

Figure 5. Scatter plot of exergy per crore of spending (X/S) score versus spend (S).

measure of scientometric performance – IITs Kharagpur, Delhi, Roorkee and Bombay rank ahead of IIT Madras. Figure 4 which is the scatter plot of exergy per faculty (X/F) score versus faculty (F) tells an entirely different story. The Institute of Chemical Technology, Mumbai is by far the best performer. In this scheme IIT Madras ranks thirteenth. Figure 5 which is a scatter plot of exergy per crore of spending (X/S) score versus spend (S) tells yet another story. Jamia Millia Islamia is the best performer, followed by Jadavpur University and the Institute of Chemical Technology, Mumbai. Now IIT Madras ranks twentieth. It would seem that throwing more money at the IITs reduces their productivity or efficiency in translating rupees to scientific wealth.

We used the bibliometric data that have been released through the NIRF 2017 rankings to see how the top 25 engineering institutions fare if only research excellence is considered. Performance is decomposed into a size-dependent exergy term and size-independent productivity and efficiency terms. The Pearson's correlation coefficients and scatter plots show that various alternative rankings can be made. A ranking based on a second-order measure of scientometric performance⁴ shows that IITs Kharagpur, Delhi, Roorkee and Bombay rank ahead of IIT Madras. If a productivity measure such as exergy per faculty (X/F) score is chosen, the Institute of Chemical Technology, Mumbai is by far the best performer; here IIT Madras ranks thirteenth. If an efficiency measure such as exergy per crore of spending (X/S) score is considered, we find that Jamia Millia Islamia is the best performer, followed by Jadavpur University and the Institute of Chemical Technology, Mumbai; here IIT Madras ranks twentieth. It also seems that higher spending only reduces productivity or efficiency in translating rupees to scientific wealth.

The ranking based on NIRF scores of IIT Madras as the best engineering institution in India is too simplistic a conclusion – it is the tragedy of the single story indeed.

1. Savithri, S. and Prathap, G., Indian and Chinese higher education institutions compared using an end-to-end evaluation. *Curr. Sci.*, 2015, **108**(10), 1922–1926.
2. Abramo, G. and D'Angelo, C. A., How do you define and measure research productivity? *Scientometrics*, 2014, **101**(2), 1129–1144.
3. Abramo, G. and D'Angelo, C. A., A farewell to the MNCS and like size-independent indicators. *J. Informetr.*, 2016; <http://dx.doi.org/10.1016/j.joi.2016.04.006>
4. Prathap, G., The Energy–Exergy–Entropy (or EEE) sequences in bibliometric assessment. *Scientometrics*, 2011, **87**(3), 515–524.
5. Prathap, G., Making scientometric sense out of NIRF scores. *Curr. Sci.*, 2017, **112**(6), 1240–1242.

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Simulation and experimental validation of hill-climbing algorithm for maximum power point tracking of solar photovoltaic plant

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Variation of solar irradiances plays an important role in changing the parameters of a photovoltaic (PV) module. This communication includes a mathematical model, system design, control algorithm and experimental set-up to obtain the maximum power point on $P-V$ and $I-V$ curves of an array. Discussions have been done on all the units of the system and a simulation model developed in MATLAB software using the proposed method. The resultant system is capable of tracking maximum power point without steady-state oscillations and errors in changing environmental conditions. The feasibility and improved functionality of the proposed system have been tested successfully in the laboratory.

Keywords: Hill-climbing algorithm, maximum power point tracking, photovoltaic solar system.

To extract the maximum power from solar arrays of a power plant, the maximum power point (MPP) is tracked on the power–voltage ($P-V$) characteristic curve, where a global and local maximum is present. This implies that for different operating points of solar arrays, different output power is obtained; however, the maximum power

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is obtained at that operating voltage of solar arrays where the global maximum of $P-V$ characteristics is present. Therefore, only at one special operating point, the maximum power can be obtained; this is known as the maximum power point in the $P-V$ characteristic curve of solar arrays. MPP changes with the environmental conditions such as change in season, temperature, unexpected rainfall, clouds, fog, solar panel shading and also depends upon the latitude of the location^{1,2}. A tracker is used to follow the constantly changing MPP on the $P-V$ characteristic curve known as maximum power point tracker (MPPT). It consists of a microcontroller to track the exact MPP and a converter to convert the generated voltage to the voltage range on which load works.

