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Modeling of Photovoltaic Module Based On Sandia Model For Photovoltaic Systems

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Abstract: This paper presents different methods for modeling a PV system based on Sandia model . The VI characteristics for PV module taking temperature and irradiance as constraints is presented in this paper . The VI characteristics for a PV system, depends not only on the material used but also on the weather conditions and the time at which the cell is exposed to the solar irradiance. These factors makes the modeling of PV module extremely non linear. To solve these non linear equations both the analytical and the empirical methods of modeling are used .

Key Words: photovoltaic module, irradiance, photovoltaic systems, performance parameters.

I. INTRODUCTION

The energy crisis in today's world is increasing exponentially due to deficient conventional energy resources . With the growing population , the energy demand has been increased many folds but the generation is limited due crisis of energy resources. This condition diverted the power producers towards distributed generation[1] , by utilizing the non conventional resources ,which are area specific. With the kind of abundance on earth, solar energy is growingly being popular in the distributed generation [2]

With the recent development in the power electronics and technologies in the field of energy storage systems ,the PV systems has attracted the generators. The installed capacity of PV systems is increasing exponentially. in spite of its high cost of generation , low efficiency and uneven distribution of solar radiations [3] . Solar insolation, cell temperature & cell output voltage are the crucial factors which effect the VI characteristics of PV module . The VI characteristics of a PV module can be explained by fig.1.1 The PV characteristics are plotted by using three classic parameters[4]:

(1) Short Circuit Current (I_{sc}): This current flows through the external circuit when both cell terminals are shorted.

(2) Open circuit voltage (V_{oc}): This is the potential developed across the cell when external resistance is very high.

(3) Maximum power (P_{max}): This power is obtained by the area of largest rectangle under the PV characteristics. By fig.1. we can depict that the area corresponding to the shaded rectangle in the characteristics shows the maximum power. The values of current & voltage for maximum power output can be seen as I_{mp} & V_{mp} respectively.

(4) Fill Factor (FF): This is the number which characterizes the cell. It is the ratio of Area B to Area A .

$$FF = \frac{Area\ B}{Area\ A} \quad (1)$$

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} \quad (2)$$

Thus we can easily depict that :

$$V_{oc} I_{sc} \times FF = V_{mp} I_{mp} = P_{max} \quad (3)$$

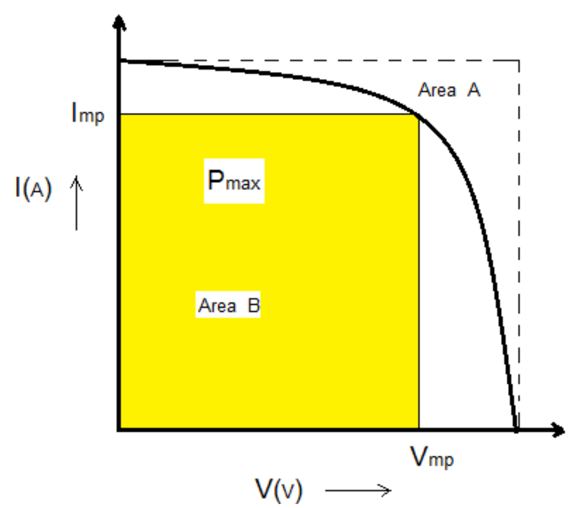

Fig.1.1 General VI characteristics of PV module

The photovoltaic conversion efficiency[5] of the solar cell including the limiting factors is given by eqn.(4)

$$\eta = \frac{\int_0^{\lambda_G} \phi(\lambda)\frac{hc}{\lambda}d\lambda}{\int_0^{\infty} \phi(\lambda)\frac{hc}{\lambda}d\lambda} \frac{E_G \int_0^{\lambda_G} \phi(\lambda)d\lambda}{\int_0^{\lambda_G} \phi(\lambda)\frac{hc}{\lambda}d\lambda} (1-R)QE_{opt}\eta_G QE_{el}\frac{A_f}{A_{tot}}\frac{qV_{oc}}{E_G}FF \quad (4)$$

In this equation:

(i) $\frac{\int_0^{\lambda_G} \phi(\lambda)\frac{hc}{\lambda}d\lambda}{\int_0^{\infty} \phi(\lambda)\frac{hc}{\lambda}d\lambda}$ is the actual power absorbed by the cell corresponding to the wavelength(λ_G) of the photons that are absorbed .This can be written as P_A.

