

Modeling of PV Array to Study The Effects of Partial Shading on Its Characteristics and MPPT

Ramprasad M. Thorat
P.G.Scholar,
Department of Electrical Engineering
SES GOI FE, Diksal (Karjat),
Maharashtra
ramprasad.thorat@gmail.com

Prof.G.S.Chaudhari
Associate professor,
Department of Electrical Engineering
GOI FE, Diksal (Karjat),
Maharashtra
gsc88@rediffmail.com

Prof.S.S.Sane
Associate professor & HOD
Department of Electrical Engineering
SES GOI FE, Diksal (Karjat),
Maharashtra
sharvari.sane@rediffmail.com

Abstract—MATLAB based modeling and simulation scheme suitable for studying the I-V and P-V characteristics of PV array under a non-uniform insolation due to partial shading and finding maximum power point from the characteristic is presented in the paper. This involved the Simulink and embedded MATLAB code for simulation. This is simple to use, accurate and economical computer aided design tool which can be used to enhance the understanding and predict the I-V and P-V characteristics of large PV arrays. It can be used to study the effect of temperature, insolation variation, varying shading patterns and the role of array configuration on the PV characteristics. Paper proposes standard algorithm to track the power peak under partially shaded conditions. The modeling and simulation of the maximum power point tracking algorithm is implemented in MATLAB / Simulink environment. The simulation results prove that with Perturb and Observe (P&O) algorithm, MPPT reaches the intended maximum power point.

Keywords: Photovoltaic (PV), Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O), current-voltage (I-V) and power-voltage characteristics.

I. INTRODUCTION

With the increasing attention and use of non-conventional energy sources, photovoltaic systems are gaining popularity and large solar farms are getting installed at suitable sites in India. A major challenge in employing the use is that photovoltaic (PV) array has nonlinear output characteristic which vary with the size (number of modules) and configuration (number of modules in series in parallel). The output characteristic is complicated if the array does not receive uniform insolation (partially shaded condition) due to passing clouds, neighboring building and towers, trees, utility and telephone poles as multiple peaks are observed in output characteristic. It is very important to understand and predict the PV characteristics in order to use a PV installation effectively.

Solar energy, radiant light and heat from the sun, has been reined by humans since ancient times using a range of ever-evolving technologies. Solar radiant energy accounts for most of the usable renewable energy on earth. Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. In this paper, the PV array is modelled and its I-V and P-V characteristics are simulated and optimized. The main encumbrance for the reach of photovoltaic systems is their low efficiency and high capital cost. Here we intend to examine a schematic to draw out maximum obtainable solar power from a PV module for use in

a DC application. The concept of MPPT is to be implemented which results in appreciable increase in the efficiency of the PV System.

It is not only the size (i.e., the total number of modules) of the PV array but also its configuration (i.e., the number of modules in series and parallel, respectively) that significantly affects its power output, and therefore, the performance of the system under partially shaded conditions. It is very important to model, study and understand the effects of radiation on PV arrays. A "simple-to-use," accurate and economical computer-aided design (CAD) tool is generally not available for the purpose. Therefore, it is felt that there is a need for a flexible, interactive, and comprehensive simulation model, which can serve as the following.

- 1) A basic tool for professionals and researchers to accurately predict the PV characteristics (including multiple peaks) and output power under different working conditions.
- 2) A design aid for users who want to build actual PV systems, study the stability and interfacing aspects (e.g., distributed generation applications) without going into the intricate details (e.g., semiconductor physics).

- 3) A tool to study the effect of array configuration on the output power for a likely/known radiation pattern.
- 4) A planning tool that can help in the installation of efficient and optimum PV arrays in a given surrounding.
- 5) A tool to develop and validate the effectiveness of existing and new MPPT schemes.

Software packages like PV-Spice, PV-DesignPro, SolarPro, PVcad, and PVsyst are available, but have one or more of the following limitations:

- 1) Commercial, proprietary in nature and expensive.
- 2) Too complex to model the shading effects.
- 3) Do not support the interfacing of the PV arrays with actual power electronic systems.

