

MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array Characteristics

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Abstract—The performance of a photovoltaic (PV) array is affected by temperature, solar insolation, shading, and array configuration. Often, the PV arrays get shadowed, completely or partially, by the passing clouds, neighboring buildings and towers, trees, and utility and telephone poles. The situation is of particular interest in case of large PV installations such as those used in distributed power generation schemes. Under partially shaded conditions, the PV characteristics get more complex with multiple peaks. Yet, it is very important to understand and predict them in order to extract the maximum possible power. This paper presents a MATLAB-based modeling and simulation scheme suitable for studying the I - V and P - V characteristics of a PV array under a nonuniform insolation due to partial shading. It can also be used for developing and evaluating new maximum power point tracking techniques, especially for partially shaded conditions. The proposed models conveniently interface with the models of power electronic converters, which is a very useful feature. It can also be used as a tool to study the effects of shading patterns on PV panels having different configurations. It is observed that, for a given number of PV modules, the array configuration (how many modules in series and how many in parallel) significantly affects the maximum available power under partially shaded conditions. This is another aspect to which the developed tool can be applied. The model has been experimentally validated and the usefulness of this research is highlighted with the help of several illustrations. The MATLAB code of the developed model is freely available for download.

Index Terms—Array configuration, maximum power point tracking (MPPT), partial shading, photovoltaic (PV) characteristics.

I. INTRODUCTION

WITH a spurt in the use of nonconventional energy sources, photovoltaic (PV) installations are being increasingly employed in several applications, such as distributed power generation and stand-alone systems. However, a major challenge in using a PV source is to tackle its nonlinear output characteristics, which vary with temperature and solar insolation. The characteristics get more complicated if the entire array does not receive uniform insolation, as in partially cloudy (shaded) conditions, resulting in multiple peaks. The presence of multiple peaks reduces the effectiveness of the existing maximum power point tracking (MPPT) schemes [1]–[3] due to their inability to discriminate between the local and global peaks. Nevertheless, it is very important to understand and predict the

PV characteristics in order to use a PV installation effectively, under all conditions.

Over the years, several researchers have studied the characteristics of PV modules and the factors that affect them [4]–[7]. Walker [4] has proposed a MATLAB-based model of a PV module to simulate its characteristics for studying the effect of temperature, insolation, and load variation on the available power. However, the model does not consider the effect of shading on the PV characteristics. Alonso-Gracia *et al.* [5] have experimentally obtained the I - V characteristics of the PV module and the constituent cells to study the effect of partial shading. However, their work is limited to module-level study and does not discuss the shading effects on an entire PV array. Kawamura *et al.* [6] have also investigated the effect of shading on the output of the PV modules and the associated change in their I - V characteristics. However, the I - V and P - V characteristics of the single module, considered in their study, do not predict the presence of multiple steps and peaks, which are common in the I - V and P - V characteristics of large PV arrays that receive nonuniform insolation. A numerical algorithm, which considers the mismatch in individual PV cells and their shading levels, has also been proposed [8] to simulate the complex characteristics of a PV array. It requires each element (each cell of the module, bypass diode, blocking diode, etc.) to be represented by a mathematical expression. This can render accurate results, though at the expense of complex modeling, involving large and complex matrix computations, more computation time and efforts, and higher memory requirement.

Some researchers have studied the effects of fluctuations in PV power on the utility and connected systems. Kern *et al.* [9] have studied the consequences of the shading of PV, due to passing clouds, on the fluctuations of PV power generation, and therefore, on the performance of the electrical utility to which it is connected. Giraud and Salameh [10], using a neural-network-based model, have also investigated the effects of passing clouds on a grid-connected PV system with battery storage. It is important to select a proper size of the PV array and batteries in such systems [11]. Otherwise, a sudden, large change in PV power because of insolation variation, caused by shading, may lead to instability. Shading caused due to passing clouds also has a financial implication on the utility. Jewell and Unruh have carried out an economic analysis to estimate the cost of the fluctuations in power generation from a PV source [12].

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.

Manuscript received October 30, 2006; revised March 25, 2007. Paper no. TEC-00506-2006.

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Digital Object Identifier 10.1109/TEC.2007.914308

From the preceding paragraphs, it may be concluded that, while it is very important to model, study, and understand the effects of shading on PV arrays, a “simple-to-use,” accurate and economical computer-aided design (CAD) tool is 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 partially shaded 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 shading 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 insolation variation, varying shading patterns (characterized by multiple peaks in the power-voltage curves), and the role of array configuration on the PV characteristics. A notable advantage of the presented paper 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 [13]–[15].

The usefulness of the proposed tool is demonstrated with the help of several illustrative examples.

II. MODEL OF A PV ARRAY

A PV cell can be represented by an equivalent circuit, as shown in Fig. 1. The characteristics of this PV cell can be obtained using standard equations [4]. For simulating an entire PV array, the model of a PV module is developed first. Each PV module considered in this paper comprises 36 PV cells connected in series providing an open circuit voltage (V_{oc}) = 21 V and a short-circuit current (I_{sc}) = 3.74 A.

The shading pattern for a large array is very complex to model. A special categorization and terminology is used in this paper

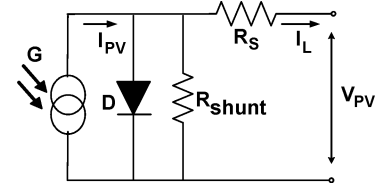


Fig. 1. Equivalent circuit of a PV cell.