(ii) $\frac{E_G \int_0^{\lambda_G} \phi(\lambda)d\lambda}{\int_0^{\lambda_G} \phi(\lambda)\frac{hc}{\lambda}d\lambda}$ is the actual power of the photons utilized to generate the electron hole pair for conduction .This can be written as P_U

(iii) $(1-R)QE_{opt}\eta_G QE_{el}$ corresponds to the efficiency of the solar cell after considering the reflection & collection losses. This can be written as $Q_C(\lambda)$.

(iv) $\frac{A_f}{A_{tot}}$ is the coverage factor.

(v) $\frac{qV_{oc}}{E_G}$ is the voltage factor .

II . SANDIA MODEL OF PV MODULE

This model developed by Sandia Laboratories[5] , [6] gives two more points on the PV characteristics apart from the traditional I_{sc} and V_{oc} points. With the help of these points the equations developed, not only gives the performance of individual cells but also describes the properties of series and parallel combinations of the cells. Sandia laboratories gave two additional points on PV characteristics which can be seen in fig 2

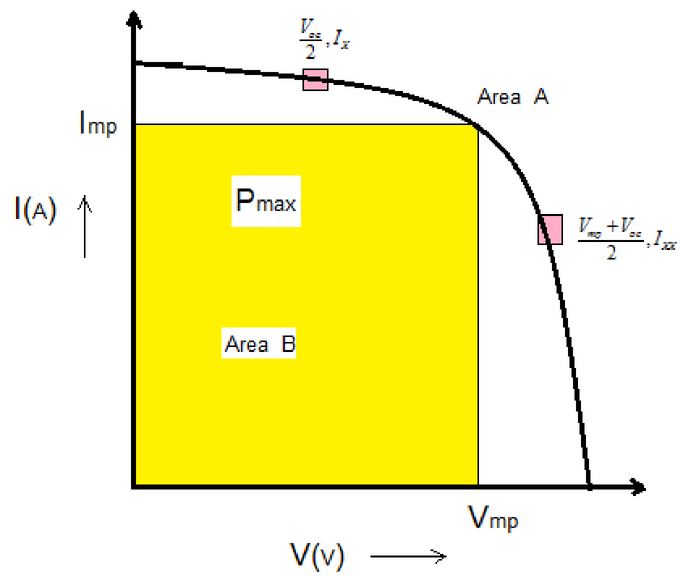

Fig.2.1 Points of Sandia Model

In the characteristic :

I_{XX} is the current corresponding to $\frac{V_{oc}}{2}$

I_X is the current at corresponding to the module voltage $\frac{V_{mp}+V_{oc}}{2}$.

The Sandia model equations can be given by:

$$I_{sc} = I_{sco}f_1(AM_a)\left\{\frac{E_b f_2(AOI) + f_d E_{diff}}{E_0}\right\}\left\{1+\alpha_{I_{sc}}(T_c - T_0)\right\} \quad (5)$$

$$I_{mp} = I_{mpo}\left\{C_0 E_e + C_1 E_e^2\right\}\left\{1+\alpha_{I_{mp}}(T_c - T_0)\right\} \quad (6)$$

$$V_{oc} = V_{oco} + N_s \delta T_c In\left(E_e\right) + \beta V_{oc}(E_e)(T_c - T_0) \tag{7}$$

$$V_{mp} = V_{mpo} + C_2 N_s \delta T_c In(E_e) + C_3 N_s \left\{\delta T_c In(E_e)\right\}^2 + \beta_{V_{mp}}\left(T_c - T_0\right) \tag{8}$$

$$P_{mp} = I_{mp} V_{mp} \tag{9}$$

$$FF = \frac{P_{mp}}{V_{oc} I_{sc}} \tag{10}$$

$$I_X = I_{Xo}\left\{C_4 E_e + C_5 E_e^2\right\}\left\{1 + \alpha_{I_{sc}}\left(T_c - T_0\right)\right\} \tag{11}$$

$$I_{XX} = I_{XXo}\left\{C_6 E_e + C_7 E_e^2\right\}\left\{1 + \alpha_{I_{mp}}\left(T_c - T_0\right)\right\} \tag{12}$$

III. MODELLING OF PHOTOVOLTAIC MODULE

The modeling of any photovoltaic module can be divided into three basic categories[7]:

1. In this category the modeling can be done by the knowledge of basic physical principle that are experimented and tested. No experimental set up is required in this case.

