Analysis of mathematical equations to extract the five parameter of Single diode model using the PV module datasheet of Photovoltaic Cell.

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Abstract: Renewable energy is the energy that is collected from the renewable sources which are naturally and replenished on a human time scale. Sunlight is the important sources of energy which can be used to provide energy in the important area such as electricity generation, conversion of solar energy into the electricity etc. But the Solar cells have a high degree of non-linearity and they possess parameter which must be accurately designed. This paper is the detailed study of the Single diode model of the PV cell with mathematical equations.These equations are used to extract the unknown parameter of the model with example of the datasheet of TSM-290-PA14.

I. INTRODUCTION

A solar cell is an electronic device which directly converts sunlight into electricity. Light shining on the solar cell produces both a current and a voltage to generate electric power. This process requires firstly, a material in which the absorption of light raises an electron to a higher energy state, and secondly, the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell. A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a *p-n* junction.[21]

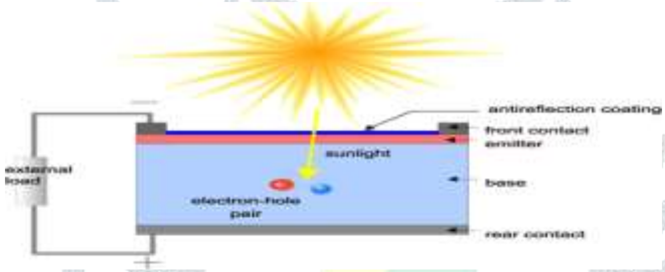

Figure 1: Schematic diagram of PV cell to generate the Sunlight [21]

The basic steps in the operation of a solar cell are:

- The generation of light-generated carriers;
- The collection of the light-generated carries to generate a current;
- The generation of a large voltage across the solar cell; and the dissipation of power in the load and in parasitic resistances.

PV cells are nonlinear in nature which generates various power and voltages according to the Irradiance and temperature. An accurate parameter estimation of PV cell using mathematical model is crucial thing but it is very important to improve quality of device or the system in terms of efficiency performance of the power generation. It helps to improve the mathematical modelling quality of the device. Accurate parameter of the device can play an important role in evaluation, optimization, supervision of the generation system So we have to focus on study accurate mathematical model with accurate parameter extraction using different mathematical modelling concept such as: [1,3,4]

- Single diode Modelling PV Cell
- Double diode Modelling PV Cell
- Triple diode Modelling PV Cell. [3,6,7,20]

In this paper we have studied in detail about Single diode Modelling PV Cell parameter extraction equations with the help of characteristics. The main objective here is to achieve a circuit based model of a Photovoltaic (PV) cell in order to estimate the electrical behavior of the practical cell with calculation of the unknown parameters which used to improve the efficiency of the cell.

II. MODELLING OF THE PHOTOVOLTAIC SOLAR CELLS:

Considering with different reference literature it's a conclusion that on account of physics driving behavior of the Solar cells there are different models. These models carrying out a non linear optimization problem with considering the I-V characteristics and the parameter estimation. The Parameters which has been calculated should be match with different data sheets which to take minimum time to compute the details. These modelling involves nonlinear I-V and P-V characteristics of diode and energy produced by the solar cell is the intrinsic properties of the semiconductor photo cell and incoming irradiance. PV cell having different known and unknown parameters. Known parameter such as open circuit voltage (Voc),Short circuit current(Isc),Current at maximum power point(Impp),Voltage at maximum power point(Vmpp).Along with unknown parameter such as series resistance (Rs),shunt resistance(Rsh),diode ideality factor(a),light generated current source(I_L),reverse saturation current (Io).These all parameters are helpful to design modelling of PV cell under standard test condition. In the Solar cell characteristics parameter of the solar cell can be identified and calculated with different weather condition, irradiance and temperature. [7,8,9,10,14]

Mathematical modelling of PV Cell using Single diode model: There are different types of circuits models are available which can be present mathematical modelling of PV cells. They are:

a) Ideal circuit model for PV cell

b) Non ideal circuit model for PV cell.

a) **Ideal circuit model for PV cell using Single diode model:** If we consider the ideal model for PV cell using single diode in this circuitry diode is connected parallel with the current source which has been generated by the light source. This ideal circuitry. Figure shows the concept of ideal circuit model for Single diode.

