Identification of Photovoltaic Source Models

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***Abstract*—This paper presents a photovoltaic (PV) model estimation method from the PV module data. The model is based on a single-diode model of a PV cell. The cell model of a module is extended to estimate the parameters of arrays. The variation of the parameters with change in temperature and irradiance is also studied. Finally, estimation of the maximum power point from the estimated parameters under varying environmental conditions is presented.**

***Index Terms*—Maximum power point tracking (MPPT), modeling, photovoltaics (PVs).**

I. Introduction

THE advancement of technology of photovoltaic (PV) systems and subsidies from numerous governments has made the production of power using PV economically viable. Countries of Western Europe have set a target PV generation capacity by 2010 in their mix of renewable energy [1]. PV generation systems have a worldwide industrial growth of around 40% per year [2]. With the increasing penetration of PV generating stations in power grids, the model of a PV power station is needed [3]. Mathematical models of PV stations can be used for power grid studies.

Of the several models available in the literature, single-diode model fairly emulates the PV characteristics. The manufacturer's datasheet provides information about certain points on the PV characteristic, referred to as remarkable points by Villalva *et al*. [4]. In this paper, parameters of the PV model are estimated from the module datasheet.

A single-diode model is shown in Fig. 1. It consists of a current source, a diode, and series and parallel resistances. The voltage–current (*V–I*) relationship of PV can be written from Kirchhoff's current law [5] as

$$I = I_{\rm ph} - I_o \left\{ \exp\left(\frac{V + IR_s}{n_s V_t}\right) - 1 \right\} - \frac{V + IR_s}{R_{\rm sh}} \quad (1)$$

where V and I are the module voltage and current, respectively; $I_{\rm ph}$ and I_o are the photo-generated current and the dark saturation current, respectively; V_t is the junction thermal voltage; R_s and $R_{\rm sh}$ are the series and parallel resistances, respectively; and n_s is the number of cells in the module connected in series.

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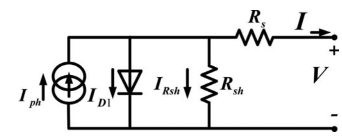

Fig. 1. Single-diode model of a PV source including series and parallel resistances.

The thermal voltage of the diode is related to the junction temperature as given by

$$V_t = \frac{kTA}{q} \quad (2)$$

where k is Boltzmann's constant, T is the junction temperature, A is the diode quality factor, and q is the electronic charge.

The model represented by (1) has five unknown parameters: $I_{\rm ph}$, I_o, V_t, R_s, and $R_{\rm sh}$. The PV modeling objective is to estimate the model parameters under *standard test conditions* (STC) and also under varying environmental conditions from datasheet information provided by the manufacturer of the module.

The PV model *parameters* are adjusted to consider the effects of changing temperature and irradiance, and then the PV model is used to estimate the maximum power point (MPP) under given environmental conditions.

II. Estimation of Parameters

Manufacturer's datasheet provides the following information about the module: short-circuit current $I_{\rm sc}$; open-circuit voltage $V_{\rm oc}$; voltage $V_{\rm mpp}$ and current $I_{\rm mpp}$ at MPP, and the number of cells n_s in the module connected in series. The datasheet also provides temperature coefficient for short-circuit current K_i and open-circuit voltage K_v. The points (0, $I_{\rm sc}$), ($V_{\rm mpp}$, $I_{\rm mpp}$), and ($V_{\rm oc}$, 0) on the *V–I* characteristic are referred to as the remarkable points [4]. Information at these points is used to estimate the parameters.

