

Parameter computation using Circuit Based approach for Two-diode model based Solar PV simulator with partial shading effect

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Abstract:

The solar photovoltaic modules can be modelled on the basis of electrical equivalent model of solar cell. In this paper the two-diode model based Solar PV simulator have been proposed with partial shading capability, bypass and blocking diode effect. The two parameters: reverse saturation current, resistances are computed using the circuit equations associated with the electrical model of solar cell. The mathematical computation of the equation for the conventional two diode model method is quite complex and may take long time for simulation. The mathematical computational scheme for modelling have been simplified for two diode model with better accuracy. The two diode based modelling method proposed for PV simulator in MATLAB-Simulink used the computational data of the first diode equation and the computation of second diode equation is replaced by the coefficient multiplied with the data of first diode. Accuracy of this simulator model is analyzed for the combined effect of irradiance and temperature as according to the standard PV module datasheet.

Keywords:

Partial shading, Solar PV, blocking diode, bypass diode MATLAB-Simulink.

1. Introduction

The energy crisis and environmental problems are related to each other in terms of fulfilling energy needs by the energy sources which can cause environmental problems like climate change/global warming problems. Renewable energy resource is evolving in the recent years rapidly and moving towards the clean and green energy technology uses. In this trend solar PV system is one of the preferable renewable energy sources and a lot of innovative research in different aspects is running to improve the solar cell and solar system. The solar cell system deals with the constraints in fundamental research of solar cell materials like open circuit voltage limitation due to energy band gap constraint and efficiency limitations due to materials functioning capability over certain wavelengths of light. These are some basic fundamental constraints. The solar cell characteristic is another consideration in the field of solar energy system. The solar cell is having exponential characteristic due to diode as according to electrical equivalent model of solar cell. There are four electrical equivalent models are available for semiconductor based solar cells as ideal diode model with no resistance, single diode model with series resistance only (appropriate model/Rs model), single diode model with series and parallel resistance both (General model/Rs-Rp model), double diode model (double exponential model). The solar cell can be modeled based upon electrical equivalent model. The series connection of solar cells formed the panel/module. The modules grouped in series combination formed the string. So, the series and parallel connection of modules/string formed the solar PV array system.

The solar cell modeling and simulation is one of the important aspects to obtain the better and more accurate solar characteristics with reduced mathematical computation effort and computational time. As the mathematical computational effort reduces the computational time may reduce with

better accuracy or maintaining good accuracy. The accurate cell characteristics are important to implement the maximum power point (MPP) tracking algorithms efficiently to improve the overall efficiency of the system. Also, the solar cell characteristic is changed suddenly with the change in weather condition so the robust MPP tracking algorithms should be implemented based upon the cell characteristics obtained from the solar cell modeling techniques. To incorporate the partial shading characteristic generation capability in solar cell simulator is very important to investigate and analyze the cell characteristics under shading conditions. The by-pass diode and blocking diode are connected in parallel with series connected solar cell/module and in series with solar string to improve the partial shading effect. The by-pass diode prevents the solar cell from hot spot effect caused due to non-uniform irradiance on solar cells/modules. So to obtain and track the best possible output power from solar PV array the characteristics should be obtained under partial shading/non-uniform irradiance condition and effects of by-pass diode and blocking diode can be investigated and analyzed based upon the PV characteristics. The PV array system poses the exponential (non-linear) I-V characteristic and also sudden and complex changes in characteristics due to weather or some other reasons. So for the modelling purpose the parameters of the system need to be tuned from experimental data sheet of practical device to obtain best possible accuracy in the simulator model. The electrical circuit model equations based mathematical modelling of PV array system can be useful and able to analyze the dynamic and complex characteristic, study of dynamic analysis of dc-dc converters based upon PV characteristic, study and analyze different array configuration and robust MPP algorithms implementation [1-3].

Several proposed modelling techniques are available in literatures based upon the single diode based modelling and double diode based modelling. The single diode based modelling technique requires less computational effort and it is easy to implement with quite good accuracy, that is why it is most commonly preferred in different papers. The double diode model offers better accuracy in comparison to single diode model and different idea was proposed to obtain easy implementation technique and maintaining better accuracy [4-6]. In these research works for modelling the system there are the techniques mentioned that how to extract electrical parameters for the model. But, still it is difficult to maintain the accuracy under low irradiance and for different combination of changes with lesser effort. The electric characteristics of PV module is analyzed in under several condition of irradiance and it suggests that the characteristics of the PV system becoming more complex for non-uniform irradiance/partial shading condition [7-11]. The complexity of characteristics depends upon the configuration of solar PV modules as the number of modules connected in series in a string decides the number of peaks in P-V characteristic under partial shading condition.