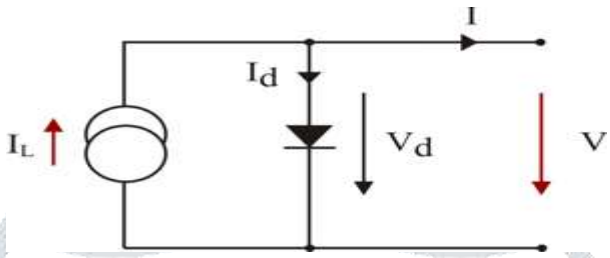

Figure 2: Ideal diode model for PV cell.

In this model I_L is the current source and output current I can be written as with the help of Kirchhoff's current law.

Total current can be written as:

$$I = I_L - I_d \text{ --(1)}$$

And I_d can be written as

$$I_d = I_S[\exp(V/nV_T) - 1] \text{ .... (2)}$$

With equation (2) we can rewrite equation (1) such as

$$I = I_L - I_S[\exp(V/nV_T) - 1] \text{ .... (3)}$$

In equation (1) I_L is the current source or the photon current at given irradiance and the temperature. Magnitude of the photon current depends on the light spectrum and characteristics of the photo cell. And quality of the semiconducting material. Photon current normally indicated as the short circuit current which has been mentioned in the manufacture's data sheets. It is specified at the standard test condition (STC) which is 1000 W/m^2, module temperature at 25^{0}C and Air mass=1.5 .Generally, photon current will be the 30 mA/cm^2 at the standard test condition Magnitude of the photon current (short circuit current directly proportional to the irradiance as the 10% lower in the irradiance then results in the 10% of lower in the output photon current. Change in photon current with temperature is not much very significant. That is about 0.05% increases per ^{0}C rise for silicon material. Output voltage V is nothing but the diode voltage that is V_d [3,4,5,8,17]

b) **Non- Ideal circuit model for PV cell using Single diode model (Practical diode model):**

In non-ideal circuit model for PV cell using Single diode model has been discussed by the behavior of series and parallel resistance connect in series and parallel combination with light generated source of PV cell. In figure 3 connections are given. This type of the model called as the Five parameter model which consist of the parameter such as:

a = Ideality factor of diode I_d = Diode current I_L = Light generated current source R_{sh}= Parallel resistance R_S= Series resistance

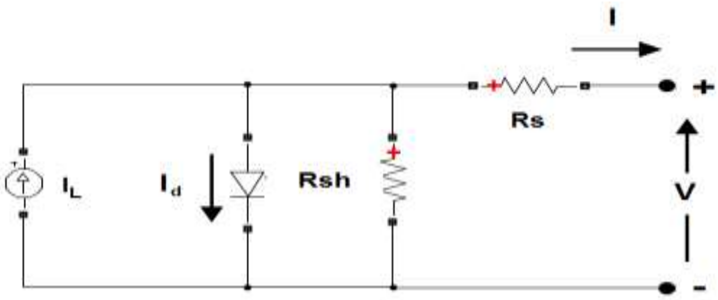

Figure 3: Practical Single diode model for PV cell.

