, the output power increases. Also, if the temperature is increased, the output power decreases.

3. MPPT techniques

The function of MPPT algorithm is to automatically find the current and voltage of PV array at which maximum output power is obtained under a given irradiance and temperature. P&O and incremental conductance algorithms based on PID controller are proposed in this paper.
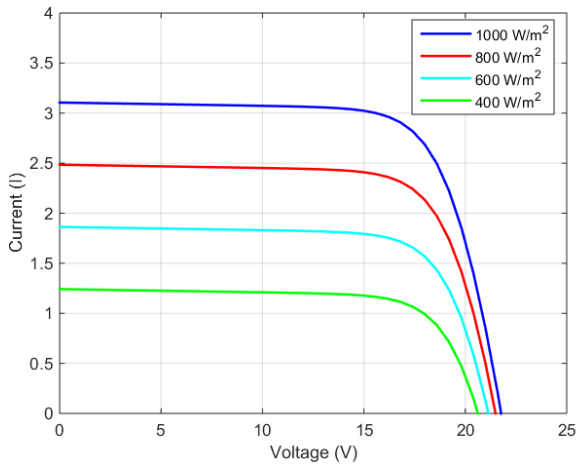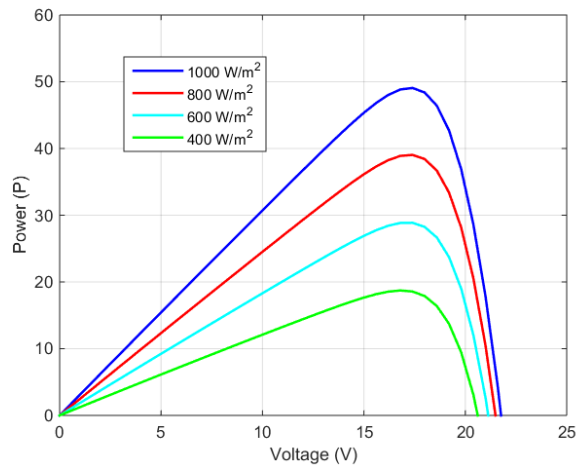
Fig. 2. The I –V curves under different irradiance, T=25°C

Fig. 3. The P –V curves under different irradiance, T=25°C
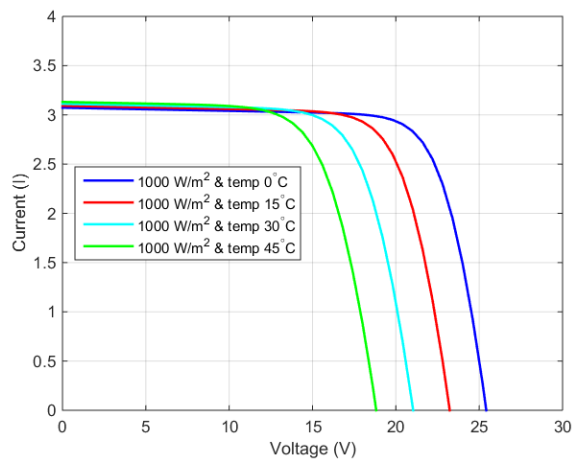

Fig.4: The I –V curves under different temperature, Irradiance=1000 W/m²
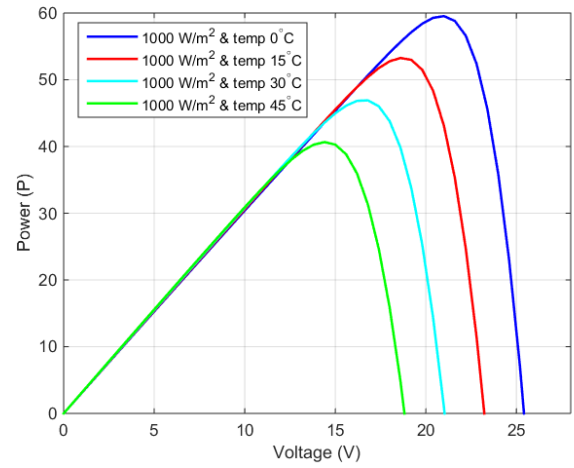

Fig.5. The P –V curves under different temperature, Irradiance=1000 W/m²

a- Perturb and Observe method

The P&O algorithm operates by periodically perturb the operating voltage and observe the output power. Then, if there is an increase in power the next perturbation is in the same direction in increasing the operating voltage, otherwise if a decreasing in output power, the direction of perturbation is reversed. The process is repeated periodically until the maximum power is obtained. The algorithm is summarized in Table 2; also the flow chart is presented in fig.6. The system then oscillates about the MPP.