The physical phenomenon of the system is important to understand the working of solar cell fundamentally. The modelling of PV array system have obtained by the proposed two model with series and parallel resistance by several researchers [12-14]. And, the usual computational method of resistance is by iteration. In this paper the modelling solar PV simulator is proposed based upon the two diode model with reduced computational effort and the resistances are calculated without iteration, by simple and direct approach using electrical equations under different condition. The difference between the first diode and second diode equations for the purpose of modelling is considered in terms of diode ideality factor. The proposed method for the modelling replaces the mathematical part of second diode by using a coefficient multiplied with the mathematical part of equation for first diode. This proposed method is just require a proper tuning of diode ideality factor diode (a) of first diode and the coefficient used in place of second diode.

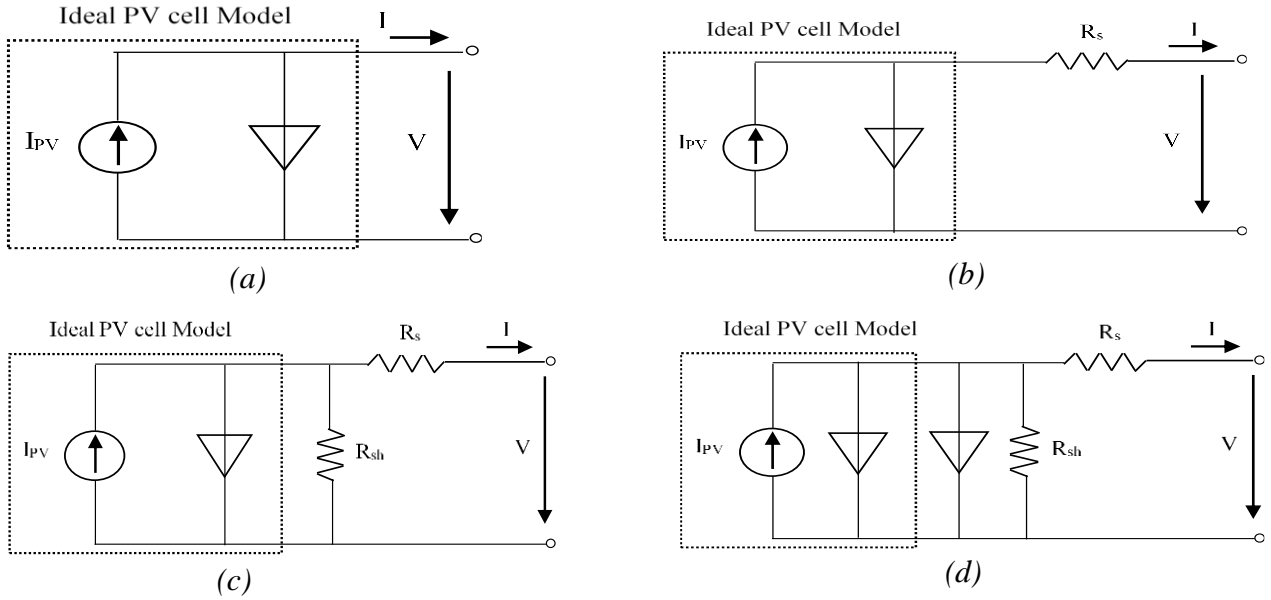


Fig. 1. Electrical model of solar cell a) Ideal model, b) single diode model with R_s , c) single diode model with R_s - R_p , d) double diode model.

2. Solar cell (Photovoltaic system)

Solar cell is the device working as to convert light into electricity and it is represented as an electrical equivalent model form as shown in Fig. 1. The basic electrical equation written for ideal PV cell model is modified as according to its different electrical equivalent model. The equations associated to the electrical models in Fig. 1 is mentioned in (1) to (4) respectively. The solar cell is modelled based upon the mathematical equations related to different models and parameters associated to these equation have to be computed.

$$I = I_{ph} - I_o \left(e^{V/NV_t} - 1 \right) \quad (1)$$

$$I = I_{ph} - I_o \left(e^{V+IR_{se}/NV_t} - 1 \right) \quad (2)$$

$$I = I_{ph} - I_o \left(e^{V+IR_{se}/NV_t} - 1 \right) - \frac{V + IR_{se}}{R_{sh}} \quad (3)$$

$$I = I_{ph} - I_{o1} \left(e^{V+IR_{se}/NV_t} - 1 \right) - I_{o2} \left(e^{V+IR_{se}/NV_t} - 1 \right) - \frac{V + IR_{se}}{R_{sh}} \quad (4)$$

The two diode model based modelling is proposed in this paper and for the modelling purpose there is one more factor is usually included in the equation that is diode ideality factor (a).