To simplify the estimation process, the term "-1" in (1) can be neglected, as the exponential term is large compared to 1. Three equations, (3)–(5), are obtained from the *V–I* characteristic by substituting the remarkable points into (1) [6]. Since there are still five unknown parameters, two more equations are needed

$$I_{\rm sc} = I_{\rm ph} - I_o . \exp\left\{\frac{I_{\rm sc}.R_s}{n_s.V_t}\right\} - \frac{I_{\rm sc}.R_s}{R_{\rm sh}} \quad (3)$$

$$I_{\rm mpp} = I_{\rm ph} - I_o . \exp\left\{\frac{V_{\rm mpp} + I_{\rm mpp}.R_s}{n_s.V_t}\right\} - \frac{V_{\rm mpp} + I_{\rm mpp}.R_s}{R_{\rm sh}} \quad (4)$$

$$I_{\rm oc} = 0 = I_{\rm ph} - I_o . \exp\left\{\frac{V_{\rm oc}}{n_s.V_t}\right\} - \frac{V_{\rm oc}}{R_{\rm sh}}. \quad (5)$$

TABLE I
LIST OF VARIABLE TRANSFORMATIONS

Datasheet values		
I_{sc}	a_1	Short-circuit current
V_{oc}	a_2	Open circuit voltage
V_{mpp}	a_3	Voltage at MPP
I_{mpp}	a_4	Current at MPP
n_s	a_5	Number of cells in series in a module
Unknown parameters		
I_{ph}	x_1	Photo-generated current
I_o	x_2	Dark saturation current
V_t	x_3	Junction voltage
R_s	x_4	Series resistance
R_{sh}	x_5	Parallel resistance
R_{sho}	x_6	Effective resistance at short circuit
Output quantities of the PV source		
I	y_1	Output current
V	y_2	Output voltage
P	y_3	Output power

It is also known that the derivative of power P with respect to voltage V is zero at MPP and is shown in [6]

$$\left.\frac{dP}{dV}\right|_{\substack{V=V_{\rm mpp}\\ I=I_{\rm mpp}}} = 0. \tag{6}$$

Four of the five equations needed to solve for the parameters are available. For the fifth and final equation, the slope of the *V–I* characteristic at short circuit is utilized as given by [6]

$$\left.\frac{dI}{dV}\right|_{\substack{V=0\\ I=I_{\rm sc}}} = -\frac{1}{R_{\rm sho}}. \tag{7}$$

For systematic mathematical representation, let the aforementioned variables be changed as given in Table I.

By neglecting the term "−1" in (1), and using the transformed variable as given in Table I, we obtain [6]

$$y_1 = x_1 - x_2 \exp\left\{\frac{y_2 + y_1.x_4}{a_5.x_3}\right\} - \frac{y_2 + y_1.x_4}{x_5}. \tag{8}$$

Rearranging (5) and using the transformed variables

$$x_1 = x_2 \exp\left\{\frac{a_2}{a_5.x_3}\right\} + \frac{a_2}{x_5}. \tag{9}$$

Substituting the value of x_1 from (9) into (8) and (3), we get

$$y_1 = x_2\left[\exp\left\{\frac{a_2}{a_5\cdot x_3}\right\} - \exp\left\{\frac{y_2 + y_1\cdot x_4}{a_5\cdot x_3}\right\}\right] + \frac{a_2 - y_2 - y_1\cdot x_4}{x_5} \tag{10}$$

$$a_1 = x_2\left[\exp\left\{\frac{a_2}{a_5.x_3}\right\} - \exp\left\{\frac{a_1.x_4}{a_5.x_3}\right\}\right] + \frac{a_2 - a_1.x_4}{x_5}. \tag{11}$$

To simplify the solution, the second term in the parentheses of (11), being insignificant compared to the first, is neglected to obtain

$$a_1 = x_2.\exp\left\{\frac{a_2}{a_5.x_3}\right\} + \frac{a_2 - a_1.x_4}{x_5}. \tag{12}$$

Equation (13) is obtained rearranging (12)

$$x_2 = \left(a_1 - \frac{a_2 - a_1 x_4}{x_5}\right)\exp\left\{-\frac{a_2}{a_5.x_3}\right\}. \tag{13}$$

Substituting the value of x_1 from (9) and x_2 from (13) into (4) and using the transformation as in Table I, we obtain

$$a_4 = a_1 - \frac{a_3 + a_4.x_4 - a_1.x_4}{x_5} - \left(a_1 - \frac{a_2 - a_1.x_4}{x_5}\right)\exp\left\{\frac{a_3 + a_4.x_4 - a_2}{a_5.x_3}\right\}. \tag{14}$$