The oscillation can be minimized by reducing the perturbation step size. However, a smaller perturbation size slows down the MPPT. A solution to this conflicting situation is to have a variable perturbation size that gets smaller towards the MPP as shown in [6] and [7]. In [8], fuzzy logic control is used to optimize the magnitude of the next perturbation. [10] Discuss improved P&O based on hysteresis band and auto-tuning perturbation step.

Table 2: Summary of P&O algorithm

Perturbation	Change of power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

b- Incremental Conductance Algorithm

The incremental conductance (IncCond) method is based on the fact that the slope of the PV power curve is

zero at the MPP, positive on the left of the MPP, and negative on the right.

$$\begin{cases} \frac{\Delta I}{\Delta V} = -\frac{I}{V}, & \text{at MPP} \\ \frac{\Delta I}{\Delta V} > -\frac{I}{V}, & \text{left of MPP} \\ \frac{\Delta I}{\Delta V} < -\frac{I}{V}, & \text{right of MPP} \end{cases} \quad (8)$$

The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$) as shown in the flowchart in Fig.7. Where V_{ref} is the reference voltage at which the PV module is forced to operate At the MPP, V_{ref} equals to V_{mpp}. Once the MPP is reached, the operation of the PV module is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP, The Incremental Conductance Algorithm decrements or Increments V_{ref} to track the new MPP.
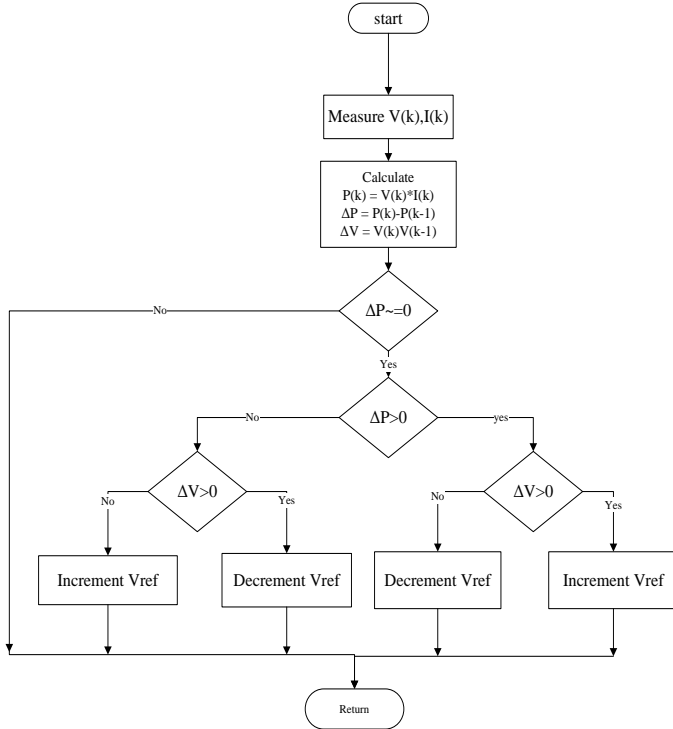