2.1. Solar PV system

Solar PV system can be formed by solar configuration of modules in series and parallel. The parameters of solar cell equations are modified with the module and array configuration and condition of maximum power point (MPP) is analysed based upon the open circuit voltage condition. The MPP condition analysis generates the equation for computation of resistances without iteration.

2.1.1 PV array equations

The output current equation for the single diode equivalent circuit in Fig. 1c is given by

$$I = I_{ph} - I_o \left(e^{\frac{q(V+IR_s)}{akT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (5)$$

To make the modelling more accurate and obtain the characteristics similar to practical solar cell the effect of maximum possible parameters should have to be incorporated in the simulator model. The above mentioned equations are specially for the modelling of single solar cell model. As the number of solar cells connected in series to form the solar module, the equation for the solar module changed with the significant change in the equation parameters. Due to connection of solar cells in series, the open circuit voltage and series resistance of solar module will become

$$V_{OC,m} = N_s V_{OC,s}, R_{s,m} = N_s R_{s,s} \quad (6)$$

To develop the model of solar PV system, the number PV modules are connected in series and parallel combination to create the system of required/desired power rating. The series and parallel combination effect on circuit equation of solar PV is incorporated as

$$R_{s,a} = R_{s,m} \frac{N_{ss}}{N_{pp}}, R_{sh,a} = R_{sh} \frac{N_{ss}}{N_{pp}} \quad (7)$$

$$I = N_{pp} I_{ph} - N_{pp} I_o \left(e^{\frac{q(V+IR_{s,a})}{N_s a k T}} - 1 \right) - \frac{V + IR_{s,a}}{R_{sh,a}} \quad (8)$$

2.1.2 Maximum power point (MPP)

Rsh is assumed to be infinite for the condition $I_{ph} = I_{sc}$ and the equation for the output voltage and output current from (1) can be written as

$$I = I_{sc} - I_o \left(e^{\frac{q(V+IR_s)}{N_s a k T}} - 1 \right) \quad (9)$$

$$V = \frac{N_s a k T}{e} \ln \left(\frac{I_{ph} + I_o - I}{I_o} \right) - R_s I \quad (10)$$

For the condition of open circuit, $V = V_{oc}$ and $I=0$, the Eq. (8) become

$$V_{oc} = \frac{N_s a k T}{e} \ln \left(\frac{I_{sc}}{I_o} + 1 \right) \quad (11)$$

By substituting the (11) in (9) and it can be rearranged as

$$\frac{I}{I_{sc}} = 1 - \left(\frac{I_{sc}}{I_o} \right)^{-1} \left(\frac{I_{sc}}{I_o} \pm 1 \right)^x \quad (12)$$

The ratio of I_{sc} and I_o is very high value because of low value of I_o therefore (12) will become more simplified as

$$\frac{I}{I_{sc}} = 1 - (\alpha)^{x-1} \quad (13)$$

where, $I_{sc}/I_o = \alpha$, $(V + IR_s)/V_{oc} = x$. Using the incremental conductance for characteristics of solar PV curve, it is well known that the incremental conductance at the MPP is zero. Therefore,

$$\frac{dP}{dV} = I + V \frac{dI}{dV} \quad (14)$$

At maximum power point (MPP) condition; $dP/dV=0$. Therefore the above equation will be

$$\frac{dI}{dV} (at MPP) = - \frac{I_{MPP}}{V_{MPP}} \quad (15)$$

2.2.1. Double diode equation

2.2. Solar PV modelling parameters

2.2.1. Short circuit current

The solar generated current of the photovoltaic cell I_{ph} is having linear relation with the change in solar irradiance and also affected by the change in the temperature. The effect of temperature and irradiance on current is shown as