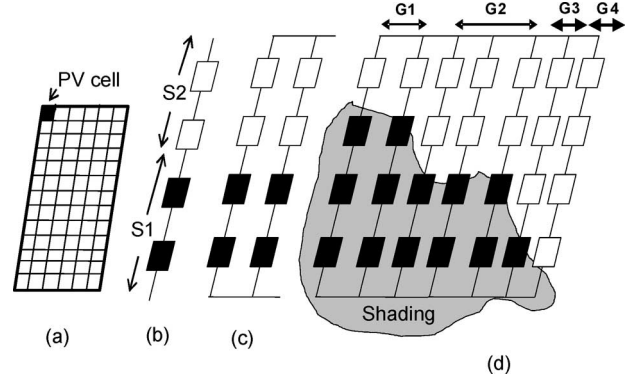


Fig. 2. PV array terminologies. (a) PV module. (b) Series-assembly with two series-connected subassemblies S1 and S2. (c) Group. (d) PV array with groups G1 to G4.

to describe the various components of a PV array. These are explained with the help of Fig. 2. 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 [Fig. 2(b)]. Series assemblies, having similar shading patterns, form a “group” [Fig. 2(c)]. 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 Fig. 2(d).

III. SIMULATION PROCEDURE

This section describes the procedure used for simulating the I - V and P - V characteristics of a partially shaded PV array. It is important to understand how the shading pattern and the PV array structure are defined in MATLAB using the proposed scheme. This procedure consists of defining groups, assemblies, etc., for use with the MATLAB model developed corresponding to Fig. 2(d). This is explained with the help of illustration 1. To begin with, a simple case is considered with just two different shades on the PV array.

A. Illustration 1

Given a PV array consisting of 1000 PV modules arranged into 100 series assemblies, connected in parallel, each having 10 modules. It is desired to obtain the I - V and P - V characteristics of the various components (module through group, as described in Fig. 2) of this PV array, which consists of three groups with different insolation patterns, as given in Table I. Groups G1 through G3 have 40, 38, and 22 series assemblies, respectively. The complete PV array is shown in Fig. 3. As seen in Fig. 3,

TABLE I
SHADING PATTERN AND CONFIGURATION OF THE ARRAY USED IN
ILLUSTRATION

Group	Number of unshaded modules in series assembly ($\lambda=1$)	Number of shaded modules in series assembly ($\lambda=0.1$)	No. of series assemblies in a group
G1	4	6	40
G2	7	3	38
G3	10	0	22

λ =Solar insolation in kW/m^2 .

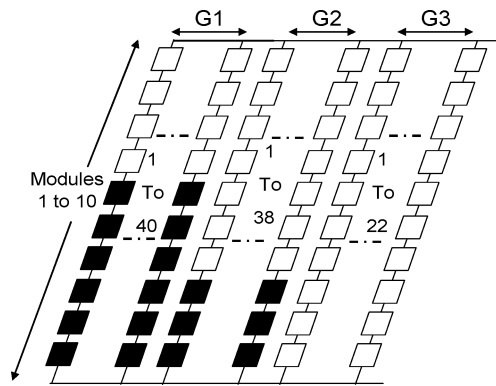


Fig. 3. PV array configuration for illustration 1, corresponding to the shading pattern of Table I.

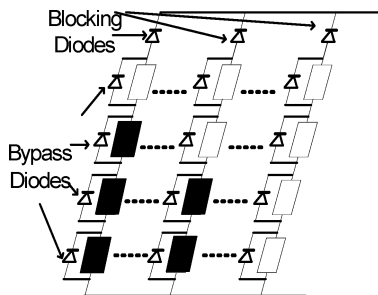


Fig. 4. PV array with bypass and blocking diodes. The dark modules imply shading.

only two different insolation levels are considered for simplicity. Shaded modules, receiving an insolation, $\lambda = 0.1 \text{ kW/m}^2$, are indicated in dark color.

The aforementioned illustration explains the method and the format in which the input parameters are fed and the array configuration is described in the software to obtain the PV characteristics.

1) *Effect of Bypass and Blocking Diodes on PV Characteristics*: Fig. 4 shows a PV array with bypass and blocking diodes connected in the array. It is important to note that the characteristics of an array with bypass and blocking diodes differ from that of an array without these diodes. The developed simulation tool has a provision to simulate the array characteristics, for any value of temperature, insolation, and for any array configuration, with and without the bypass and blocking diodes. Illustration 1 considers the case where bypass diodes are connected across every module and at least one blocking diode is connected in series with each of the series assemblies, as shown in Fig. 4. To

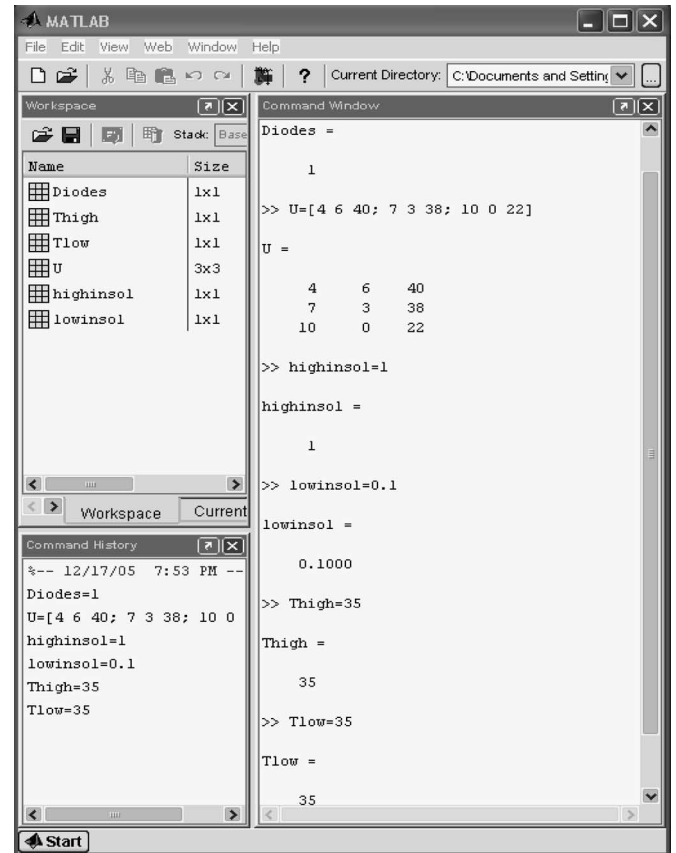


Fig. 5. Screen shot of the MATLAB command window showing how the input parameters are fed and array configuration is described in the software.

learn more on how the characteristics differ in these two cases, an illustration (illustration 2) is included in a later section.

