

MATHEMATICAL MODELLING AND OPTIMIZATION OF POLY-CRYSTALLINE PHOTOVOLTAIC MODULE

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Abstract

This work proposes modeling and optimization of poly-crystalline photovoltaic (PV) module, validated with experiment, using single diode (SDM) and double diode model (DDM). The PV cell is treated as an equivalent electrical circuit with series and shunt resistance. The weather data like temperature and irradiance are used as input variables. The operating current and maximum power point is obtained using three variables: current, voltage and power. Experiment was setup in Nagpur city, in the deccan plateau situated in central India. This place is suited for PV installation due to high average solar insolation period throughout the year. The outputs of the PV model is optimized using genetic algorithm (GA) and simulated annealing (SA) algorithm and, validated against the experiments with variable load conditions. The metaheuristics optimization techniques worked well for this model and improves the accuracy and precision of current-voltage (I-V) and power voltage (P-V) curve. The present work compares the errors of the SA and GA algorithm, used for extracting the five key points of (I-V) curves using normalized sum of squared errors (NSSE). The proposed model optimization results are in close agreement with experimental results.

Keywords: Double diode; NSSE; optimisation (GA and SA); photovoltaic model; single diode

Introduction

The reserve of fossil fuels are reducing and the global warming effect are looming large, therefore, the demand for alternative energy has increased exponentially (Krismadinata *et al.*, 2013). Among all the alternative energy, the prime attention has been focused on solar energy, which is the mother of all forms of energy sources. The solar energy is either used as solar thermal or through solar photovoltaic (PV).

Energy generation through PV systems have attracted the researchers greatly in the last few decades due to its promising potential as a clean and sustainable energy source for future generation energy demand. Also, it is available free all around the globe. The performance of the devices working on solar energy utilization are analysed experimentally or through simulations. Simulating the systems under artificial conditions saves the

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time and money. I-V and P-V characteristics are of two important aspects of modelling PV module systems under various climatic conditions to analyse its performance. However, the simulation needs the different parameters related to the environment conditions (Babu and Gurjar, 2014).

PV modules are fundamental power conversion unit of a PV generator system. PV systems are arrangements of modules for the conversion of solar energy into electrical energy. Higher cost of module discourages its use for optimum and utmost utilization of available solar energy. It becomes an inevitable requirement to ensure its performance, reliability and accuracy in the various environmental conditions before its actual installations (Ishaque *et al.*, 2011). So, it needs to be simulated and optimized for the various parameters associated with it and the environmental conditions which keeps on changing during the day time. The behaviour and characteristics of PV panel can be analyzed beforehand through modeling and simulation. The high demand of PV model at the present time leads to research and development for its utilization for power generation.

PV cell is the basic unit of PV module. It is assumed to be an equivalent electrical circuit with series and shunt resistance. It consist of five parameter model with I , I_{01} , A_1/A_2 , R_s and R_{sh} . There are many ways of modeling but, single diode (SDM) and double-diode(DDM) models are mostly used to simulate the PV characteristics [3]. The SDM itself can imitate fairly and accurately the PV characteristics. However, DDM help to capture the effect of recombination of carriers additionally and gives higher accuracy as compared to the SDM.

I-V characterization using modelling has a long history of investigation for decades and it is still considered to be an important tool along with different algorithms and techniques. Wolf *et al.* (1977) investigated the double exponential in the I-V characteristics in the late seventies. They established the relation between saturation current and exponential term of the I-V characteristics for the space applications of the silicon PV. Chan and Phang (1987) presented the I-V characterization for the extraction of SDM and DDM parameters analytically using lumped circuit model. They concluded that the accuracy of the model did not apply to full range of R_s and I_{ph} for SDM and for DDM, there existed a wide range of validity. Syafaruddin *et al.* (2009) presented neural network (NN) approach for the PV module parameters optimization of solar irradiance and temperature. They found the close agreement of the results with the experimental work. Celik and Acikgoz (2007) modelled the mono crystalline PV modules with four and five parameter model and verified the result

with experimental outcomes. They concluded that the five parameter give better result than four parameter model for the peak radiation conditions.

AlHajri *et al.* (2012) performed optimal extraction parameters with pattern search (PS) optimization technique with SDM and DDM for module modeling. They optimized with PS algorithm and found the algorithm to be promising. Aparicio *et al.* (2013) modelled PV panel with free software QUCS using a generic diode for adjusting curves. Siddiqui and Abido (2013) estimated the five and seven parameters PV electrical model with evolutionary algorithm using I-V curve. They used TSO and found the higher accuracy of the results when used for electrical algorithm. Pereira *et al.* (2014) modelled PV system with MPPT and validated it with experimental results. They concluded that the PPT algorithm can be used for modeling and validation for the solar irradiance, which didnot vary quickly. Ghani *et al.* (2014) performed simulation using single diode. They simulated the system with the determined parameters of I_{ph} , I_0 , R_s , R_{sh} , and n , using the Lambert W-function and compared it with experimentaly obtained points of I-V curve. They concluded that PV systems can be modelled with small variations in the solar cell parameters.

Jacob *et al.* (2015) worked on parameter extraction using AIS for modelling PV module. They found the result better than GA and PSO algorithms. Hasan and Parida (2016) gave a comprehensive review on electrical characteristics of PV panel with electrical equivalent circuit using equations and experiments under actual environmental characteristics. They indentified that the changing environmental conditions affects the PV panel operation for the maximum power point (MPP). They concluded that the environmental conditions like effect of shading and variation in availability of solar irradiance must be included in modelling for maximizing the overall performance of the PV systems. The PV panel power generation can be specifically designed for given set of environmental conditions. Babu *et al.* (2016) extracted seven parameters for two diode solar PV model using FWA. They claimed it to be equally useful like GA and PSO algorithms. They modelled both mono crystalline (SM55 and SP70) and multi crystalline (Kyocera 200GT) modules.