This model is also called as the practical model of PV cell using single diode. And this model having the improved the effect of series and the shunt resistance. It is an schematic and equivalent circuit for the practical simulation purpose of The PV cell. In this parameter the series resistance and the parallel resistance plays the very important role such as: [8,9,11] So with all mathematical concept we have output equation of practical single diode model such as:

$$I = I_L - I_d - I_{sh} \ldots\ldots(4)$$

In above equation I_d (diode current) can be calculated as

$$I_d = I_O(\exp(\frac{V+IR_s}{n_s V_T}) - 1 \ldots\ldots(5)$$

$$I = I_L - I_O(\exp(\frac{V+IR_s}{n_s V_T}) - 1) - \frac{V+IR_s}{R_{sh}} \ldots\ldots(6)$$

In this way Single diode model consist of five unknown parameters such as [I_O, a, R_{sh}, $R_{S,}$(I_{ph}) I_L]. These five parameters we have to extract with considering all possible condition along with modelling concept. Practical diode model explained with different parasitic element added with series and parallel combination with basic diode element.[7,8,14,18,19]

III. PARAMETER EXTRACTION OF PV CELL MODEL:

As we know that the output of PV cell can be predicted use the parameterized model such as we discussed in the above details such as Single diode, Two diode and three diode model for the PV Solar cell system. The parameters can be obtained from the data sheet which can be measured the Current-Voltage (I-V) and Power-Voltage(P-V) characteristics Parameter estimation is shown the better results as compared to the manufacturing data sheets of the PV module or the PV cell. Parameters of the PV model can be estimated by using the two main types for the better approach that methods are Data-Sheet and the measurement based.

There are the different types of parameter estimation or the extraction.

A) Five Parameter estimation or the extraction. With Single diode mathematical model

B) Seven Parameter estimation or the extraction. With Double diode mathematical model

C) Nine parameter estimation or the extraction. With Three diode mathematical model. [11.12,13]

A) Five parameter extraction of the Single diode model of PV cell using data sheet TSM-290-PA14. [21,22]

As per the discussion we take example of the parameter extraction of single diode model using standard data sheet of TSM-290-PA14. For these purposes we need to understand which parameter has been extracted and what are the equations and the conditions to be considered for the same that thing we have to do step by step.

First consider which parameter to be extracted they are:

R_{sh} = Shunt Resistance R_s = Series resistance I_0 = Reverse saturation current

a = Diode ideality factor I_{ph} = Photon current

Parameter extracted = [R_{sh} , R_s , I_0 , a , I_{ph}]

As per the requirement we have to consider the data sheet available parameter which is given under standard test condition along with specification of the PV cell or the module. That are given as

Data obtained/estimated from the data sheets at the STC:

Open citcuit voltage = V_{OC} Short circuit current = I_{SC}

Voltage at maximum power point= V_{mp} Current at maximum power point= I_{mp}

Number of the cell in series= N_S Slope of I-V curve at open circuit

Slope of I-V curve at short circuit.

And along with data we have following data should be considered which is available with data sheets.

ELECTRICAL DATA @ STC	TSM-285 PA14	TSM-290 PA14	TSM-295 PA14	TSM-300 PA14	TSM-305 PA14
Peak Power Watts-P_{MAX} (Wp)	285	290	295	300	305
Power Output Tolerance-P_{MAX} (%)	0/+3	0/+3	0/+3	0/+3	0/+3
Maximum Power Voltage-V_{MP} (V)	35.6	36.1	36.4	36.9	37.0
Maximum Power Current-I_{MP} (A)	8.02	8.04	8.07	8.13	8.25
Open Circuit Voltage-V_{OC} (V)	44.7	44.9	45.2	45.3	45.4
Short Circuit Current I_{SC} (A)	8.50	8.53	8.55	8.60	8.75
Module Efficiency η_m (%)	14.7	14.9	15.2	15.5	15.7

Values at Standard Test Conditions STC (Air Mass AM1.5, Irradiance 1000W/m², Cell Temperature 25°C).
Power measurement tolerance: ±3%

Electrical Data

MECHANICAL DATA	
Solar cells	Multicrystalline 156 × 156mm (6 inches)
Cell orientation	72 cells (6 × 12)
Module dimensions	1956 × 992 × 46mm (77 × 39.05 × 1.81 inches)
Weight	27.6kg (60.8 lb)
Glass	High transparency solar glass 4.0mm (0.16 inches)

