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A Simplified Method for Parameter Determination of a Photovoltaic Module using Manufacturer's data

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ABSTRACT

Accurate and fast modelling and simulation of Photovoltaic module requires careful determination and identification of the unknown parameters required in fitting the voltage-current and power-voltage curves to replicate an actual system. The main objective of this study is to determine ideality factor (A), saturation current (I_o), photocurrent (I_{ph}), series resistance (R_s) and shunt resistance (R_{sh}), the five unknown parameters using I_{sc}, I_{mpp}, V_{mpp}, and V_{oc} available from manufacturer's datasheet. A single diode equivalent circuit has been used to formulate a simple method for evaluating ideality factor (A), saturation current (I_o) and photocurrent (I_{ph}) by first assuming that the photovoltaic array has negligible series resistance (R_s) and infinite parallel resistance (R_{sh}). Additional analysis of series and parallel resistance have been carried out for fine tuning the voltage-current and power-voltage curves to fit the experimental data. The model presented in this work has been simulated using the GNU Octave open-source software. The photovoltaic modules with International Electrotechnical Commission (IEC) 61215 standards have been selected from Solarex-MSX60, BP- SX150 and Kyocera-KK280P. The extracted parameters produced results for the output power with an error of less than 0.5% for all the modules.

1. Introduction

Photovoltaic solar arrays have played a significant role as a source of renewable energy [1]. Modelling and simulation of these solar modules prior to implementation in a solar plant are important for designing reliable and efficient systems [2]. Solar array models require elaborate definitions of several parameters that greatly influence the optimization of their efficiency.

A single diode equivalent circuit offers a simple and easy to implement model that produces simulated data that matches the experimental data or the information provided in the manufacture's datasheet. [3–7]. The single diode model requires precise evaluation of I_{sc}, I_o, I_{mpp}, I_{ph}, A, R_s, R_{sh}, V_{oc} and V_{mpp}. The data sheet provides I_{sc}, V_{mpp}, I_{mpp} and V_{oc}, the four crucial parameters that are essential for evaluation of its performance at STC. These parameters can be used as the optimum operating points for characterization of the system [8]. The other parameters should be determined in order to have an ideal model that matches the datasheet information. Different mathematical techniques have been reported to determine the five unknown parameters [5, 9, 10]. A datasheet-based approach has been applied to iteratively determine the Io, Iph, Rs and Rsh where ideality factor was arbitrarily chosen and gradually adjusted to tune the PV curve, making the technique tedious and time consuming [11]. In this work we propose to determine the ideality factor and the diode saturation current parameters to coarse tune the PV curve at STC. The I_{ph}, R_s and R_{sh} can thereafter be estimated to fine tune the curves.

Models based on manufacturers' data offer an affordable and quick method of characterization of the PV solar array. Their main drawback is that the data is available at STC and experimental procedures must be performed in order to obtain data at various environmental conditions [12]. The experimental procedure requires equipment for room temperature controls, generation of different irradiance levels, current and voltage measurements. The main purpose of this study is to develop a simple algorithm for modeling a solar module using an equivalent circuit with a single diode. The algorithm interactively determines the unknown parameters of a diode model for solar modules that have datasheet information at STC and other environmental condition at $800 W/m^2$ with nominal operating cell temperature (NOCT).

2. A Single Diode Equivalent Circuit

Figure 1 shows the single diode equivalent circuit. The light generated current source is connected in series to Rs and in parallel to both the diode and shunt resistor.

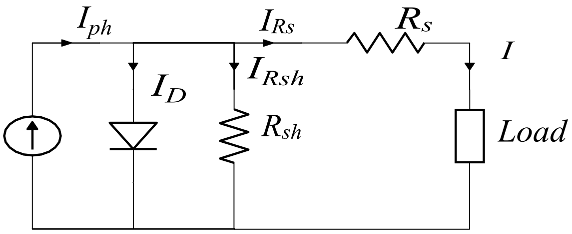


Figure 1: A Single Diode Equivalent Circuit

Using Kirchhoff's current and voltage laws, we relate
$I_{ph} - I_D = I_{R_{sh}} + I_{R_s}$. (1)

and the output voltage (V) can be given as
$V = V_{ph} - V_{R_s} = V_{R_{sh}} - V_{R_s} = V_D - V_{R_s}$. (2)
The Shockley's diode equation [13] for current-voltage characteristic gives I_D as
$I_D = I_o exp\frac{qV_D}{AkT} - I_o$. (3)

Combining the three equations (1-3) and taking $I = I_{R_s}$ and $V_D = V_{R_{sh}} = V + IR_s$, we can write the P-V single diode model equation as follows

$I = I_{R_s} = I_{ph} - I_D - I_{R_{sh}} = I_{ph} - I_o exp\frac{q(V+IR_s)}{AkT} + I_o - \frac{V+IR_s}{R_{sh}}$. (4)

Where, *q* charge of an electron and *k* is the Boltzmann's.

