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Solar photovoltaic module performance characterisation using single diode modeling

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Abstract. Single or double diode electrical modeling of SPV module gives valuable results which will help to identify the exact behavior of SPV module under the normal operating condition. Accurate modelling of SPV module will also help to calculate internal resistances (R_s, R_{sh}) and parasitic of the SPV module. The main contribution of this work is the stepwise simplification of the current equation of single and double diode electrical model of SPV module. Then the single diode model of SPV module having 36 SPV cells in series is simulated in LTspice simulator. Simulated results are compared with labelled electrical parameters which shows close proximity to the labelled parameter at particular values of series and shunt resistance. This paper also presents the effect of variation in series resistance (R_s) and shunt resistance (R_{sh}) on the performance of the SPV module under normal operating condition. The dependency of SPV electrical parameters (I_{max}, V_{max}, P_{max}, FF, η) with the variation of series resistance (R_s) and shunt resistance (R_{sh}) is simulated, and the effects are discussed in details.

1 INTRODUCTION

In 1839, A French Physicist, E. Becquerel has investigated and observed Photovoltaic (PV) effect which converts incident light energy into electrical energy. Now a days Solar Photovoltaic (SPV) energy is most evolving and fast growing technique to fulfills the need of electricity of mankind [1-3]. The SPV cell is the basic unit of SPV module. SPV Cells are connected in series to get an output of the desired value of voltage. Similarly, the dimension of SPV cells will decide the current rating pf SPV module.

The parameters like module temperature (T_m), incident solar irradiation (G), and load impedance states the conversion efficiency (η) of photovoltaic module [4-7]. The major disadvantage of commercially available SPV module is its low conversion efficiency ($\eta < 20\%$) and the non–linearity of the output I-V curve [8, 9]. In normal operating condition, meteorological data such as solar irradiance (W/m^2), ambient temperature (^0C), humidity ($\%Rh$), and wind velocity (mph), etc. varies unpredictably. This uncertain variation affects current, voltage and hence power output generated by the SPV module [10, 11].

Manufacturers provide labelled electrical parameters (specification given on backside of SPV panel) and performance characteristic curves of SPV module for optimized power generation. This parameters are captured indoor under Standard Test Condition (STC) where $G = 1000\ W/m^2$, $T_m = 25^0C$ and AM (Air Mass) = 1.5 [12]. Commonly, SPV cell is modeled using a single diode model circuit equivalence [13]. To improve precision and accuracy, it can be modeled using a double diode model circuit equivalence [14]. Proper electrical modelling of SPV module will help to predict accurate performance actual operation condition [15].

In section 2, a need for SPV module performance characterisation is described with some definitions of significant parameters. Single and double diode modeling is compared with mathematical derivations of currents in section 3. In section 4, the single diode model of ASP-12-75W_p SPV module is simulated in SPICE simulator. In section 5, the results of the simulation are presented and compared for variation in series and parallel resistance. The conclusion of the work is presented in section 6.

2 CHARACTERISATION

Performance characterisation of SPV module/cell by tracing I-V and P-V curves is helpful while designing new SPV power plant. It also useful for scheduling Operation and Maintenance (O&M) of the SPV power plant [16]. Fig. 1 shows that during curve SPV cell/module is swept under different load conditions using variable resistor [17]. SPV cell is an active device which generates energy from incident solar light. Fig. 2 shows that, the I-V and P-V curve of an illuminated SPV cell.

I-V and P-V characteristic curve is used for extracting some important performance parameters like short circuit current (I_{sc}), open circuit voltage (V_{oc}), Maximum power (P_{max}), voltage at maximum power (V_{max}), current

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at maximum power (I_{max}), conversion efficiency (η) and field factor (*FF*) [18].

