Mathematical Modeling of Solar Photovoltaic System Using Matlab/Simulink

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Abstract- *Renewable energy is considered as next alternative to fossil fuels and nowadays, it attracts much attention in agriculture and environmental protection. Application of solar photovoltaic system is drying and dehydration of products, heating, irrigation, greenhouse and power generation etc. Temperature and sun radiation varies nonlinearly. Power generation varies with reference to radiation and temperature in photo-voltaic (PV) system. PV characteristic is nonlinear and PV cell is the basic unit for electricity generation. To get the characteristic response of PV, it aimed to develop a solar cell/panel model and array on a platform like MATLAB. In this paper, step by step procedure has been defined for modelling solar cell, module, and array models of the photovoltaic system. The PV array characteristic are simulated for different irradiance and temperature variation. The output characteristic of the reference model matches with simulated results. The output reduced when the solar irradiation reduced from 1000 to 200 W/m2. As the reference temperature increased, the output voltage increase, whereas the output current increases slightly. This model would be useful for check the effect of different parameters like series resistance, shunt resistance etc. It would also be useful for investigating the working parameters like temperature & radiation condition and different series and parallel combinations of panels. This modelling is useful in investigating the performance of solar arrays in different applications of solar power generation, as well as modelling provides a major role in the mounting of PV panels*

Keywords- Photovoltaic system, MATLAB, irradiance, solar arrays.

I. INTRODUCTION

So as to realize the influence of the solar energy the project starts to describe the energy situation nowadays. Energy is an issue that touches every person on the planet. At present in the world, especially in industrialized and emergent countries, energy has become vital for all the human beings. Accordingly the energy demand has been increasing dramatically in the last years.

Because of the greenhouse effect, environmental impact and the increasing cost of the fossil fuel-based energy sources, much more energy usage from renewable sources and more efficient utilization of conventional sources is becoming to be indispensable. The World Resource Institute estimates that 61.4% of global greenhouse emissions come from energy consumption. Thereby a solution that reduces these pollutants should include investment in the fields of renewable sources and energy efficiency in order to allow energy to play its role in the economy without endangering the environment. [1]
The increasing of the electricity price and the increasing of the environmental impact the world is suffering, solar energy may be considerably accepted one of the key solutions.

Solar energy is radiant light and heat coming from the solar radiation. It is a renewable source since the methods used to transform the solar energy into electricity don’t produce any smoke or pollutants. However since the power generated by this source comes from the sunlight, it cannot be used during the night, and even during some days when the weather is completely cloudy, rainy, snowy or another natural factors. Solar energy can mainly be divided in two mainly sources; it can be exploited through the solar thermal and solar photovoltaic (PV) routes for various applications. The research has been focused on photovoltaics within the solar energy.

Solar photovoltaic modules are manufactured by semiconductor materials and they turn the radiant energy coming from the sun into direct current and therefore, electricity. The competitiveness of this field is increasing; in 2013, for the first time in more than a decade, solar was over all other renewable energy technologies in the sense of new generating capacity installed with an increase of 29 percent compared with 2012. [2] .Worldwide total PV installations represented 1.8 GW in 2000 and 71.1 GW in 2011 with a growth rate of 44%. [3].

This has led to a situation where the electricity from solar panels costs as much or is even cheaper than electricity purchased from the grid is within reach.

Nonetheless, solar power generation has still some problems as follows: the conversion efficiency of solar cells is lower, and the output power of photovoltaic (PV) array has great relationship with irradiation and temperature.[4]

Regardless the problems described above, one of the most important and critical problems on the photovoltaics field is the shadowing effect. Shaded conditions is sometimes inevitable because some parts of the photovoltaic system receives less intensity of sunlight due to several factors such as clouds, the time of the day, the season of the year or even shadows from neighbouring objects.[5] When the light is falling on a solar cell, it behaves as the following formula (1.1), obtained from the Ideal Diode Law [6]:

$$I_L = I_2 - I_o\left[exp\left(\frac{qV}{aKT}\right) - 1\right] \quad (1.1)$$

Where IL is the light-generated current, I_2 is the current,I_0 is the current when no light is falling on the cell: it increases as T increases, and it increases as material quality increases, q is the charge on an electron k is Boltzmann's constant, T is absolute temperature, a is the ideality factor (between 1 and 2). It increases as the current decreases.