Fig. 5 shows a screen shot of the MATLAB command window through which the given array configuration, temperature, and the insolation level(s) are described to the software. The matrix U of size $G \times 3$, where G is the number of groups, represents the array configuration. Each row indicates a group with a particular shading pattern on the series assemblies within that group. The elements of each row represent the number of unshaded and shaded modules, respectively, in a series assembly, and the number of such series assemblies in the group. This implies that the first row of U is same as the first row of Table I corresponding to G1 and so on. “Diodes = 1” indicates the presence of bypass and blocking diodes, while their absence is indicated by entering “Diodes = 0.” “Highinsol” and “Lowinsol” are the insolation levels ($\lambda = 1$ and $\lambda = 0.1 \text{ kW/m}^2$) on the unshaded and shaded modules, respectively. Similarly, “Thigh” and “Tlow” denote the working temperatures (in degrees Celsius) of the respective modules.

Once the information is fed into the software, various windows pop up on the monitor, as shown in Fig. 6. These windows display the $I-V$ and $P-V$ characteristics of different components of the PV array described in Fig. 2.

The $I-V$ and $P-V$ characteristics of the two PV (shaded and unshaded modules of Fig. 3) modules at the same temperature but at different insolation levels are shown in Fig. 6. It is

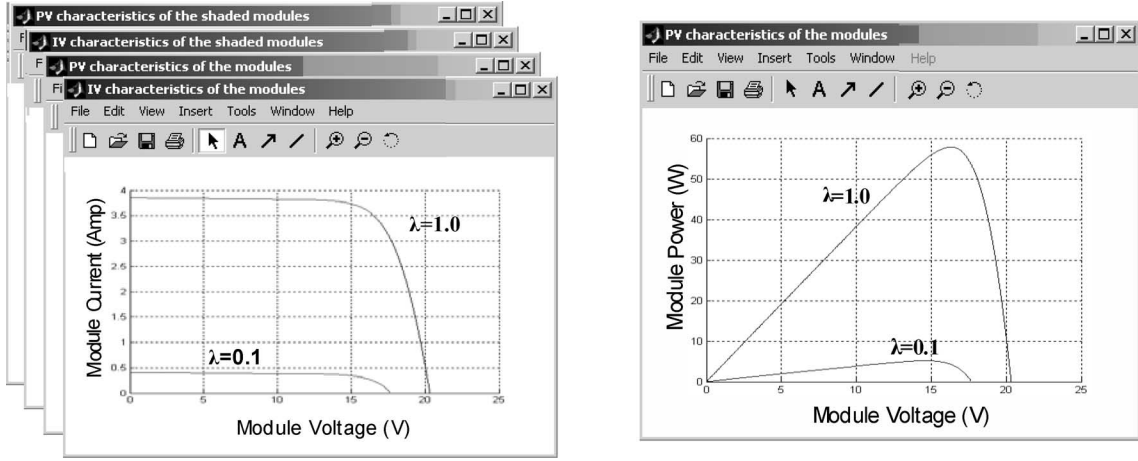


Fig. 6. Characteristics of the PV modules under different insolation levels ($\lambda = 1$ and $\lambda = 0.1$ kW/m²). (a) I - V characteristics. (b) P - V characteristics.

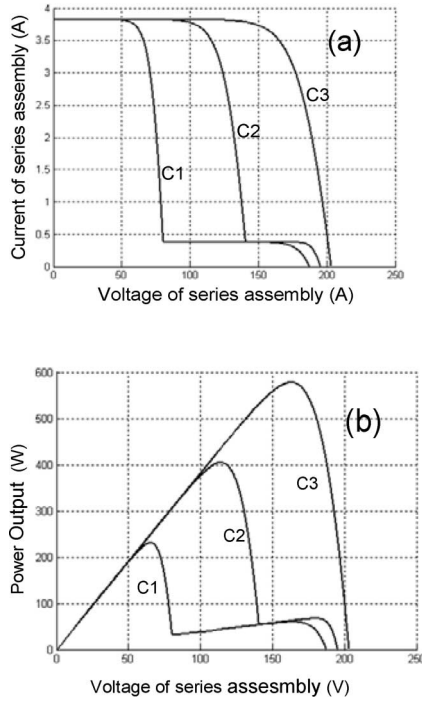


Fig. 7. Characteristics of series assemblies with different insolation levels. (a) I - V characteristics. (b) P - V characteristics.

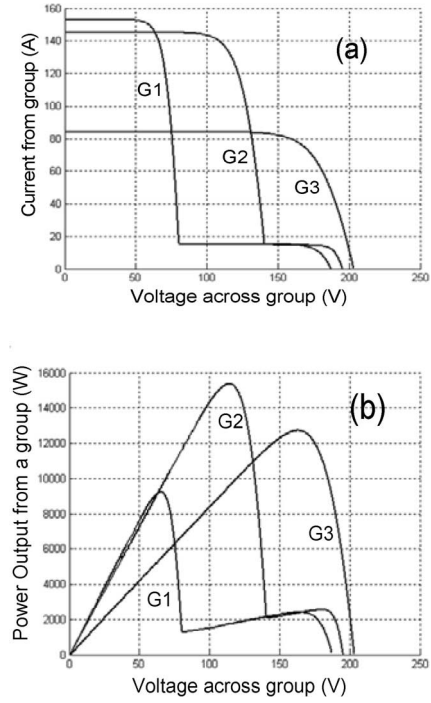


Fig. 8. Output characteristics of the groups (parallel-connected series assemblies). (a) I - V characteristics. (b) P - V characteristics.

assumed that a shaded module consists of at least three shaded cells displaying the characteristics shown in Fig. 6(a) and (b). If these two PV modules are connected in series, they will conduct the same current, but the voltage across them will be different. In order to obtain the I - V characteristics of the series-connected modules (series assembly) conducting a current I_o , the voltages across these modules, V_1 and V_2 , are added to determine the resultant output voltage. The characteristics for series assembly are, thus, obtained internally by the software by applying similar procedure at all the points on the I - V curve of the series-connected modules.