$$I_{ph} = (I_{ph_N} + k_i \Delta T) \frac{G}{G_N} \quad (16)$$

2.2.2. Open circuit voltage

Open circuit voltage of solar cell V_{OC} is altered with the change in the temperature. As comparison to the effect of temperature and irradiance, the effect of irradiance is dominant on the current and the effect of the temperature is dominant on the voltage of solar PV cell. The effect of temperature on open circuit voltage is given by

$$V_{OC} = V_{OC_N} k_v (T - T_N) \quad (17)$$

2.2.3. Reverse saturation current

The reverse saturation current I_o can be calculated using Eq. (8) for single diode model of solar PV system. In this equation the temperature variation is considered for calculation of current and relation between temperature and reverse saturation current is computed using the temperature coefficient solar PV cell.

$$I_o = \frac{(I_{ph_N} + k_i \Delta T)}{\exp[(V_{oc_N} + k_v \Delta T)/aV_t] - 1} \quad (18)$$

2.2.4. Proposed Series and parallel resistance computation

The computation of solar cell resistances having different conditions and for a cell considered to be having losses less than 1% due to its series and 1% due to its parallel resistance then the conditions for the resistances is defined as [15]

$$R_p > \frac{V_{OC}}{0.01 I_{SC}} \quad (19)$$

$$R_s < \frac{0.01 V_{OC}}{I_{SC}} \quad (20)$$

The series and parallel resistances can be extracted by the equations using MPP condition of solar PV cell. This is one of the simplest method proposed to find out the value of resistance without iteration. The derivative of (13) with respect to voltage (V) will also give the incremental conductance equation at MPP

$$-\frac{I_{MPP}}{V_{MPP}} = -I_{SC} \frac{1 + R_s \left(-\frac{I_{MPP}}{V_{MPP}}\right)}{V_{oc}} (\alpha)^{x-1} \ln(\alpha) \quad (21)$$

$$\ln(\alpha) = \frac{\ln\left(1 - \frac{I}{I_{SC}}\right)}{x} \quad (22)$$

By taking natural log of (13) and it can be written as shown in (22). The value of series resistance can be calculated easily by using above two equation. The value of the parameters at MPP conditions under standard test condition (STC) for above equations is used. The STC condition for solar PV; Temperature=298 K and irradiance = 1000W/m². The above equation will give the value

of series resistance only. In the same way as above; derivative of (5) is calculated for MPP condition to extract the shunt resistance value. Derivative of (5) for MPP condition will be

$$\frac{I_{MPP}}{V_{MPP}} = I_{SC} \frac{1 + R_s \left(-\frac{I_{MPP}}{V_{MPP}} \right)}{V_{OC}} (\alpha)^{x-1} \ln(\alpha) + \frac{I + R_s \left(-\frac{I_{MPP}}{V_{MPP}} \right)}{R_{sh}} \quad (23)$$

By using the value of series resistance calculated with help of (21) and (22) the value of shunt resistance can easily be calculated from (23). The value of series resistance is calculated by assuming the value of shunt resistance as infinite and once it is known the shunt resistance calculated from same equation. This is the proposed simplified method to calculate the series and parallel resistance without iteration.

2.2.4. Double diode equation for modelling

The equation of the double diode model have been modified for the implementation of proposed modelling method by replacing part of second diode by a coefficient in the equation. The solar cell characteristics is obtained using this method. Tuning of ideality factor of diode (α) and coefficient use for second diode to obtain the best possible accuracy. The equation (24) represents the double diode equation considering reverse saturation current of the diodes are same. (24) and (25) is modified into (26).

$$I = I_{ph} - I_o \left(e^{\frac{q(V+IR_s)}{a_1 kT}} - 1 \right) - I_o \left(e^{\frac{q(V+IR_s)}{a_2 kT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (24)$$

$$I = I_{ph} - I_{d1} - I_{d2} - \frac{V + IR_s}{R_{sh}} \quad (25)$$

$$I = I_{ph} - I_{d1} - \alpha * I_{d1} - \frac{V + IR_s}{R_{sh}} \quad (26)$$

3. MATLAB/Simulink Model Development

The proposed method of modelling based upon two diode model is developed in MATLAB/Simulink environment as shown in Fig. 2 and the parameters of modelling have been extracted. It is required to analyze the results of Solar PV simulator to understand the characteristics of solar PV system under non-uniform conditions and test the accuracy of the model. The PV