Finding the derivative of y_3 with respect to y_2 and substituting it into (6) gives [6]

$$a_4 = \frac{a_3 B.\exp\{D\} + a_3/x_5}{1 + B.x_4\exp\{D\}. + x_4/x_5} \tag{15}$$

where $B = (a_1.x_5 - a_2 + a_1.x_4/a_5.x_3.x_5)$, $D = a_3 + a_4.x_4 - a_2/a_5.x_3$.

Finding the derivative of y_1 as given in (8) with respect to y_2 under short-circuit conditions, using the value of x_2 from (13), substituting it into (7), and using the fact that $x_6 \approx x_5$, we get [6]

$$\frac{1}{x_5} = \frac{B\exp\{E\} + 1/x_5}{1 + B.x_4\exp\{E\} + x_4/x_5} \tag{16}$$

where $E = a_1.x_4 - a_2/a_5.x_3$.

Finally, five equations, (9) and (13)–(16), are obtained to determine the five unknown parameters. It is seen that (14)–(16) are transcendental in nature, necessitating numerical method solutions. Furthermore, these three equations are completely independent of x_1 and x_2, and hence, the numerical method problem reduces to the determination of three unknowns from three equations: x_3, x_4, and x_5, which can be solved for using the Gauss–Seidel method; and then these values are used to obtain the values of first x_2 and then x_1 from (13) and (9), respectively.

III. GAUSS–SEIDEL METHOD TO ESTIMATE THE PARAMETERS

The Gauss–Seidel method is an iterative method by which transcendental equations can be solved by expressing the equations in the following form:

$$x^{k+1} = f\left(x^k\right) \tag{17}$$

where x is the unknown variable whose value is to be determined and k is the kth iteration.

A new value of x^{k+1} is obtained by using the old value of x^k on the right-hand side of (17). The process is repeated until the absolute difference between the old and the new values is below acceptable limits. To employ the Gauss–Seidel method to determine the values x_3, x_4, and x_5, (14)–(16) are rearranged to get the form

$$x_3 = \frac{a_4.x_4 + a_3 - a_2}{J} \tag{18}$$

where

$$J = a_5.\ln\left\{\frac{[a_1 - a_4].[x_4 + x_5] - a_3}{a_1.[x_4 + x_5] - a_2}\right\}$$

$$x_4 = \frac{a_2 - a_3 + a_5 x_3.\ln(M)}{a_4} \tag{19}$$

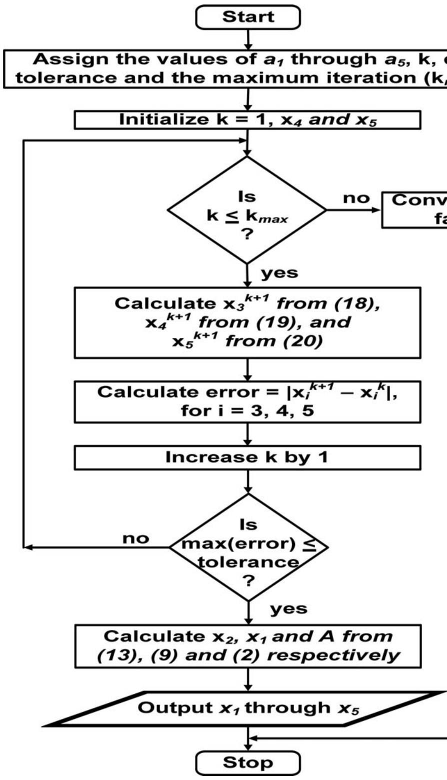

Fig. 2. Flowchart for finding the unknown parameters using the Gauss–Seidel method.

