ISSN: 0369-8963
PERIODICO di MINERALOGIA Volume 91, No. 3, 2022

Solar Photovoltaic Array Physical Modelling and Characteristics Evaluation in MATLAB/Simscape using Parameter Extraction Technique

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Abstract

High performance solar array modelling in MATLAB/Simscape is proposed in this paper. Evaluating a solar array under all possible circumstances is essential for continuous tracking of dynamically varying maximum power point. Modelling optimisation is based on two considerations first, physical modelling second calculation of unknown solar array parameters. Main focus is achieving better efficiency of solar array in various applications by evaluating its performance in planning and operational phase for better economic return. The proposed model validation is performed by comparing power output data with available ortiz model predictions and hardware results. The results reveal the sustainability of adopted method of modelling and identified as best one.

Key words: *MATLAB/Simscape, Maximum power point tracking, Parameter extraction · Solar PV array, Physical modelling.*

Introduction

The availability of reliable accurate model is essential for the dissemination of PV technology to access maximum power point. Different solar cell models have been developed to describe its electrical behaviour under static and dynamic weather conditions. The V-I and P-V relationship of a solar cell is described by a mathematical equation, they are implicit and nonlinear. A PV cell can be characterised by at least three parameters such as light generated current (I_{ph}), diode reverse saturation current (I_o) and ideality factor(a) [1]. In order to account the effect structural resistances of solar cell and leakage current a series resistance and parallel resistances are included in the modelling. Four parameter model is developed by neglecting parallel resistance [2]. This model assumes that the slope of the I-V curve is flat at short circuit condition. But this assumption is not valid for amorphous PV cells. Five parameter modelling is done by including parallel resistance. Generally, these five parameters are estimated under standard test condition. Among series resistance, parallel resistance and ideality factor any one of parameter is kept constant for estimating maximum power point. This approach also reduces the accuracy of modelling [2]. The series resistance, parallel resistance and ideality factor pertaining to a solar panel change according to weather conditions. Hence new two equations are proposed and solved using Gauss-Seidel (G-S) method to obtain them dynamically [3]. This paper combines the advantages of estimation of series resistance, parallel resistance and ideality factor at STC using fast convergence technique i.e., Newton Raphson method and implementation of values extracted parameters in MATLAB/Simscape model of solar PV array to evaluate maximum power point under dynamically varying weather conditions.

This paper is organised as follows: section 2 deals with equivalent circuit model of solar cell, section 3 deals with Ortiz mathematical modelling, section 4 deals with Modelling of solar array in MATLAB/Simscape and section 5 deals with hardware results.

 https://doi.org/10.37896/pd91.3/91325

Equivalent circuit model of solar cell

A solar cell equivalent circuit of four parameters modelling is shown in Figure 1. It consists of a series resistance (R_{se}) and a parallel resistance (R_{sh}). In order to account the effect structural resistances a series resistance is included in the model and to account a leakage current a parallel resistance is included in the model[3]. The influences of R_{se} and R_{sh} are stronger in the voltage source region and current source regions respectively.

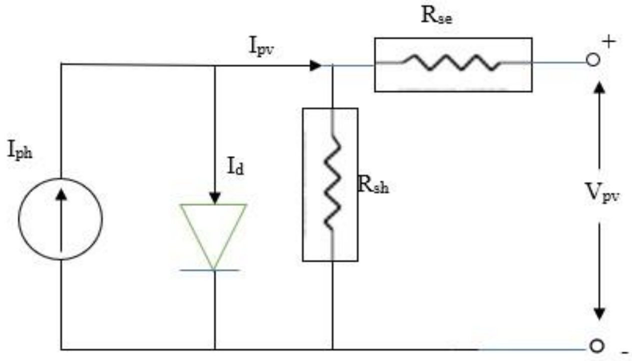

Figure 1 Equivalent circuit diagram of a solar cell

The basic equation from the theory of semiconductor that mathematically describes the electrical behaviour of solar cell is given in equation (1).

$$I = I_{ph} - I_o \left(exp\left(\left(\frac{qV}{akT} \right) \right) - 1 \right) \tag{1}$$

where,
I_{ph} = Photo generated current (Amps)
I_o = Reverse saturation current of diode (Amps)
a = Ideality factor
q = Electron charge (1.6021 x 10^{-19} C)
k = Boltzmann constant (1.38 x 10^{-23} J/K)
V = PV cell voltage (Volts)
I = Load current (Amps)