3. Mathematical Modelling of Photovoltaic Panel Using Manufacturers' Data

Information provided in the manufacturer's datasheet can be used to solve equation (4) by making a few assumptions of known facts. We assume that the solar module has identical solar cells in series (Ns) and that the connection between the metal grid and the n-substrate, the p-n junction and the connection between the p-substrate and the metal base offer very little series resistance (Rs). In addition, the shunt resistance (Rsh) which depends on the design of the solar module has very high values. Therefore, we can first disregard the Rs and Rsh in equation (4), which gives us the optimum values for other parameters. Rs and Rs will however be reconsidered later for different ideal factor values. Thus, equation (4) can be written as

$I = I_{ph} + I_o - I_o exp\frac{qV}{AkT}$. (5)

We also assume that the short circuit current Iph is equivalent to Isc and I = 0 at open voltage. These assumptions can be implemented in equation (5) to get

$I_{sc} = I_o exp\frac{qV_o}{AN_skT} - I_o$. (6)

Taking logarithms on either side of equation (6), gives

$ln(I_{sc} - I_o) - ln(I_o) = \frac{V_o}{AN_sV_t}$. (7)

Where, Vt = kT/q is the thermal voltage.

Again, at maximum power point, we can rewrite equation (5) as

$$I_{mpp} = I_{sc} + I_o - I_o exp\frac{V_{mpp}}{AN_sV_t}. \quad (8)$$

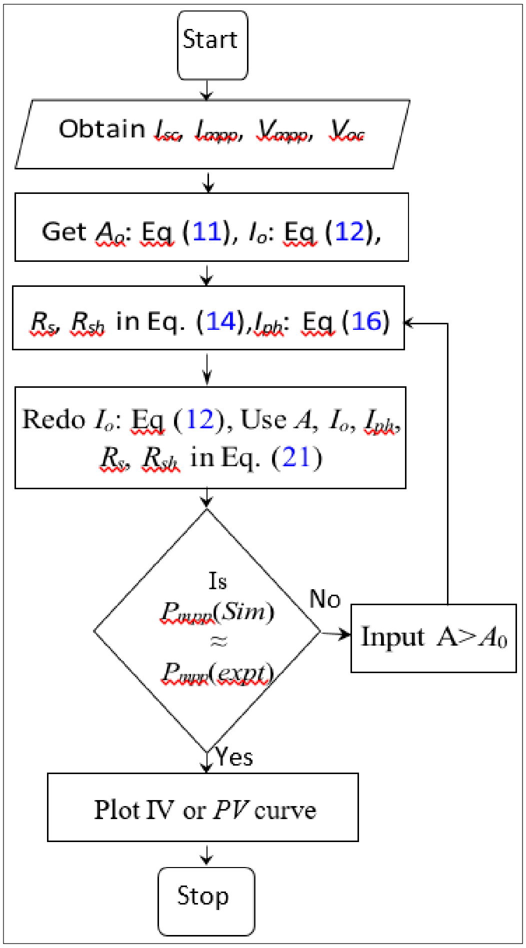
Also,

$$ln(I_{sc} + I_o - I_{mpp}) - ln(I_o) = \frac{V_{mpp}}{AN_sV_t}. \quad (9)$$

Finally, we can derive the ideality factor from equations (7) and (9) in terms of I_{mpp}, I_{sc}, V_{oc} and V_{mpp} as

$$A = \frac{V_{oc}-V_{mpp}}{AN_sV_t[ln(I_{sc})-ln(I_{sc}-I_{mpp})]}. \quad (10)$$

The flowchart given in Figure 2 shows the algorithm used in this work. Several steps are taken systematically to evaluate and check the different parameters that are lacking for the model.



- First, the I_{sc}, I_{mpp}, V_{mpp} and V_{oc} values are chosen from the datasheet or experimental results of the module.
- Second, the optimal ideality factor (A_o) is calculated using equation (11).
- Third, A_o is used to calculate the saturation current using equation (12).
- Fourth, the R_s and R_{sh} are iteratively extracted by varying the series resistance from zero to 1Ω using equation (14) as shown in Figure 3.
- Fifth, new values of A are used to recalculate I_o.
- Sixth, the values of A, I_o, R_s and R_{sh} are used to calculate I_{ph}.
- Seventh, all the calculated parameters are used in equation (21) to determine the current-voltage and power-voltage relationships.

Figure 2: An algorithm for plotting IV and PV curves and evaluating the A, I_o, I_{ph}, R_s, R_{sh} using I_{sc}, I_{mpp}, V_{mpp} and V_{oc}

- Eighth, the simulated output power values ($Pmpp(Sim)$) are compared to the datasheet or experiment value ($P_{mpp}(expt)$). This process is repeated until $P_{mpp}(Sim) \approx P_{mpp}(expt)$.
- Finally, the I-V and P-V curves are plotted and evaluated to validate the entire process.