This paper presents a MATLAB-based simulator cum learning tool, which can be used to enhance the understanding and predict the I-V and P-V characteristics of large PV arrays. It can be used to study the effect of temperature and solar radiation variations, and the role of array configuration on the PV characteristics. A notable advantage of the presented model is that the PV array model can be interfaced with the models of actual systems (e.g., power electronic converters) making it possible to simulate complete PV systems and their interaction with other systems. The reason for using MATLAB is that it is available in most academic, research, and industrial organizations and considered useful for several engineering disciplines. It provides several features that can be used to simulate highly complex systems, electronic and power electronic circuits and systems, and distributed generation power systems. The usefulness of the proposed tool is demonstrated with the help of results.

A major challenge in the use of PV is posed by its nonlinear I-V characteristics, which result in a unique maximum power point (MPP) on its P-V curve. The matter is further complicated due to the dependence of these characteristics on solar insolation and temperature. As these parameters vary continuously, MPP also varies. Considering the high initial capital cost of a PV source and its low energy conversion efficiency, it is imperative to operate the PV source at MPP so that maximum power can be extracted. In general, a PV source is operated in conjunction with a dc-dc power converter, whose duty cycle is modulated in order to track the instantaneous MPP of the PV source. Several tracking schemes have been proposed. Among the popular tracking schemes are the perturb and observe (P&O) or hill climbing, incremental conductance, short circuit current, open-circuit voltage, and ripple correlation approaches. P & O algorithm is used in this paper work.

II. MODELING THE SOLAR CELL

Solar cells consist of a p-n junction fabricated in a thin wafer or layer of semiconductor. In the dark, the I-V output characteristic of a solar cell has an exponential characteristic similar to that of a diode. When exposed to light, photons with energy greater than the band-gap energy of the semiconductor are absorbed and create an electron-hole pair. These carriers are swept apart under the influence of the internal electric fields of the p-n junction and create a current proportional to the incident radiation. When the cell is short circuited, this current flows in the external circuit; when open circuited, this current is shunted internally by the intrinsic p-n junction diode. The characteristics of this diode therefore set the open circuit voltage characteristics of the cell.

Thus the simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell. The diode determines the I-V characteristics of the cell. Increasing sophistication, accuracy and complexity can be introduced to the model by adding in turn,

- Temperature dependence of the diode saturation current I_0 .
- Temperature dependence of the photo current I_L .
- Series resistance R_s , which gives a more accurate shape between the MPP and the open circuit voltage.
- Shunt resistance R_p in parallel with the diode.
- Either allowing the diode quality factor n to become a variable parameter (instead of being fixed at either 1 or 2) or introducing two parallel diodes (one with $A = 1$, one with $A = 2$) with independently set saturation currents.

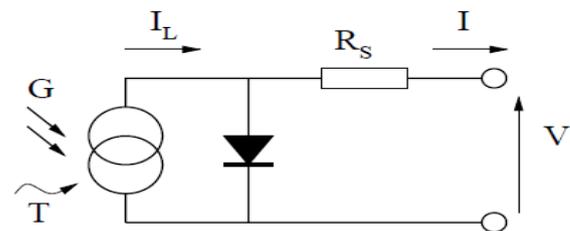


Figure 1: Circuit diagram of the PV model.

For this work, a model of moderate complexity is used. The model included temperature dependence of the photo-current I_L and the saturation current of the diode. A series resistance R_s is included, but not a shunt resistance. A single shunt diode is used with the diode quality factor set to achieve the best curve match. This model is a simplified version of the two diode model. The circuit diagram for the solar cell is shown in Figure.