Bana and saini (2016) presented SDM and DDM with Simulink for PV module. They compared the simulated and manufacturer's data for various environmental conditions. They concluded that the DDM gave better performance with low solar intensity and shadding conditions. Kichou *et al.* (2016) simulated the two PVGS for power output and fault detection using five different

algorithms (LMA, GA, PSO, DE and ABC) and 5 parameter model. They concluded that the ABC model higher accuracy in the simulation, independently of the solar cell technology with least value of RMSE and MAE values of 6.61% and 2.66% respectively.

Chin *et al.* (2016) gave a hybrid computational method for a two DDM of the PV module. Out of seven parameters, three (I_{PV} , I_{o1} , and R_p) were estimated analytically and rest, A_1 , A_2 , I_{o2} and R_s , using DE algorithm. The method gave accurate model for simulation method. Barth *et al.* (2016) extracted the electrical parameters from a PV panel standard datasheet for SDM and DDM to determine the I-V characteristics. They used cuckoo search algorithm (CSA). However the results were not very accurate. Park and Choi (2017) presented PSIM simulation model for PV module and Powell's optimization technique with online parameter tuning, utilizing the datasheet values of standard test conditions (STC). The selected five model parameter for the time varying irradiance. They found the accurate results and in accordance with the EN50530 standards.

Park and Choi (2017) optimized the partially shaded PV array using grasshopper algorithm for maximizing the power output from the PV array. He compared the results with several other existing techniques like CO TCT, Su Do Ku connections and algorithm line genetic (GA). They found it reliable for the analysis. Jordehi (2018) optimized the PV module using ELPSO algorithm on monocrystalline silicon solar cell (STM6-40/36) and thin film cell (PVM 752 Ga). He concluded that the ELPSO algorithm results were better than many existing algorithms (CPSO, GA, ABC, BSA, PS, and Newton) but ABC had the best results. Bouakkaz *et al.* (2020) performed a dynamic simulation in open loop, in the presence of a feedback controller. They considered the environmental conditions including the various faults. They concluded that the MFO based MPPT technique using sliding mode controller improved the performance of PV modules.

In the current study, the modelling of SDM and DDM has been presented and its optimization has been compared with SA and GA algorithms. The results obtained from both the models has also been optimized and compared with experimental values. The experiment was conducted in VNIT, Nagpur, India. For comparison of both models, normalized sum of squared errors (NSSE) has been calculated at five key points for I-V and P-V curve.

The rest of the paper is configured as: Section 2 discusses the modelling methodology used in the paper. Both SDM and DDM equations has been used. Section 3 presents the details of experiments

conducted. The optimization methodology is presented in section 4. Section 5 discusses the modelling and experimental results. The conclusion from the study is presented in section 6.

Modeling of PV Panel

There are many mathematical models available for modelling PV cell. Some of the models are simple and some are complex, considering different reverse saturation current (I_o). The PV cell converts the sun rays or photons directly into electric power, Shannan *et al.* (2013). Among the various mathematical models available in the literature, the SDM and DDM is used in the present work. To achieve better accuracy, both circuits are considered with series and shunt resistance. The accuracy of the model is higher if the carrier recombination is considered in the model, which is there in the case of DDM, Baig *et al.* (2020).

Single Diode Model (SDM)

This is one of the simplest and widely used model. The current source generates the light and it varies linearly with solar energy, is kept parallel to a diode. The equivalent circuit of an ideal SDM cell is shown in Figure 1.

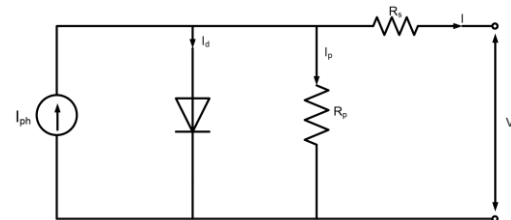


Figure 1. Single Diode model (SDM)

Applying kirchhoff law, current is given by:

$$I = I_{ph} - I_d - I_p \quad (1)$$

Putting the values of I_{ph} , I_d , and I_p , the Equation (1) can be written as:

$$I = I_{ph} - I_o \times \left(\exp\left(\frac{V + IR_s}{a}\right) - 1 \right) - \frac{V + IR_s}{R_p} \quad (2)$$

where,

I_{ph} = Light-generated current or photocurrent: It is generated directly by incident of sunlight on the PV cell. This current varies linearly with sun irradiation and depends on temperature.

I_s = Diode saturation current: It is a part of the reverse current in a diode caused by diffusion of minority carriers from the neutral regions to the depletion region.

R_s and R_p = Series and parallel resistance. These are considered due to the presence of internal resistances, the power loss takes place in the cell. So, these parasitic resistances can be segregated into series resistance (R_s), and parallel resistance (R_p).

For ideal case, R_s is zero and R_p is infinity.

‘a’ is the variable taken as: $a = A \times N_s \times V_t$ (3)

The photocurrent is calculated as

$$I_{ph} = \frac{G}{G_{ref}} \times (I_{ph,ref} + \mu_{sc} \times \Delta T) \quad (4)$$

where, $I_{ph,ref}$ = Light-generated current at standard condition, μ_{sc} = Current temperature co-efficient (in), G = Actual sun irradiation (W/m^2), G_{ref} = Standard sun irradiation (W/m^2), ΔT = It is the difference between actual temperature and nominal temperature (in Kelvin) i.e. ($T_c - T_n$).