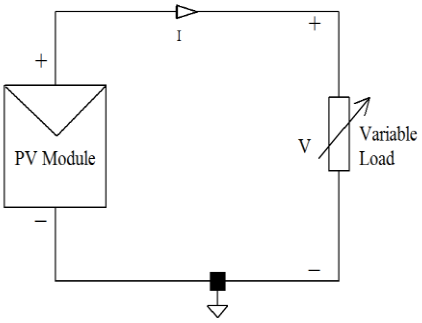

Fig. 1. Characterisation of SPV module

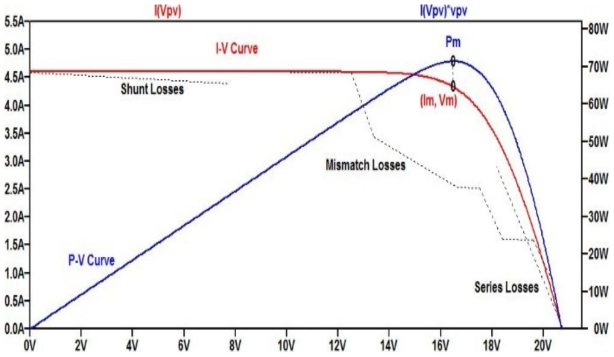

Fig. 2. I-V and P-V Curve

2.1 Significance of Series Resistance (R_s)

Slope near V_{oc} is determined by series resistance (R_s) as shown in Fig. 2 and the value of R_s is calculated by using Equation 1;

$$R_s = -\left(\frac{dV}{dI}\right)_{V=V_{oc}} \tag{1}$$

Resistance due to SPV cell metallization, SPV cell solder bonds, emitter–base region, cell interconnected bus-bars and junction box terminations implies finite value of series resistance in electrical equivalence circuit modeling. The ideal value of *Rs* is 0 [19]. The value of I_{sc} is reduced due to high value of R_s, which shows inverse relation between them.

2.2 Significance of Shunt Resistance (R_{sh})

The ideal value of R_{sh} is infinite but finite value of R_{sh} due to manufacturing defects , device degradation and parallel high conductivity paths through or on the solar cell edges results slope near I_{sc} [19, 20]. This effect is shown in Fig. 2 and the value of R_{sh} is calculated by using Equation 2;

$$R_{sh} = -\left(\frac{dV}{dI}\right)_{I=I_{sc}} \tag{2}$$

The low value of R_{sh} leading to higher power loss at output [21].

3 MODELING OF SPV CELL

SPV cell is modeled as a current source (I_{pv}) in parallel with a P-N junction diode in a single diode electrical equivalent circuit model [22]. SPV cell behaves like an only diode if there is no incident light present (dark condition $G = 0$) to generate any current. With an increase in the intensity of incident light, the current generated by the SPV cell increases [23]. Fig. 3 shows the only diode, and the current flowing through it is given by Equation 3;

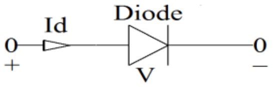

Fig. 3. Single Diode

$$I_d = I_o\left(e^{\frac{qV}{akT_m}} - 1\right) \tag{3}$$

put;

$$v_t = \frac{akT_m}{q} \tag{4}$$

Equation 5 becomes;

$$I_d = I_o\left(e^{\frac{V}{v_t}} - 1\right) \tag{5}$$

a is ideality factor of diode which is ranging between 1 and 2 (given in datasheet of diode). Considering a = 1 at 300 K temperature, value of V_t becomes 25.86 mV.

3.1 Single Diode Modeling (Ideal)

Fig. 4 shows ideal SPV cell single diode model (Considering $R_s = 0$ and $R_{sh} = \infty$);

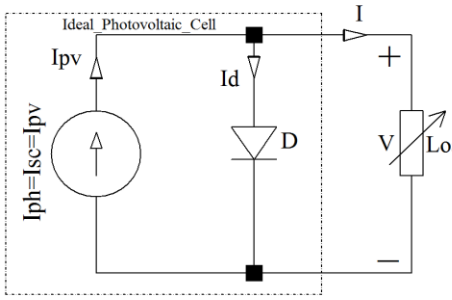

Fig. 4. Simplified Single Diode Modeling of SPV cell (Ideal)

The equation of current flowing through the load is given by Equation 6;

$$I = I_{pv} - I_d \tag{6}$$

$$I = I_{pv} - I_o\left(e^{\frac{V}{v_t}} - 1\right) \tag{7}$$

Fig. 5 shows practical SPV cell single diode model (Considering $R_{sh} = \infty$);

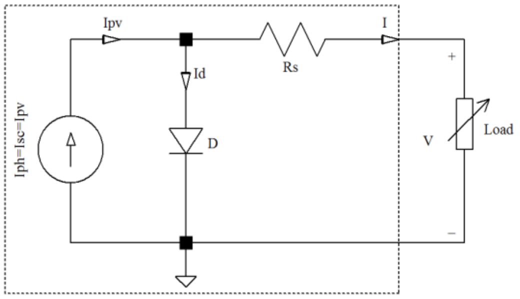

Fig. 5. Single Diode Modeling of SPV cell with R_s

The equation for practical SPV cell considering R_s only is given by Equation 8;

$$I = I_{pv} - I_o\left(e^{\frac{(V+I\,R_S)}{v_t}} - 1\right) \tag{8}$$

Fig. 6 shows practical SPV cell single diode model considering finite values of R_s *and* R_{sh}.