The equations which describe the I-V characteristics of the cell are,

$$I = I_L - I_0 (e^{(V+IR_s)/nkT} - 1) \quad \dots(1)$$

$$I_L = I_{L(T1)} (1 + K_0 (T - T1)) \quad \dots(2)$$

$$I_{L(T1)} = G * I_{SC(T1, nom)} / G_{(nom)} \quad \dots(3)$$

$$K_0 = (I_{SC(T2)} - I_{SC(T1)}) / (T2 - T1) \quad \dots(4)$$

$$I_0 = I_{0(T1)} * (T/T1)^{3/n} * e^{-qV_g/nk*(1/T)-(1/T1)} \quad \dots(5)$$

$$I_{0(T1)} = I_{SC(T1)} / (e^{qV_{OC(T1)}/nkT1} - 1) \quad \dots(6)$$

$$R_s = -dV/dI_{V_{OC}} - (1/X_v) \quad \dots(7)$$

$$X_v = I_{0(T1)} * q/nkT1 * e^{qV_{OC(T1)}/nkT1} \quad \dots(8)$$

All of the constants in the above equations can be determined by examining the manufacturer’s ratings of the PV array, and then the published or measured I-V curves of the array. As a typical example, the BP Solar 250/1 module will be used to illustrate and verify the model.

The photo-current $I_L(A)$ is directly proportional to irradiance $G(W/m^2)$. When the cell is short circuited, negligible current flows in the diode. Hence the proportionality constant in equation (3) is set so the rated short circuit current I_{SC} at is delivered under rated irradiation (usually 1 Sun = 1000W/m²).

For the BP Solar 250/1, $I_{SC} = 3.22A$ at 1 Sun at $T_1 = 25^\circ C(298K)$, so $I_{L(T1)} = 3.228 A/Sun$. The relationship between the photo-current and temperature is linear (eq. 2) and is deduced by noting the change of photo-current with the change of temperature (eq.4). For the BP 250/1, temperature coefficient of I_{sc} is 0.68 mA/module/ $^\circ C$. When the cell is not illuminated, the relationship between the cell’s terminal voltage and current is given by the Shockley equation. When the cell is open circuited and illuminated, the photo-current flows entirely in the diode. The I-V curve is offset from the origin by the photo generated current I_L (eq. 1). The value of the saturation current I_0 at 25⁰C is calculated using the open circuit voltage and short circuit current at this temperature (eq. 6). An estimate must be made of the unknown “ideality factor”. It takes a value between 1 and 2, being near one at high currents, rising towards two at low currents. A value of 1.771 is used in the model.

The relationship of I_0 to temperature is complex, but fortunately contains no variables requiring evaluation (eq 5). The series resistance of the panel has a large impact on the slope of the I-V curve at $V = V_{OC}$. Equations 7 and 8 are found by differentiating equation 1, evaluating at $V = V_{OC}$, and rearranging in terms of R_s . For the BP Solar 250/1, a value of total panel series resistance is R_s can be calculated from equation 7.

The BP Solar 250/1, a typical 50W PV module, was chosen for modeling. The module has 36 series connected polycrystalline cells. The key specifications are shown in table. The model was evaluated using MATLAB m-file programming. The model parameters at 25⁰C are,

Table 1: Technical specifications for BP Solar 250/1 module.

Parameter	Value
Typical Peak Power (Pmax)	50 W
Voltage @ maximum power (V mp)	17.00 V
Current @ maximum power (I mp)	2.94 A
Short-circuit current (Isc)	3.22 A
Open-circuit Voltage (Voc)	21.2 V

Parameters are evaluated during execution using the equations listed above using the above data points contained in the script. The current I is then evaluated using these parameters, and the variables Voltage, Irradiation, and Temperature. If one of the input variables is a vector, the output variable (current) is also a vector. The inclusion of a series resistance in the model makes the solution for current a recurrent equation (refer to eq 1). A simple iterative technique initially tried only converged for positive currents.

The shading pattern for a large array is very complex to model. A special categorization and terminology is used to describe the various components of a PV array.

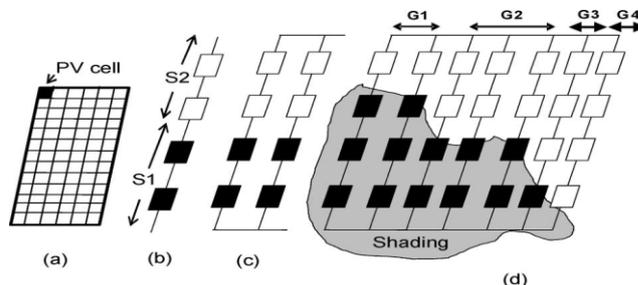


Figure 2: PV array terminologies. (a) PV module. (b) Series-assembly with two series-connected subassemblies S1 and S2. (c) Group. (d) PV array with groups G1 to G4.