The characteristic curve represent all of the combinations of current and voltage at which the module or cell can be operated or loaded. Normally simple in shape, these curves actually provide the most complete measure of the health and capacity of a PV module or array, providing much more information than traditional electrical test methods [9]

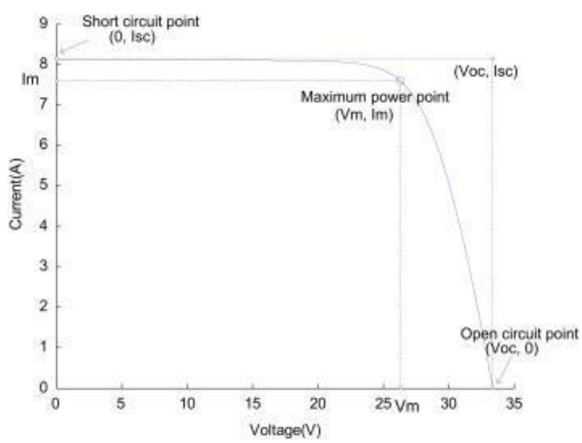

Fig. 1. Characteristic I-V curves of a solar c el l [10]

Here two different parameters have to be introduced:

- **Short circuit current Isc :** Is the maximum current, given when voltage is 0.
- **Open circuit voltage Voc:** Is the maximum voltage, given at zero current.

There is also a relevant point, MPP is the maximum power point, therefore the point where the product of Vmp*Imp is at its maximum value.

Another important parameter is the fill factor (FF) is the ratio between Pmax and Isc*Voc. It gives an information about the quality of the solar cell, if it increases so do the quality of the solar cell.

II. METHODOLOGY

The equivalent circuit of a PV cell is shown in Fig.2. The current source Iph represents the cell photocurrent. Rsh and Rs are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of Rsh is very large and that of Rs is very small, hence they may be neglected to simplify the analysis (Pandiarajan and Muthu 2011). Practically, PV cells are grouped in larger units called PV modules and these modules are connected in series or parallel to create PV arrays which are used to generate electricity in PV generation systems. The equivalent circuit for PV array is shown in Fig. 3. The voltage–current characteristic equation of a solar cell is provided as (Tu and Su 2008; Salmi et al. 2012): Module photo-current Iph: Here, Iph: photo-current (A); Isc: short circuit current (A) ; Ki: short-circuit current of cell at 25 °C and 1000 W/m^2;T: operating temperature (K); Ir: solar irradiation (W/m^2).Module reverse saturation current Irs:Here, q: electron charge, = 1.6 × 10−19C; Voc: open circuit voltage (V); Ns: number of cells connected in series; n: the ideality factor of the diode; k: Boltzmann's constant, = 1.3805 × 10−23 J/K.

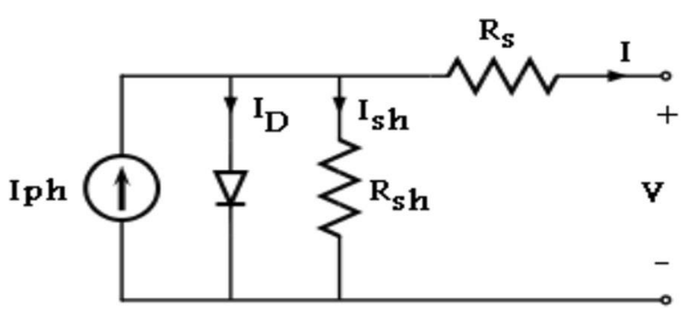

Fig. 2. PV cell equivalent circuit [19]

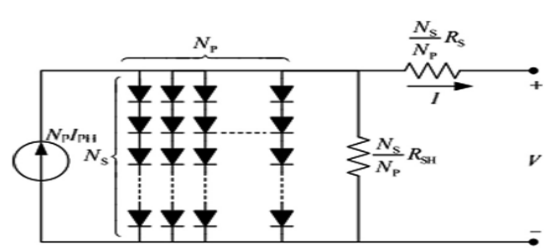

Fig. 3. Equivalent circuit of solar array[22]

The module saturation current I_0 varies with the cell temperature, which is given by:

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{q \times E_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \quad (2.1)$$

$$I = N_p \times I_{ph} - N_p \times I_0 \times \left[exp\frac{\frac{V}{N_S} + I \times R_S/N_p}{n \times V_t} - 1\right] - I_{sh} \quad (2.2)$$

with

$$V_t = \frac{K \times T}{q} \quad (2.3)$$

and

$$I_{sh} = \frac{V \times N_S/N_p + I \times R_S}{R_{sh}} \quad (2.4)$$

Here: Np: number of PV modules connected in parallel; Rs: series resistance (Ω); Rsh: shunt resistance (Ω);Vt: diode thermal voltage (V).