where

$$M = \frac{a_5 x_3 . (a_4 x_4 + a_4 x_5 - a_3)}{a_1 x_4 a_3 + a_1 x_5 a_3 + a_4 a_2 x_4 - a_4 a_1 x_4^2 - a_4 a_1 x_5 x_4 - a_3 a_2}$$

$$x_5 = \frac{a_5 x_3 x_4 + a_5 x_3 x_5 + N}{a_5 x_3 + N} \tag{20}$$

where

$$N = x_4 . \exp\left\{\frac{a_1 x_4 - a_2}{a_5 x_3}\right\} . (a_1 x_4 + a_1 x_5 - a_2) .$$

It is observed that (18) is an explicit equation, whereas (19) and (20) are implicit. x_3, as in (18), is a function of the known quantities as well as x_4 and x_5. So, the values of x_4 and x_5 must be known prior to the evaluation of x_3. Therefore, in this case, using the Gauss–Seidel method, only two unknowns need to be initialized before x_3 is calculated. Next, with the calculated value of x_3, the values of x_4 and x_5 can be evaluated.

A. Gauss–Seidel Method Algorithm

The flowchart for the Gauss–Seidel method which is used to find the values of the unknown parameters is shown in Fig. 2.

B. Initialization

As seen previously, only two unknown parameters, x_4 and x_5, have to be initialized. Studies of numerous modules have shown that, for a module, the value of x_4 is generally in the range of milliohms, whereas the value of x_5 is in the range of kilohms. Therefore, x_4 and x_5 can be initialized at 0 and 1 kΩ, respectively. In most cases, convergence is obtained with the aforementioned initialization. However, there may be some cases where the Gauss–Seidel method may fail to converge or converge at a wrong place. In that case, the initialization is done randomly with a constraint that x_5 is much greater than x_4. Closer the initialization is to the actual value, faster will be the convergence. The *successive under-relaxation* (SUR) technique may be used if the solution fails to converge.

TABLE II
DATASHEET VALUES AND ESTIMATED PARAMETERS OF A MODULE

Datasheet Values		Estimated Parameters	
I_{sc}	*7.36 A*	I_{ph}	*7.36 A*
V_{oc}	*30.4 V*	I_o	*0.104 μA*
V_{mpp}	*24.2 V*	A	*1.310*
I_{mpp}	*6.83 A*	R_s	*0.251 ohm*
n_s	*50*	R_{sh}	*1168 ohm*
Temperature coefficients			
K_i	*0.057%*	K_v	*-0.346%*

IV. CASE STUDY

A case study to find the parameters of the PV module produced by Mitsubishi Electric, PV-MF165EB3, is conducted under STC and under varying environmental conditions. Table II lists values provided on the datasheet, followed by the values of the unknown parameters estimated by the Gauss–Seidel method.

It is observed from the results shown in Table II that the value of the series resistance is very small compared to the parallel resistance as expected. The photo-generated current is almost equal to the short-circuit current.

V. MODELING OF STRINGS AND ARRAYS

A PV source is commercially available in the form of a module in which a number of cells are connected in series. However, for large power and voltage applications, a combination of these modules is needed. A number of modules are connected in series to give a higher voltage. This series combination of the modules is called a string. To increase the current rating of the source, these strings are connected in parallel to form an array.

A conceptual diagram of a string is shown in Fig. 3. It shows that the circuit elements that form a series combination in a string can be lumped to give an equivalent single-diode model of the string, which consists of the same circuit elements as that of one module, but with values of the parameters different, depending on the number of modules connected in series [7].

For a string, the values of the equivalent photo-generated current and the dark saturation current remain the same as that of the module. The diode quality factor too remains the same as that of the module. However, the series and parallel resistances of the string acquire values that are as many times the values for the module as there are modules in the string.