A “subassembly” is formed with several series-connected PV modules receiving the same level of insolation. Several such series-connected subassemblies, each with a different level of insolation, form a series assembly. Series assemblies, having similar shading patterns, form a “group”. Various groups (with i^{th} group represented by “ G_i ”), having different shading patterns and connected in parallel, form a PV array, as shown in figure.

III. V-I CHARACTERISTICS OF A PV CELL

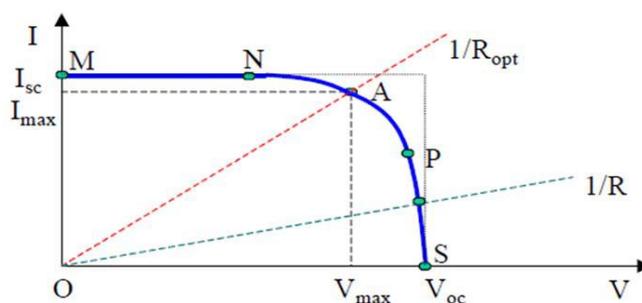


Figure 3. Typical V-I Characteristics of a PV cell

In the above representation of I-V characteristic, a sign convention is used, which takes as positive the current generated by the cell when the sun is shining and a positive voltage is applied on the cell's terminals.

A real solar cell can be characterized by the following fundamental parameters:

Short Circuit Current

It is the greatest value of the current generated by a cell. It is produced under short circuit conditions, $V = 0$.

Open circuit voltage:

Corresponds to the voltage drop across the diode (p-n junction), when it is traversed by the photocurrent I_{ph} (namely $I_D = I_{ph}$) when the generator current is $I = 0$. It reflects the voltage of the cell in the night and it can be mathematically expressed as:

$$V_{oc} = \frac{mkT_c}{e} \ln\left(\frac{I_{ph}}{I_0}\right) = V_t \ln\left(\frac{I_{ph}}{I_0}\right)$$

Where, V_t - known as thermal voltage and T_c is absolute cell temperature.

Maximum power point

Is the operating point A (V_{max} , I_{max}) at which the power dissipated in the resistive load is maximum, $P_{max} = I_{max} * V_{max}$.

Maximum efficiency

It is the ratio between the maximum power and the incident light power.

IV. MAXIMUM POWER POINT TRACKING (MPPT)

MPPT relates to the solar cell itself. Each solar cell has a point at which the current (I) and voltage (V) output from the cell result in the maximum power output of the cell. In the diagram below the curve is an example of the standard output expected from a solar cell, the maximum power point is at the position marked on the diagram.

The principle is that if the output from the cell can be regulated to the voltage and current levels needed to achieve a power output at this point, then the power generated by the solar cell will be used most efficiently.

MPPT ensures that you get the most power possible from your solar panels at any point in time. It is particularly effective during low light level conditions. These calculations result in an output that delivers maximum current at the required voltage at any point in time. During low light level situations it will compensate for the low light level and find the new point at which the solar cell delivers its maximum power output.

A MPPT solar regulator will simulate the load required by the solar panel to achieve the maximum power from the cell. The regulator will work out at which point the cell will output the maximum power and derive from this V and I outputs required for maximum power to be achieved. It will then

calculate the load that it must simulate based on these voltage and current levels $R=V/I$. The regulator, now receiving the maximum amount of power in, will then regulate the output according to what it is designed for.

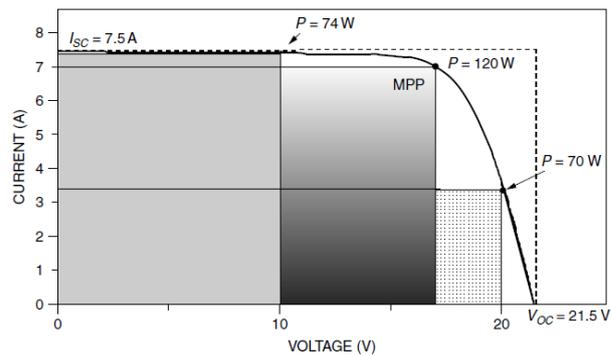


Figure 4. Pmax point

MPPT is a technique that grid-tie inverters, solar battery chargers and similar devices use to get the maximum possible power from one or more photovoltaic devices, typically solar panels, though optical power transmission systems can benefit from similar technology. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions. MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads, including power grids, batteries, or motors.