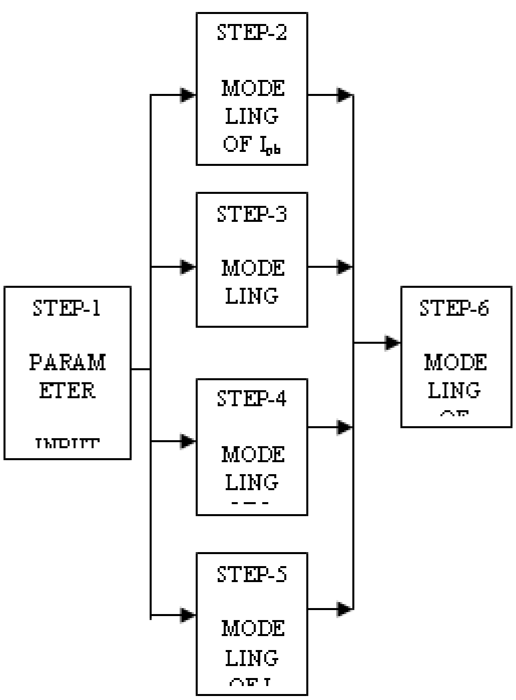

Fig. 4:Solar Cell modeling block

Reference model

The 400 W solar power array is taken as the reference module for simulation and the detailed parameters of array is given in Table 1.

Table 1 Electrical characteristics data of DS-400W PV array

NAME	Value
Rated power (Vmp)	400W
Voltage at maximum power (Vmp)	18V
Current at maximum power (Imp)	5.55A
Open circuit voltage (V_{OC})	21.6V
Short circuit current (I_{SC})	6.11A
Total number of cells in parallel (N_p)	36
Maximum system voltage	1
Range of operation temperature	1000

Step by step procedure for modeling of photovoltaic arrays with tags:

A mathematical model of PV array including fundamental components of diode, current source, series resistor and parallel resistor is modeled with Tags in Simulink environment (http://mathwork.com). The simulation of solar module is based on equations given in the section above and done in the following steps.

Step 1: Provide input parameters for modeling: Tr is reference temperature = 298.15 $^{\circ}$K; n is ideality factor = 1.2; k is Boltzmann constant = 1.3805×10^{-23} J/K; q is electron charge = 1.6 × 10^{-19}; I_{sc} is PV module short circuit current at 25 $^{\circ}$C and 1000 W/m^2 = 6.11 A; Voc is PV module open circuit voltage at 25 $^{\circ}$C and 1000 W/m^2 = 0.6 V; E_{g0} is the band gap energy for silicon = 1.1 eV. Rs is series resistor, normally the value of this one is very small = 0.008Ω; R_{sh} is shunt resistor, the value of this is so large = 1000 Ω .

Step 2 : Modelling of I_{ph}(Module photocurrent):Module photon-current is given in Eq. (2.5) and modeled as Fig.5 (I_{r0} = 1000 W/m^2). Initially, in system block, degree Celsius temperature(operating temperature) was converted into degree Kelvin and then given to subsystem. As per Eq.2.5, I_{ph} was photocurrent and modelled in MATLAB as shown below where its subsystem was also shown and all parameters were defined say I_{ph} (photo current), I_{sc} (short circuit current of module), K_i (Solar cell temperature coefficient of the short-circuit current (in °K or °C), T_i (operating temperature), Ir (solar irradiance). Modeling was shown in Fig.3.4.

$$I_{ph} = [I_{sc} + K_i(T_i - 273)] \times I_r/1000 \quad (2.5)$$

Step 3: Modelling of I_{sh} (Module shunt saturation current): Module shunt saturation current was modeled in MATLAB as shown in Fig. 6. .As per Eq.2.6, where and value were given for panel and array modeling and V was open circuit volt-age so it was same as Voc say 21.6 V and R_S and R_{sh} represent the series and parallel resistances of the cell. Modeling was very simple just using adder, multiplier and divider blocks its shows in equation (2.6)

$$I_{sh} = \frac{V\left(\frac{N_P}{N_S}\right)+I*R_S}{R_{sh}} \qquad (2.6)$$

Step 4: Modeling of I_{rs} (Module reverse saturation current): Module reverse saturation current was modelled in MATLAB as shown in Fig. 6 as per Eq.2.7 where different constants are taken as k: Boltzmann's constant 1.380658×10^{-23} J/K q: electron charge $1.60217733 \times 10^{-19}$ C etc.

$$I_{rs} = I_{sc} / \left[\exp\left(\frac{qV_{oc}}{N_s knT}\right) - 1\right] \qquad (2.7)$$

Step 5: Modeling of Io (Module saturation current): Modeling of module saturation current was modeled in MATLAB as shown in Fig.7 .