Fig. 6: Flowchart of the P&O algorithm

4. PV system configuration

The complete MATLAB/SIMULINK model of the PV system is shown in Fig.8; the modelled system consists mainly of the developmental model of PV panels, a DC-DC boost converter, and a load. In addition, it contains MPPT algorithm implemented by Simulink blocks, PID controller and PWM to derive the converter. The DC/DC boost converter is designed such that a dc link maintains a roughly constant voltage of 30V at the output of the converter. The DC/DC boost converter parameters are shown in Table 3.
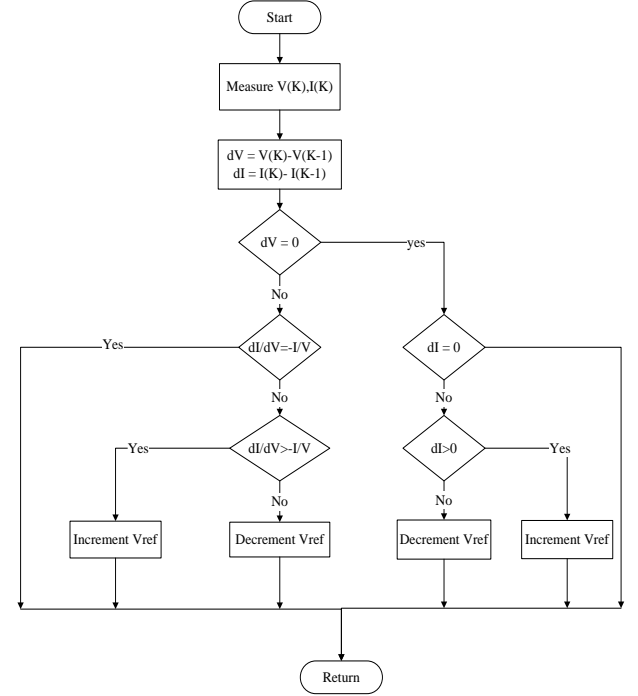

Fig. 7: Flowchart incremental conductance algorithm

Table 3: DC-DC boost converter parameters

Parameter	Value
L	50 mH
C_1	680 μF
C_2	1640 μF

The dc voltage transfer function for the boost converter can be written as:

$$V_{pv} = V_0(1 - D) \quad (9)$$

Where V_{pv}: is the voltage across the PV module at any weather condition V_o is the output voltage of boost converter, and D is the duty ratio, which serves as a control input. The controller algorithm adjusts the DC/DC converter duty ratio to track the operating point to the maximum output power delivered from the PV module.
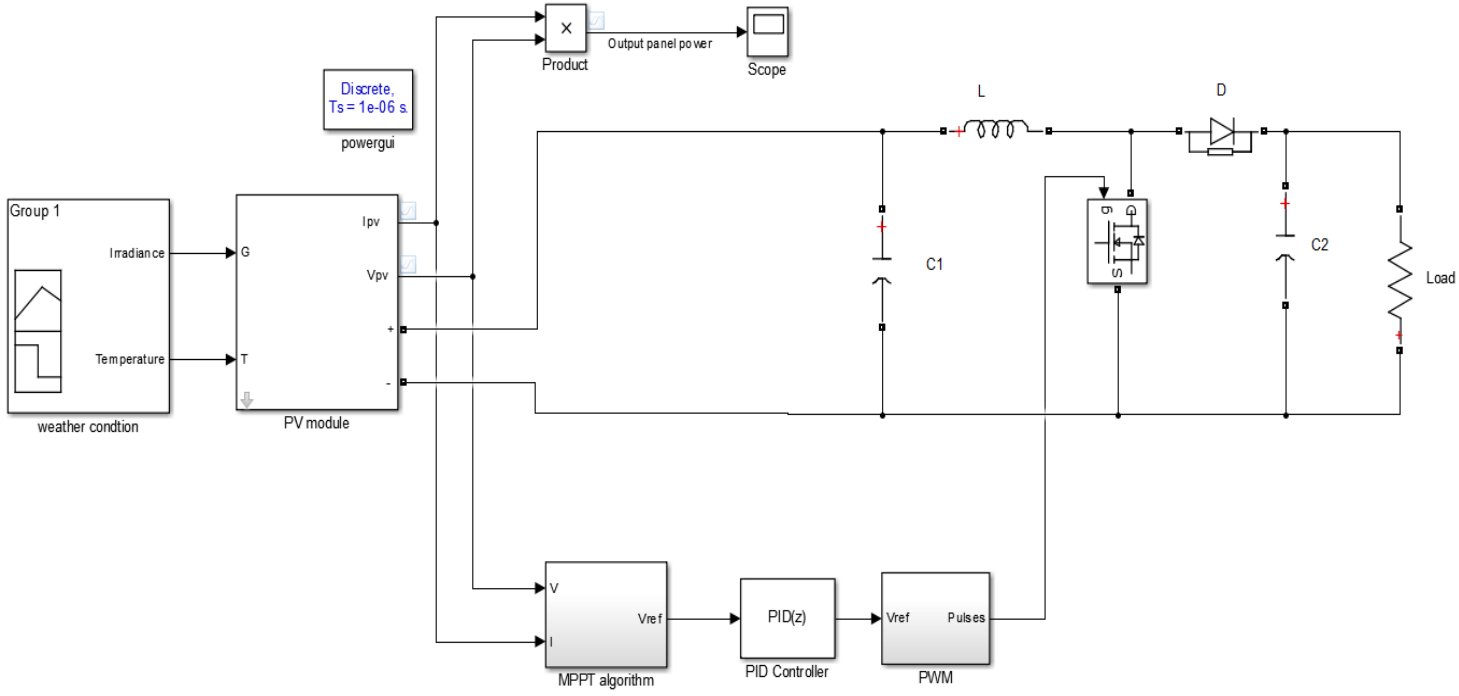
Fig. 8: PV system configuration