For the dark current characteristic, the diode ideality factor A is typically 2 at low currents, and A is typically 1 for silicon at high currents. It depends on PV cell technology. In this case, A is taken reasonably as 1.3 with reference to Barth *et al.* (2016) N_s is number of PV cell in series.

Junction thermal voltage V_t is estimated as

$$V_t = K \cdot T_c / q; \quad (5)$$

where

K = Boltzmann constant = $1.3806503 \times 10^{-23}$ (J/K),
 q = electron charge = 1.607×10^{-19} C and T_c = Cell temperature.

Parameters Determination of SDM

The number of parameters varies depending on the chosen model and on the basis of assumptions assumed by the researchers. In the present study four parameters were determined (I_{ph} , I_o , R_s , R_p) and A is assumed to be constant in the SDM.

Light-generated Current (LGC) or Photocurrent (I_{ph}):

This is the current generated by PV cell and it depends on both the irradiance and temperature is given by Equation 3. G and G_{ref} are the actual and sun irradiation at STC ($1000 W/m^2$). $\Delta T = (T_c - T_n)$ is the difference of actual and nominal temperature (in Kelvin).

Diode Saturation Current (I_o):

I_o is a part of the reverse current in a diode due to diffusion of minority carriers from the neutral to the depletion region.

For a single diode model it can be estimated by:

$$I_o = \frac{(I_{sc,STC} + K_1 \Delta T)}{\exp((V_{oc,STC} + K_v \Delta T) / a V_t) - 1} \quad (6)$$

Series and Shunt Resistance (R_s And R_p):

R_s and R_p are chosen to make the computed ($P_{m,ref}$) and experimental maximum power at STC (P_{mexp}), equal.

$$I_{mp,ref} = \frac{P_{m,ref}}{V_{mp,ref}} = \frac{P_{mexp}}{V_{mp,ref}}$$

$$= -I_{ph,ref} - I_{o,ref} \left[\exp\left(\frac{V_{mp,ref} + I_{mp,ref} R_s}{a} - 1\right) \right] - \frac{V_{mp,ref} + R_s I_{mp,ref}}{R_p}$$

$$R_p = \frac{V_{mp,ref} + I_{mp,ref} R_s}{I_{sc,ref} - I_{sc,ref} \left\{ \exp\left[\frac{V_{mp,ref} + R_s I_{mp,ref} - V_{oc,ref}}{a}\right] \right\} + I_{sc,ref} \left\{ \exp(-V_{oc,ref} / a) \right\} - (P_{mexp} / V_{mp,ref})} \quad (7)$$

The iteration begins with $R_s = 0$ and R_p is calculated. Corresponding maximum power (P_{mref}) is calculated. Error between modelled and experimental maximum power is calculated. Value of R_s is increased by 0.01 at every iteration. There is only one pair of (R_s, R_p) which gives perfect match between experimental and modelled maximum power. The obtained values are 0.05Ω and 528.34Ω for R_s and R_p , respectively.

Double Diode Model (DDM)

In this model, two diodes are used to model the dark current, I_d . Two diodes are used to obtain higher accuracy in obtaining I-V characteristic curve. This model recombines the depletion region losses, which was neglected in SDM. This model has the similarity in thermal voltage (V_t) but different in ideality factors and saturation currents, to that of SDM. Figure 2 shows the DDM equivalent electrical circuit:

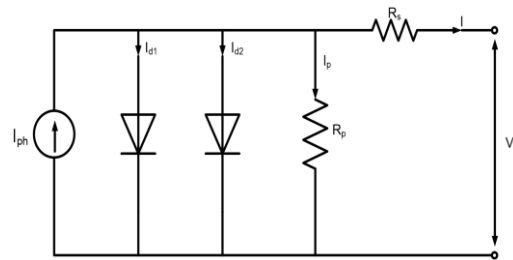


Figure 2. Double diode model (DDM)

The output current (I) is estimated using

$$I = I_{ph} - I_{d1} - I_{d2} - I_p \quad (8)$$

$$I = I_{ph} - I_{o1} \left(\exp \left(\frac{q(V + I R_s)}{A_1 \times k \times T_c} \right) - 1 \right) - I_{o2} \left(\exp \left(\frac{q(V + I R_s)}{A_2 \times k \times T_c} \right) - 1 \right) - \left(\frac{V + I R_s}{R_p} \right) \quad (9)$$

where I_{o1} , I_{o2} and A_1 , A_2 for two dark currents I_{d1} and I_{d2} . A_1 and A_2 represent the diffusion and recombination current components. Defining the new variable 'p' such that $(A_1 + A_2)/P = 1$ as given by Bana and Saini (2016).

According to Shockley's theory of diffusion, A_1 should be one but the value of A_2 is preferred to be less than or equal to 1.2. We have taken $A_2 = 1.2$.

Parameter Determination of DDM

Bellia *et al.* (2014), considered I_{ph} , I_0 , R_s , R_p , and A_1/A_2 five parameters depending on the irradiation and PV cell temperature. Few researchers have neglected R_s , R_p whereas, some have included these considering to be crucial in determining the internal characteristics of the PV module. Its value need to be determined carefully and accurately. In DDM, the five parameters needs to be determined are: I_{ph} , I_{o1} , I_{o2} , R_s , R_p .

Line Group Controller (LGC) or Photocurrent (I_{ph}):

LGC or Photocurrent is determined by Equation 3 similar to that of SDM.