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{q \times E_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \qquad (2.8)$$

Modelling of saturation current was done as per Eq.3.8, whose parameters were Irs: Module reverse saturation current; T_R: Solar cell absolute reference temperature at STC, in K; T: absolute operating temperature of solar cell, in K; q:Electron charge, $1.60217733e^{-19}$ Cb; k Boltzmann's constant; $1.3806503 \times 10^{-23}$ J/K and the ideality factor Modified.

Step 6 : Modelling of I(Module output current):

The modelling of module output current is given in Fig. 9.Complete simulation model with step 1 to step 5 .Step 1 to step 4 was done and combine together in step 5 as per Eq.2.9 complete block schematic is shown in Fig. 3.8. The solar PV array includes six modules and each module has 36 solar cells connected in series. Therefore, the proposed model of solar PV array is given in Fig. 3.11.

$$I = N_p * I_{ph} - N_p * I_o * \left[exp\left(\frac{\frac{V}{N_s} + I \times R_S / N_p}{n \times V_t}\right) - 1\right] - I_{sh} \qquad (2.9)$$

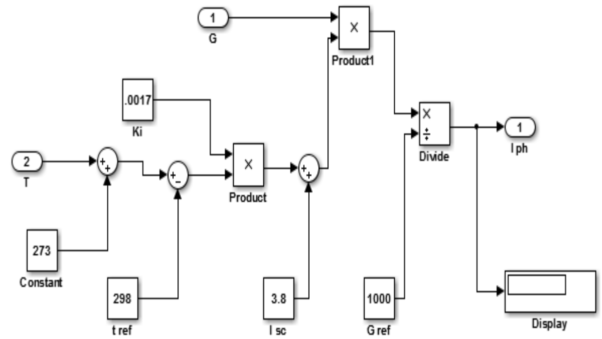

Fig. 5 Modeled circuit for Eq. (2.5)

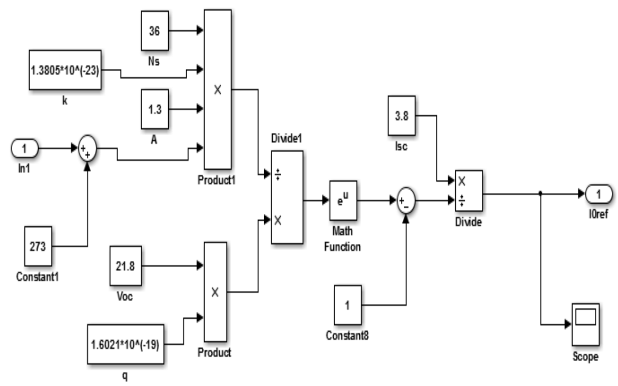

Fig. 6 Modeled circuit for Eq. (2.7)

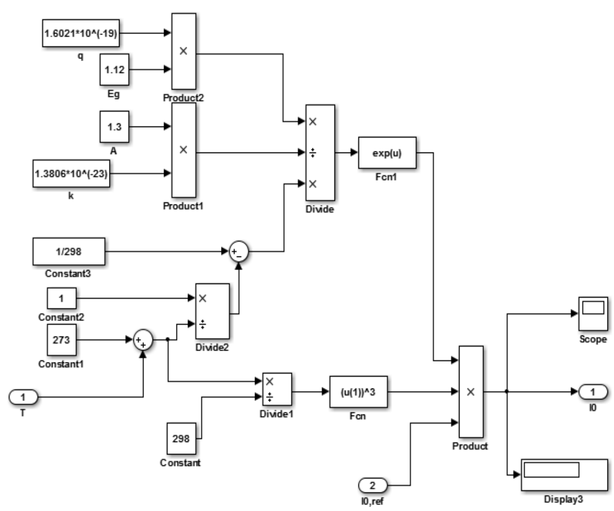

Fig. 7 Modeled circuit for Eq. (2.8)

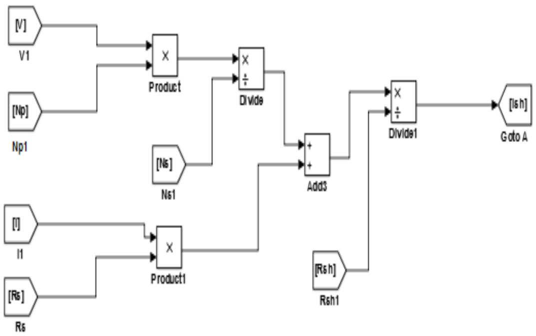

Fig. 8 Modeled circuit for Eq. (2.6)