Mechanical Data

TEMPERATURE RATINGS	
Nominal Operating Cell Temperature (NOCT)	45°C (±2°C)
Temperature Coefficient of P_{MAX}	- 0.44%/°C
Temperature Coefficient of V_{OC}	- 0.33%/°C
Temperature Coefficient of I_{SC}	0.046%/°C

MAXIMUM RATINGS	
Operational Temperature	-40~+85°C
Maximum System Voltage	1000V DC(IEC)/ 600V DC(UL)
Max Series Fuse Rating	15A

TEMPERATURE DATA MAXIMUM RATINGS

FIGURE 4 : DATA SHEET SPECIFICATION OF THE PV CELL TSM-290-PA14 [21,22]

PARAMETER EXTRACTION THAT IS PHOTON CURRENT I_L:

Photon Current I_L is equal to the short circuit current with equation and the standard condition assumption:
As per the name implies the short circuit means we have shorted the output terminal of the circuit with this reference output current $I = I_{SC}$ and it is the maximum possible current of the PV cell.

where output voltage $V = 0$ With the small value of series resistance (R_S)

Means overall $I = I_{SC} = I_L$ with considering below circuit diagram:

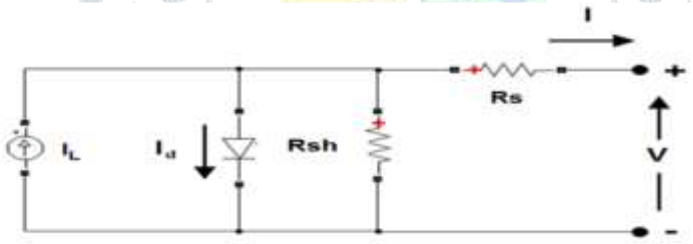

Figure 5 : PV model consider for the calculation of the photo current

At standard condition and with help of data sheet we have:

$I = I_{SC} = I_L$ And $I_{SC} = I_L = I_{ph}$ that means photo current

$I_{SC} = I_L$ = 8.53 A from data sheet. And another condition says as the arbitrary condition we ca calculate the photon current with a such equations.

$$I_L = (I_{sc_{STC}} + K_I \Delta T)\frac{G}{G_{STC}}$$ G_{STC} = Solar irradiance in W/m^2 at STC=1000 W/m^2

G = Solar irradiance in W/m^2 at a given condition. $I_{sc_{STC}}$ = Short circuit current from data sheet at STC=8.53A K_I =Temperature co-efficient of I_{SC} =0.046%/^{0}C ΔT =Temperature difference from STC

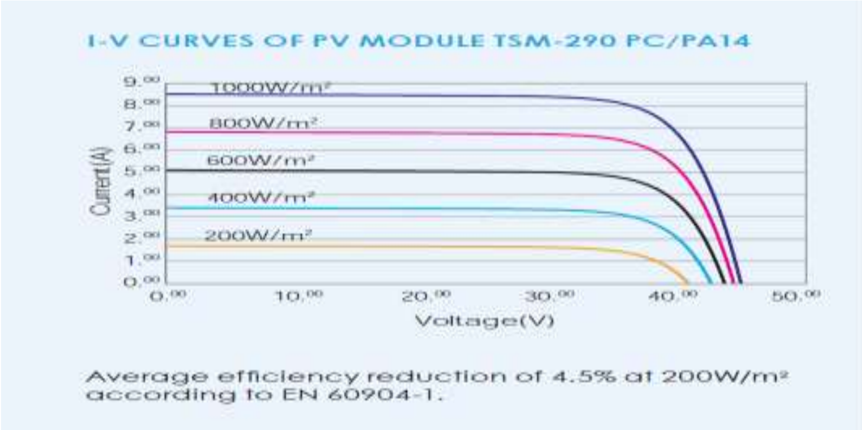

Figure 6 : I-V curves for the PV module for the irradiance parameter.