4. Analysis of Ideality Factor(A) and Saturation Current (I_o)

The ideal factor linearly depends on the saturation current values between 0 and 0.3A, as depicted in equation (10) and as shown in Figure 2. The saturation current range has been arbitrarily chosen between 0 and 0.3A for initial proof of principle. To determine the dimension of optimum ideality factor (A_o) accurately, we have assumed that the saturation current is negligible in relation to both I_{sc} and I_{mpp}. Therefore, the threshold ideality factor can be determined using

$$A = \frac{V_{oc} - V_{mpp}}{AN_sV_t\left[ln(I_{sc}) - ln\left(I_{sc} - I_{mpp}\right)\right]} \text{ . (11)}$$

The saturation current can be estimated by rearranging equation (6) to get

$$I_o = \frac{I_{sc}}{exp\left(\frac{V_{oc}}{AN_sV_t}\right) - 1} \text{ . (12)}$$

5. Analysis of Series and Parallel Resistance

The series and parallel resistances can be determined by re-evaluating equation (4) using values of A, I_o, I_{mpp} and V_{mpp} at a maximum power point. This will yield,

$$I_{mpp} = I_{ph} + I_o - I_o exp\left(\frac{V_{mpp} + I_{mpp}R_s}{AN_sV_t}\right) - \frac{V_{mpp} + I_{mpp}R_s}{R_{sh}}\text{. (13)}$$

Assuming $I_{sc} \approx I_{ph}$, equation (13) can be reorganized to give

$$R_{sh} = \frac{V_{mpp} - I_{mpp}R_s}{I_{ph} - I_{mpp} - I_o\left(exp\left(\frac{(V_{mpp} + I_{mpp}R_s)}{nN_sV_t}\right) - 1\right)} \text{ . (14)}$$

An iterative evaluation of series and parallel resistance shows that there are positive values of R_{sh} for A> A_o as R_s increases from zero as illustrated in Figure 3

6. Analysis of Photocurrent (Iph)

The photocurrent can be evaluated by making similar assumption at short circuit point, where *I* = I_{sc} and V=0. Applying this assumption in equation (4), we can deduce

$$I_{sc} = I_{ph} - I_o exp\frac{I_{sc}R_s}{AN_sV_t} + I_o - \frac{I_{sc}R_s}{R_{sh}} \text{ . (15)}$$

On the right hand side of equation (15), the second and third terms have very small currents in the range of Nano- or micro-amperes, whereas the first and fourth terms are in amperes. Therefore, the second and third terms can be ignored and after rearrangement, we can rewrite equation (15) as

$$I_{ph} = I_{sc} + \frac{I_{sc}R_s}{R_{sh}} \text{ . (16)}$$

Equations (1) to (16) can be tested by applying values of I_{sc}, V_{oc}, I_{mpp} and V_{mpp}, which are readily available from the module's datasheet under nominal test conditions of 1.5 air mass, 1000 W/m^2 and 298.15K.

7. Analysis of output power (P)

The output power can be determined by simply multiplying the output voltage and the output current of equation (4) as

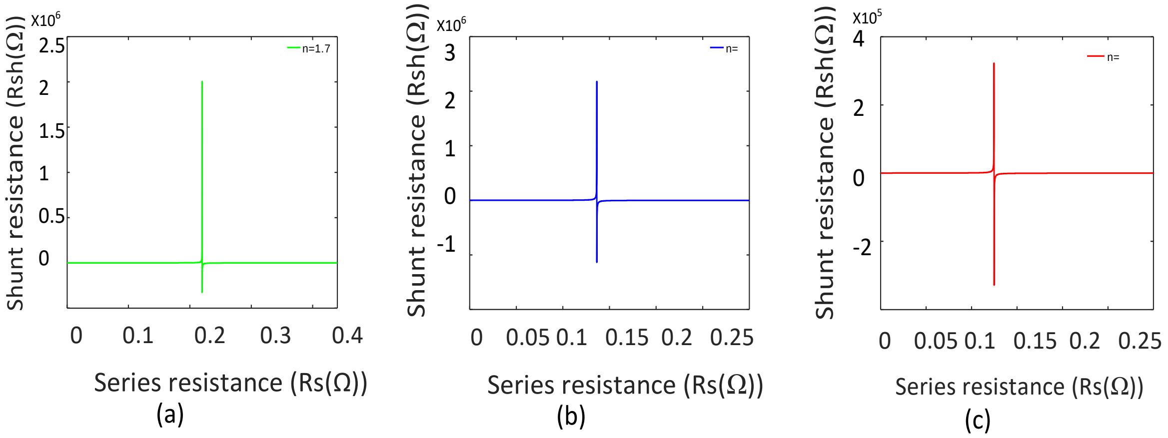
$$P = VI = V\left(I_{ph} + I_o - I_o exp\left(\frac{V + IR_s}{AN_sV_t}\right) - \frac{V}{R_{sh}} - \frac{IR_s}{R_{sh}}\right) \text{ . (17)}$$

Table 1 summarizes the data sheet values for Solarex MSX60, BP SX150 and Kyocera KK280P in nominal test environment, their respective simulated data and derived parameter values for $A \approx A_o$, I_o, I_{ph}, R_s and R_{sh}.