Diode Saturation Currents (I_{o1} and I_{o2}):

In case of DDM, the values of I_{o1} and I_{o2} are obtained using iteration, which is complex and needs high computation time. Therefore, I_{o1} and I_{o2} has been taken as equal values based on the assumptions of the researcher work of Bana and Saini (2016) and Ishaque *et al.* (2011).

The equations for I_{o1} and I_{o2} can be written as:

$$I_o = I_{o1} = I_{o2} = \frac{(I_{sc,STC} + K_1 \Delta T)}{\exp((V_{oc,STC} + K_2 \Delta T)/((a_1 + a_2)/p)V_T) - 1} \quad (10)$$

Series and Shunt Resistance (R_s and R_p):

R_p and R_s are obtained through iterations. Few researchers tried to evaluate these two parameters independently, but didn't get satisfactory result. In the present work, R_p and R_s are calculated iteratively (Initiated with $R_s = 0$) to make the P_{mref} is equal to P_{mexp} at STC conditions then calculating the R_p value simultaneously. The experimental value of P_{mexp} at STC, was provided by the manufacturer of ASP 72C 200 PV modules (200W). There is only one pair of (R_s , R_p) which gives perfect match between experimental and modelled maximum power. At MPP condition, the R_p can be evaluated as:

$$R_p = \frac{V_{mp} + I_{mp} R_s}{\left[I_{ph} - \left\{ I_0 \left(\exp \left(\frac{V_{mp} + I_{mp} R_s}{V_t} \right) + \exp \left(\frac{V_{mp} + I_{mp} R_s}{(p-1)V_t} \right) - 2 \right\} \right] - \left\{ \frac{P_{max,E}}{V_{mp}} \right\}} \quad (11)$$

The initial conditions for series and shunt resistance is given by :

$$R_s = 0; \quad R_p = \left(\frac{V_{mp}}{I_{sc} - I_{mp}} \right) - \left(\frac{V_{oc} - V_{mp}}{I_{mp}} \right) \quad (12)$$

Values of R_s and R_p for two diode model are found to be 0.26Ω and 293.98Ω respectively.

Experimental Methodology

The modeling results has been compared and validated with the experimental results. The experimentes has been conducted on



Figure 3. Experimental setup arrangement on the rooftop

poly-crystalline module (model: ASP-72C-200). The experimental setup consisted of 200W PV module, situated at the rooftop of Mechanical Workshop in VNIT, Nagpur (21.123°N, 79.0515°E), located at 312.42 m above sea level. The PV module was kept tilted at an angle equal to the latitude of the place, facing south. Figure 3 shows the the PV panel arrangement over rooftop. The specifications of the experimental setup are mentioned in Table 1 and the block diagram is presented in Figure 4. The parameters and its set value are same as that is mentioned by Bastidas-Rodriguez *et al.* (2017). These are standards provided by the manufactures about irradiance, temperature and air mass (AM). The PV module used for the experiment purposes consists of 72 cells. MATLAB programme is used to obtain I-V curves and P-V curves for simulating the various irradiances and temperatures values. The experiments were performed at constant and variable load conditions. While the former is used to calculate current, voltage and ultimately the maximum power with variation in temperature and irradiance throughout day, the later is used to calculate the performance curve I-V and P-V at constant load with time.

Optimization

Genetic Algorithm (GA)

The five parameters of the SDM and DDM are evaluated using a system of six non linear equations and a single objective function. This was done to find out the dependency of these parameters on the environmental conditions. The traditional methods like Newton-Raphson cannot be used as the equations are more than the number of unknowns. Moreover, values of the selected parameters have different ranges (like I_{ph} is in amperes, while I_{sat} is in nano-amperes) and transcendental and non-linear nature of the equations.

The solution of the non-linear equation system is posed as an optimization problem consisting of combination of the non-linear functions as a cost function (FC) which is to be minimized:

$$FC(I_{ph}, I_{sat}, \eta, R_s, R_h) = \sum_{i=1}^6 F_{pi}^2 \quad (13)$$

Simulated Annealing (SA) Optimization:

SA technique proposed by Kirkpatrick *et al.* (1983) was considered for the optimization. SA emulates the physical gradual cooling process

Table 1. Specifications of PV system arrangement with data acquisition system

Equipment's Name	Specification
Multi-Channel Data Logger	Model: Unilog (16 Channel Universal Process Data Recorder) Make :Process Precision Pune
Pyranometer for Global Radiation	Model: Digital Solar Radiation Recorder Make: Virtual Electronics Company
Solar Panel plus Mounting Stand	200 W Rating Make: Akshaya Solar Power
Multimeter	Model: DTI (1400369)(0-600V)(0-40A) Make: MECO India
Thermocouples	4 Nos Model- PT 100
Load	21 Bulbs 10 W 12 V Rating

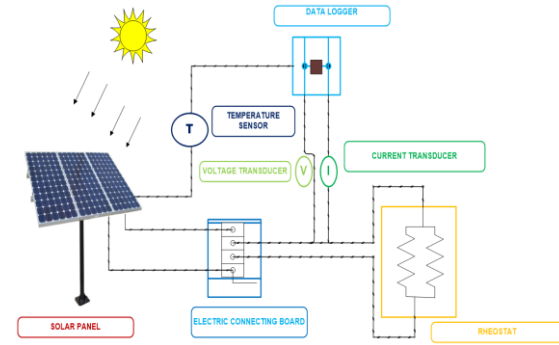


Figure 4. Block diagram of experimental setup with data acquisition system

(called annealing) that produces high quality crystals with better strength properties. The two major steps in SA are the transition mechanism between states and the cooling schedule with objective to find the state with minimum energy. This model generates a sequence of states of a solid and assumes that the probability for a physical system to have a certain energy level E is proportional to Boltzmann factor $\frac{E}{e^{k_B T}}$, where k_B denotes the Boltzmann constant, when the thermodynamic equilibrium is reached at a given temperature T . A probability distribution with a scale proportional to the control parameter, i.e. temperature, governs the distance of the new solution candidate from the existing solution. In order to form the objective function, the I-V relationships are rewritten in the following homogeneous equations:

For the double diode model

$$f_i(V_L, I_L, I_{ph}, I_{SD1}, I_{SD2}, R_s, R_{sh}, n_1, n_2, \dots) = 0 \quad (14)$$

For the single diode

$$f_i(V_L, I_L, I_{ph}, I_{SD1}, R_s, R_{sh}, n) = 0 \quad (15)$$

Initial guess solution was obtained by equation:

$$I_{ph,0} \approx I_{sc} \quad (16)$$

$$I_{o,0} = I_{ph} \cdot \exp(-V_{oc}/a) \quad (17)$$

$$A_0 = \frac{\alpha V_{oc} - (V_{oc}/T)}{V_t \left(\frac{\alpha I_{sc}}{I_{ph}} - \frac{3}{T} \frac{E_g}{kT^2} \right)} \quad (18)$$

$$R_{s,0} = \frac{x \cdot a - V_m}{I_m} \quad (19)$$

and,

$$R_{p,0} = \frac{x \cdot a}{I_{ph} - I_m - I_o(e^x - 1)} \quad (20)$$

Result and Discussion

In this section the modelling, optimization and experimental results are presented and discussed. The section contains two subsection.

Comparison of Single Diode and Double Diode with Experimental Validation

The modelling results obtained from SDM and DDM is presented in Figures 5-10, is discussed in this section. The experimentation was conducted through out the day in the interval from morning 9 AM to evening 4 PM and parameters were recorded with the I-V and P-V curve variation maintained by varying the load using rheostat.

During morning and evening hours as the solar radiation is less, the power generated by PV panels are also low that can be seen from the above graph. The actual power generated found through experimentation and predicted power output modelled using two modeling methodology SDM and DDM are changing in the same manner. The power generated is more during 10 AM to 2 PM (noon hours) and lesser during morning and evening hours. It is evident from the above curves that the DDM results are better than the SDM for all the hours of the day. The DDM results are closer to the experimental results than SDM.