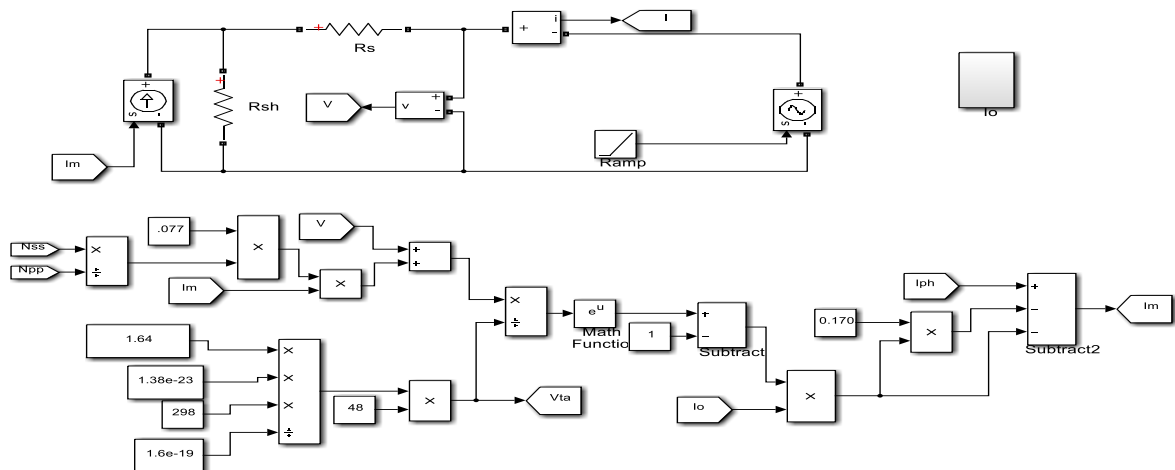


Fig. 2. MATLAB/Simulink model for solar cell module using modified double diode equation.

reference model is developed using the proposed method in MATLAB/Simulink. The electrical parameter specification for KD180GX is mentioned in Table 1 for STC condition. The developed model have been enabled with the capability of partial shading illustration and partial shading condition is analysed using this developed PV simulator model with the effect of bypass diode, blocking diode and array configuration under partial shading condition.