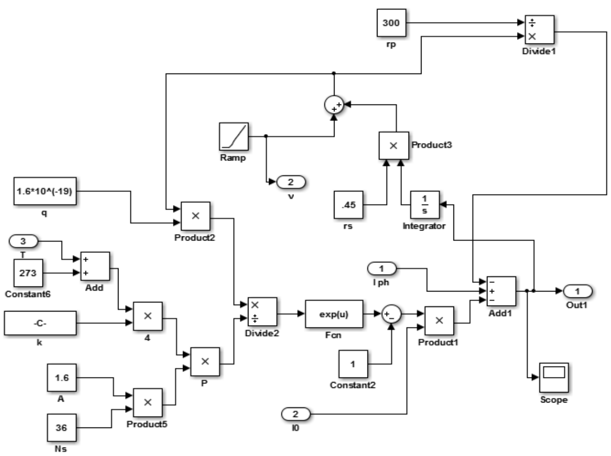

Fig. 9 Modeled circuit for Eq. (2.9)

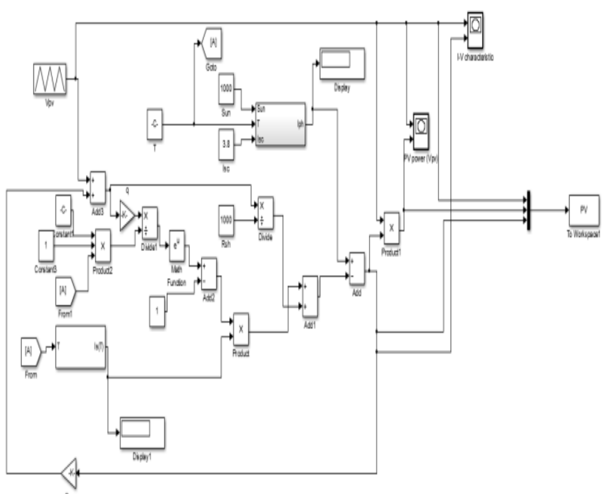

Fig. 10. Simulation model of solar PV cell

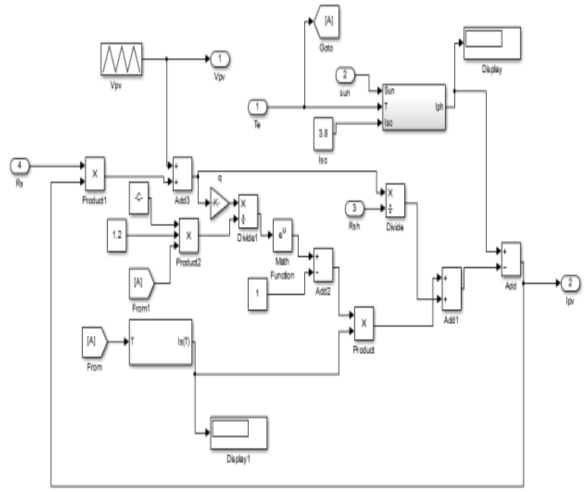

Fig. 11 Simulation model of solar PV module

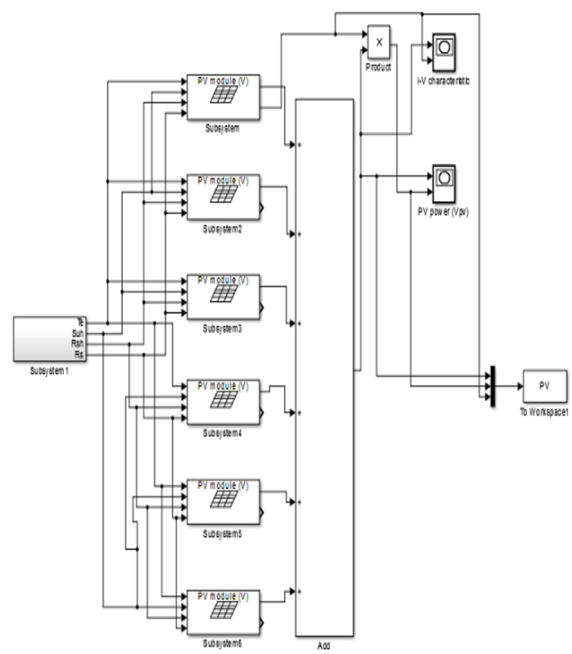

Fig. 12 Simulation model of solar PV Array

III. RESULTS AND DISCUSSION

(i) I–V and P–V characteristics for the PV array under variable temperature and fix irradiation are obtained as in Fig.13 and Fig.14. Here reference temperature variations are 5°C, 10°C, 15°C 20°C, 25°C at 1000W/m^2 irradiance. Here, the reference temperature varies from then output current increases as well as output power increases.