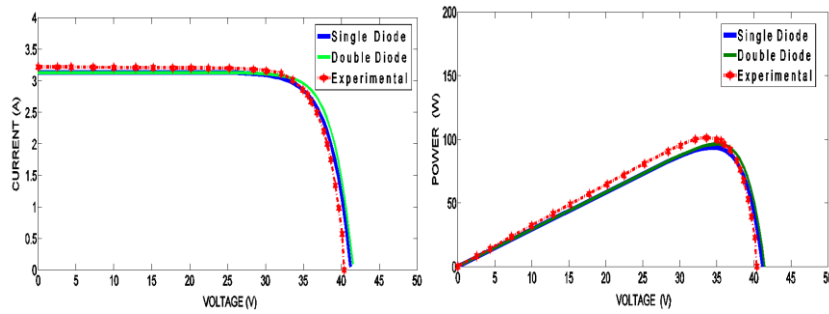


Figure 5. IV, PV Curve at 09:00 AM

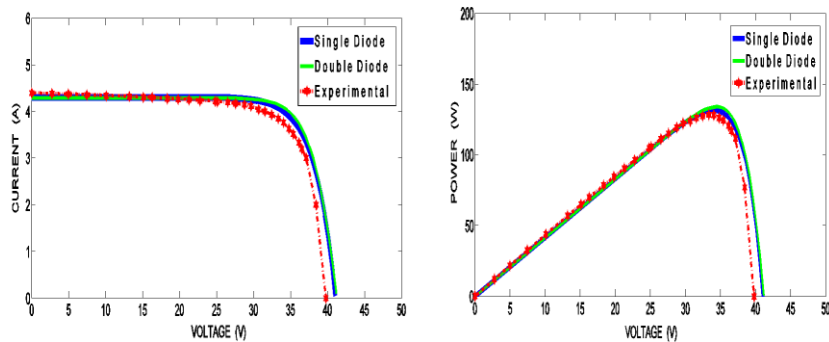


Figure 6. IV, PV Curve at 10:00 AM

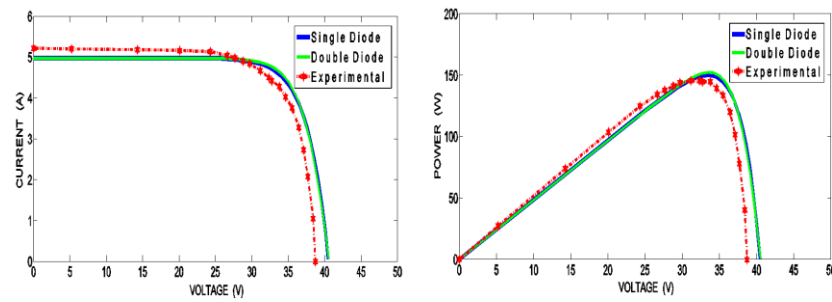


Figure 7. IV, PV Curve at 12:00 PM

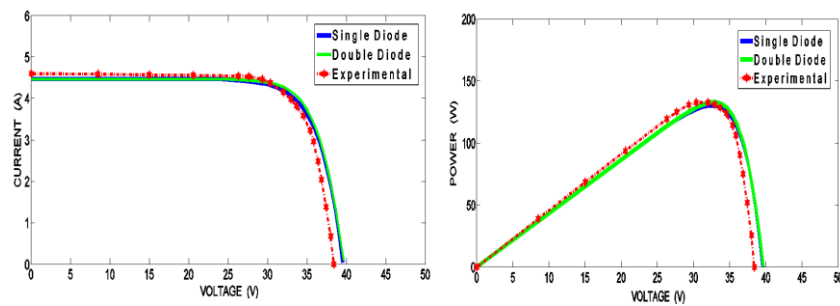


Figure 8. IV, PV Curve at 02:00 PM

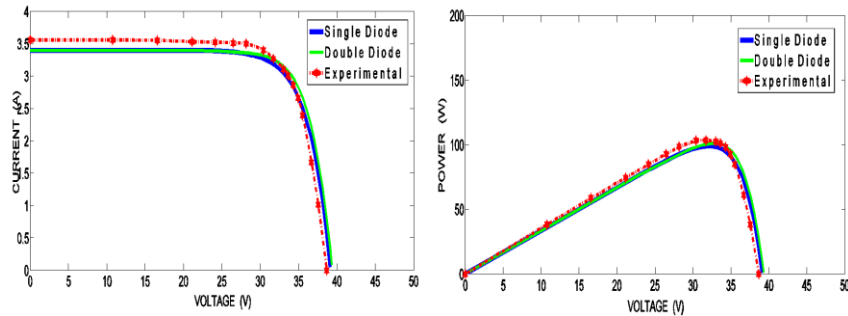


Figure 9. IV, PV Curve at 03:00 PM

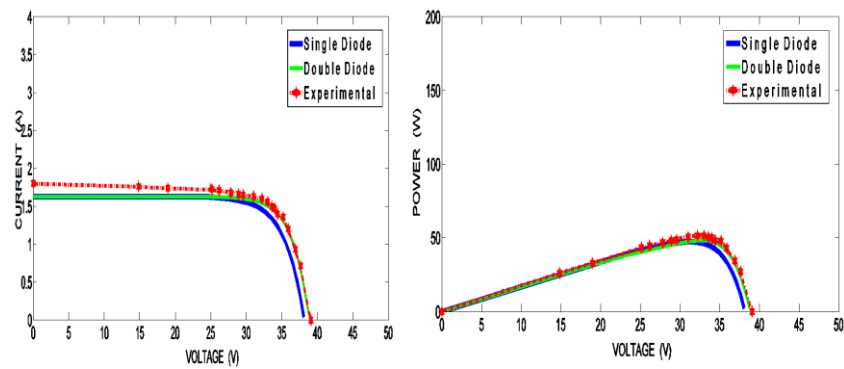


Figure 10. I-V and P-V curve for a day

For comparison of both models, error is calculated by selecting five key points of I-V and P-V curves as given by King *et al.* (2003). The normalized sum of squared errors (NSSE) is calculated at five key points for IV and PV curve. NSSE is defined as given by Bastidas-Rodriguez *et al.* (2017) as follows:

$$NSSE(\%) = \frac{\sum_{k=1}^H (y(k) - y_e(k))^2}{\sum_{k=1}^H (y(k))^2} \quad (21)$$

y and y_e represent the reference and estimated values, and H represents the number of data.

NSSE values obtained with single diode and double diode models is compared to experimental results are presented in Table 2. The error obtained for both I-V curve and P-V curve is compared. The maximum error obtained between modelling predictions and experimental results is less than 8.44 percentage. Most of the errors are less than 5 percentage as can be seen from Table 2. The solar radiation and ambient temperature during the same time is also tabulated in table.

At lower values of irradiance and temperature (9AM), DDM is found to be more accurate than SDM. The error calculated between SDM and experimental is 1.26% and 2.5% for I-V and P-V curve respectively. Whereas the error obtained between DDM and experimental values are 0.85 and 2.0 percentage for I-V and P-V curve respectively, under the same condition. The difference in the errors obtained between DDM and SDM compared to experimental results are in the range of -1.60% to 3.75%. As the radiation increases SDM seems to becoming more accurate. As can be seen by

comparing the NSSE errors obtained at 10 AM both SDM and DDM have quite similar values. At noon hours during higher radiation level (12 PM and 2 PM), SDM seems to give better results compared to DDM as per Table 2.

In afternoon period (after 2PM), solar radiation starts decreasing in intensity and so the panel temperature. The error obtained through DDM is lesser than SDM because DDM considers the recombination losses. The error calculated between DDM and experimental results are less than 2 percentage at lower radiation conditions. It can be concluded that DDM gives more accurate results than SDM for low radiation level and vice versa at higher radiation level but DDM requires more complex calculations and more computation time than SDM. The results are found to be comparable with the study of authors Bellia *et al.* (2014) and Bana and Saini (2017).