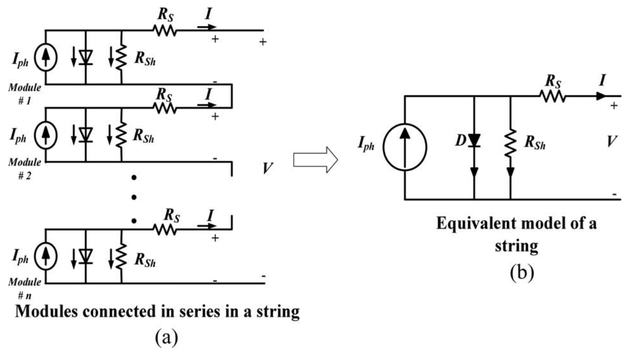

Fig. 3. Equivalent lumped circuit for a string consisting of modules in series.

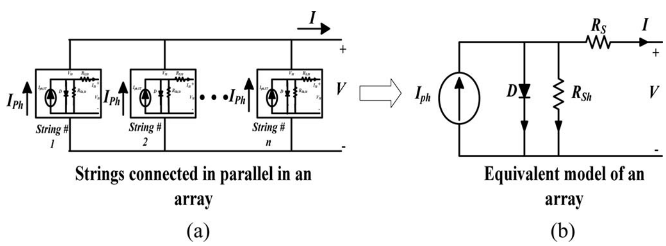

Fig. 4. Equivalent lumped circuit for an array consisting of strings in parallel.

Similarly, a number of strings connected in parallel to increase the current output of the PV source can be represented by an equivalent lumped circuit, as shown in Fig. 4 [7]. In this case, the values of photo-generated current and the dark saturation current of the array are as many times the value for one string as there are strings in the array. While series and parallel resistances get divided by the number of strings in the array, diode quality factor remains the same as that of the string.

A. Design of an Array

Let an array be designed for 80 kW. The maximum system voltage specified by the National Electric Code (NEC) is 600 V. The system voltage as defined by NEC is 1.25 times the open-circuit voltage under STC [8]. For PV-MF165EB3 modules, the open-circuit voltage under STC is 30.4 V. Therefore, a maximum of 15 modules can be connected in series to form a string. If the array is controlled to operate at MPP, and if all modules in the array are identical in all respects and assumed to operate under identical environmental conditions, then each module in the array will also operate at MPP. At MPP under STC, the array voltage is 363 V and the power produced by one module is 165.29 W, and hence, by one string is 2.47 kW. Therefore, 32 strings in parallel will be able to produce approximately 80 kW of power.

B. Estimating Array Parameters

Array parameters can be estimated from datasheet values of the module and from the number of modules in series–parallel combination in the array. If the number of modules connected in series in a string is N_{ss} and the number of strings connected in parallel to form an array is N_{pp}, then the specifications of the array will be as shown in Table III, assuming identical characteristics of each module and identical operating conditions.

TABLE III
DATASHEET VALUES OF AN ARRAY IN RELATION TO A MODULE

Module Datasheet Values	Equivalent Array Values
I_{sc}	$I_{sc} \times N_{pp}$
V_{oc}	$V_{oc} \times N_{ss}$
V_{mpp}	$V_{mpp} \times N_{ss}$
I_{mpp}	$I_{mpp} \times N_{pp}$
n_s	$n_s \times N_{ss}$

TABLE IV
ESTIMATED PARAMETERS OF AN ARRAY IN RELATION TO A MODULE

$N_{ss} = 15, N_{pp} = 32$		
Equivalent Array Parameters		Relationship with Module Parameters
I_{ph}	235.57 A	$I_{ph} \times N_{pp}$
I_o	3.314 µA	$I_o \times N_{pp}$
A	1.310	A
R_s	0.117 ohm	$R_s \times N_{ss} / N_{pp}$
R_{sh}	547.77 ohm	$R_{sh} \times N_{ss} / N_{pp}$

Using the data for the array as given in Table III and the Gauss–Seidel method to estimate the parameters, the equivalent lumped parameter model of the array is obtained. For the 80 kW array consisting of PV-MF165EB3 modules of Table II, with 15 modules per string and 32 strings in parallel, the estimated parameters are shown in Table IV.

From Table IV, it is seen that an alternative approach can be adopted to estimate the equivalent lumped parameters of an array, where the parameters of the module are estimated by first using the method described previously. Then, using information of the number of modules in a string and number of strings in parallel, parameters of the array can be calculated [9].