Parameter extraction that is Shunt resistance (R_{Sh}):

Shunt resistance value we can calculate from the I-V curve but that curve at the short circuit current condition and it can be calculated as

$$R_{Sh} = -\frac{dV}{dI} \quad \text{…………………………….. (7)}$$

It is inverse of the slope of I-V curve at short circuit current. Actually, this value is not given in the data sheet so we have to estimate this with the help of I-V curve and considering the horizontal and the vertical slope details we have the following details with particular angle and parameter range

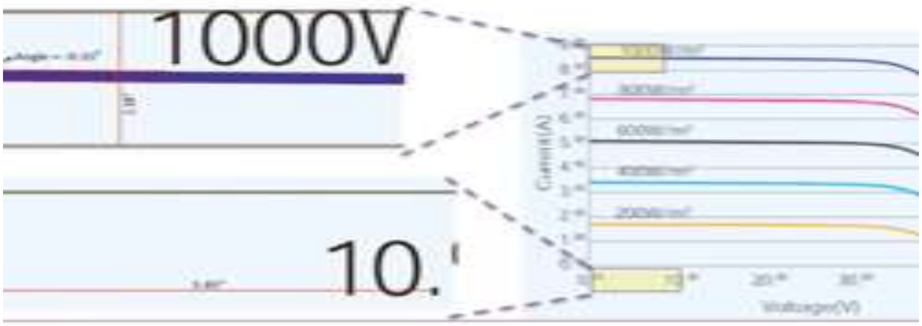

Figure 7 : I-V curves for the PV module for the irradiance parameter

With this help of the I-V curve and considering the horizontal and the vertical slope details we have the following details with particular angle and parameter range

Angle of I-V curve at short circuit = -0.55^0

Y axis scale = 1/2.18 A/inch X axis scale = 10/5.65 V/inch

With these all details we can calculate the slope equations for the same by using formula

$$\left.\frac{dI}{dV}\right| = \tan(-0.55) * \frac{1}{2.18} * \frac{5.65}{10} = -2.488*10^{-3} A/V \quad \text{………………………………..(8)}$$

at short circuit current condition,but we know the formula

$$R_{Sh} = -\frac{dV}{dI} \text{ at short circuit condition …………………………………….. (9)}$$

then by putting the values in the above equation and calculate the R_{Sh}

$$R_{Sh} = -\frac{dV}{dI} = \frac{-1}{-2.488*10^{-3}} = 402\Omega \quad \text{…………………………………….. (10)}$$

Hence we can estimate the shunt resistance with above formula

Parameter extraction that is Series Resistance (Rs):

For the calculation for the series resistance we have the formula

$$Rs = -\frac{dV}{dI} - \frac{V_T}{I_{SC}} \quad \text{…………………………………. (11)}$$

$$\left.\frac{dV}{dI}\right| \text{ at open circuit voltage condition. } V_T = \frac{N_S akT}{q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(12)}$$

Where 'a' is required with standard condition.

As per the details again datasheet not provide us for the slope parameter so we need to calculate the same. For this purpose we need the reference of the slope details horizontal as well as vertical graph parameter and the angle range.