MPPT Algorithm

Perturb and Observe (P&O)

In this algorithm, a slight perturbation is introduced in the system. Due to this perturbation, the power of the module alters. If the power enhances due to the perturbation, then the perturbation is carried on in that direction. After the maximum power is accomplished, the power at the next instant decrements and hence the perturbation reverses.

Among different MPPT algorithms, P&O algorithm is elementary and also gives desirable results. This algorithm is chosen and certain changes are made in the current work. The flow chart of the method is shown in the figure 5. The algorithm takes the values of current and voltage from the solar photovoltaic module. Power is computed from the assessed voltage and current. The values of voltage and power at k^{th} instant are put in. Then next values at $(k+1)^{th}$ instant are measured again and power is calculated from the duty cycle (nearer to unity). Depending on the sign of $dP(P(k+1) - P(k))$ and $dV(V(k+1) - V(k))$ after subtraction the algorithm decide

whether to increase the duty cycle or to reduce the duty cycle. The algorithm is elementary and has only one loop.

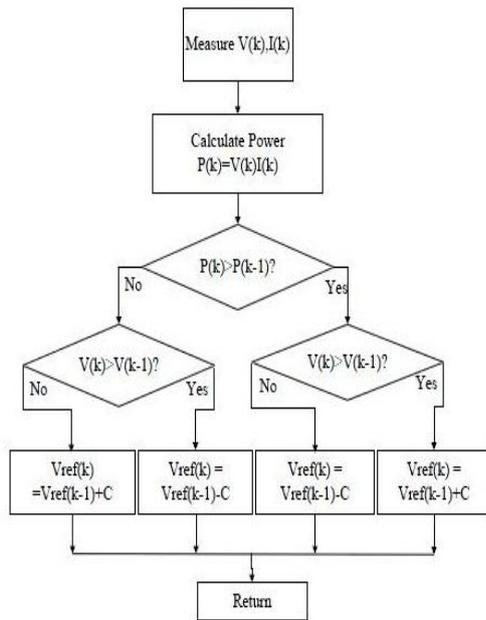


Figure 5. Flow Chart of P&O Algorithm

V.SYSTEM MODEL

PV Array Model with 10 Strings of 50 Modules of BP Solar 250/1 giving 25 kW Peak, a plotting function for graphs and a function for P&O MPPT algorithm; forming a complete model in MATLAB is shown in figure6.

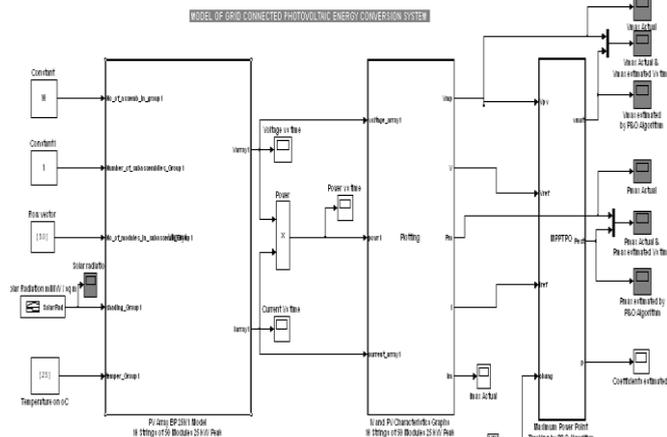


Figure 6: PV array model block diagram (functions) with BP Solar 250/1 (50 W max) of 10 strings of 50 modules each (Total : 10*50*10 W = 25 kW).