Fig. 7 shows the resulting characteristics of series assemblies C1, C2, and C3 belonging to groups G1, G2, and G3, respec-

tively. If similar series assemblies having identical insolation patterns are connected in parallel to form a group, the current output is multiplied, but there is no change in the output voltage. Fig. 8 shows the characteristics of these groups. To obtain the overall resultant characteristics of all these groups (i.e., of the entire array), a common voltage is considered, while the current output of each of these groups is added to obtain the resultant current. The resultant characteristics of the PV array are shown in Fig. 9.

IV. SIMULATION RESULTS WITH THE PROPOSED MODEL

This section describes the usefulness of the proposed simulation model in simulating and understanding the effect of

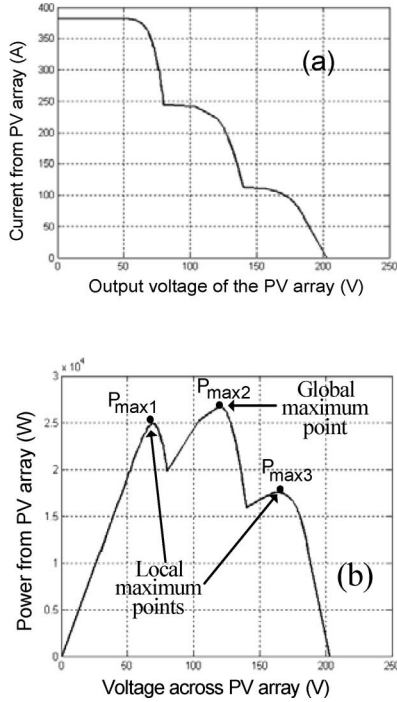


Fig. 9. Output characteristics of the entire array considered in illustration 1. (a) I - V characteristics. (b) P - V characteristics.

bypass and blocking diodes, array configuration, varying insolation level(s), and different shading pattern(s) on the global peak power and its position. This is studied with the help of illustrations 2, 3, and 4, given next.

A. Illustration 2

The effect of the bypass and blocking diodes on the PV characteristics under partially shaded conditions has been simulated for the array described in Table I.

The curves C1, C2, and C3, in Fig. 10, represent the I - V and P - V characteristics of the array in the following three cases, respectively: 1) under uniform insolation ($\lambda = 1 \text{ kW/m}^2$); 2) under partially shaded condition ($\lambda = 1$ and $\lambda = 0.1 \text{ kW/m}^2$) and without diodes; and 3) under partially shaded condition as in case (2), but with diodes.

It is seen from the I - V characteristics shown in Fig. 10(a) that the presence of bypass diodes will allow the unshaded modules of all the series assemblies to conduct their maximum current at a given insolation and temperature. On the other hand, if the bypass diodes are not present, the shaded modules will limit the current output of the unshaded modules of the series assembly. This may not only lead to a thermal destruction of the PV modules but may also decrease the available output power from the PV array. The blocking diodes will prevent the reverse current through the series assemblies, which generate lower output voltage as compared to the others connected in parallel. This reverse current may cause excessive heat generation and thermal breakdown of PV modules. Fig. 10 reveals that the array having these diodes introduces multiple steps in the I - V characteristics

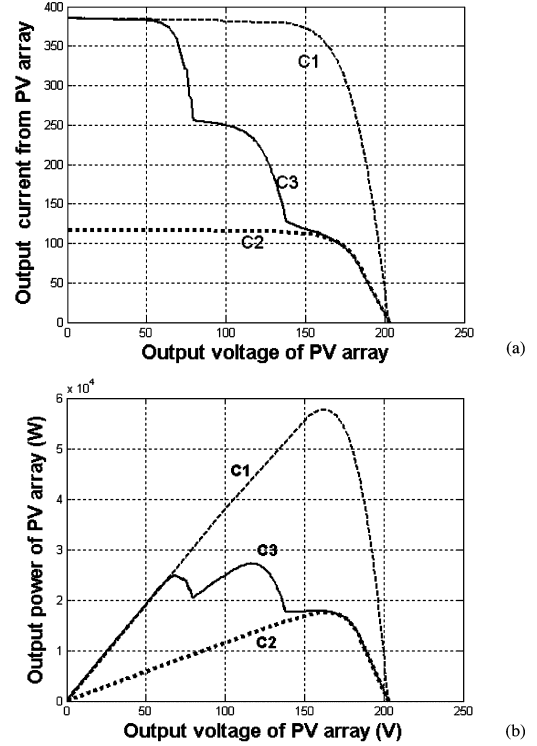


Fig. 10. Three different cases discussed in illustration 2. (a) I - V curves. (b) P - V curves.

and multiple peaks in the P - V characteristics, under the partially shaded conditions.

B. Illustration 3

The objective of this illustration is to simulate the response of a partially shaded PV array with different configurations. Consider an array of 300 PV modules organized into three groups G1, G2, and G3 with three, five, and x series assemblies, respectively, where x is obtained by deducting the number of series assemblies of G1 and G2 from the total parallel-connected series assemblies. Each row of Table II describes the different array configuration considered. It is assumed that four modules of the series assemblies of group G1, six modules of the series assemblies of G2, and none in G3 experience a low insolation ($\lambda = 0.5 \text{ kW/m}^2$).