Various algorithms have been proposed that run on the microcontroller to track the MPP. These are classified based on the indirect, direct and intelligent controlling techniques respectively. The indirect control methods such as curve fitting, look-up tables, constant voltage/current and pilot cell method help in predicting the approximate MPP using algorithms based on empirical data. These data include typical mathematical equations obtained from the geographical conditions, solar irradiance data, and electrical and mechanical parameters of solar photovoltaic (PV) modules. These methods are not applicable for module shading conditions and fast changing environmental conditions of the location of the plant. The direct control methods such as perturb and observe (P&O), hill-climbing and incremental conductance technique are based on sampling and modulation control. The flexibility of these techniques provides a significant solution in case of changing environmental conditions. The artificial control methods such as fuzzy logic control, artificial neural network, genetic algorithm and practical swarm optimization are globally accepted and highly efficient techniques to track MPP and can be combined with the direct methods to obtain optimum results²⁻⁵.

MPP has to be tracked not only electrically but also mechanically by tracking the position of the Sun on the defined latitude, so as to obtain the maximum irradiance and output power. The energy extracted at the optimal conditions can be utilized to serve load directly, can be stored in some other form in batteries for later use and can also be used for electrolysis to produce H_2 compound for further use in fuel cells³. Typically, the grid-connected PV system has multiple power stages where the MPPT algorithm is applied at the DC-DC converter stage and voltage-level transmission.

The aim of this work is to prove experimentally the accuracy of the hill-climbing algorithm, which is adaptive to the fast-changing levels of solar irradiance and the implementation complexity of this algorithm, is comparatively lesser than all other methods^{4,5}.

The work also describes the P&O method in detail with the mathematical representation, simulation and experimental validation of the hill-climbing algorithm.

The P&O method is an iterative approach which is easy to understand and implement. Here, the operating point of solar PV systems revolves around the MPP output from the modules, i.e. the operating voltage is varying at regular intervals and oscillates near the MPP (dP/dV) of the $P-V$ characteristic curve. The rate of change of power with respect to voltage (dP/dV) gives positive values before it reaches the MPP, zero at the peak value and negative values after crossing the peak of power point (Figure 1). This method is advantageous in terms of accuracy and easy implementation, while it is not suitable for the rapidly changing environmental conditions. Perturbation in duty cycle is continued in the same direction if the system is getting increased power at the load end; otherwise the direction of perturbation is reversed to reach the peak of power^{5,6}. Whereas it is observed that with the increase in duty cycle oscillations in the power also increase. The variations near the peaks of $P-V$ and $I-V$ curves can be minimized by reducing the perturbation step size, therefore using the fundamental principle of perturb and observe with modesty can be sub categorized as hill climbing, beta method, incremental conductance (INC) method, estimated perturb-perturb and three-point weight comparison method. The hill-climbing algorithm involves perturbation in duty cycle with minimum step size is used in this experimental set-up⁶.

The hill-climbing method involves perturbation in the duty cycle of the DC-DC power converter, which perturbs the PV array current and consequently the operating voltage of the array. The change in duty cycle (ΔD) can be obtained by observing and recording the operating region of the curve and changes are made in the direction to approach the MPP on the $P-V$ characteristic curve^{6,7}.

The mathematical equations involved are discussed by taking the simplest model of PV cell (Figure 2) consisting of a current source in parallel with a diode shunt resistance (R_{SH}) and series resistance (R_s). The photo current I_p has a linear relationship with $I_{p(T_{ref})}$ the photo current at reference temperature (T_{ref}) and constant (K) which is dependent on short-circuit current of cells in the module, as shown in eq. (1) and $I_p(T_{ref})$ is proportional to the nominal radiations corresponding to temperature.

$$I_p = I_{p(T_{ref})} * (1 + K(T - T_{ref})), \tag{1}$$

where $I_{p(T_{ref})} = \frac{G_T}{G_{(T_{ref})}} * I_{SC(ref)}$ and $K = \frac{I_{SC(T)} - I_{SC(T_{ref})}}{T - T_{ref}}$.