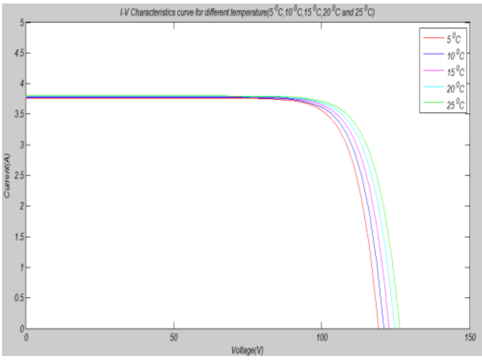

Fig. 13 I-V characteristic of solar PV system Modelling with different reference Temperature

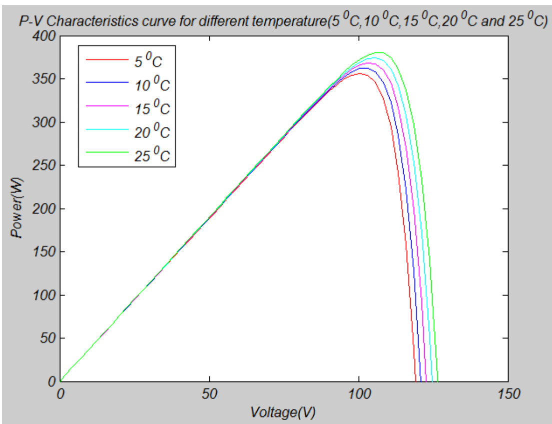

Fig. 14 P-V characteristic of solar PV system Modelling with different reference Temperature

(ii) I–V and P–V characteristics for PV array under varying irradiation of 200W/m^2, 400W/m^2, 600W/m^2, 800W/m^2, 1000W/m^2 with constant temperature say 25°C are given in Fig. 15 and Fig. 16. When the irradiation increases, the current and voltage output increase. This results in rise in power output in this operating condition.

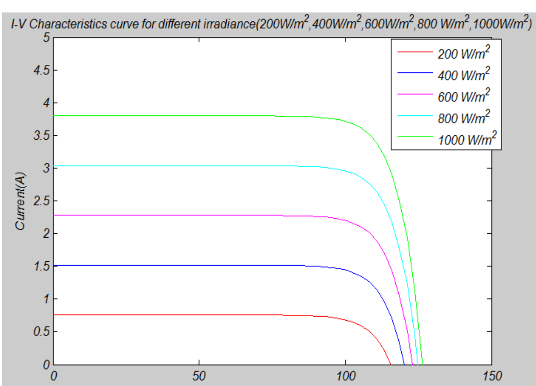

Fig. 15 I-V characteristic of solar PV system Modelling with different irradiance**.**

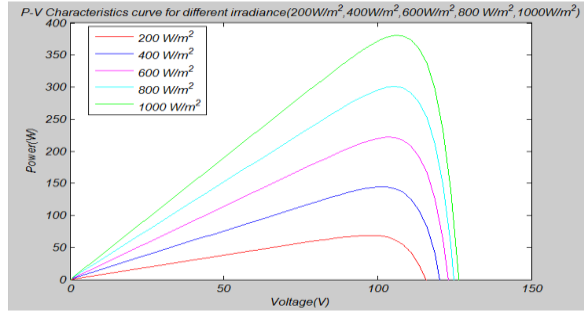

Fig. 16 P-V characteristics of solar PV system Modelling with different irradiance

(iii) I-V and P-V characteristics for different series resistance are shown in Fig. 17 & Fig. 18.When increase the series resistance then output power decreases.