Optimization

The five parameters of the SDM and DDM are evaluated using a system non linear equations with a single objective function to find out the dependency of these parameters on the ambient conditions. Optimization of SDM and DDM at 9 AM, 2 PM, and 4 PM are done by two techniques which are genetic algorithm (GA) and simulated annealing (SA). The results obtained after optimization of single and double diode models are shown below. First results from optimization of SDM results are discussed followed by DDM optimization. The fitness function as given by Bastidas-Rodriguez *et al.* (2017) is maximised by using GA and SA optimization technique, to estimate the parameters of PV module (ASP-72C-200). The five key points of IV curve and PV curve

Table 2. NSSE obtained in I-V and P-V values obtained from modeling

Time	Radiation (W/m ²)	Temperature (°C)	NSSE (%) for SDM		NSSE (%) for DDM	
			NSSE(%) for I-V curve	NSSE(%) for P-V curve	NSSE(%) for I-V curve	NSSE(%) for P-V curve
9:00 AM	521.25	30.25	1.26	2.51	0.85	2.00
10:00 AM	712.75	36.95	1.23	3.20	1.35	3.50
12:00 PM	822.25	43.25	2.87	7.56	3.10	8.44
2:00 PM	736.50	47.79	0.87	4.60	0.99	5.26
3:00 PM	560.42	45.85	0.28	0.35	0.22	0.19
4:00 PM	270.25	39.71	2.95	5.57	1.32	1.82

Table 3. Iterations required in SDM & DDM

Time	No. of iterations in GA		No. of iteration in SA	
	SDM	DDM	SDM	DDM
9:00AM	199*20=3980	51*20=1020	4910	3231
2:00AM	153*20=3060	51*20=1020	6621	3000
4:00AM	161*20=3220	51*20=1020	3794	3096

for different irradiance and temperature are selected as given by King *et al.* (2003) to calculate errors and comparison with experimental values. The iterations required in SDM and DDM for GA and SA optimisation is given in Table 3.

Optimization of Single Diode Model

In this section the experimental result, SDM modeling results and optimized electrical parameters using GA and SA algorithm are presented and discussed. The electrical parameters has been presented at various ambient conditions from morning 9 AM to 4 PM. The results presented

in Figures 11-13 and discussed at morning (9 AM), noon (2 PM), and afternoon (4 PM) conditions. The error obtained from SDM modeling and optimised results compared to experiments has been compared in Table 4.

Optimization of Double Diode Model

In this section the experimental result, DDM modeling results and optimized electrical parameters using GA and SA algorithm are presented and discussed. The electrical parameters has been presented at various ambient conditions from morning 9 AM to 4 PM. The results presented

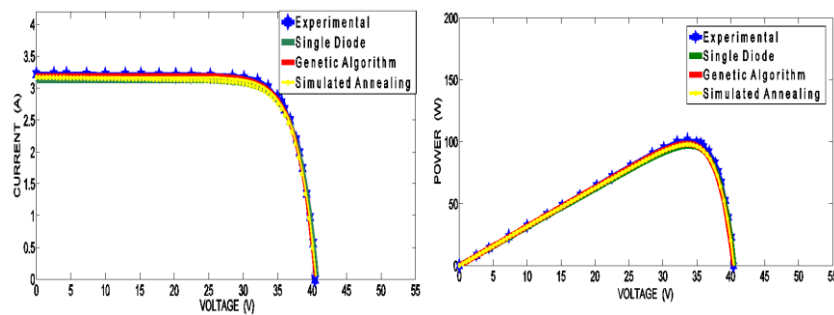


Figure 11. IV, PV Curve at 9 AM using optimization

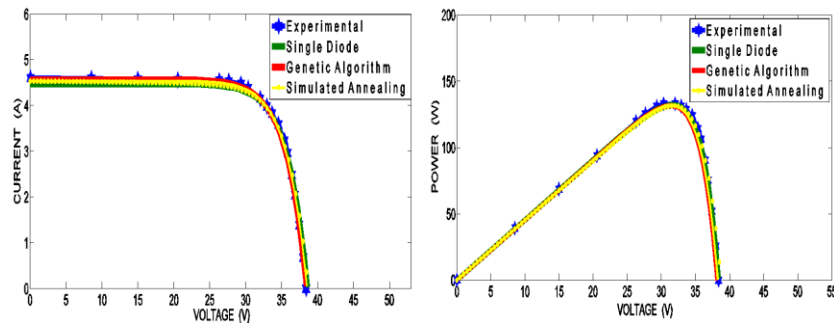


Figure 12. IV, PV Curve at 2 PM using Optimization

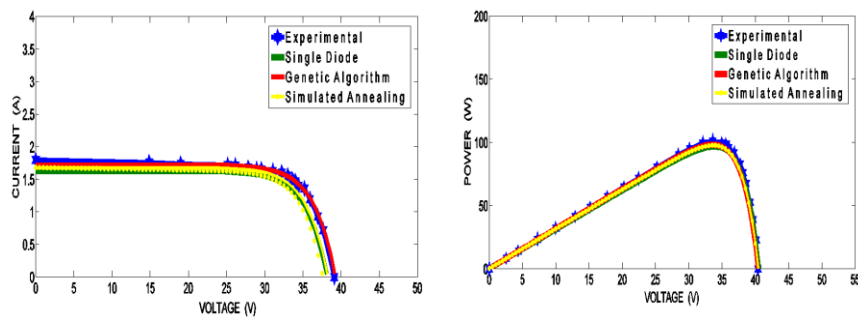


Figure 13. IV, PV Curve at 4 PM using optimization

Table 4. NSSE % values for GA & SA optimization

Time Radiation (W/m ²) Temperature (°C)			9:00AM 521.25 30.25	2:00PM 736.50 47.79	4:00PM 270.25 39.71
NSSE (%) in SDM		for I-V curve	1.26	0.87	2.95
		for P-V urve	2.51	4.60	5.57
NSSE (%) in Optimized SDM	GA	for I-V curve	0.07	0.13	0.40
		for P-V curve	0.13	0.32	0.67
	SA	for I-V curve	0.09	0.36	2.06
		for P-V curve	0.13	0.94	4.13
NSSE (%) IN DDM		for I-V curve	0.85	0.99	1.32
		for P-V curve	2.00	5.26	1.82
NSSE (%) in optimized DDM	GA	for I-V curve	0.08	0.17	0.10
		for P-V curve	0.13	0.43	0.07
	SA	for I-V curve	0.11	0.59	0.48
		for P-V curve	0.19	1.50	0.48