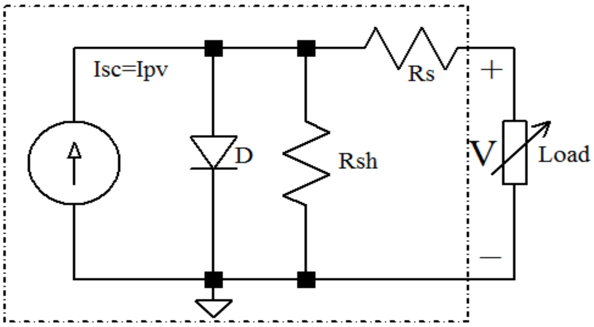

Fig. 6. Single Diode Modeling of SPV cell with R_s and R_{sh}

Considering R_s and R_{sh}, the single diode model equation becomes;

$$I = I_{pv} - I_d - I_{Rsh} \tag{9}$$

$$I = I_{pv} - I_o\left(e^{\frac{(V+I\,R_S)}{v_t}} - 1\right) - \frac{V+IR_S}{R_{sh}} \tag{10}$$

Commonly, 36 or 72 cells are connected in series to get desired voltage value at output of SPV module. Different current rating of SPV module depends on physical size of each cell. Cell is bigger in dimension has more current rating. Considering N_s as a number of cells are connected in series, equation of practical SPV module becomes;

$$I = I_{pv} - I_o\left(e^{\frac{(V+I\,R_S)}{N_S v_t}} - 1\right) - \frac{V+IR_S}{R_{sh}} \tag{11}$$

This single diode modeling with R_s and R_{sh} is also known as five parameter model (I_o, η, R_s, R_{sh}, I_{pv}) [13]

3.2 Double Diode Modeling

To increase the precision and accuracy of the equivalence circuit model, many researchers have added several diodes and resistances in series or in parallel with the current source [24]. Fig. 7 shows that, double diode model of the SPV cell considering effect of R_s and R_{sh}. Double diode model considers the effect of recombination of parallel diode [23]. At low value G and low value of T_m, this model will give significant and more accurate results. Double diode model has better ability to give mode precise and sharp I-V and P-V characteristics curve under normal as well as partial shading operating condition [25].

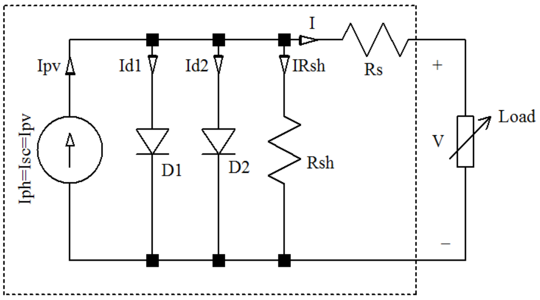

Fig. 7. Double Diode Modeling of SPV cell with R_s and R_{sh}

The current flowing through load using double diode model is given by Equation 12;

$$I = I_{pv} - I_{d1} - I_{d2} - I_{Rsh} \tag{12}$$

$$I = I_{pv} - I_o\left(e^{\frac{(V+I\,R_S)}{N_{S1} v_{t1}}} - 1\right) - I_o\left(e^{\frac{(V+I\,R_S)}{N_{S2} v_{t2}}} - 1\right) - \frac{V+IR_S}{R_{sh}} \tag{13}$$

3.3 Summary of comparison between single and double diode modeling

Table 1. Comparison of single and double diode model

Quantities	Single Diode	Double Diode
Computation time for parameter extraction	Shorter	Longer
Unknown parameters	Less	More
Accuracy	Good	Better
I–V and P–V characteristics	Smooth	Sharp
Consider recombination effect	No	Yes

4 SPICE SIMULATION OF SINGLE DIODE MODELING

Labelled parameter of ASP-12-75W_p SPV module is used as a reference which are calculated under standard test condition, 1000W/m^2 and T=25^0C given in Table 2.