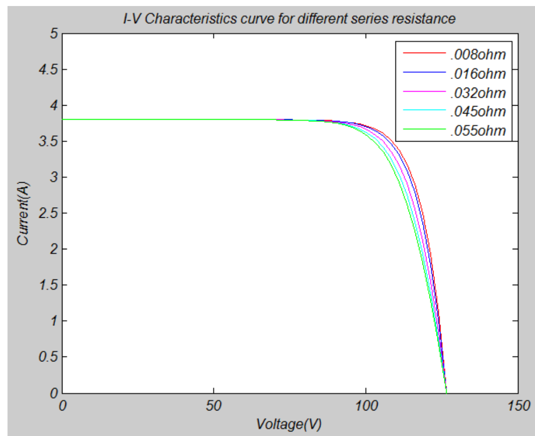

Fig. 17 I-V characteristics of solar PV system Modelling with different series resistance

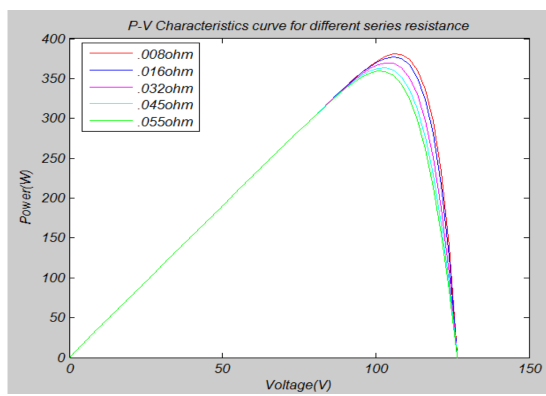

Fig. 18 P-V characteristics of solar PV system Modelling with different series resistance

(iv) I-V and P-V characteristics for different shunt resistance are shown in Fig. 19 & Fig. 20.When we increase the shunt resistance there is no effect come out in the output current and power. P–V characteristics under varying shunt/parallel resistance R_{sh}, constant temperature and irradiation are shown in Fig. 19.When R_{sh} varies between 1000 and 1 Ω, the current output, voltage and output power decreases.

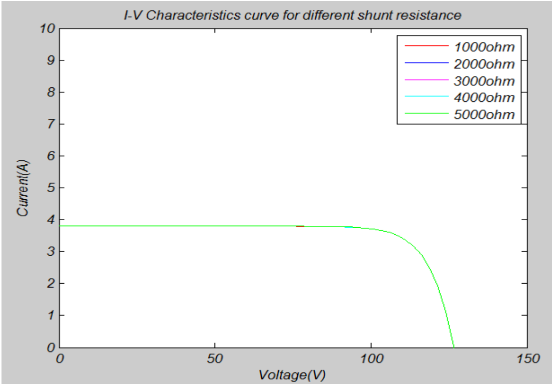

Fig. 19 I-V characteristics of solar PV system Modelling with different shunt resistance**.**

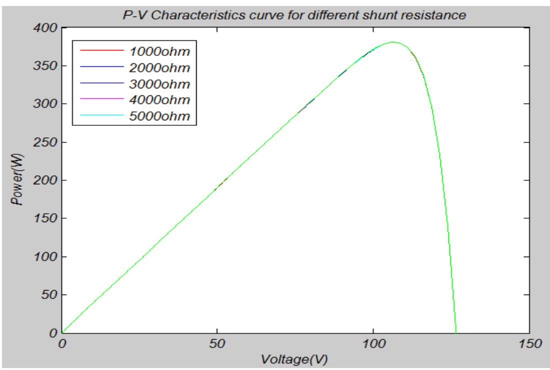

Fig. 20 P-V characteristics of solar PV system Modelling with different shunt resistance

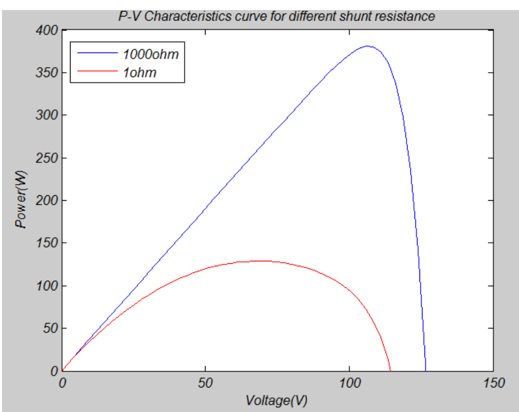

Fig. 21 P-V characteristics of solar PV system Modelling with 1000ohm and 1ohm shunt resistance

This MATLAB/Simulink model is a dynamic model for any solar array modelling. This modelling helps to understand the the I-V and P-V operating principles and tool for predicting the behaviour of PV array under any variable environmental condition as well as variable parameters like series resistance, shunt resistance, ideality factor, operating temperature etc.

IV. CONCLUSION

Stepwise procedure for modelling solar array in MATLAB with user-friendly stimulation tool is shown in each step, which will help further modelling the solar system and I-V & P-V characteristic. So that any system behaviour can be predicted for any number of cell, panel, or array under any variable of environmental condition like temperature, irradiance, series re-sistance, shunt resistance, etc. The present model is the dynamic model for further modelling solar PV systems using the maximum power point tracking technique and its performance analysis for power generation application in a solar PV system.