VI. Temperature and Irradiance Dependence

Photo-generated and dark saturation currents are functions of environmental conditions. Irradiance on the PV module is the cause of production of the photo-generated current which is directly proportional to irradiance and is also a function of temperature. With change in environmental conditions, the remarkable points of PV module change. Since short-circuit current is directly proportional to the photo-generated current, it is also directly proportional to the irradiance. The photo-generated current and the short-circuit current as functions of irradiance are given, respectively, in [6]

$$x_1(G) = x_1(G_{\mathrm{stc}}) \cdot \frac{G}{G_{\mathrm{stc}}} \tag{21}$$

$$a_1(G) = a_1(G_{\mathrm{stc}}) \cdot \frac{G}{G_{\mathrm{stc}}} \tag{22}$$

where G and G_{stc} are the irradiance under given condition and under STC, respectively.

Open-circuit voltage of PV source, however, is not directly proportional to the irradiance. It is obtained rearranging (9) as shown in [6]

$$a_2(G) = a_5.x_3 \ln\left(\frac{x_1(G).x_5 - a_2(G)}{x_2.x_5}\right). \tag{23}$$

The datasheet of PV modules provides temperature coefficient for short-circuit current and open-circuit voltage K_i and K_v, respectively. Short-circuit current and open-circuit voltages as functions of temperature are given, respectively, in [6]

$$x_1(T) = x_1(T_{\mathrm{stc}}) + K_i(T - T_{\mathrm{stc}}) \tag{24}$$

$$x_2(T) = x_2(T_{\mathrm{stc}}) + K_v(T - T_{\mathrm{stc}}). \tag{25}$$

Dark saturation current is a function of temperature alone, and is independent of irradiance. It can be found out from (13) by expressing the variables as functions of temperature, as shown in [6]

$$x_2(T) = \left(a_1(T) - \frac{a_2(T) - a_1(T)x_4}{x_5}\right)\exp\left\{-\frac{a_2(T)}{a_5.x_3}\right\}. \tag{26}$$

Similarly, x_1 as a function of temperature can also be derived from (9) as shown in [6]

$$x_1(T) = x_2(T)\exp\left\{\frac{a_2(T)}{a_5.x_3}\right\} + \frac{a_2(T)}{x_5}. \tag{27}$$

VII. Estimation of the MPP

It is always desired that the maximum available energy be derived from PV sources. For this purpose, the PV sources are operated at MPP under the given environmental conditions. This paper proposes to estimate the MPP from the estimated parameters R_s, R_{sh}, and A, and the estimated V_{oc} and I_{sc} under the given operating conditions.

To estimate the MPP, first the open-circuit voltage and short-circuit current for the operating condition are estimated. Next, (14) is rearranged and the datasheet values are written as functions of temperature and irradiance, as shown in (28). Similarly, (15) is also rewritten with datasheet values as a function of temperature and irradiance, as given by (29):

$$a_3(G,T) = a_2(G,T) - a_4(G,T).x_4 + a_5x_3.U \tag{28}$$

where

$$U = \ln\left\{\frac{[a_1(G,T) - a_4(G,T)].[x_4 + x_5] - a_3(G,T)}{a_1(G,T).[x_4 + x_5] - a_2(G,T)}\right\}$$

$$a_4(G,T) = \frac{(a_3.Q(G,T)/a_5.x_3.x_5) + (a_3/x_5)}{1 + (Q(G,T).x_4/a_5.x_3.x_5) + (x_4/x_5)} \tag{29}$$

where

$$Q(G,T) = [a_1(G,T).(x_4 + x_5) - a_2(G,T)] \cdot \exp\left\{\frac{a_3(G,T) + a_4(G,T).x_4 - a_2(G,T)}{a_5.x_3}\right\}.$$