However the diode current I_D and current across shunt resistance (I_{SH}) are proportional to the cell voltage (V_{cell}) and current (I_{cell}), as given in eqs (2) and (3) respectively, and cell current (I_{cell}) can be mathematically calculated using eq. (4)

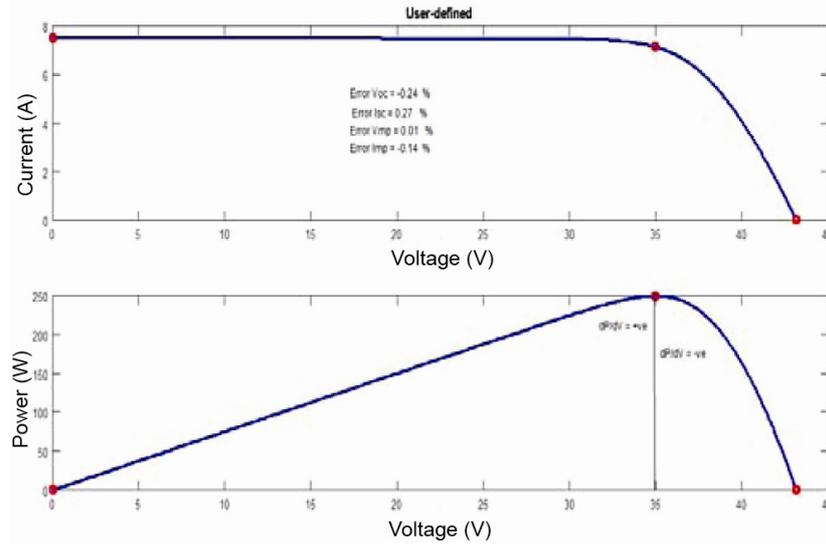


Figure 1. $I-V$ and $P-V$ graphs of polycrystalline photovoltaic collector.

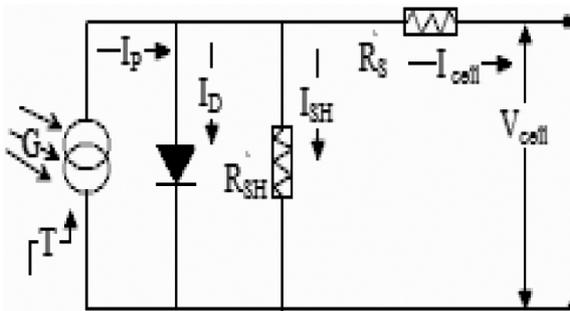


Figure 2. Basic model of photovoltaic cell.

$$I_D = I_0 \left[\exp\left(\frac{V_{cell} + I_{cell} \times R_S}{V_T}\right) - 1 \right], \quad (2)$$

$$I_{SH} = \frac{V_{cell} + I_{cell} \times R_S}{R_{SH}}, \quad (3)$$

$$I_{cell} = I_p - I_0 \left[\exp\left(\frac{V_{cell} + I_{cell} \times R_S}{V_T}\right) - 1 \right] - \frac{V_{cell} + I_{cell} \times R_S}{R_{SH}}. \quad (4)$$

The power (P) obtained from the single PV module is given in eq. (5), where N_s and N_p are the number of photovoltaic cells in series and parallel respectively.

$$P = (N_s * N_p) V_{cell} * I_{cell}. \quad (5)$$

The theoretical value of maximum/peak voltage (V_{mp}) and current (I_{mp}) can be obtained using eqs (6) and (7) respectively

$$V_{mp} = V_{mp(ref)} \left[1 + 0.0539 \log\left(\frac{G_T}{G_{(T_{ref})}}\right) + \beta \Delta T \right], \quad (6)$$

where $\Delta T = T_{cell} - T_{cell(ref)}$ and β is the voltage temperature coefficient ($V/^\circ C$)

$$I_{mp} = I_{SC(ref)} \left[1 - K_1 \left\{ \exp\left(\frac{V_{mp} - \Delta V}{K_2 \times V_{OC(ref)}}\right) - 1 \right\} \right] + \Delta I, \quad (7)$$

where $K_1 = \left(1 - \frac{I_{mp(ref)}}{I_{SC(ref)}} \right) \exp\left(-\frac{V_{mp(ref)}}{K_2 \times V_{OC(ref)}}\right)$ and

$$K_2 = \frac{\left(\frac{V_{mp(ref)}}{V_{OC(ref)}} - 1\right)}{\ln\left(1 - \frac{I_{mp(ref)}}{I_{SC}}\right)}.$$

Therefore, the maximum power (P_{mp}) = $V_{mp} \times I_{mp}$ and to find the peak in the $P-V$ graph of the PV module, this expression of power needs to be differentiated with respect to voltage and equated to zero. Thus we get

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I \frac{dV}{dV} + V \frac{dI}{dV} = I_{mp} + V_{mp} \frac{dI_{mp}}{dV_{mp}} = 0. \quad (8)$$

When the cells in a module are connected in series string, the cell voltage (V_{cell}) and current (I_{cell}) cumulatively become the module voltage (V_{PV}) and current (I_{PV}).