2. In this type of modeling the physical structure is known and the parameters are to be calculated from the data given and the equations defined for a particular module[8].

3. This type the modeling is done with the help of complex neural networks . exclusively using the experimental data.

In general either two diode model (double exponential model) or single diode model is used for the modeling of PV module. The two experimental models used are shown in fig.3.1 & fig.3.2.

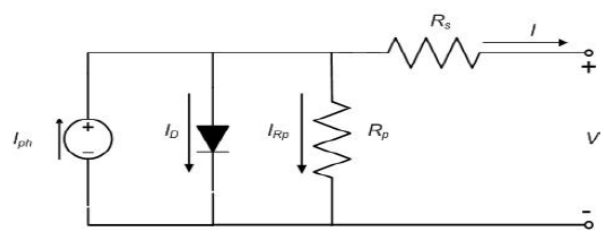

Fig.3.1 Single diode model

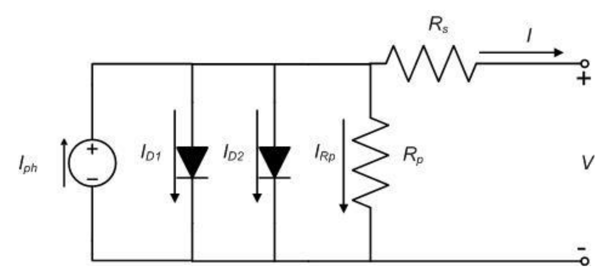

fig.3.2. Double diode model

In this paper type two modelling is discussed i.e. knowing the physical structure, the parameters are calculated by the data provided by the manufacturer and the equations derived for the PV module.

The equations for current can be given for both the models as[8]:

For single diode model:

$$I = I_{ph} - I_0\left\{\exp\left[\frac{q(V + IR_s)}{AkT}\right] - 1\right\} - \frac{V + IR_s}{R_p} \tag{13}$$

For double diode model

$$I = I_{ph} - I_{s1}\left\{\exp\left[\frac{q(V+IR_s)}{kT}\right]-1\right\} - I_{s2}\left\{\exp\left[\frac{q(V+IR_s)}{AkT}\right]-1\right\} - \frac{V+IR_s}{R_p} \quad (14)$$

Where,

I_0- dark saturation current

I_{ph}- photogenerated current

I_{s1}-saturation current due to diffusion

I_{s2}- saturation current due to recombination in the space charge layer.

I_{Rp}- current flowing in the shunt resisitance

R_s- cell series resistance

R_p-cell shunt resistance

A-diode quality factor

q-dielectric charge

k-boltzman constant, ,1.38 x 10^{-23} J/K

T-the ambient temperature in Kelvin

The three crucial points on PV characteristic curve are I_{sc}, V_{oc} & the points corresponding to maximum power i.e. V_{mp} & I_{mp}.

Now at open circuit point on VI curve $V = V_{oc}$ & $I = 0$, substituting these values in equation (3.1), we see:

$$I_{sc} = I_{ph} - I_0\left\{\exp\left[\frac{qI_{sc}R_s}{AkT}\right]-1\right\} - \frac{I_{sc}R_s}{R_p} \quad (15)$$

Similarly at short circuit point , $I = I_{sc}$ & $V = 0$, eqn (13) become:

$$I_{sc} = I_{ph} - I_0\left\{\exp\left[\frac{qI_{sc}R_s}{AkT}\right]-1\right\} - \frac{I_{sc}R_s}{R_p} \quad (16)$$