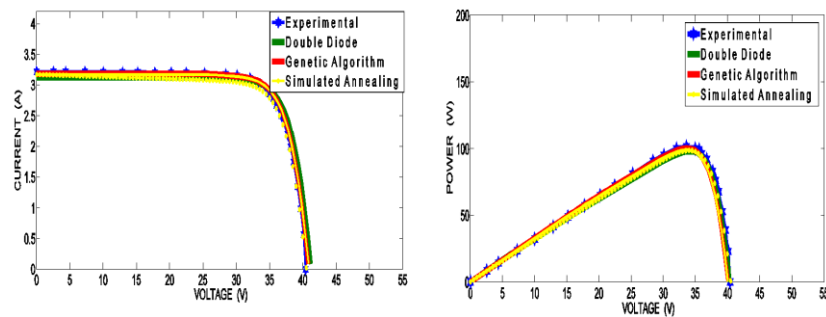


Figure 14. IV, PV Curve at 9 AM using optimization

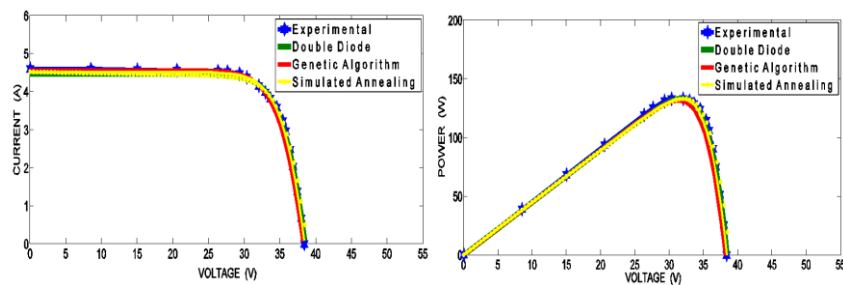


Figure 15. IV, PV Curve at 2 PM using optimization

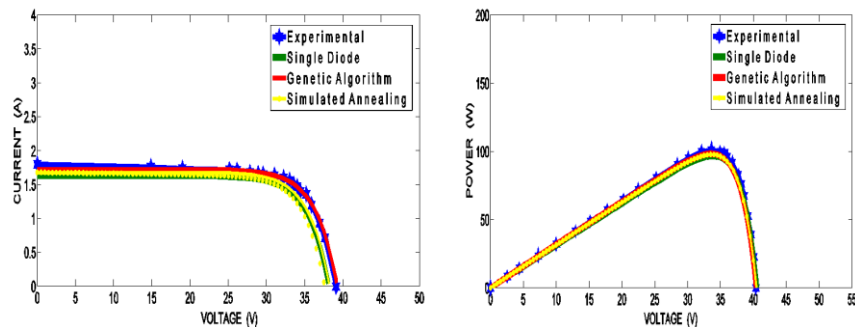


Figure 16. IV, PV Curve at 4 PM using optimization

in Figures 14-16 and discussed at morning (9 AM), noon (2 PM), and afternoon (4 PM) conditions. The error obtained from DDM modeling and optimised results compared to experiments are presented in Table 4. NSSE values obtained with two optimization techniques are presented in Table 4 at different time of the day. It can be concluded from the table that optimization has reduced the error values substantially. The maximum percentage error obtained using optimization is 4.127% for SDM using SA algorithm.

The errors obtained with GA are found to be less than SA technique. At high temperature and irradiance (during noon) SDM optimized with the GA is found to be more accurate. At Low irradiance and temperature (during morning and noon hours) DDM optimized with GA is found to be more accurate.

In each case, it is found that GA leads to better results than SA. Also the number of iterations required for GA are less than that of SA for obtaining convergence as shown in Table 3. So, GA leads to better results and faster execution than SA. The minimum NSSE (%) obtained for I-V curve is of 0.28 for SDM whereas, it is of 0.22 for DDM. The maximum NSSE (%) obtained for I-V curve is of 2.95 for SDM whereas, it is of 0.22 at 12 PM for DDM. The minimum NSSE (%) obtained for P-V curve is 0.35 and 0.19 at PM for SDM and DDM, respectively. The maximum NSSE (%) obtained for P-V curve is of 7.56 and 8.44 at 12 PM for SDM and DDM, respectively. When SDM is optimized, the average NSSE% obtained for I-V and P-V curve are 0.20 and 0.37 for GA and 0.84 and 1.70 for SA. The average NSSE (%) for I-V and P-V curve are 1.65 and 4.23 for SDM and 1.05 and 3.02 for DDM respectively.

Conclusions

In the present work, SDM and DDM model were used to demonstrate the modeling of PV module and predict the electrical performance. Validation of the models is done with ASP-72C-200 module and the measurements were carried out in Nagpur, India. Optimisation of both SDM and DDM was done in order to find the optimum point for the operation of PV cell. Error analysis was done using NSSE throughout the day for determining the accuracy of model. On Comparison of SDM and DDM, at lower radiation, difference in error of DDM was found to be lesser than that of SDM due to consideration of recombination losses in DDM.

The study also includes the optimization of the modeling results using GA and SA algorithm. In each case, it was found that GA leads to better

results than SA. Also the number of iterations required for GA are less than that of SA for obtaining convergence. So, GA leads to better results and faster execution than SA

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