PV panels are connected in series (N_s) to raise the current and in parallel (N_p) to raise the voltage rating of an array. [4]. The mathematical model of practical single solar panel is represented by Equation (2).

$$I = I_{ph} - I_o \left(e^{\left(\frac{q(V+IR_{se})}{akTN_s} \right)} - 1 \right) - \frac{V+IR_{se}}{R_{sh}} \tag{2}$$

where,
I_{ph} = Photo generated current (Amps)
I_o = Diode saturation current (Amps)
a = Ideality factor
q = Electron charge (1.6021 x 10^{-19} C)
k = Boltzmann constant (1.38 x 10^{-23} J/K)
V = PV cell voltage (Volts)
I = Load current (Amps)
R_{se} = Series resistance (Ohms)
R_{sh} = Parallel resistance (Ohms)

 https://doi.org/10.37896/pd91.3/91325

The photo generated current is the electricity generated by the solar radiation. Its dependency on irradiance and temperature is given by empirical Equation (3).

$$I_{ph}\,(G,T) = \left(\frac{G}{G_{std}}\right)\left[I_{phstd} + K_{isc}(T - T_{std})\right] \quad (3)$$

where,
I_{ph} = Photo generated current (Amps)
G = Irradiance (W/m^2)
T = Temperature (K)
G_{std} = Standard Irradiance (1000 W/m^2)
T_{std} = Standard reference temperature of PV cell (298 Kelvin)
I_{phstd} = Photo generated current standard irradiance and temperature (Amps)
K_{isc} = Temperature co-efficient of short circuit current

Reverse saturation current of diode is because of diffusion of charges from n-side to p-side and p-side to n-side of the photovoltaic cell which is strongly dependent on the temperature. This dependency is represented by the following empirical Equation (4). A rise in the operating temperature of a solar cell reduces the band gap, thus slightly rises the short circuit current decreases the open circuit voltage of a solar cell for a given irradiance,

$$I_o\,(T) = I_{ostd}\left(\frac{T}{T_{std}}\right) e^{\left[\frac{qE_g}{ak}\left(\frac{1}{T_{std}} - \frac{1}{T}\right)\right]} \quad (4)$$

where,
I_o =Reverse saturation current of diode (Amps)
I_{ostd} =Reverse saturation current of diode at standard irradiance and temperature (Amps)
a = Ideality factor
q = Electron charge (1.6021 x 10^{-19} C)
k = Boltzmann constant (1.38 x 10^{-23} J/K)
E_g = Band gap energy (eV)
T = Temperature (K)
T_{std} = Standard reference temperature of PV cell (298 Kelvin)

PV Modelling in MATLAB/Simscape

In this paper an 80W solar array is considered for modelling. Two numbers of ELDORA 40W solar modules are connected in parallel to form 80W solar array. This module is made of 36 multi-crystalline silicon cells in series with 40 W maximum power at STC. Table 1 illustrates the data sheet of the module. A physical modelling and simulation are done with the combined use of Simscape and Simulink environment in MATLAB software. MATLAB versions has the feature of an in-built PV cell block in simscape [5], which represents a single solar cell as a parallel current source I_{ph}, an exponential diode D and a shunt resistance R_{sh} that are connected in series with a resistance R_{se}. Figure 2 represents the solar cell available in MATLAB/Simscape.Unfortunately manufacturer data sheet doesn't have the values of R_{se} , R_{sh} and ideality factor n. So, it is necessary to find values of the above said parameters pertaining to a solar panel. There are different parameter extraction techniques available in literature [6-8]. In this research work Newton Raphson iterative technique is used for finding five unknown parameters.

Table 1 Electrical specifications of a 40W solar panel

Test Module ELDORA- 40W Parameters	Values
Nominal Power (P_{max})	40 W
Open circuit voltage (V_{oc})	21.9 V
Short circuit current (I_{sc})	2.45 A
Voltage at maximum power (V_{mpp})	17.4 V
Current at maximum power (I_{mpp})	2.3 A
Number of cells in series (Ns)	36
Temperature co-efficient of Voc (Kvoc)	-0.123 V/^{o}K
Temperature co-efficient of Isc (Kisc)	0.0032 A/^{o}K