Equations (28) and (29) are now solved using the SUR technique. This technique is a modification of the Gauss–Seidel technique, and is used in cases where the possibility of the solution to diverge is high. In this technique, a transcendental equation as shown in (17) is solved by introducing an extrapolation factor ω (<1), which is used for the weighted average between the previous and the current iterations. Equation (17) is modified to give the form of

$$x^{k+1} = (1-\omega)x^k + \omega f(x^k). \tag{30}$$

Writing (28) and (29) in the form shown in (30) and solving in the same fashion as in Gauss–Seidel technique, the values of a_3 and a_4 under the given environmental conditions are obtained. To start the SUR technique, the variables x_3 and x_4 should be initialized first. Initialization is a critical step in the solution of the MPP. If the initialization is not close to the actual values, then the solution may diverge or converge at the wrong points. The relationship of voltage and current at MPP to the open-circuit voltage and short-circuit current, respectively, remains almost constant [10]. Using this fact, to find the exact MPP, this paper proposes to initialize the voltage and current at MPP from the known open-circuit voltage and the short-circuit current under the given environmental conditions as given by

$$x_3(G,T) = x_2(G,T).\frac{x_3(G_{\mathrm{stc}},T_{\mathrm{stc}})}{x_2(G_{\mathrm{stc}},T_{\mathrm{stc}})} \tag{31}$$

$$x_4(G,T) = x_1(G,T).\frac{x_4(G_{\mathrm{stc}},T_{\mathrm{stc}})}{x_1(G_{\mathrm{stc}},T_{\mathrm{stc}})}. \tag{32}$$

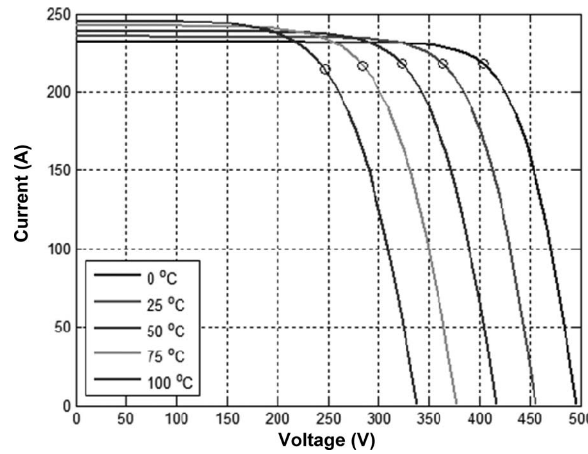

Fig. 5. Voltage–current characteristics of the PV array at an irradiance of 1 kW/m^2 with varying temperature.

VIII. Simulation Results

Effects of change in temperature and irradiance can be studied by plotting the *V–I* and voltage–power (*V–P*) characteristics at different temperatures and irradiances. A program is developed in the MATLAB m-file to plot these curves. The program also estimates the values of the voltage and current at MPP. Figs. 5–8 show the 80 kW PV array characteristic (*V–I* and *V–P*) under different operating conditions with PV-MF165EB3 modules. The data used for the array are given in Table IV.

The MPPs, estimated by the aforementioned method, are marked on the curves by a small circle on each curve. The PV voltage–current characteristic curves are plotted using (1)

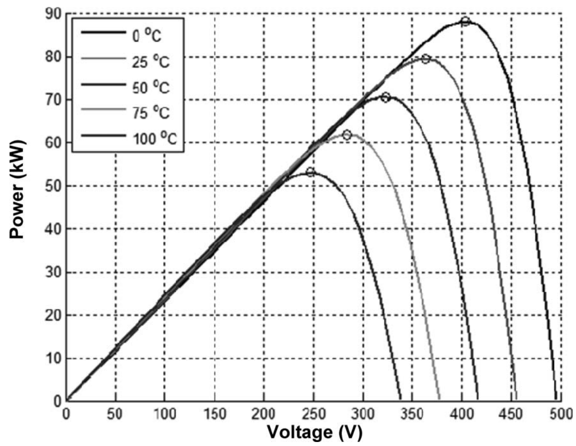

Fig. 6. Voltage–power characteristics of the PV array at an irradiance of 1 kW/m^2 with varying temperature.