Figure 3 shows a block diagram representation of the experimental set-up. Here the output from the PV modules with specifications in Table 1 acts as the input of DC/DC

converter; the control loops of the converters are also shown. The duty cycle of the DC/DC converter can be changed manually and automatically according to requirement. The DC/DC converter is further connected to the DC/AC converter through a DC-link capacitor and the LC-filter is applied before AC power is delivered to the load.

The output from the PV modules varies with the amount of irradiance, angle of incidence and temperature and the characteristics of the PV array can be obtained. Further in order to track MPP, the voltage and current are sensed and scaled to the 2.0–5.5 V range with the help of an operational amplifier and given as input to the analog channel of the PIC16F877A microcontroller for taking the necessary control actions.

The microcontroller tracks the variation of dP/dV which is either positive, negative or zero. If it is zero, it does not make any change in the control signal. However, if it is positive, there is an increase in the duty cycle (D) and if it is negative, the duty cycle is decreased. The microcontroller sends the necessary signal to the pulse width modulation (PWM) generator which generates gate pulses for triggering the inverter^{6–8}.

The hill-climbing algorithm presented next and Figure 4 are based on perturbation in duty cycle at a fixed tilt, which is widely used because of its simple feedback structure and fewer parameters.

Table 1. Module specifications

Parameters	Quantity
Cells per module (N_{cell})	36
Maximum power (P_{max})	250 W
Open circuit voltage (V_{oc})	43.2 V
Short circuit current (I_{sc})	7.5 A
Voltage at maximum power point (V_{mp})	35 V
Current at maximum power point (I_{mp})	7.14 A
Temperature coefficient of V_{oc} (% °C)	-0.027269
Temperature coefficient of I_{sc} (% °C)	0.061694

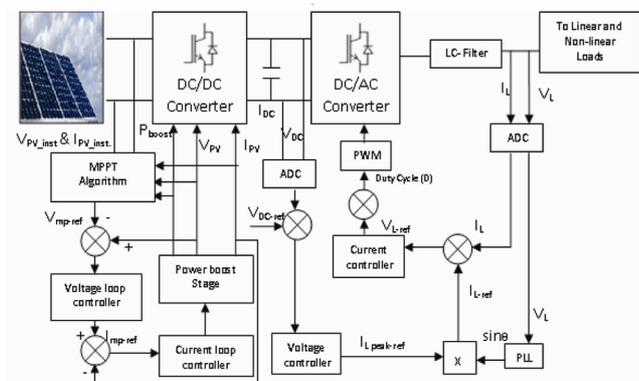


Figure 3. Block diagram of the entire system.

Algorithm used for MPPT is discussed as follows^{8,9}.
 Step 1: Sensing and measuring the voltage and current of PV array.

Step 2: Calculate the instantaneous power (P_{in}).

Step 3: Initializing the duty cycle (D) to a particular value.

Step 4: Check the difference between instantaneous power (P_{in}) and predecessor power (P_p).