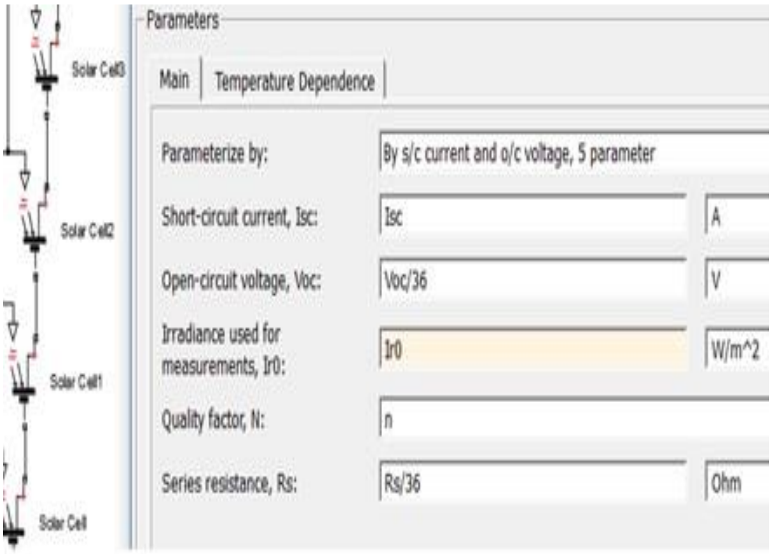

Figure 2. Solar cell block modelling in MATLAB/Simscape

Extraction of PV Module Parameters

Mathematically, estimation of five unknown parameters required five independent equations. The five equations which represents the nonlinear characteristics of solar panel are derived from the basic solar panel output voltage and current relationship transcendental Equation (1). Among five equations, first three equations are derived from Equation (2) by applying three different significant operating conditions of PV panel such as short circuit, open circuit, and MPP conditions. The remaining two equations are derived by differentiating the solar panel power equation and current equation with respect to voltage. [3]. These five nonlinear equations are not solved analytically, an efficient Newton Raphson iterative method is used for solving these equations. The derivation of required five equations are given below:

Under the short circuit condition, panel offers almost zero resistance which act as short circuit. Therefore, the voltage across the panel is zero and the current through the panel is short circuit current. This boundary condition is applied in the basic equation of solar panel i.e. Equation (2) then the derived equation is as follows:

$$I_{sc} = I_{ph} - I_o \left(e^{\left(\frac{qI_{sc}R_{se}}{akTN_s}\right)} - 1 \right) - \frac{I_{sc}R_{se}}{R_{sh}} \quad (5)$$

 https://doi.org/10.37896/pd91.3/91325

After some approximation, the equation of light generated current I_{ph} is obtained as below Equation (6),

$$I_{ph} = \frac{I_{sc}\,(R_{se}+R_{sh})}{R_{sh}} \quad (6)$$

Under the open circuit condition, panel offers almost infinite resistance which act as open circuit. Therefore, the voltage across the panel is infinite and the current through the panel is almost zero. This boundary condition is applied in the basic equation of solar panel i.e., Equation (2) then the derived equation is as follows:

$$0 = I_{ph} - I_o e^{\left(\frac{qV_{oc}}{N_s k\,T}\right)} - \frac{V_{oc}}{R_{sh}} \quad (7)$$

Equation (7) is rearranged and the reverse saturation current of diode is obtained as follows:

$$I_o = (I_{ph} - \frac{V_{oc}}{R_{sh}})\, e^{-\frac{-qV_{oc}}{N_s kT}} \quad (8)$$

Equation. (8) is substituted with Equation (6) and then the new equation of saturation current of diode is derived as follows:

$$I_o = \left(\frac{I_{sc}\,(R_{se}+R_{sh})-V_{oc}}{R_{sh}}\right) e^{\frac{-qV_{oc}}{N_s k\,T}} \quad (9)$$

Under the maximum power point condition, PV panel generates maximum power P_{max}. Then, the voltage across the panel is considered as V_{mpp} and the current through the panel is considered as I_{mpp}. This boundary condition is applied in the basic of solar panel i.e., Equation (2) then the derived equation is as follows:

$$I_{mpp} = I_{ph} - (e^{\frac{q\,(V_{mpp}+I_{mpp}R_{se})}{N_s k\,T}} - 1) - \left(\frac{V_{mpp}+I_{mpp}\,R_{se}}{R_{sh}}\right) \quad (10)$$