5. Simulation model and results

To analyze and compare the performance of the MPPT method, we carried out the simulation for two cases. The first case, the temperature is maintained constant (25°C) and the irradiance decreases from 1000 W/m² to 800 W/m² and then decreases to 600 W/m², Fig. 9 show output power under different irradiance with and without P&O algorithm the operating point is close to the MPP during the simulation also the response is very fast, while without P&O algorithm the output power is less. Fig. 10 show output power under different irradiance with and without incremental conductance algorithm. The second case, the irradiance is maintained constant 1000 W/m² and the temperature increases from (25°C) to (35°C) and then increases to (45°C), Fig. 11 show the output power under different irradiance with and without using incremental conductance algorithm, Fig. 12 show output power under different irradiance with and without P&O algorithm.

In order to validate the effectiveness of two MPPT methods, a comparative study is done between P&O based on PID and incremental conductance based on PID. The static tracking efficiency of two MPPT methods under different irradiance are simulated. The static MPPT efficiency is given by:

$$\eta_{static} = \frac{P_o}{P_{max}} \qquad (10)$$

Where P_o represents the output power of the PV module under steady state, P_{max} is the maximum power of the PV module under certain conditions [3]. From the results in Table 4 the static tracking efficiency of Incremental Conductance method is higher than Perturb and Observe method.

Table 4: Tracking efficiency of MPPT during irradiance change

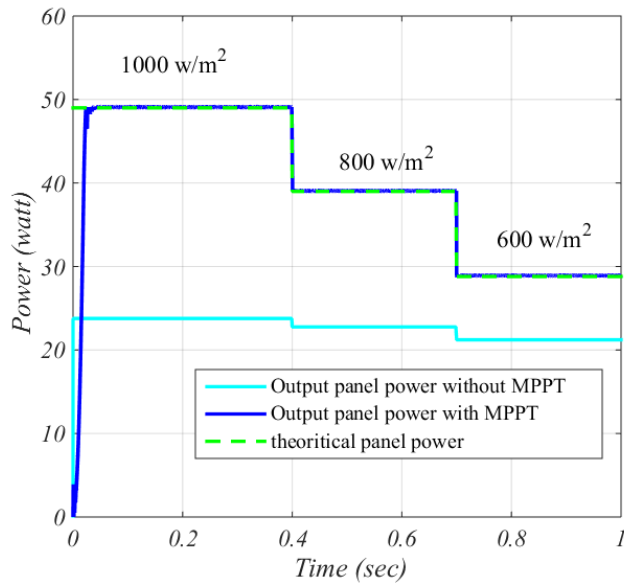| Irradiance	Tracking efficiency of P&O algorithm	Tracking efficiency of IncCond algorithm
1000 W/m²	99.85%	99.94%
800 W/m²	99.82%	99.93%
600 W/m²	99.80%	99.90%