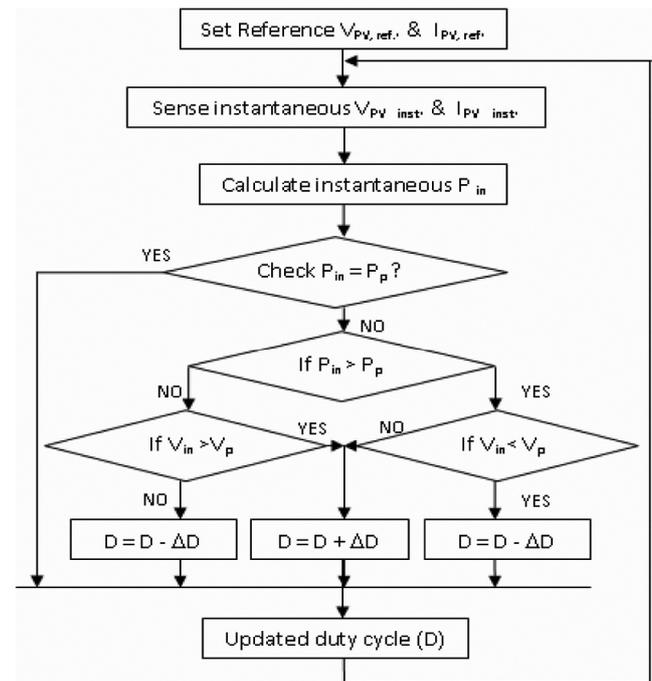


Figure 4. Flow chart of hill-climbing algorithm.

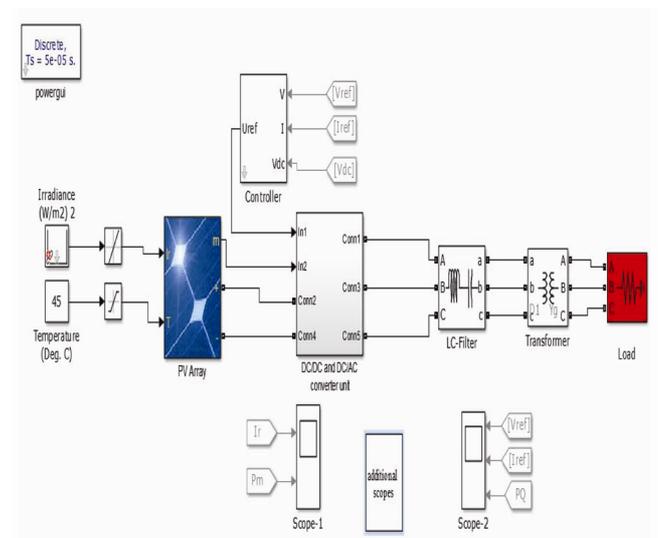


Figure 5. Simulation model for maximum power point tracking (MPPT).

Table 2. Variation parameters with respect to change in irradiance

Array parameters	Irradiance level (W/m ²)				
	1000	800	600	400	200
Light generated current (I_p , A)	7.524	5.1906	4.1382	3.0096	1.5048
Diode saturation current (I_D , A)	7.9265e-12	7.4619e-12	7.2698e-12	7.0759e-12	6.8539e-12
Diode ideality factor	1.6939	1.676	1.663	1.648	1.621
Shunt resistance (R_{SH} , Ω)	942.1596	1407.7176	1732.8651	2144.7174	2530.61467
Series resistance (R_S , Ω)	0.47815	1.38415	1.80964	2.17014	2.64315

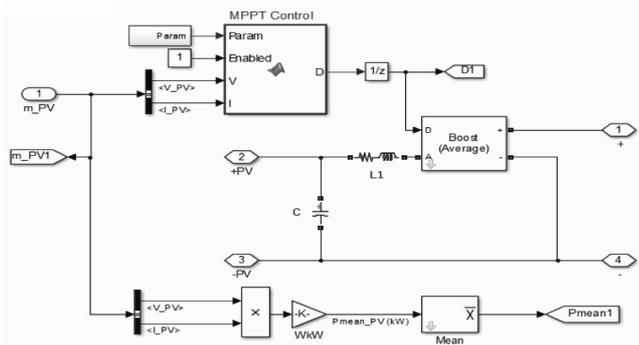


Figure 6. Simulation block of MPPT control.

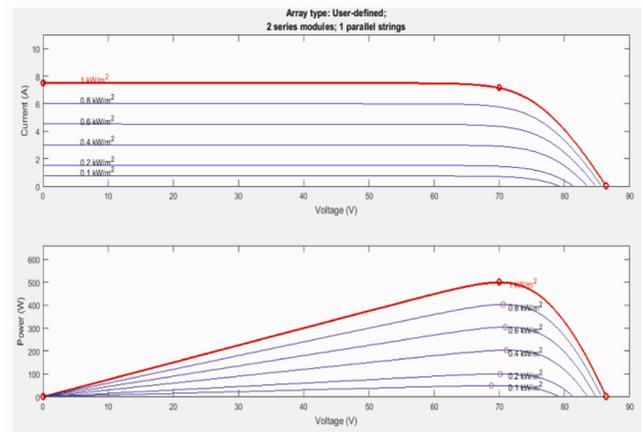


Figure 8. Array@ 25°C at the specified irradiance.