Equations. (6) and (9) are substituted in the Equation. (10) and rearranged, by which equation of I_{mpp} is delivered as follows:

$$I_{mpp}=(\frac{I_{sc}(R_{se}+R_{sh})-(V_{mpp}+I_{mpp}R_{se})}{R_{sh}})-(\frac{I_{sc}\,(R_{se}+R_{sh})-V_{oc}}{R_{sh}})(e^{\frac{q(V_{mpp}+I_{mpp}\,R_{se}-V_{oc})}{N_s kT}}) \quad (11)$$

Equations (6), (9) and (11) are the first three nonlinear equations of solar panel. Then the remaining two equations are to be derived. When the PV panel is working under MPP condition, there is no further change of voltage is needed towards optimum voltage. Hence, derivative of power with respect to voltage is zero at MPP and the same is expressed as

$$\left.\frac{dp}{dv}\right| = 0 \quad (12)$$

$$\because I = I_{mpp}\;;\; V = V_{mpp} \quad (13)$$

General equation of power i.e., $P=VI$ is substituted in Equation. (13),

$$\left.\frac{dp}{dv}\right| = \frac{d(IV)}{dV} = I + \frac{dI}{dV}V = I_{mpp} + \frac{dI_{mpp}}{dV_{mpp}}V_{mpp} \quad (14)$$

From Equations. (11) and (14), $\frac{dp}{dv}$ is derived as follows,

$$\left.\frac{dp}{dv}\right| = 0 = I_{mpp} + \frac{V_{mpp}\left\{\frac{-1}{R_p} - \frac{(I_{sc}(R_s+R_p)-V_{oc})}{R_p}e^{\frac{q(V_{mpp}+I_{mpp}\,R_s-V_{oc})}{N_s kT}}\right\}}{\left\{1+\frac{qR_p}{N_s kT}\frac{(I_{sc}(R_s+R_p)-V_{oc})}{R_p}e^{-\frac{q(V_{mpp}+I_{mpp}\,R_s-V_{oc})}{N_s kT}}+\frac{R_s}{R_p}\right\}} \quad (15)$$

Equation (15) is the fourth equation of solar PV panel. The derivative of the current with respect to voltage at the short circuit condition is determined by the shunt resistance R_{sh}.

$$\left.\frac{dp}{dv}\right| = \frac{-1}{R_{sh}} \tag{16}$$

$$\because\ I = I_{sc}\ ;\ V = 0$$

From Equation (2.16), *dI /dV* is derived as follows:

$$\left.\frac{dp}{dv}\right| = \frac{-1}{R_{sh}} = \frac{\left\{\frac{-1}{R_p} - \frac{(I_{sc}(R_s+R_p)-V_{oc})}{R_p} e^{\frac{q(V_{mpp}+I_{mpp}R_s-V_{oc})}{N_s kT}}\right\}}{\left\{1+\frac{qR_p}{N_s kT}\frac{(I_{sc}(R_s+R_p)-V_{oc})}{R_p} e^{-\frac{q(V_{mpp}+I_{mpp}R_s-V_{oc})}{N_s kT}} + \frac{R_s}{R_p}\right\}} \tag{17}$$

Equation (17) is the fifth required equation of solar PV panel. Improper selection of the initial values R_{se} and R_{sh} of the PV module may fail to converge. So, it is necessary to select proper initial values. Initial values are given in Equations (18) and (19) are considered.

$$R_{seinitial} = \frac{V_{oc}}{I_{sc}} - \frac{V_{mpp}}{I_{mpp}} \tag{18}$$

$$R_{shinitial} = \frac{V_{mpp}}{I_{sc}-I_{mpp}} \tag{19}$$

The first three Equations. (6), (9), and (11) are rearranged in convenient way to find the three unknown parameters such as ideality factor *a*, series resistance R_{se}, and parallel resistance R_{sh}, which are given by Equations (20), (21), and (22), respectively.

$$V_t = \frac{a\,kT}{q} = \frac{V_{mpp}+I_{mpp}R_{se}-V_{oc}}{N_s ln\frac{I_{sc}(R_{se}+R_{sh})-V_{oc}}{((I_{sc}-I_{mpp})(R_{se}+R_{sh})-V_{mpp})}} \tag{20}$$

$$R_{se} = \frac{V_{oc}-V_{mpp}+N_s V_t S}{I_{mpp}} \tag{21}$$

$$S = ln\frac{N_s V_t\left(I_{mpp}(R_{se}+R_{sh}) - V_{mpp}\right)}{\left(I_{sc}V_{mpp}(R_{se}+R_{sh}) + I_{mpp}R_{se}(V_{oc}-I_{sc}R_{se}-I_{sc}R_{sh}) - V_{mp}V_{oc}\right)}$$

$$R_{sh} = \frac{(N_s V_t(R_{se}+R_{sh}) + R_{se}\,(I_{sc}(R_{se}+R_{sh})-V_{oc}))e^{\frac{q(I_{sc}R_{se}-V_{oc})}{N_s kT}}}{N_s V_t + (I_{sc}(R_{se}+R_{sh})-V_{oc}))e^{\frac{q(I_{sc}R_{se}-V_{oc})}{N_s kT}}} \tag{22}$$