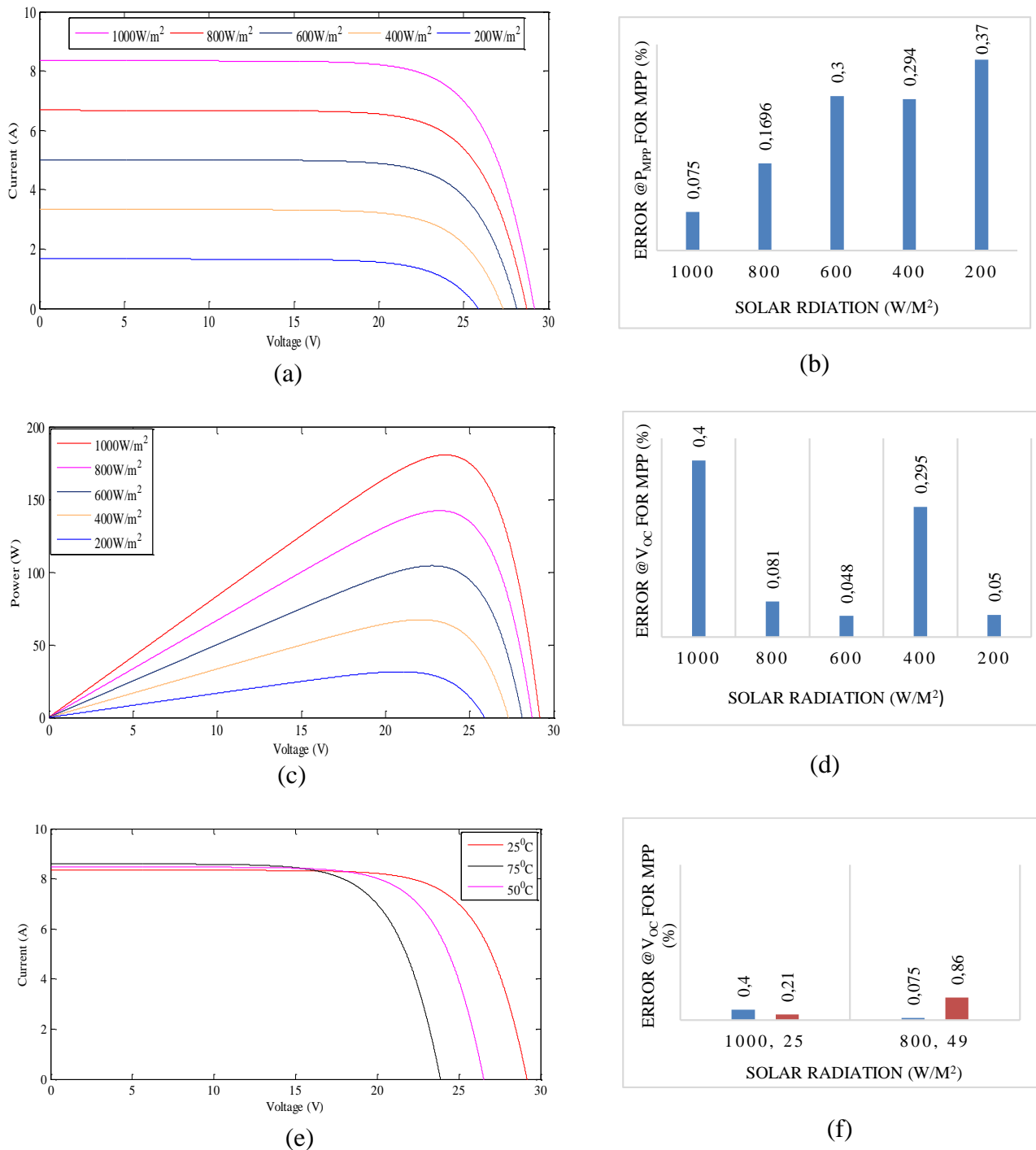


Fig. 3. Solar PV characteristics: a) I-V characteristic, b) error for MPP power, c) P-V characteristic, d) error for V_{oc} relative to MPP, e) I-V characteristic for temperature change, f) error in P_{MPP} and V_{oc} for 1000 W/m² and 25°C and 800 W/m² and 49°C.

4. Model Validation and Results

The proposed two diode based solar PV simulator model and parameters computed from the method discussed in this paper is validated under various conditions for KD180GX and the accuracy of the PV simulator is validated based upon the error in model results and manufacturer data sheet. This method of modelling only requires the tuning between diode ideality factor and the coefficient used for computation of second diode. The overall computational procedure is reduced as shown in Fig. 2 for generation solar current.

4.1. Irradiance and temperature effect

The data provided by the manufacturers are specified for the standard test condition (STC). Standard test conditions are irradiance= 1000 W/m², temperature= 25 °C/298K, AM 1.5. I-V and P-V curves for different irradiance level is shown in Fig. 3a and Fig. 3c and the error in reference to maximum power and open circuit voltage corresponds to maximum power under different irradiation level condition is shown in Fig. 3b and Fig. 3d. The PV data is also specified for the case irradiance= 800 W/m², temperature= 49 °C/322K. The error is defined for the difference in simulated value and measured value for P_{MP} and V_{OC} corresponding to each P_{MP}.

The PV system is affected by the temperature of panel and it is changed due to losses and heat generated by radiation. The combined effect of temperature and irradiance is specified in PV data for the case irradiance= 800 W/m², temperature= 49°C/322K and the error under this condition is shown in Fig. 3f I-V characteristics obtained for the change in temperature levels as shown in Fig. 3e. So, the combined effect of irradiance and temperature provides better information about the accuracy how simulator is behaving for the change in radiation and temperature simultaneously.

4.2. Partial shading condition and array configuration

To generate the characteristics for illustration the controlled voltage source with ramp signal shown in Fig. 2 is used to run the simulation model and validate the PV characteristics. For the validation of PV array curve under non-uniform condition 3 modules in series (N_{ss} = 3) and 2 parallel string (N_{pp}=2) i.e. 3×2 arrangement is considered. The different condition of shading is taken to generate the PV characteristics for non-uniform condition. The conditions of partial shading is mention in Table 2 and Table 3 corresponding results is shown in Fig. 4a to 4b and Fig 4e to 4f respectively. The improvements in the characteristics of PV array under partial shading is achieved by using the bypass diode connected in parallel to each module and blocking diode connected in series with each string. The bypass diode effect in Fig. 4a to 4b and Fig. 4e to 4f and blocking diode effect in Fig. 4d to 4e is validated using PV simulator. To analyse the effect of change in configuration of array, the characteristics obtained in Fig.4d and Fig.4e is for two modules in series and 3 parallel connected strings. And, the characteristics obtained in Fig.4a-4b is for the 2 string connected in parallel, each having 3 modules in series. The number of peaks for the PV characteristics changes as the configuration changes from 3 series connected modules to 2 modules. Therefore, for practical designing of PV array; it is very important to decide the number of modules connected in series should be minimum.