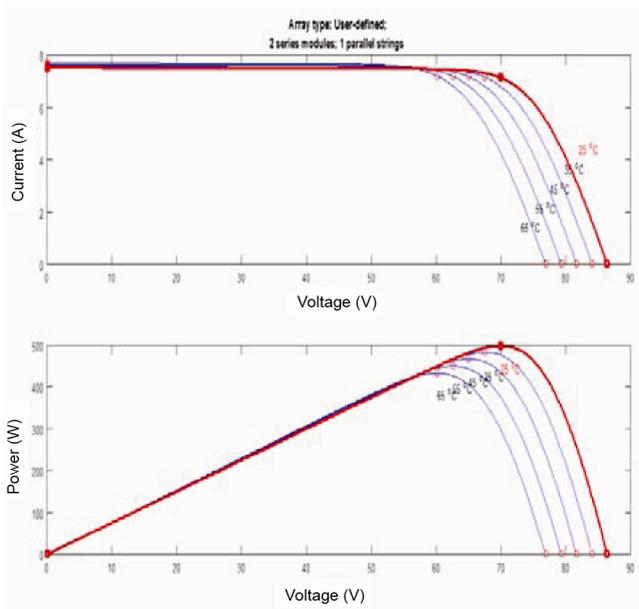


Figure 7. Array @1000 W/m² and specified temperature.

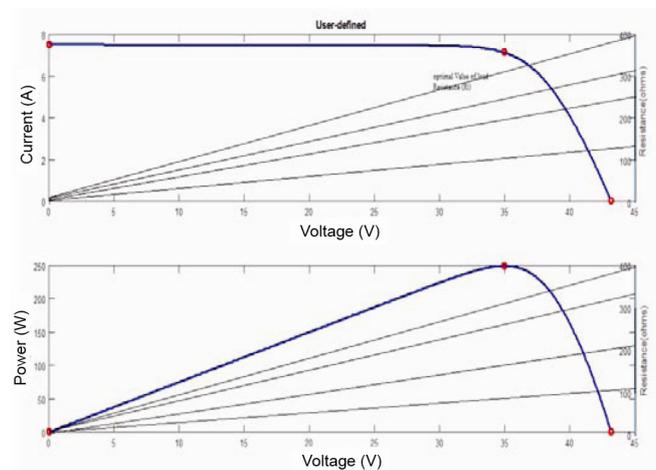


Figure 9. P-V and I-V curve for different values of load resistance.

Step 5: If the change in power is positive, increase the D value; if it is negative, decrease the D value; if there is no change in power, D value is retained.

Step 6: Sense the PV array voltage and current.

Step 7: Calculate the modified instantaneous power.

Step 8: Repeat step 4.

The above algorithm for MPPT is transferred into the microcontroller using MPLAB IDE. The hill-climbing

algorithm depends on the variations in irradiance and the corresponding modulation index can be obtained. Furthermore, based on the panel input parameters such as voltage current and power, the duty cycle of the inverter is varied manually in order to track the maximum power^{10,11}. The output voltage generated by the inverter is directly proportional to the duty cycle and the DC voltage across the DC link capacitor.

The simulation model of the proposed method has been developed (Figure 5) to see its performance characteristics.

Whereas the module specifications are taken to be the same as those of the experimental set-up, the irradiance ranges from 100 to 1000 KW/m² and the temperature range is taken from 25°C to 65°C, which is chosen based on the actual working conditions of the set-up.

Therefore, the results obtained from the simulation model are almost similar to those of experiments and keeping STC (i.e. standard test conditions: irradiance 1000 W/m², temperature 25°C, and air mass (AM) 1.5) in mind. Figure 6 shows the MPP control block of the model.

Figure 7 shows the $P-V$ and $I-V$ graphs of arrays at fixed irradiance level, i.e. 1000 W/m² with change in module temperature. Figure 8 shows the maximum power obtained with change in irradiance at fixed module temperature, i.e. 25°C.