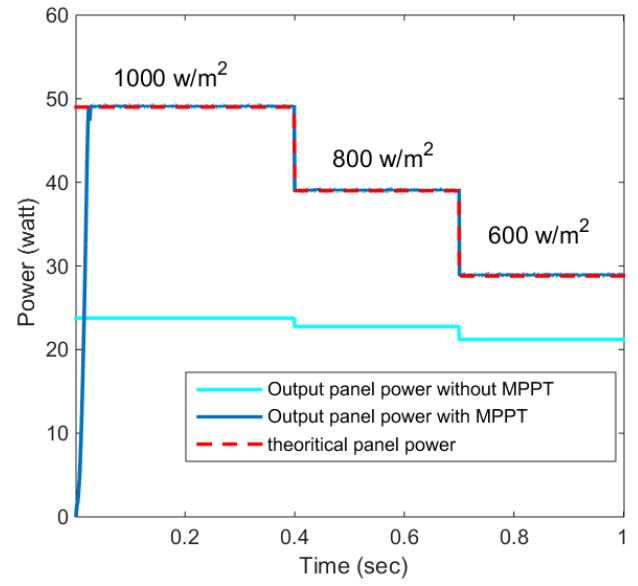Fig. 9: Output power under different irradiance using P&O algorithm.

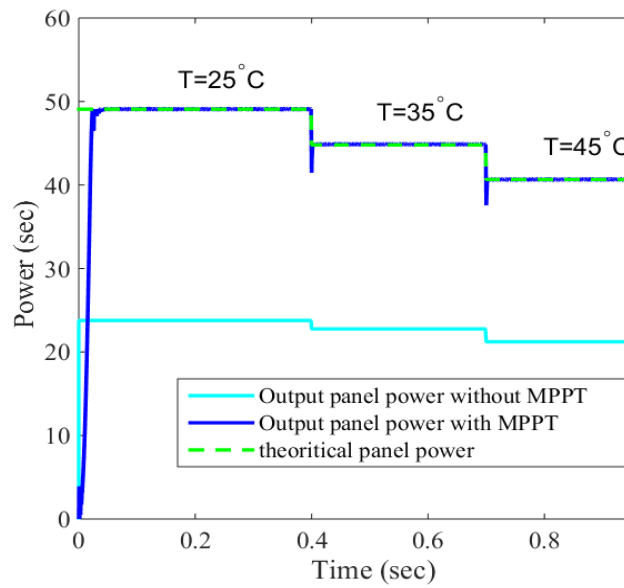Fig. 11: Output power under different irradiance using incremental conductance algorithm.

Fig. 10: Output power under different temperature using P&O algorithm.
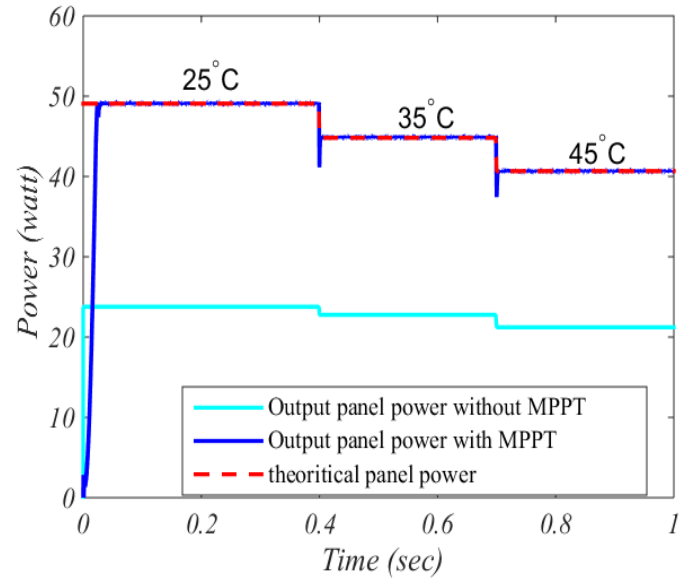

Fig. 12: Output power under different temperature using incremental conductance algorithm.

6. Experimental

Experimental work was conducted to verify the MATLAB simulation. Texas instrument solar explorer kit has been used to control the output power the PV module. A 49 watt PV emulator which consist of synchronous buck boost converter in the kit is used to emulate the PV module, the experimental setup is shown in Fig.13 which consist of PV emulator with parameter shown in table 1 connected to boost converter with parameter shown in table 3 then the variable resistor connect as a load to the boost converter. The control signal generated by the F28M35H52C1 control card is connected to boost converter.