Fig. 11 shows that the peak power from the PV array under nonuniform insolation is dependent on the configuration in which the modules are connected. It shows the existence of multiple peaks, whose number is equal to the number of different shading patterns on the PV array. Fig. 11 reveals that maximum power is obtained with "C6," which represents the array configuration having 30 series assemblies, each with 10 series-connected modules. Therefore, it is desirable to have a large number of parallel-connected series assemblies, each with a lower number of series-connected modules in it.

C. Illustration 4

A PV array consisting of 900 modules is considered. With the array configuration and shading pattern as defined in Table III,

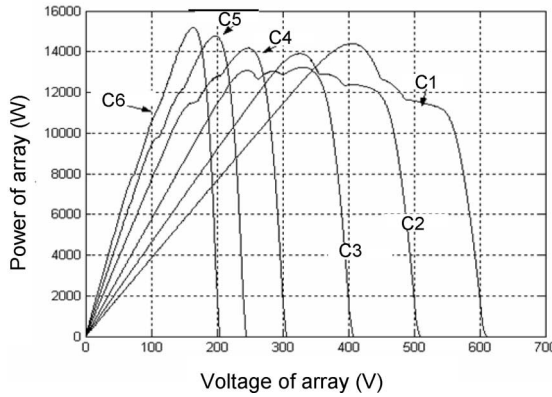
TABLE II
 VARIOUS CONFIGURATIONS OF THE PV ARRAY FOR ILLUSTRATION 3

Curve	G1			G2			G3			Array configuration
	U	S	N _s	U	S	N _s	U	S	N _s	
1	26	4	3	24	6	5	30	0	2	30 × 10
2	21	4	3	19	6	5	25	0	4	25 × 12
3	16	4	3	14	6	5	20	0	7	20 × 15
4	11	4	3	9	6	5	15	0	12	15 × 20
5	8	4	3	6	6	5	12	0	17	12 × 25
6	6	4	3	4	6	5	10	0	22	10 × 30

U: Number of unshaded modules in a series assembly; S: Number of shaded modules in a series assembly; N_s: Number of series assemblies in a group.

 TABLE III
 PV ARRAY CONFIGURATION TO STUDY THE GLOBAL PEAK AND ITS POSITION

Group	U	S	N _s
G1	3	7	15
G2	5	5	15
G3	6	4	20
G4	8	2	20
G5	10	0	20


 Fig. 11. P - V curves showing the effect of array configuration. “C i ” implies a curve for the i th configuration of Table II.

it is desired to investigate the P - V curves of this array as the insolation changes in steps of 0.15 kW/m^2 . The response is shown in Fig. 12.

Fig. 12 shows the resulting P - V characteristics at various insolation levels. It is observed that the number of prominent peaks increases with decrease in the insolation level on the shaded modules. At higher insolation levels, the global peak lies toward the voltage source region and shifts more toward the current source region with a decrease in the insolation.

V. GENERALIZED MODEL AND EVALUATION OF MPPT

This section discusses a generalized model, which can be used to simulate PV characteristics under partial shading. Unlike the model presented in Section III, which considers only two different shades, this model can accept different levels of insolation, temperature, shading patterns, and array configurations. Illustration 5 discusses this model and the input interface.

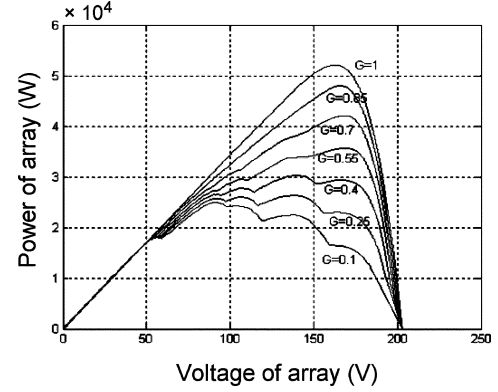
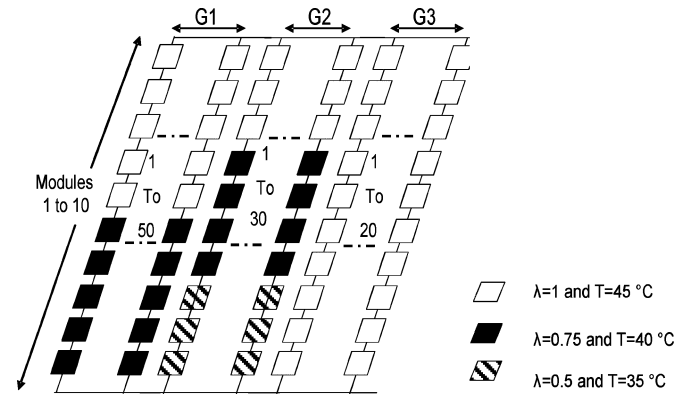

 Fig. 12. P - V curves for different insolation levels and identical shading pattern.


Fig. 13. PV array configuration for illustration 5.

A. Illustration 5

Considering a more complex case, it is desired to obtain the P - V characteristic of an array consisting of 1000 (10×100) modules and receiving insolation at several different levels. The array is arranged into three groups G1, G2, and G3 with 50, 30, and 20 series assemblies, respectively, as shown in Fig. 13. It also shows the insolation level and the temperature of the different modules. A snapshot of the MATLAB command window, shown in Fig. 14, depicts the manner in which one can feed the information into this generalized program.