The transcendental Equations (20), (21), and (22) are solved by the N-R method and the values of *a*, R_{se}, and R_{sh} are obtained.

Newton- Raphson Method for Solving PV System Equations

Newton's method is used for solving the non-linear system of equations of solar photovoltaic system. Because of its convergence speed Newton-Raphson method is chosen. The flowchart for evaluation of parameters of the PV module is shown in Figure.3. The errors of *a*, R_{se} and R_{sh} in the two consecutive iterations are taken as $1 * 10^{-6}$. MATLAB/m-file coding is done for the Newton - Raphson method and executed successfully. After the estimation of three unknown parameters, the remaining I_{ph} and I_o parameters are obtained using the Equations (6) and (9). The estimated values are listed in Table 2.

Table 2. Evaluated solar panel parameters

Solar panel parameters	Calculated values using N-R Method
Series Resistance (R_{se})	0.010 Ω
Parallel Resistance (R_{sh})	188.02 Ω
Ideality factor (a)	1.743
Photo generated current (I_{ph})	2.45 A
Reverse saturation current of Si diode (I_o)	$2.97 * 10^{-8}$ A
Time of computation	0.9 Sec

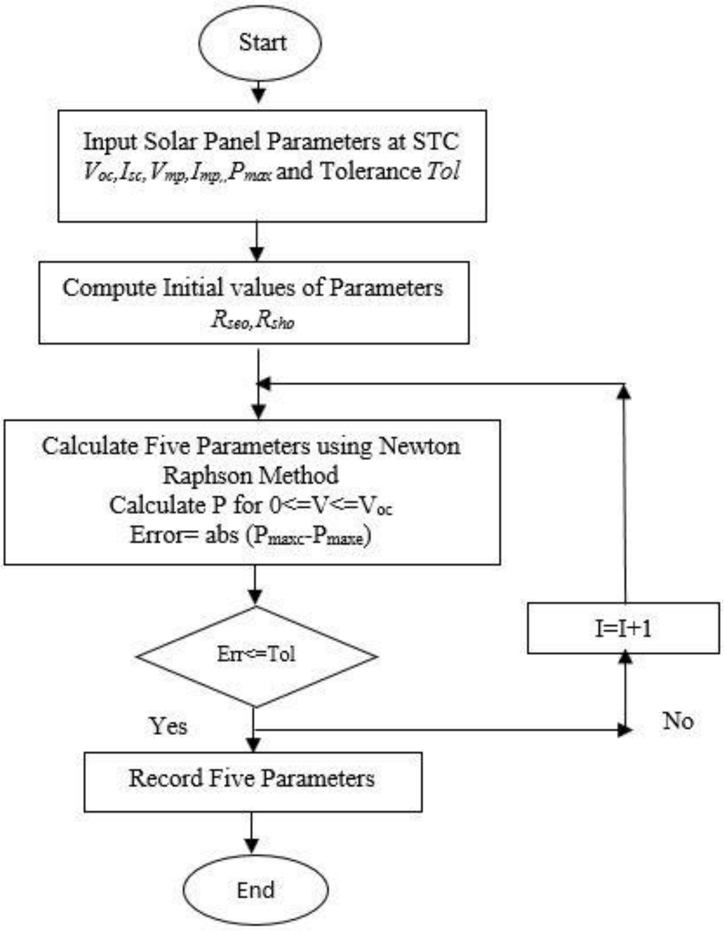

Figure 3 Flow chart for evaluation of solar PV parameters

After the estimation of photo current (I_{ph}), diode saturation current (I_o), series resistance (R_{se}), parallel resistance (R_{sh}) and ideality factor (a) , a MATLAB/Simscape simulation model is developed by connecting 36 solar cell blocks in series to form 40W panel. Then two 40W panels are connected in parallel to form an 80W solar array. The developed MATLAB/Simscape simulation model of 80W solar array is shown in Figure 4.