And at maximum power point i.e. at $V = V_{mpp}$ & $I = I_{mpp}$

$$I_{mpp} = I_{ph} - I_0\left\{\exp\left[\frac{q\left(V_{mpp}+I_{mpp}R_s\right)}{AkT}\right]-1\right\} - \frac{V_{mpp}+I_{mpp}R_s}{R_p} \quad (17)$$

Hence we can write:

$$-\frac{I_{mpp}}{V_{mpp}} = -I_0\left\{\frac{q}{Akt}\left(1-\frac{I_{mpp}}{V_{mpp}}R_s\right)\exp\left[\frac{q\left(V_{mpp}+I_{mpp}R_s\right)}{}\right]\right\}-\frac{1}{R_p}\left[1-\left(\frac{I_{mpp}}{V_{mpp}}\right)R_s\right] \quad (18)$$

Eqn no. 13 to 18 helps to calculate the values of five parameters i.e. $I_{ph}, I_{o,} A, R_s \,\&\, R_p$. On the other hand the values of $V_{oc}, I_{sc}, V_{mpp}, I_{mpp}, \left.\frac{dI}{dV}\right|_{V=0} \,\&\, \left.\frac{dI}{dV}\right|_{I=0}$ can be obtained by any numerical technique such as the NR method. By applying the NR method the elements of Jacobian matrix are calculated and can be summarized as below :

$$J(1,1)=1 \;;$$
$$J(1,2)=-\exp\left(\frac{qV_{oc}}{AkT}\right)+1$$
$$J(1,3)=-\frac{qI_0V_{oc}\exp\left(\frac{qV_{oc}}{AkT}\right)}{A^2kT}$$
$$J(1,4)=0$$
$$J(1,5)=-\frac{V_{oc}}{R_p^2} \quad (19)$$

Similarly other Jacobian elements are calculated:

$$J(2,1)=1$$
$$J(2,2)=-\exp\left(\frac{qV_{oc}}{AkT}\right)+1$$
$$J(2,3)=\frac{qI_0I_{sc}R_s\exp\left(\frac{qI_{sc}R_s}{AkT}\right)}{A^2kT}$$
$$J(2,4)=-\frac{qI_0I_{sc}\exp\left(\frac{qI_{sc}R_s}{AkT}\right)}{AkT}-\frac{I_{sc}}{R_p}$$
$$J(2,5)=\frac{I_{sc}}{R_p^2} \quad (20)$$
$$J(3,1)=0$$
$$J(3,2)=-\frac{q(1-\frac{R_s}{R_{so}})\exp\left(\frac{qV_{oc}}{AkT}\right)}{AkT}$$
$$J(3,3)=\frac{qI_0(R_{so}-R_s)\exp\left(\frac{qV_{oc}}{AkT}\right)(AkT+qV_{oc}}{A^3k^2T^2R_{so}}$$

$$J(3,4)=\frac{qI_0(R_{so}-R_s)\exp\left(\frac{qV_{oc}}{AkT}\right)}{AkTR_{so}}+\frac{1}{R_pR_{so}}$$

$$J(3,5)=\frac{1-\frac{R_s}{R_{so}}}{R_p^2} \tag{21}$$

$$J(4,1)=0$$

$$J(4,2)=-\frac{q(1-\frac{R_s}{R_{so}})\exp\left(\frac{qI_{sc}R_s}{AkT}\right)}{AkT}$$

$$J(4,3)=\frac{qI_0(R_{sho}-R_s)\exp\left(\frac{qI_{sc}R_s}{AkT}\right)(AkT+qI_{sc}R_s}{A^3k^2T^2R_{sho}}$$

$$J(4,4)=\frac{qI_0(R_{sho}-R_s)\exp\left(\frac{qI_{sc}R_s}{AkT}\right)}{AkTR_{sho}}-\frac{q^2I_0(1-\frac{R_s}{R_{sho}})I_{sc}\exp\left[\frac{qI_{sc}R_s}{AkT}\right]}{A^2k^2T^2}+\frac{1}{R_pR_{sho}}$$

$$J(4,5)=\frac{R_{sho}-R_s}{R_p^2R_{sho}} \tag{22}$$

$$J(5,1)=0$$

$$J(5,2)=-\frac{q(1-\frac{I_{mpp}}{V_{mpp}})\exp\left(\frac{q(V_{mp}+I_{mpp}R_s)}{AkT}\right)}{AkT}$$