It is observed from the previous illustrations that the number of peaks is equal to the number of groups. In this illustration, the array has three different groups and three different shades. But Fig. 15 shows four different peaks (or steps), indicating that the number of peaks, their magnitudes, and the overall nature of the PV curve is dependent on the temperature of the modules, the insolation level, the shading pattern, and the array configuration. A generalized program, such as the one illustrated before, can provide a better solution to learning and understanding the behavior of a PV array in a complex scenario.

B. Illustration 6

Illustration 6 is included to study the effectiveness of an MPPT algorithm to track the global peak of the P - V characteristics (for partially shaded conditions), such as the one shown in

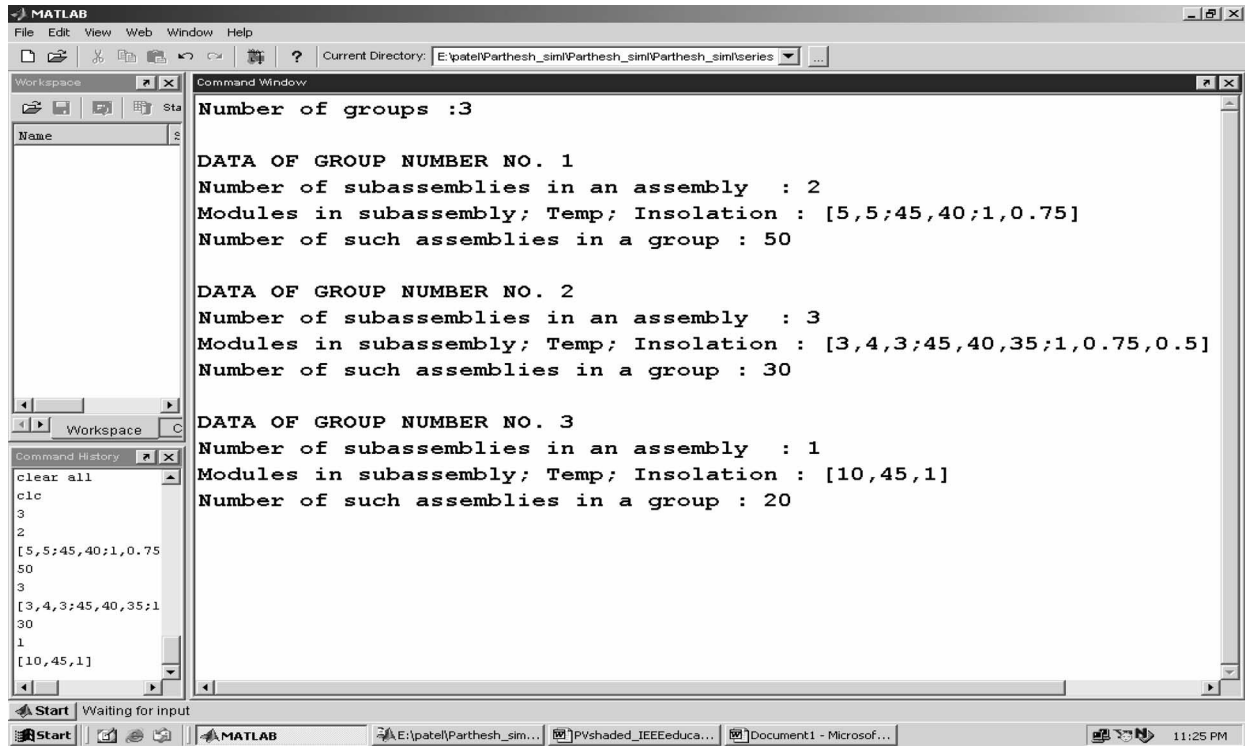


Fig. 14. Screen shot of the MATLAB command window showing how the input parameters are fed into the model to simulate a more complex and generalized array.

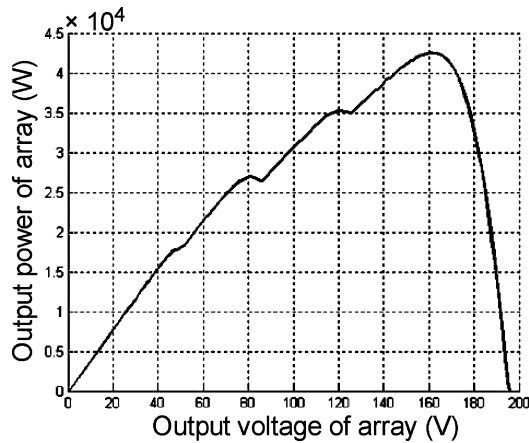


Fig. 15. P - V curve for the array of illustration 5.

Fig. 3. A two-stage power electronic system, shown in Fig. 16, comprising a boost-type dc-dc converter and an inverter, is used to feed the power generated by the PV array to the grid and grid-connected loads. The conventional hill climbing method is used for MPPT. The performance of this method, in tracking global MPP, is tested for two different cases for an array given in Table I (illustration 2): 1) under uniform insolation ($\lambda = 1 \text{ kW/m}^2$) and 2) under partially shaded condition ($\lambda = 1$ and $\lambda = 0.1 \text{ kW/m}^2$).

It is assumed that the array initially receives uniform insolation of $\lambda = 1 \text{ kW/m}^2$ [case 1]. A step change in insolation level (from $\lambda = 1$ and $\lambda = 0.1 \text{ kW/m}^2$) is considered at $t = 0.3 \text{ s}$ that causes partial shading of the array [case 2]. The P - V

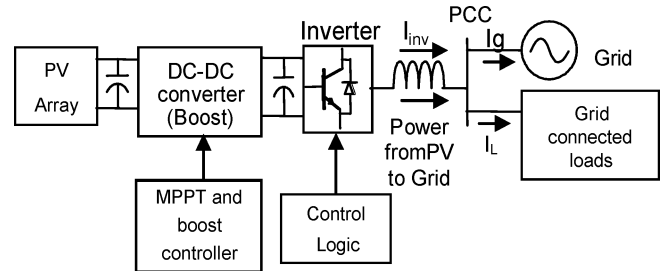


Fig. 16. System configuration for PV-based system feeding power into the grid.

characteristics for this case are shown in Fig. 10(b). The results for this illustration are shown in Figs. 17 and 18.