Table 2. Labelled Specification of SPV Module

ASP-12-75W_p SPV Mono–crystalline (1000 W/m^2, 25°C)	
Electrical Parameter	**Specification at STC**
Maximum Power (P_{max})	75 W_p
Voltage at Maximum Power (V_{max})	17.60 V
Current at Maximum Power (I_{max})	4.26 A
Open Circuit Voltage (V_{oc})	21.5 V
Short Circuit Current (I_{sc})	4.60 A
Number of series connected SPV cell (N_s)	36

Single diode model of complete SPV module having 36 SPV cells (N_s = 36) in series is simulated in SPICE simulation software assuming all cells are identical and having equal solar radiation. Photon current ($I_{pv} = I_{sc}$) flowing through SPV cell is directly proportional to input incident light energy [12]. Leakage current of diode is considered as 1 nA. Current controlled current source (CCCS) having current gain 1 is used which gives same current at output of voltage controlled voltage source (VCVS). VCVS is used to multiply single cell voltage with number of cells in series in the SPV module (N_s*E_{pv0}). Considering uniform operating condition, multiplication of SPV cell output with 36 will shows that there is no possibility under consideration of partial shading condition in simulation. Fig. 8 shows the single diode model of SPV module.

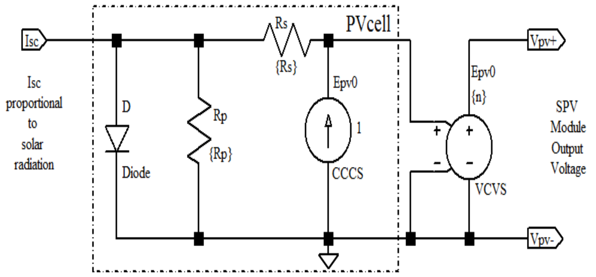

Fig. 8. Simulated single diode model (X1)

Current source of 4.60 A represents I_{sc} of SPV module (ASP-12-75W_p) which is proportional to solar radiation incident on SPV module. Fig. 9 shows the final equivalence model of SPV panel with X1 is the solar panel symbol assuming internal resistance of voltmeter ($R_{internal}$) is 0.01 Ω.

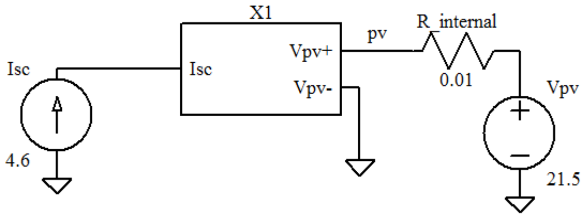

Fig. 9. Complete model in SPICE Simulator

5 RESULTS AND DISCUSSIONS

In order to validate single diode modeling and SPICE simulation for above SPV module, the specified values of the ASP-12-75W_p SPV module are compared with simulation results for different combination of R_s and R_{sh}. In this section, effect of variation of R_s and R_{sh} on characteristic curve is observed carefully. The I–V and P–V characteristic curves from SPICE simulation of single diode model of SPV module are presented in this section. The effect of R_s and R_{sh} variation on SPV module characteristics curve is validated.

5.1 Effect on R_s

In this case, the series resistance R_s of single diode model was varied in multiple of 10 from 0.0001Ω to 1Ω with all other parameters kept constant (R_{sh} = 1KΩ). The results (I– V and P–V curves) are presented in Fig. 10 to Fig. 14. From this figures, it may be noted that with increase in series resistance (R_s), the slope near V_{oc} decreases which effectively decreases output power of SPV module and it is tabulated in Table 3.

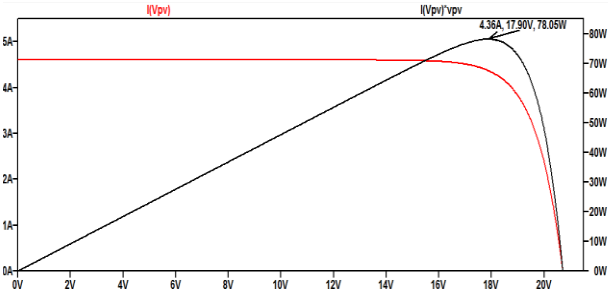

Fig. 10. I-V and P-V Curve with $R_s = 10^{-4}\,\Omega$ and $R_{sh} = 1\ K\Omega$