REFERENCES

[1] Esram T. &Chapman P.L.(2007), Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques. IEEE Transactions on Energy Conversion 22(2) 439-449 doi: 10.1109/TEC.2006.874230.

[2] Habbati B., Ramdani Y.& Moulay F. (2014) A detailed modeling of photovoltaic module using MATLAB , NRIAG Journal of Astronomy and Geophysics(3)53-61 http://dx.doi.org/10.1016/j.nrjag.2014.04.001

[3] Kyocera (2009). KC200GT High Efficiency Multi crystal Photovoltaic Module Datasheet. https://www.energy mat-ters.com.au /images/kyocera/KC200GT.pdf

[4] Marcelo G.M. (2016). Modelling and Control of Grid-connected Solar Photovoltaic Systems, Renewable Ener-gy - Utilisation and System Integration, Wenping Cao and Yihua Hu, Intech Open, http://dx.doi.org/10.5772/62578

[5] https://www.intechopen.com/chapters/50017

[6] Motan N., Abu-Khaizaran M. & Quraan M.(2018). Photo-voltaic array modelling and boost-converter controller-design for a 6kW grid-connected photovoltaic system - DC stage. IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe. 1-6, doi: 10.1109/EEEIC.20 18.8494003.

[7] Nguyen, X.H. & Nguyen, M.P. (2015). Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink. Environ Syst Res 4(24) https://doi.org/10.1186/s40068-015-0047-9

[8] Natarajan P. & Ranganath M. (2011). Development of power electronic circuit oriented model of photovoltaic module International Journal of Advanced Engineering Technology 2(4) 118-127.

[9] Tsai, Huan-Liang, Ci-Siang, Tu & Yi-Jie, Su. (2008). Development of generalized photovoltaic model using MATLAB/SIMULINK. Lecture Notes in Engineering and Computer Science. 2173.

[10] Tummuru N. R., Mishra M. K. & Srinivas S.(2015). Dynamic energy management of renewable grid integrated hybrid energy storage system. IEEE Transactions on industrial Electronics, (62)12, 7728-7737. doi: 10.1109/TIE.2015.2455063
[11] Umanand L. (2007). Photovoltaic System Design. CEDT-Indian Institute of Science, Banglore, NPTEL course material.
[12] Ibbini MS et al (2014) Simscape solar cells model analysis and design. In: Zaharim A, Sopian K, Bulucea A, Niola V, Skala V (eds) 8th International conference on renewable energy sources (RES' 14), 2nd International conference on environmental informatics (ENINF'14), Kuala Lumpur, Malaysia, 23–25 April 2014, WSEAS Press
[13] Jena C, Das A, Paniigrahi CK, Basu M (2014) Modelling and simulation of photovoltaic module with buck-boost converter. Int J Adv Eng NanoTechnol 1(3):4
[14] Mohammed SS (2011) Modeling and simulation of photovoltaic module using Matlab/Simulink. Int J Chem Environ Eng 2(5):6
[15] Pandiarajan N, Muthu R (2011) Mathematical modeling of photovoltaic module with Simulink. International Conference on Electrical Energy Systems (ICEES 2011), p 6
[16] Panwar S, Saini RP (2012) Development and simulation photovoltaic model using Matlab/Simulink and its parameter extraction. International conference on computing and control engineering (ICCCE 2012)
[17] Salmi T, Bouzguenda M, Gastli A, Masmoudi A (2012) Matlab/simulink based modelling of solar photovoltaic cell. Int J Renew Energy Res 2(2):6
[18] Savita Nema RKN, Agnihotri Gayatri (2010) Matlab/Simulink based study of photovoltaic cells/modules/arrays and their experimental verification. IntJ Energy Environ 1(3):14
[19] Sudeepika P, Khan GMG (2014) Analysis of mathematical model of PV cell module in Matlab/Simulink environment. Int J Adv Res Electr Electr Instrum Eng 3(3):7
[20] Tu H-LT, Su Y-J (2008) Development of generalized photovoltaic model using MATLAB/SIMULINK. Proc World Congr Eng Comput Sci 2008:6
[21] Varshney A, Tariq A (2014) Simulink model of solar array for photovoltaic power generation system. Int J Electr Electr Eng 7(2):8
[22] Venkateswarlu G, Raju PS (2013) Simscape model of photovoltaic cell. Int J Adv Res Electr Electr Instrum Eng 2(5):7