$$J(5,3)=\frac{(V_{mpp}-I_{mpp}R_s)[AkT+q(V_{mpp}+I_{mpp}R_s)]qI_0\exp\left(\frac{q(V_{mp}+I_{mpp}R_s)}{AkT}\right)}{A^3k^2T^2R_{sho}}$$

$$J(5,4)=\frac{qI_0I_{mp}\exp\left(\frac{q(V_{mp}+I_{mpp}R_s)}{AkT}\right)}{AkTR_{sho}}-\frac{q^2I_0(1-\frac{I_{mpp}R_s}{V_{mpp}})\,\mathrm{I}_{mp}\exp\left(\frac{q(V_{mp}+I_{mpp}R_s)}{AkT}\right)}{A^2k^2T^2}+\frac{I_{mp}}{R_pV_{mp}}$$

$$J(5,5)=\frac{1-\frac{I_{mpp}R_s}{V_{mpp}}}{R_p^2} \tag{23}$$

The Jacobian elements are evaluated in MATLAB by using the Symbolic toolbox and numerical solution are obtained by using the optimization toolbox.

IV. SIMULATION & RESULTS

1) The first characteristics fig.4.1 depicts the VI characteristics of the PV module at a different irradiation in the multiples of 1000W/m^2 (1 sun) and at constant temprature (25^oC). These characteristics shows that with the increase of irradiation the open circuit voltage increases. The relation between the irradiance and the short circuit current is linear.

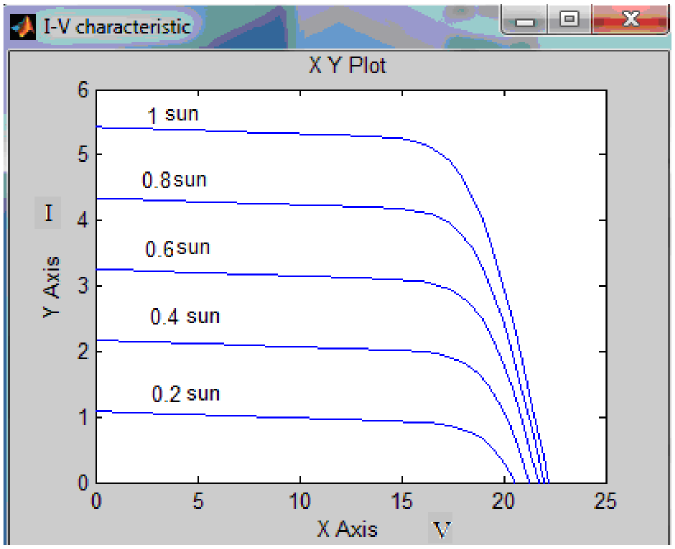

Fig.4.1 VI characteristics of PV module at different irradiation &constant temprature ($25^{o}C$).

2) This characterictrics depicts the variation of power output of the PV module at constant temprature ($25^{o}C$). but at different irradiations in the fractional multiples of $1000W/m^2$. $1000W/m^2$ equals 1 sun. $800W/m^2$=0.8 sun , $600W/m^2$=0.6 sun , $400W/m^2$=0.4 sun , $200W/m^2$=0.2 sun.

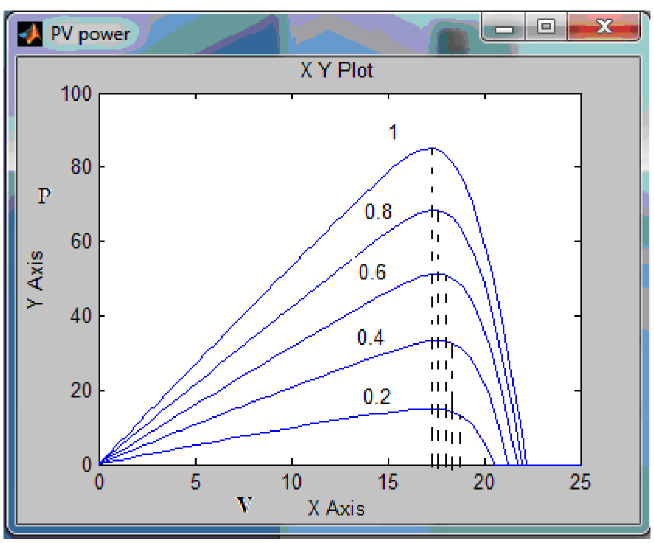

Fig.4.2 PV characteristics depicting the variation of power and voltage with irradiance.