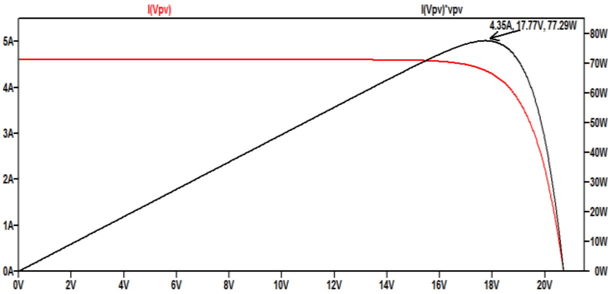

Fig. 11. I-V and P-V Curve with $R_s = 10^{-3}\,\Omega$ and $R_{sh} = 1\ K\Omega$

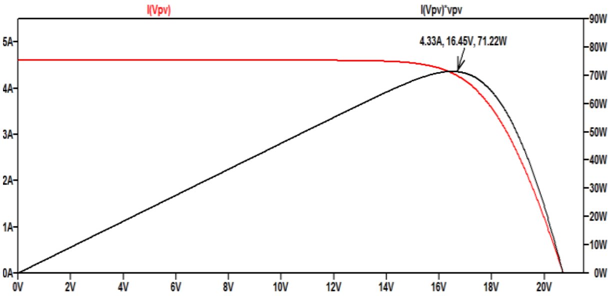

Fig. 12. I-V and P-V Curve with $R_s = 10^{-2}\,\Omega$ and $R_{sh} = 1\ K\Omega$

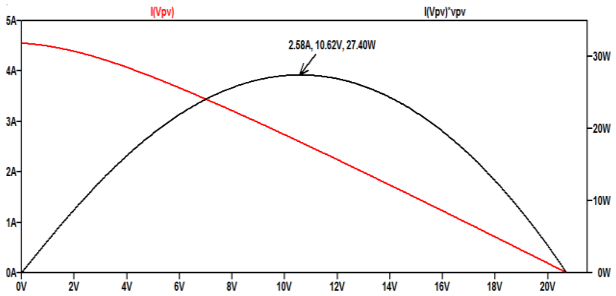

Fig. 13. I-V and P-V Curve with $R_s = 10^{-1}\ \Omega$ and $R_{sh} = 1\ K\Omega$

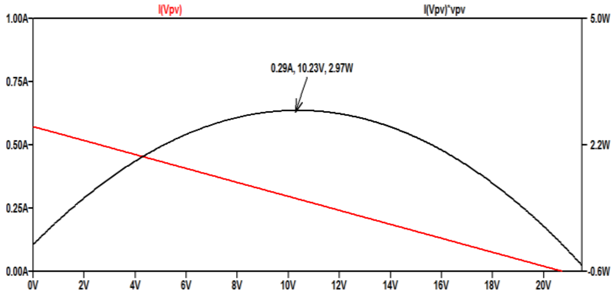

Fig. 14. I-V and P-V Curve with $R_s = 1\Omega$ and $R_{sh} = 1$ KΩ

Table 3. Effect of R_s Variation

	Value				
R_s (Ω)	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1
R_{sh} (Ω)	**1 KΩ**				
I_{max} (A)	4.36	4.35	4.33	2.68	0.29
V_{max} (V)	17.90	17.77	16.45	10.62	10.23
P_{max} (W_p)	78.05	77.29	71.22	27.40	2.97

5.2 Effect on R_{sh}

In this case, the shunt resistance (R_{sh}) of single diode model was varied in multiple of 100 from 0.1Ω to 10$M\Omega$ with all other parameters kept constant ($R_s = 0.01\Omega$). The results (I–V and P–V curves) are presented in Fig. 15 to Fig. 19. From this figures, it may be noted that with increase in shunt resistance (R_{sh}) the slope near I_{sc} changes and output power increases which is tabulated in Table 4.