It is observed that, until $t = 0.3 \text{ s}$, at which shading occurs, the PV array's voltage and current are maintained at 162 V and 357 A, respectively, corresponding to the maximum power point. The effect of shading (at $t = 0.3 \text{ s}$) is to shift the operating point from 162 V, 57.8 kW to 68 V, 24.6 kW [Fig. 10(b)]. This new operating point is the local maximum, with a surplus power of about 2.4 kW still remaining to be tracked. At $t = 0.6 \text{ s}$ and $t = 0.8 \text{ s}$, the load is increased to 8 and 12 times, respectively, as compared to that before $t = 0.6 \text{ s}$. As a rigid grid voltage is considered at the point of common coupling (PCC), it is observed from Fig. 18 that a sudden partial shading effect at $t = 0.3 \text{ s}$ decreases the inverter and the grid currents. At $t = 0.6 \text{ s}$, when the load increases, the grid current decreases further as the inverter continues to feed the same power, and therefore, the same current corresponding to the local maxima. It can also

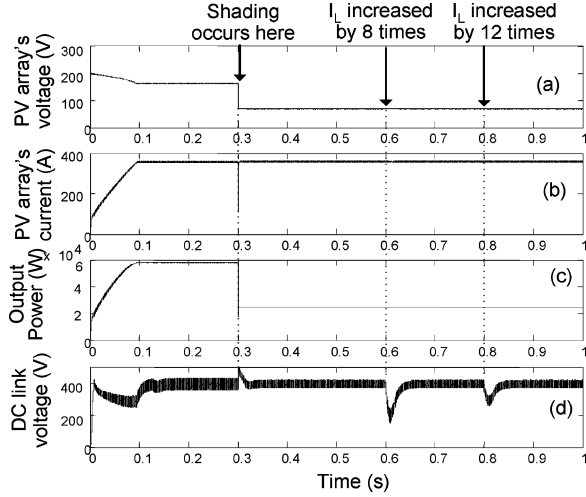


Fig. 17. (a)–(c) Output voltage, current, and output power from the PV array. (d) Output voltage of the boost converter (illustration 6).

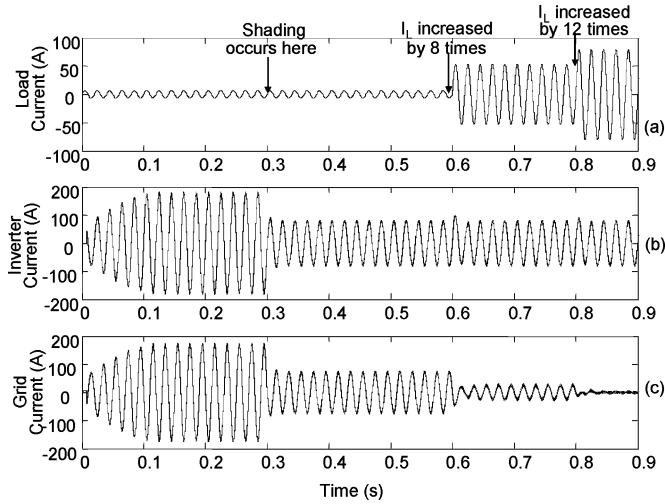


Fig. 18. (a) Variation in the load current I_L . (b) Current fed from inverter I_{inv} . (c) Grid current I_g (illustration 6).

be observed from Fig. 18 that no power is transferred to the grid, after $t = 0.8$ s. In fact, the grid has to supply the power. If the grid is replaced by a weak source, it may lead to a collapse of the system. This illustration highlights the limitation of the conventional MPPT schemes when multiple peaks are present. They cannot distinguish between the global and local peaks.

VI. TESTING AND VALIDATION OF MODEL

The simulation model was tested with an actual PV array, shown in Fig. 19, comprising two groups, each with two series assemblies of six 38FR36 PV modules. The rating of the PV modules are $P_{max} = 38$ W, $I_{MPP} = 2.29$ A, $V_{MPP} = 16.6$ V, $I_{sc} = 2.55$ A, and $V_{oc} = 21.5$ V at an insolation level of 1000 W/m² and 25 °C temperature. The measurements were recorded with and without the bypass diodes (connected across the shaded modules) and blocking diodes (one connected in series with each series assembly).

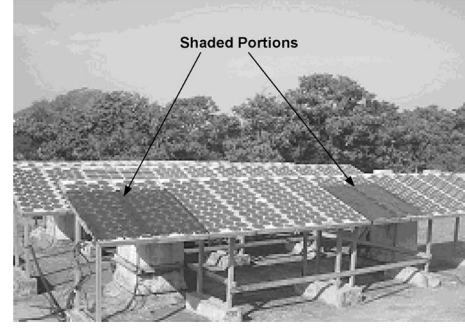


Fig. 19. Experimental setup for validation of the model.