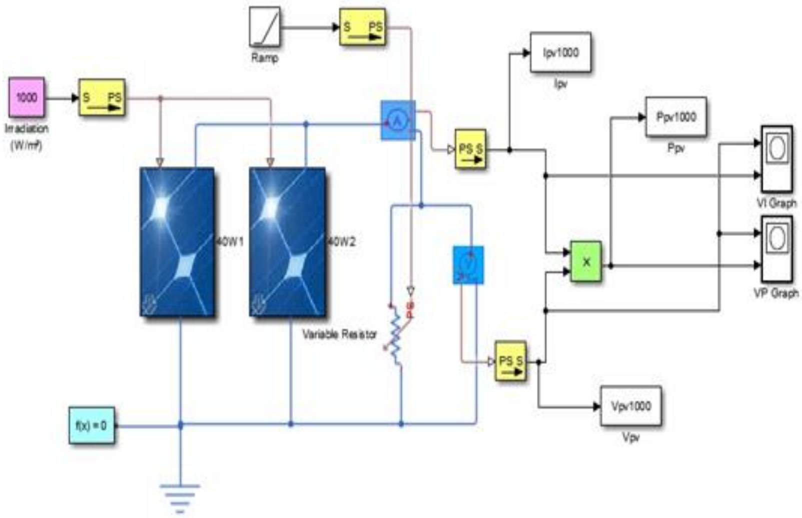

Figure 4 MATLAB/Simscape model of 80W solar array

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Solar Array model Evaluation

The MATLAB/Simscape model is simulated for 2 sec and its V-I and P-V characteristics are obtained for standard test condition i.e., irradiance at 1000 W/m^2, temperature at 25^{o}C. Efficiency of the model is 99.97%. According to the parameters provided by manufacturer, theoretical fill factor and efficiency of panel are calculated as Fill Factor= P_{max} / (I_{SC} V_{OC}) = 0.745 and H = P_{max}/ P_{in} ; Pin = G. A_c = 20%. Practical efficiency is always 20% - 40% which is less than theoretical efficiency. From literature review it is found that the efficiency polycrystalline solar cell is around 18% [9]. Data set consists of 329 patterns of PV insolation (G), temperature (T), PV optimum voltage (V_{optpv}), PV current (I_{optpv}) and the corresponding maximum power (P_{optpv}) of an 80W solar array with 30Ω resistive load is obtained through MATLAB simulation model. Simulation observations are tabulated in Table 3.

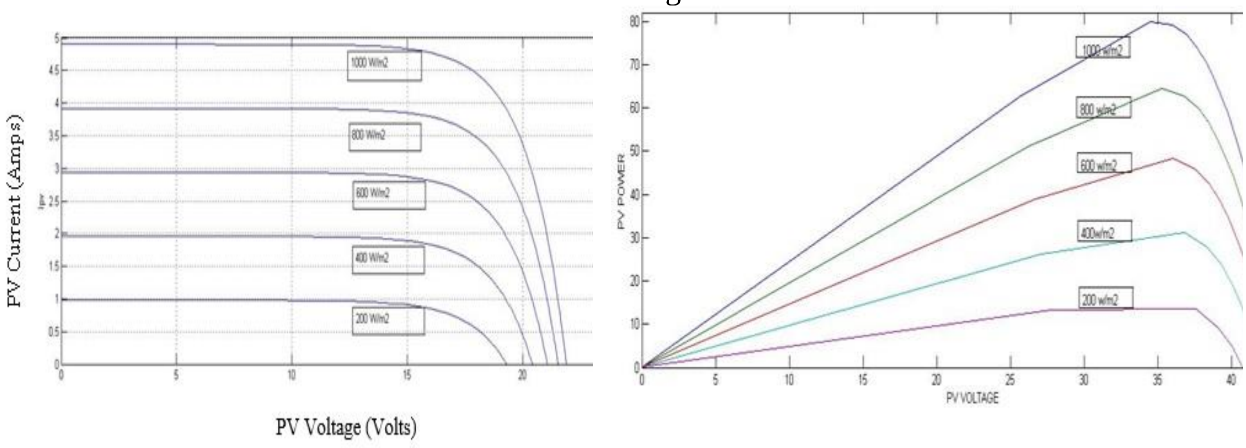
Table 3 Simulation results obtained from simscape model