It is clearly inferred from the Fig. 4a to 4b and Fig. 4e to 4f that by the use of bypass diode the performance of PV system under non-uniform weather case, improves much significantly and provides better output power. When shading occurs, the shaded modules behaves as a load and causes heavy drop in the resultant output current. Therefore the performance of output power reduced. It also leads to the damage of shaded module due to hot spot effect. After that, cumulative effect comes into the picture and shaded module string started acting as load. And, the current started to flow from the healthy string to damaged string. Therefore, overall performance of the system disturbed and chance of the module damage may become very high. The bypass diode prevents the shaded modules and bypass the current through diode. The blocking diode in each string prevents the reverse flow of current from healthy string to shaded/damaged string. The number of maxima and minima in a PV characteristic is depend upon the number of modules

connected in series in a string. The effect of shading on I-V and P-V characteristics are illustrated with and without bypass diode. The effect of blocking diode is illustrated in Fig. 4d to 4e. The dotted red line in the figure showing the characteristic for the case with; blocking diode case and blue line showing the characteristic for the case; without blocking diode. There is a difference in open circuit voltage and peak power for V-I and P-V characteristics respectively.

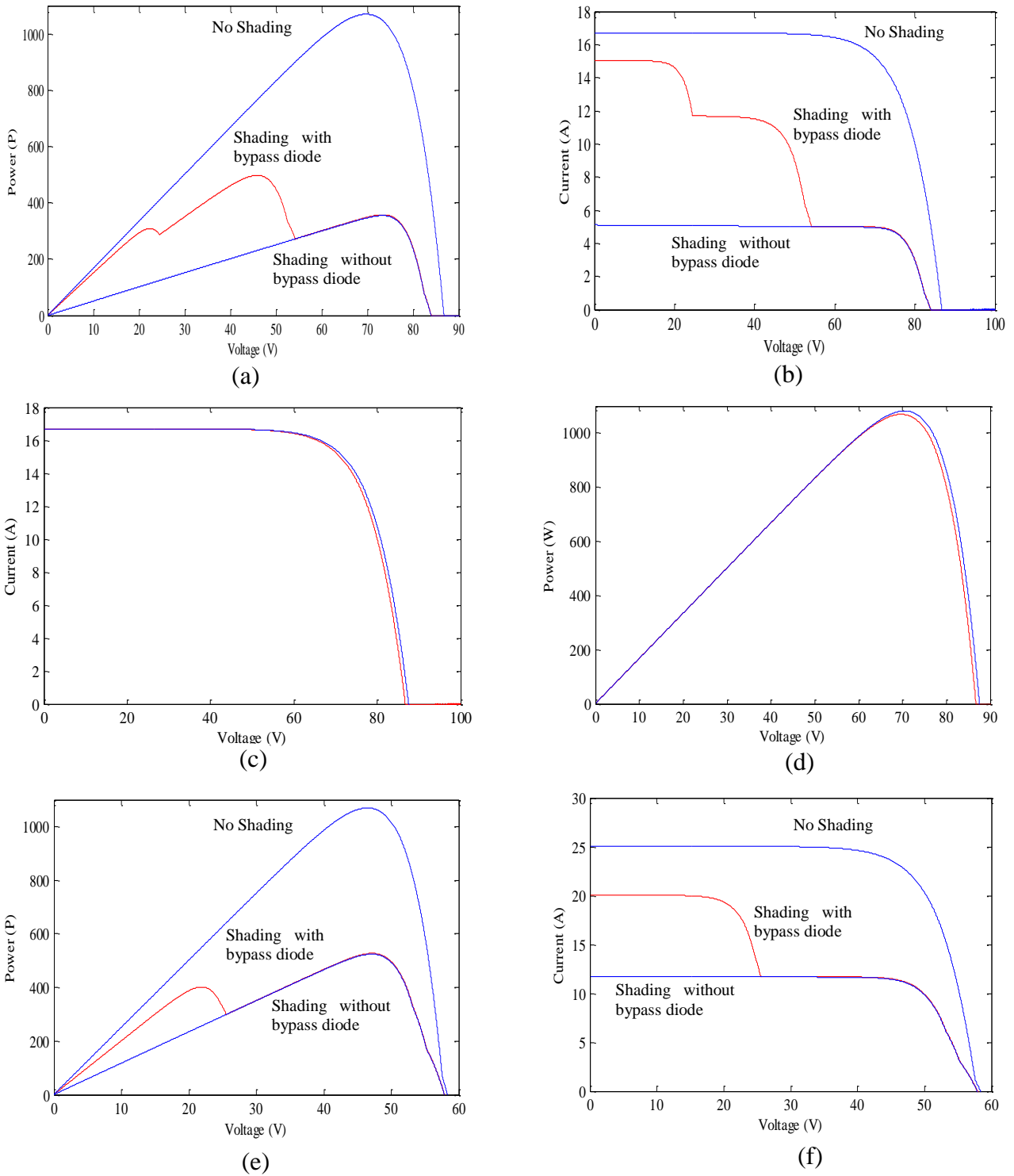


Fig. 4. Solar PV characteristics under partial shading: a) P-V characteristic for 3x2 array, b) I-V characteristic for 3x3 array, c) I-V characteristic for blocking diode effect, d) P-V characteristic for blocking diode effect, e) P-V characteristic for 2x3 array, f) I-V characteristic for 2x3 array.

Table 1. Parameters of the Kyrocera (KD180GX)

I_{SC}	8.35 A
I_{mpp}	7.63 A
V_{OC}	29.5 V
V_{mpp}	23.6 V
P_{mpp}	180 W
N_s	48
k_v	-0.106 V/K
k_I	.005 A/K

Table 2. Irradiance level for 3×2 array under partial shading

Irradiance (W/m ²) 1 st string	Irradiance (W/m ²) 2 nd string
600	800
200	400
1000	800

Table 3. Irradiance level for 3×2 array under partial shading

Irradiance (W/m ²) 1 st string	600	200
Irradiance (W/m ²) 2 nd string	800	400
Irradiance (W/m ²) 3 rd string	1000	800

5. Conclusion