Inputs (Variable parameters) allowed in the PV model:

- Simulation time: 1 sec.
- Number of assemblies in a group : 10
- Number of sub-assemblies in a group: 1
- Number of modules in a sub-assembly of a group: 50
- Temperature : 25°C and Solar radiation in mW/ m²

VI. SIMULATION RESULTS

The PV array model is simulated for above mentioned inputs where solar radiation varies in steps every 0.2 s in the way described in above figure, producing changes in the maximum power drawn from the PV array. Figure 7 and 8 shows simulated P-V and I-V characteristic respectively of a BP Solar 250/1 PV module with 10 strings of 50 modules each (25 kW peak) with solar radiation of 0.6mW/m² (600W/m²) and working temperature of 25°C. PV array exhibits a highly nonlinear radiation and temperature dependent P-V and I-V characteristic curve. Such characteristics can be obtained for different configurations under solar radiation and temperature changes.

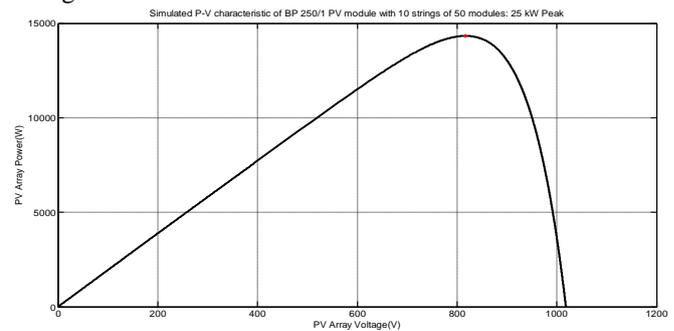


Figure 7: Simulated P-V characteristic of a BP Solar 250/1 PV module.

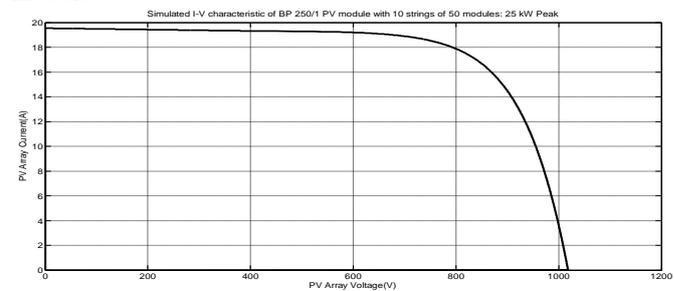


Figure 8: Simulated I-V characteristic of a BP Solar 250/1 PV module.

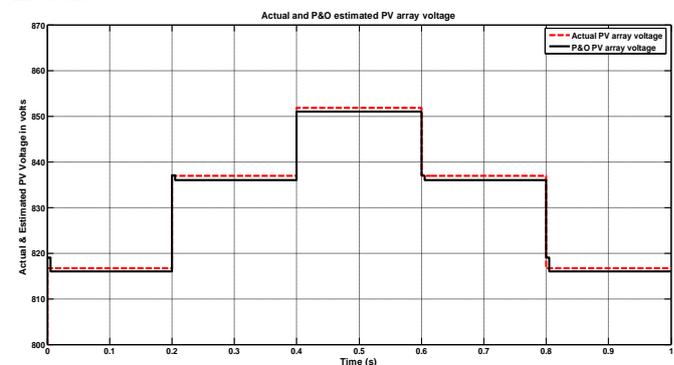


Figure 9: Simulated result for actual and P&O estimated PV array voltage (V) versus time (s).

Figure 9 and 10 show simulated result of actual and P&O estimated PV array voltage (V) and power in (kW) versus time (s) respectively. P&O method proves to be accurate following

the Maximum Power Point (MPP) and corresponding array voltage.

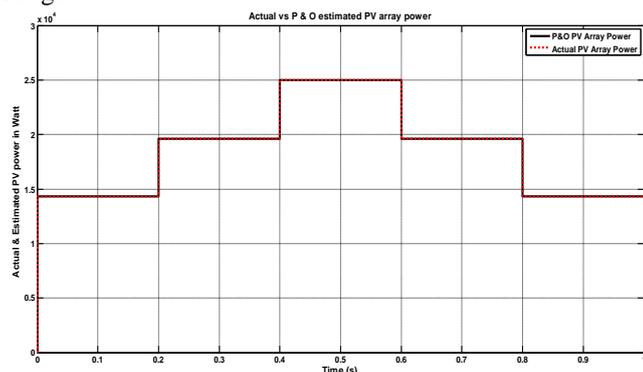


Figure 10: Simulated result for actual and P&O estimated PV array power (kW) versus time (s).