Test Point	Temperature (^{o}C)	Irradiance (W/m^2)	Simulation V_{pv} output (Volts)	Simulation I_{pv} output (Amps)	simulation P_{pv} output (Watts)
1	25	1000	17.40	4.60	17.31
2	10	260	4.58	1.21	4.61
3	15.7	420	7.54	1.99	7.24
4	20.7	332	6.60	1.60	6.57
5	4.8	100	1.85	0.49	1.89
6	30.3	681	12.74	3.37	12.33
7	35.6	430	8.22	2.17	8.01
8	40.4	698	13.99	3.70	13.54
9	45.3	739	14.10	3.73	14.01
10	50	250	4.99	1.32	4.23
11	50.5	900	16.07	4.25	15.88

The dependency of solar panel to insolation and temperature are shown in Figure 5a and 5b.

Effect of Solar Irradiance Variations

Solar array V-I and P-V characteristics are obtained for various irradiance levels such as 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2 and 1000 W/m^2. However, the temperature is fixed as constant at 25^{o}C. The characteristics are shown in Figure 5a and 5b.



(a) (b)

Figure 5 PV array characteristics for various irradiation levels (a) V-I characteristics and (b) V-P characteristics

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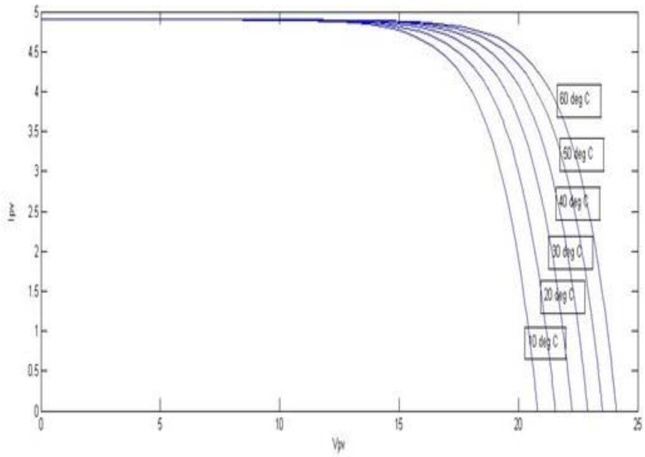
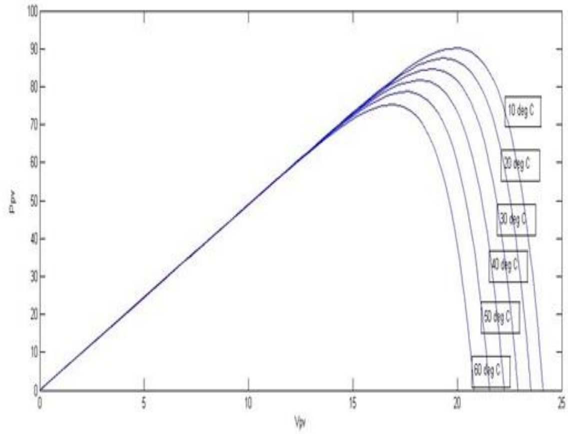
From the V-I and P-V characteristics, it is observed that for the same temperature level, the current I_{pv} is increased significantly with increasing in irradiation level, but the voltage V_{pv} has not changed much. Hence, the MPP meets the change. When irradiation increases, maximum output current I_{mpp} increased and the maximum output voltage V_{mpp} changed small. The output power of PV modules strongly depends on the solar irradiance and it is increased almost linearly with the increase in solar irradiance.

Effect of Temperature Variations

Solar array V-I and P-V characteristics are obtained for various temperature levels from 10ºC to 60℃ with step increase of 10℃ are shown in Figure 6a and 6b. However, irradiance id fixed as constant at 1000 W/m^2.





(a) **(b)**

Figure 6 PV array characteristics for various Temperature levels (a) V-I characteristics and (b) V-P characteristics

From the characteristics it is observed that the temperature changes mainly affect the PV voltage. When the temperature increases, voltage drops sharply for the temperature increase from 25℃ to 50℃.