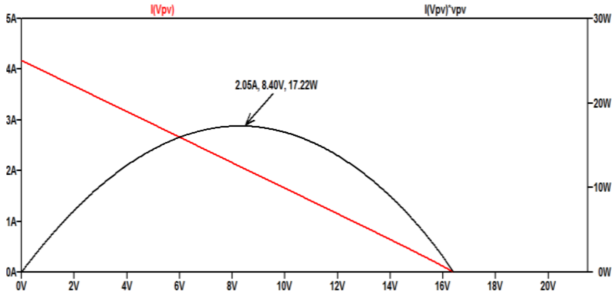

Fig. 15. I-V and P-V Curve with $R_{sh} = 0.1\Omega$ and $R_s = 0.01\Omega$

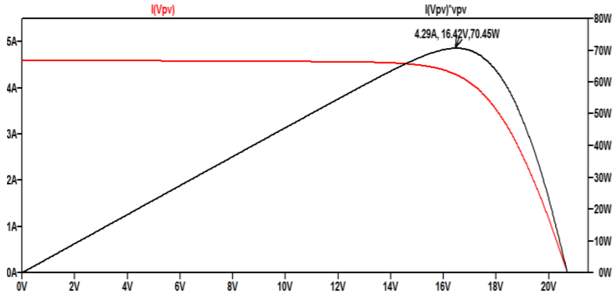

Fig. 16. I-V and P-V Curve with $R_{sh} = 10\Omega$ and $R_s = 0.01\Omega$

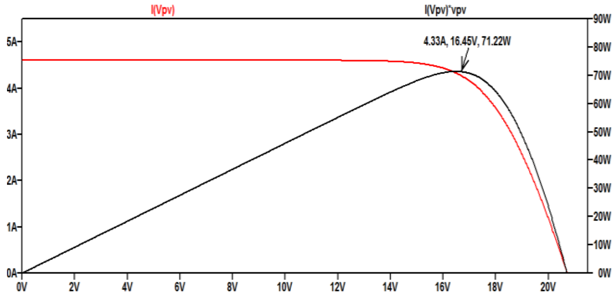

Fig. 17. I-V and P-V Curve with $R_{sh} = 1K\Omega$ and $R_s = 0.01\Omega$

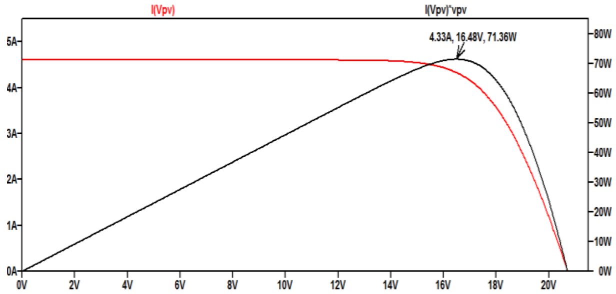

Fig. 18. I-V and P-V Curve with $R_{sh} = 100K\Omega$ and $R_s = 0.01\Omega$

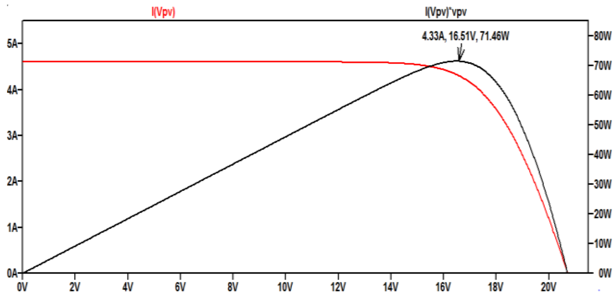

Fig. 19. I-V and P-V Curve with $R_{sh} = 10M\Omega$ and $R_s = 0.01\Omega$

Table 4. Effect of R_{sh} Variation

Value					
R_s (Ω)	**0.01**				
R_{sh} (Ω)	0.1	10	10^3	10^5	10^7
I_{max} (A)	2.05	4.29	4.33	4.33	4.33
V_{max} (V)	8.40	16.42	16.45	16.48	16.51
P_{max} (W_p)	17.22	70.45	71.22	71.36	71.46

6 CONCLUSION

A detailed comparative study of single and double diode electrical modeling was carried with their advantages and disadvantages. The ideal value of series resistance(R_s) is 0, but finite value shows the change in the slope of a curve near V_{oc}. Similarly, the ideal value of shunt resistance (R_{sh}) is ∞, but finite value shows the change in slope of curve near I_{sc}. The results presented in the above section clearly shows that as R_s increases the output power decreases. Similarly increases in R_{sh} value, the output power increases. The implemented single diode model of SPV module gives results having close proximity with a labelled specification of ASP-12-75W_p SPV module with a low value of R_s and high value of R_{sh} under normal operating conditions at a constant temperature and constant solar irradiance

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