The results analysed with the change in load resistance are shown in Figure 9, where the optimal load resistance obtained is 400 Ω and there is effect on output power. However, with the change in duty cycle, the output power also gets affected. Figure 10 shows the path followed by the hill-climbing method with change in irradiance. The data logger and plotter unit is used to check the continuous follow-up of the MPP when the hill-climbing algorithm is implemented. Table 2 shows the effect of solar irradiance on the module parameters.

It is observed that the photo module current (I_p), the diode current (I_D) and diode ideality factor decrease with the reducing irradiance level. Also, the series module resistance (R_s) and shunt module resistance (R_{SH}) increased with reducing irradiance levels.

The results obtained using the hill-climbing algorithm can efficiently capture maximum solar energy across a wide range of radiations at the chosen plant location. This algorithm performed exactly as expected, because of its adaptive variants, lesser sensitivity to noise and lesser implementation complexity. The mathematical model of solar cells is self-explanatory in terms of gaining MPP. The simulation has been done using MATLAB software, which shows the effectiveness and feasibility of the proposed algorithm. The hill-climbing path is being followed

with the changing levels of irradiance fall on the solar array. The results obtained are showing the significance and tracking performance of hill climbing algorithm, which is identical in time varying conditions.

1. Subudhi, B. and Pradhan, R., A comparative study on maximum power point tracking techniques for photovoltaic power systems. *IEEE Trans. Sustain. Energy*, 2013, **4**(1), 89–98.
2. Verma, D., Nema, S. and Dash, S., Maximum power point tracking (MPPT) techniques: recapitulation in solar photovoltaic systems. *Renew. Sustain. Energy Rev.*, 2016, **54**, 1018–1034.
3. Salas, V., Olias, E., Barrado, A. and Lázaro, A., Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. *Sol. Energy Mater. Sol. Cells*, 2006, **90**(11), 1555–1578.
4. Jain, S. and Agarwal, V., Comparison of the performance of maximum power point tracking schemes applied to single-stage grid-connected photovoltaic systems. *IET Electr. Power Appl.*, 2007, **1**(5), 753–762.
5. Alajmi, B. N., Ahmed, K. H., Finney, S. J. and Williams, B. W., Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in micro grid standalone photovoltaic system. *IEEE Trans. Power Electron.*, 2011, **26**(4), 1022–1030.
6. Peftitsis, D., Adamidis, G. and Balouktsis, A., A new MPPT method for photovoltaic generation systems based on hill climbing algorithm. In IEEE 18th International Conference on Electrical Machines, 2008.
7. Marnoto, T., Sopian, K., Daud, W. R. W., Algoul, M. and Zahaim, A., Mathematical model for determining the performance characteristics of multi-crystalline photovoltaic modules. In Proceedings of the 9th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering, Trinidad and Tobago Islands, Caribbean Sea, USA, 2007, pp. 79–84.
8. Liu, F., Kang, Y., Zhang, Y. and Duan, S., Comparison of P&O and hill climbing MPPT methods for grid-connected PV converter. In 3rd IEEE Conference on Industrial Electronics and Applications, Singapore, 2008, pp. 804–807.
9. Kong, K. C., Mamat, M. B., Ibrahim, M. Z. and Muzathik, A. M., New approach on mathematical modeling of photovoltaic solar panel. *Appl. Math. Sci.*, 2012, **6**(8), 381–401.
10. Nguyen, X. H. and Nguyen, M. P., Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink. 2015, pp. 1–13; doi:10.1186/s40068-015-0047-9.
11. Sera, D., Mathe, L., Kerekes, T. and Spataru, S. V., On the perturb-and-observe and incremental conductance MPPT methods for PV systems. *IEEE J. Photovolt.*, 2013, **3**(3), 1070–1078.

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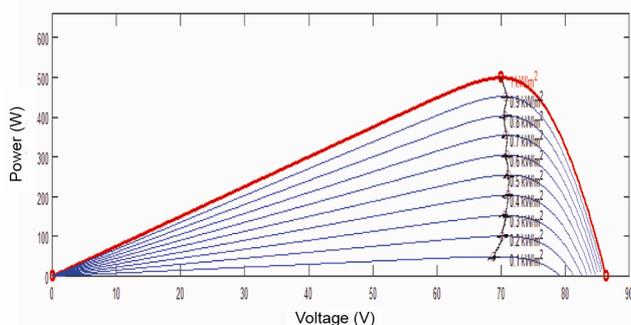


Figure 10. Maximum power point tracking by hill-climbing at varying irradiance.