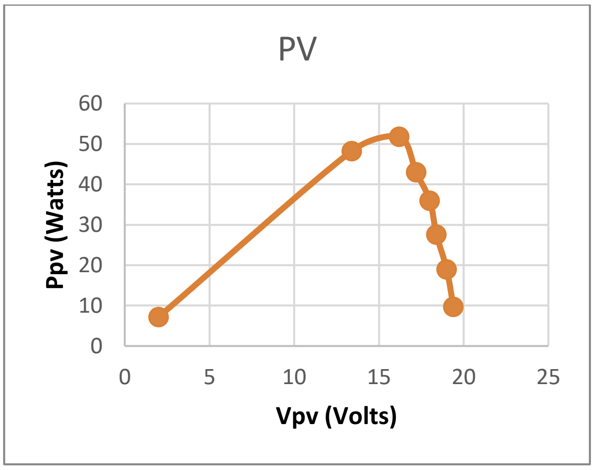
4. Evaluation of Solar Array V-I and P-V Characteristics in Hardware

In order to validate the developed model, experiments have been done on real solar array, which is shown in Figure 7. The results obtained from experimental setups are listed in Table 4 and the characteristics are shown in Figure 8. The experimental results which are obtained on a sunny day exhibited a good agreement with the simulated characteristics. Thus, it laid the foundation for further research in MPPT techniques in solar PV applications.

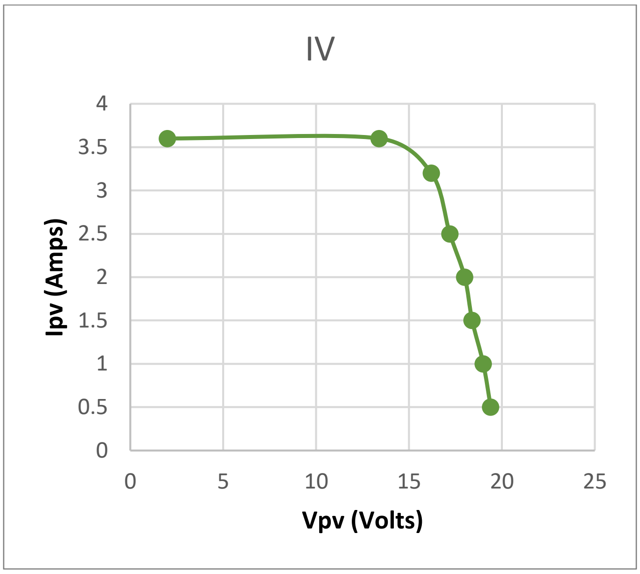
Figure 7 Solar array hardware setup

Table 4 Real time solar array parameter variations

Time (Hr)	Solar Irradiation (W/m^2)	Panel Temperature (°C)	Current (Amps)	Voltage (Volts)	Power (Watts)	Resistance (Ohms)
10:00	620	46	0.5	19.4	9.7	38.8
			1	18.6	18.6	18.6
			1.5	17.8	26.7	11.86
			2	16.2	32.4	8.1
			2.5	5	12.5	2
11:00	988	50.8	0.5	19.4	9.7	38.8
			1	19	19	19
			1.5	18.4	27.6	12.26
			2.5	17.2	43	6.88
			3.2	16.2	51.84	5.06
			3.6	13.4	48.24	3.72
12:00	1135	54.8	0.5	19.8	9.9	39.6
			1	19	19	19
			1.5	18.6	27.9	12.4
			2	18	36	9
			2.5	17.6	44	7.04
			4	7	28	1.75
14:00	1018	54	0.5	19.6	9.8	39.2
			1	19	19	19
			1.5	18.4	27.6	12.26
			2.5	17	42.5	6.8
			3.1	16	49.6	5.16
15:00	795	48.3	0.5	19.8	9.9	39.6
			1	19	19	19
			1.5	18.3	27.45	12.2
			2	17.6	35.2	8.8
			2.5	16.6	41.5	6.64
			3	10.4	31.2	3.46



(a)



(b)

Figure 8. a) Solar V-P sample characteristic with respect to Table 4 :14 Hrs b) V-I sample characteristic with respect to Table 4 :14 Hrs

Conclusion

This chapter proposed the physical modelling and its evaluation of an 80W solar array under various irradiance and temperature levels. Physical modelling in MATLAB/Simscape software was proposed and the obtained model had an efficiency of 99.97%. Newton-Raphson parameter extraction technique and its implementation through MATLAB m-file coding was proposed to find the unknown parameters which is generally not given in manufacturer's data sheet for the benefit of solar PV users. The presented simulation and hardware evaluation results of solar PV array showed that when irradiation increases, maximum output current I_{mpp} increases and the maximum output voltage V_{mpp} will be changed by small amount and the rise in temperature affects the open circuit voltage V_{oc} at the same time it gives rise to the short circuit current I_{sc}.

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