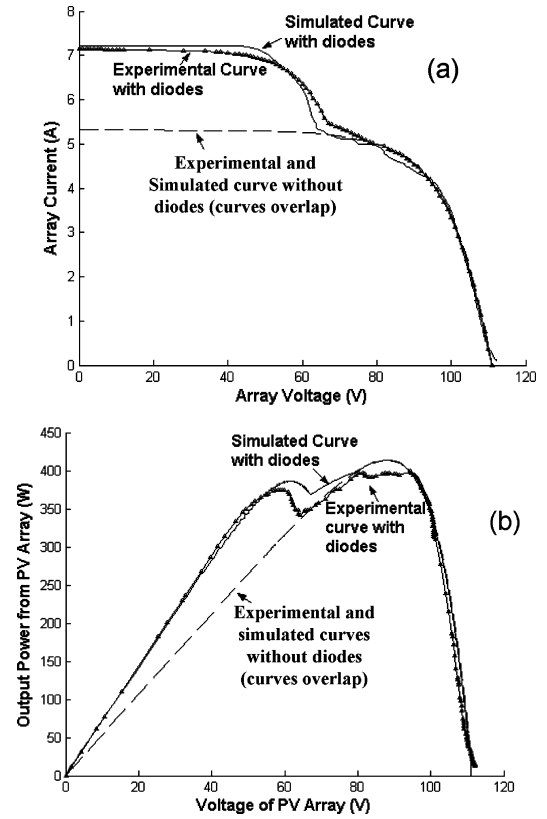


Fig. 20. Simulation and experimental results on the test setup. (a) I – V characteristics. (b) P – V characteristics.

Fig. 20 shows the simulated and experimental results. The shading effect was artificially generated by covering two modules of each series assembly of the first group with partially transparent gelatin paper. It is observed that the simulated results closely match the measured values. The average solar flux on the tilted array for the simulation model was considered as 680 W/m² that is in accordance with the solar flux at 2:10 P.M. on November 12 at Bombay, India [16]. The discrepancies in the curves at some points may be due to two reasons: 1) the change in irradiation over a time span during which the measurements were carried out and 2) voltage drop across the diode is neglected in the simulation.

Fig. 20 shows the characteristics of the PV array used for experiments. As expected and discussed in illustration 2, the

presence of diodes introduces an additional peak in the P - V characteristic and generates more output power compared to the case where the diodes are absent.

VII. CONCLUSION

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 partially shaded conditions is described. The PV curves show multiple peaks under partially shaded conditions. 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 nonuniform insolation conditions. The generalized model is available for free download from the following Web site: <http://www.ee.iitb.ac.in/uma/~phiren/>.

REFERENCES

- [1] E. Koutroulis, K. Kalaitzakis, and N. C. Voulgaris, "Development of a microcontroller-based photovoltaic maximum power point tracking control system," *IEEE Trans. Power Electron.*, vol. 16, no. 1, pp. 46–54, Jan. 2001.
- [2] K. H. Hussein and I. Muta, "Maximum photovoltaic power tracking: An algorithm for rapidly changing atmospheric conditions," *Proc. Inst. Electr. Eng. Gener., Transmiss. Distrib.*, vol. 142, no. 1, pp. 59–64, Jan. 1995.
- [3] S. Jain and V. Agarwal, "A new algorithm for rapid tracking of approximate maximum power point in photovoltaics systems," *IEEE Power Electron. Lett.*, vol. 2, no. 1, pp. 16–19, Mar. 2004.
- [4] G. Walker, "Evaluating MPPT converter topologies using a MATLAB PV model," *J. Electr. Electron. Eng. Aust.*, vol. 21, no. 1, pp. 49–56, 2001.
- [5] M. C. Alonso-Gracia, J. M. Ruiz, and F. Chenlo, "Experimental study of mismatch and shading effects in the," *Solar Energy Mater. Solar Cells*, vol. 90, no. 3, pp. 329–340, Feb. 2006.
- [6] 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.
- [7] T. Shimizu, M. Hirakata, T. Kamezawa, and H. Watanabe, "Generation control circuit for photovoltaic modules," *IEEE Trans. Power Electron.*, vol. 16, no. 3, pp. 293–300, May 2001.
- [8] V. Quaschnig and R. Hanitsch, "Numerical simulation of current-voltage characteristics of photovoltaic systems with shaded solar cells," *Solar Energy*, vol. 56, no. 6, pp. 513–520, Feb. 1996.
- [9] E. C. Kern, E. M. Gulachenski, and G. A. Kern, "Cloud effects on distributed photovoltaic generation: Slow transients at the Gardner, Massachusetts photovoltaic experiment," *IEEE Trans. Energy Convers.*, vol. 4, no. 2, pp. 184–190, Jun. 1989.
- [10] F. Giraud and Z. Salameh, "Analysis of the effects of a passing cloud on a grid-interactive photovoltaic system with battery storage using neural networks," *IEEE Trans. Energy Convers.*, vol. 14, no. 4, pp. 1572–1577, Dec. 1999.
- [11] M. G. Jaboori, M. M. Saied, and A. R. Hanafy, "A contribution to the simulation and design optimization of photovoltaic systems," *IEEE Trans. Energy Convers.*, vol. 6, no. 3, pp. 401–406, Sep. 1991.
- [12] W. T. Jewell and T. D. Unruh, "Limits on cloud-induced fluctuation in photovoltaic generation," *IEEE Trans. Energy Convers.*, vol. 5, no. 1, pp. 8–14, Mar. 1990.
- [13] N. Reddy and V. Agarwal, "Utility interactive hybrid distributed generation scheme with compensation feature," *IEEE Trans. Energy Convers.*, vol. 22, no. 3, pp. 666–673, 2007.
- [14] V. F. Pires, J. Fernando, and A. Silva, "Teaching nonlinear modeling, simulation, and control of electronic power converters using MATLAB/SIMULINK," *IEEE Trans. Educ.*, vol. 45, no. 3, pp. 253–261, Aug. 2002.
- [15] E. Allen, N. LaWhite, Y. Yoon, J. Chapman, and M. Ilic, "Interactive object-oriented simulation of interconnected power systems using SIMULINK," *IEEE Trans. Educ.*, vol. 44, no. 1, pp. 87–94, Feb. 2001.
- [16] S. P. Sukhatme, *Solar Energy: Principles of Thermal Collection and Storage*, 2nd ed. New Delhi, India: Tata McGraw-Hill, 1996.



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