The circuit based approach to extract parameter for solar PV modelling have been implemented successfully in MATLAB/Simulink. In this paper, the parameter extraction is achieved under practical consideration and solar PV simulator have been developed based upon proposed modified two diode equation with partial shading capability. According to the practical requirement of solar PV rating value, this PV simulator can easily be modified into particular arrangements of solar PV module/array with the selection of irradiance for each module. The real time effect of partial shading on each modules of solar PV array have been realized and analysed by taking in consideration of individual modules and strings. The parameters for each string/module can be set independently to investigate the overall behaviour of solar PV system. The proposed modelling method may be capable to model the PV array of any type of materials very easily. It allows to combine with power electronic circuit and simulate the overall control circuit design to obtain robust MPPT methods under partial shading conditions.

Nomenclature

I_{ph} photocurrent, A

$I_{ph,N}$ photocurrent STC, A

I_{SC} short circuit current, A

I_d diode current, A

I PV output current, A

V_{OC} Open circuit voltage, V

$V_{OC,N}$ Open circuit voltage STC, V

$V_{OC,s}$ Open circuit voltage for a solar cell, V

$V_{OC,m}$ Open circuit voltage for a solar module, V

V PV Output voltage, V

I_{MPP} Current at MPP, A

V_{MPP} Voltage at MPP, V

P_{MPP} Power at MPP, W

I_o reverse saturation current of diode, A

$I_{o,N}$ reverse saturation current of diode STC, A

R_s series resistance, Ω

$R_{s,c}$ series resistance for a solar cell, Ω

$R_{s,m}$ series resistance for a solar module, Ω

$R_{s,a}$ series resistance for a solar array, Ω

R_{sh} Shunt resistance, Ω

$R_{sh,a}$ Shunt resistance for a solar array, Ω

N_S number of cells in series

N_{SS} number of modules in series

N_{PP} number of modules in parallel

q fundamental charge, C

a, a_1, a_2 diode ideality factor

k boltzman constant, $m^2 \text{ kg} / (s^2 \text{ K})$

T temperature, $^{\circ}\text{K}$

T_N temperature STC, $^{\circ}\text{K}$

V_t thermal voltage, V

G irradiance, W/m^2

G_n irradiance, STC 1000 W/m^2

k_v voltage coefficient, V/K

k_i current coefficient, A/K

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