Fig.14and Fig.15 gives the experimental results of MPPT methods when the PV system works on steady state. The output power is plotted versus running time at the conditions that the solar radiation changes from 1000 W/m^2 to 800 W/m^2 then to 600 W/m^2. Table 5 shows the power extracted from the PV module by P&O method and IncCond method. From the results the efficiency of IncCond method is higher than P&O method, also the two MPPT methods can reach faster to steady state and get output maximum power from the PV module.
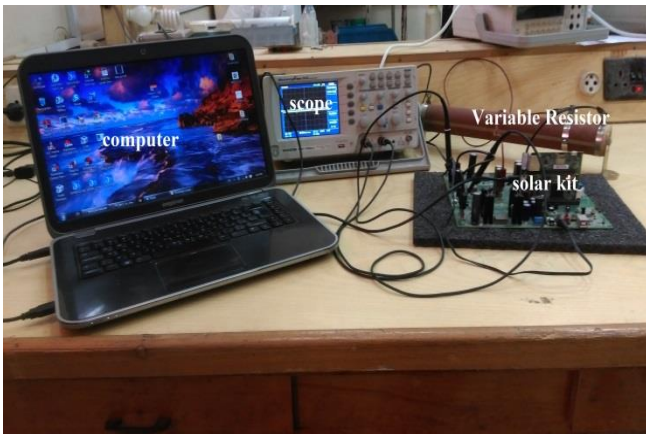

Fig. 13: Experimental setup

Table 5: PV power extracted by P&O method and IncCond method.

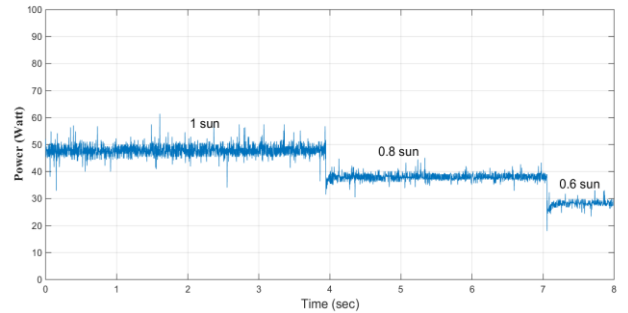| Irradiance (W/m^2)	Theoretical panel power (watt)	P&O algorithm		IncCond algorithm	
		P_{PV} (watt)	% loss	P_{PV} (watt)	% loss
1000	49.00	47.45	3.16%	47.52	3.02%
900	44.08	42.43	3.74%	42.53	3.51%
800	39.03	37.49	3.94%	37.62	3.61%
700	33.96	32.67	3.80%	32.71	3.68%
600	28.86	27.74	3.88%	27.83	3.56%
500	23.79	22.86	3.91%	22.90	3.74%
400	18.72	17.85	4.64%	17.89	4.43%
300	13.63	12.97	4.84%	12.99	4.69%
200	8.63	8.08	6.37%	8.12	5.91%

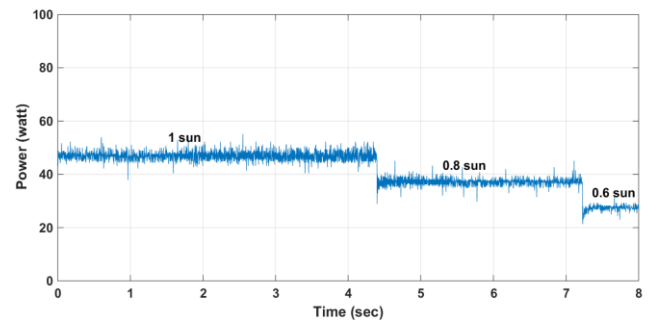Fig. 14: Transient response P&O MPPT method for change in irradiance.

Fig. 15: Transient response IncCond MPPT method for change in irradiance.

7. Conclusions

This paper proposes a comparison between perturb and observe method based on PID controller and incremental conductance method based on PID controller. The simulations have been done in MATLAB/SIMULINK, first a simulation of the real PV module is constructed to show the nonlinear characteristic of PV module due to changing the weather condition (irradiance and temperature). From the test the incremental conductance based on PID. The experimental results show that, Perturb and Observe method based on PID controller and Incremental Conductance method based on PID controller has fast response to reach the MPPT with solar radiation change, also the efficiency of IncCond method higher than the efficiency of P&O method

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