V.CONCLUSION

Approach to the PV modelling have been presented. In this paper the electrical parameters are extracted from the manufacturers datasheet and the Sandia database. This paper contributes the calculation of accurate values of the parameters using the Newton Raphson method We have seen that from the Sandia database we can extract much more information as compared to the manufacturers database/specification Independent analytical equations for the PV module BPMSX60 & BPMSX64 are derived with the help of Sandia Model Points.The electrical parameters are extracted successfully from the sandia Model and the corresponding characteristics are plotted.

VI. FUTURE SCOPE

For the modelling of non linear equations of PV module ,some more advanced features must be incorporated in the MATLAB so that the whole PV power system can be modelled taking all the subsystems constituting it.

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APPENDIX-A

1.DATA SHEETS FOR BPMSXS60 & BPMSX 64

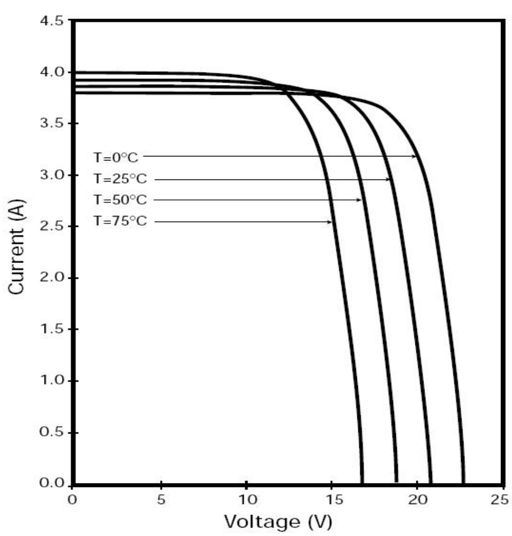
Electrical Characteristics[1]

	BP MSX 60	BP MSX 64[4]
Maximum power (P_{max})[2]	60W	64W
Voltage at P_{max} (V_{mp})	17.1V	17.5V
Current at P_{max} (I_{mp})	3.5A	3.66A
Minimum P_{max}	58W	62W
Short-circuit current (I_{sc})	3.8A	4.0A
Open-circuit voltage (V_{oc})	21.1V	21.3V
Temperature coefficient of I_{sc}	(0.065±0.015)%/°C	
Temperature coefficient of V_{oc}	-(80±10)mV/°C	
Temperature coefficient of power	-(0.5±0.05)%/°C	
NOCT[3]	47±2°C	
Maximum system voltage	600V (U.S. NEC rating) 1000V (TÜV Rheinland rating)	
Maximum series fuse rating	20A	

Notes

1. These data represent the performance of typical MSX 60 and MSX 64 modules as measured at their output terminals, and do not include the effect of such additional equipment as diodes or cables. The data are based on measurements made in accordance with ASTM E1036 corrected to SRC (Standard Reporting Conditions, also known as STC or Standard Test Conditions), which are:
   - illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5 (ASTM E892 global spectral irradiance);
   - cell temperature of 25°C.
2. During the stabilization process which occurs during the first few months of deployment, module power may decrease approximately 3% from typical P_{max}.
3. The cells in an illuminated module operate hotter than the ambient temperature. NOCT (Nominal Operating Cell Temperature) is an indicator of this temperature differential, and is the cell temperature under Standard Operating Conditions: ambient temperature of 20°C, solar irradiation of 0.8 kW/m², and wind speed of 1 m/s.
4. The power of solar cells varies in the normal course of production; the MSX 64 is assembled in limited quantities using cells of slightly higher power than the MSX 60.

MSX 60 I-V Curves



MSX 64 I-V Curves