VII. CONCLUSION

An accurate PV module electrical model is presented and demonstrated in MATLAB for a typical 50W BP 250/1 solar module. The PV array consists of 10 strings of 50 modules, making up the peak installed power of 25 kW. Given solar insolation and temperature, the model returns a current vector for a given voltage vector. A method to obtain the I–V and P–V characteristics of a PV array, having a large number of series- and/or parallel-connected modules, under varying temperature and solar radiation is described.

The existing MPPT schemes, which assume a unique maximum power point, therefore, remain inadequate. The magnitude of the global peak is dependent on the PV array configuration and shading pattern besides the commonly known factors, i.e., insolation level and temperature. It is demonstrated that, if the likely shading pattern on the PV array is known, the simulation model is handy to design the most optimum configuration of the PV array to extract the maximum power. The results obtained with this model can be effectively used with off-line capabilities of MATLAB/SIMULINK to investigate the effectiveness of MPPT methods working under non-uniform insolation conditions.

REFERENCES

- [1] S. Liu and R. Dougal. Dynamic multiphysics model for solar array Energy Conversion, IEEE Transaction, Vol. 17, pp. 285-294, Jun 2002.
- [2] C. M. J.A. Gow. Development of a photovoltaic array model for use in power- electronics simulation studies in Electric Power Applications, IEEE Proceedings, Vol. 146, pp. 193-200, March 1999.
- [3] G. Walker. Evaluating MPPT converter topologies using MATLAB PV model, J. Elect. Electron. Eng., Australia, IE Aust., Vol. 21, No. 1, pp. 49–56, 2001.
- [4] W. Xiao, W. Dunford, and A. Capel. A novel modeling method for photovoltaic cells, Power Electronics Specialists Conference, 2004. PESC 04, IEEE 35th Annual, Vol. 3, pp. 1950-1956, June 2004.
- [5] D. Hohm and M. Ropp. Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point track-ing test bed, Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE, pp. 1699-1702, 2000
- [6] A. Kassem and M. Hamad. Microprocessor- based controller Multi –Function for Solar Tracking System, IEEE Proceedings, 2011.
- [7] D. Sera, T. Kerekes, R. Teodorescu, and F. Blaabjerg. Improved MPPT method for rapidly changing environmental conditions, Proceedings IEEE Int. Ind. Electron. Symp., Jul. 2006, Vol. 2, pp. 1420–1425.
- [8] V. Salas, E. Olias, A. Barrado, and A. Lazaro. Review of the maximum power point tracking algorithms for standalone photovoltaic systems, Sol. Energy Mater. Sol. Cells, Vol. 90, No. 11, pp. 1555–1578, July 2006.
- [9] M. C. Alonso-Gracia, J. M. Ruiz, and F. Chenlo. Experimental study of mismatch and shading effects in the Solar Panel, Solar Energy Mater. Solar Cells, Vol. 90, No. 3, pp. 329–340, Feb. 2006.
- [10] H. Kawamura, K. Naka, N. Yonekura, S. Yamanaka, H. Kawamura, H. Ohno, and K. Naito. Simulation of I–V characteristics of a PV module with shaded PV cells, Solar Energy Mater. Solar Cells, Vol. 75, No. 3/4, pp. 613– 621, Feb. 2003.
- [11] H. Patel and V. Agarwal. MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array, IEEE Transactions On Energy Conversion, Vol. 23, No. 1, pp. 302–310, March 2008.
- [12] H. Patel and V. Agarwal. Maximum Power Point Tracking Scheme for PV Systems Operating Under Partially Shaded Conditions, IEEE Transactions On Industrial Electronics, Vol. 55, No. 4, pp. 1689–1698, April 2008.