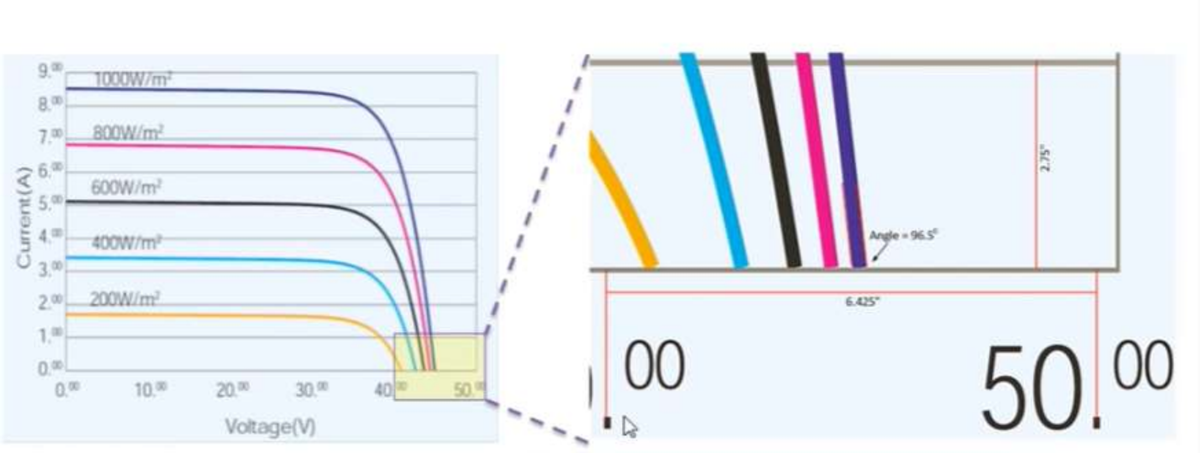

Figure 8: I-V curves for the PV module for the irradiance parameter.

Angle of I-V curve at open circuit = 96.5^0

Y axis scale = 1/2.75 A/inch

X axis scale = 10/6.425 V/inch

With these all details we can calculate the slope equations for the same by using formula

$$\frac{dV}{dI} = -\tan(96.5-90) * \frac{10}{6.425} * \frac{2.75}{1} = -4.877V / A \text{ at open circuit condition.}$$

To solve the remaining equations, we have gone through the nonlinearity equations and that can be find by following equations such as:

$$I_O = \frac{I_{SC} - \frac{V_{OC}}{R_{sh}}}{e^{\frac{V_{OC}}{V_T}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(13)}$$ To solve the saturation current or the output diode current.

$$R_S = -\frac{dV}{dI} - \frac{1}{\left(\frac{I_O q}{N_S akT}\right)\exp\left(\frac{V_{oc} q}{N_S akT}\right)} \quad \ldots\ldots\ldots\ldots \text{(14)}$$

to calculate series resistance value for the datasheet parameter which are given below.

I_{sc} = 8.53 V_{OC} = 44.9 V_{mp} = 36.1 I_{mp} = 8.04 $\frac{dV}{dI} = -4.877$ $\frac{dI}{dV} = -2.48797 * 10^{-3}$ N_S = 72

q = charge of an electron in coulombs (1.602 * 10^{-19}) k = Boltzman constant (1.38 *10^{-23} j/k)

T = temperature in K(298)

With this detail we have the parameter calculation with the data sheet such as

$$I_O = 3.352 * 10^{-8} \quad a = 1.254 \quad R_s = 0.212$$

IV. Results and Discussion

As we know that the output of PV cell can be predicted use the parameterized model such as we discussed in the above details such as Single diode.The parameters can be obtained from the data sheet which can be measured the Current-Voltage (I-V) and Power-Voltage(P-V) characteristics Parameter estimation is shown the better results as compared to the manufacturing data sheets of the PV module or the PV cell. Parameters of the PV model can be estimated by using the two main types for the better approach that methods are Data-Sheet and the measurement based. In some former approach for example Single diode model's parameter can be determined the parameter estimation with standard test condition specifications. Some of the parameter estimated the initial values of the parameters and then minimizes the cost functions using the measured data. Along with all discussion we have calculated or the extract the five parameter of the single diode model using simple analytical equations.

They are:

Parameter extracted = [R_{sh} , R_s , I_0 , a , I_{ph}]

Parameter extracted = [402 Ω, 0.212 Ω ,3.352*10^{-8},1.254 ,8.53A]

In this way we can extract the five parameters of the single diode model with the help of data sheet.

V. CONCLUSION

In this paper we can calculate all unknown five parameters with the help of mathematical single diode model and the data sheet of PV module TSM-290-PA14.This characteristics parameter and the extraction of the same are used to improve the ability of the model which has been applicable for the power generation and better quality of the module.

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