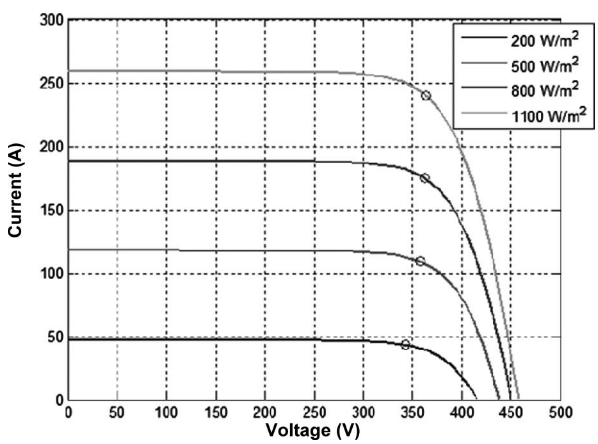

Fig. 7. Voltage–current characteristics of the PV array at 25 °C and varying irradiance.

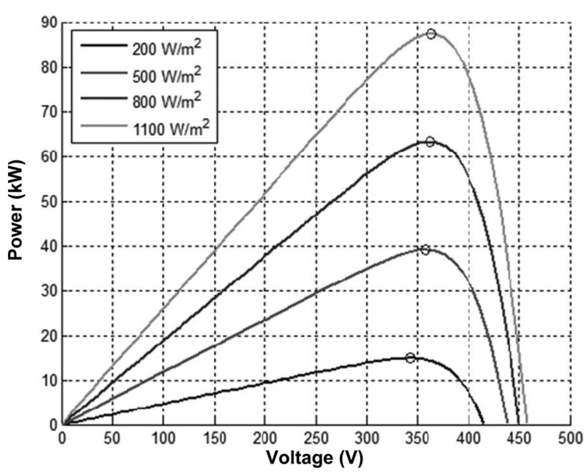

Fig. 8. Voltage–power characteristics of the PV array at 25 °C and varying irradiance.

with the help of the SUR technique, since (1) is a transcendental equation. The *V–P* characteristics are obtained by taking the product of the voltage and current. Table V lists the MPP of the array under different environmental conditions as estimated by the mentioned algorithm. It is seen that the estimated values of the MPP lie at the maxima of the power curves, verifying that the estimated values of the MPP under different environmental conditions are close to the actual values. The shapes of the *V–I* and the *V–P* curves for a module and that of an array are exactly the same; the only difference in the plot is that the voltage and the current get multiplied as mentioned in Table III.

TABLE V
MPP UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

Irradiance (kW/m^2)	Temperature (°C)	V_{mpp} (V)	I_{mpp} (A)	P_{mpp} (kW)
1000	0	403.74	217.94	87.99
	25	363.00	218.56	79.34
	50	323.13	218.13	70.48
	75	284.31	216.93	61.68
	100	246.71	214.76	52.98
200	25	342.44	43.25	14.81
500		357.76	109.25	39.09
800		362.20	175.02	63.39
1100		363.01	240.12	87.17

IX. CONCLUSION

To study the effect of integration of PV power generating sources into the power grids, modeling of the PV sources becomes indispensable. The PV generating models are needed for short circuit and voltage stability studies of power grids.

This paper demonstrates a step-by-step methodology to estimate the lumped equivalent parameters of the single-cell PV model, PV string model, and PV array model from PV data sheets provided by manufacturers. The estimation of parameters is performed under standard test conditions. The refinement of the parameters under change in irradiance and temperature is also presented.

Simulation program is developed in MATLAB to demonstrate the proposed method. The results of the voltage–current and voltage–power characteristics for different temperatures and irradiances are presented. The estimated MPP corresponds to the data used in the analysis.

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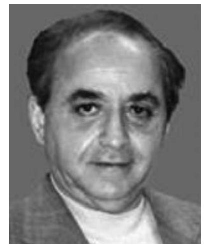

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