Table 1: Datasheet values for MSX60, BP SX150 and KK280P at STC and NOCT for KK280P

	V_{oc} [V]	V_{mpp} [V]	N_s	I_{sc} [A]	I_{mpp} [A]	A_o	I_o [A]	P_{mpp} [W]	ΔP_{mpp}%
MSX60	21.1	17.1	36	3.8	3.5	1.7034	5.80E-6	59.56	-0.48
BPSX150	43.5	34.5	72	4.75	4.35	1.9663	3.04E-5	150.13	0.04
KK280P	38.9	31.5	60	9.53	8.89	1.7775	6.51E-6	280.36	0.12

Figure 3 shows the Solarex MSX60, BP SX150 and Kyocera KK280P R_{sh} versus R_s curves. These plots have been used to verify the choice of R_s and R_{sh} values as described in algorithm step 4.



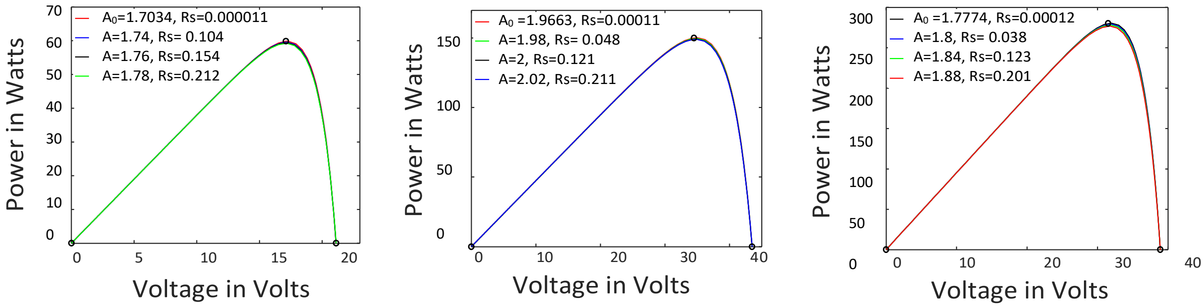
(a) (b) (c)

Figure 3: A graph of Rsh Vs Rs for MSX60, BP SX150 and Kyocera KK280P

The proposed model was tested using the P-V characteristic curves shown in Figure 4 at STC. They demonstrate the values of R_s for different ideality factors starting with the optimum ideality factor (A_o). The curves converge at V_{OC} but differ significantly at P_{mpp} due to the different values of A, I_o, I_{ph}, R_s and R_{sh} given in Table 2. Table 2 shows the data from this model, which provides satisfactory results for R_s and I_{ph} in comparison with data in[14]-[18]. However, other parameters differ due to the different choices of ideality factor.

Table 2: Extracted five parameters

MSX60							
Our Method					Ref. [14]	Ref. [15]	Ref. [16]
A	1.7034	1.74	1.76	1.78	1.27	1.404	1.277
$I_o(A)$	5.80E-06	7.69E-06	8.92E-06	1.03E-05	5.95E-08	3.29E-07	6.45E-08
$R_s(\Omega)$	1.1E-05	0.104	0.154	0.212	0.234	0.169	0.2165
$R_{sh}(\Omega)$	121330	22263	3220	3554	9	638	275
$I_{ph}(A)$	3.8	3.8000	3.8002	3.8002	3.8000	3.8010	3.8130
BP SX150							
Our Method					Ref. [15]	Ref. [17]	Ref. [18]
A	1.9663	1.98	2	2.02	1.4851	1.64	1.642
$I_o(A)$	3.04E-05	3.30E-05	3.72E-05	4.18E-05	6.17E-07	2.80E-06	2.84E-06
$R_s(\Omega)$	0.00011	0.048	0.121	0.211	0.4543	0.31256	0.3315
$R_{sh}(\Omega)$	268260	9606	4907	12747	960	1799	4368
$I_{ph}(A)$	4.7500	4.7500	4.7501	4.7501	4.7522	4.7508	4.7500
KK280P							
Our Method							
A	1.7775	1.8	1.84	1.88	-	-	-
$I_o(A)$	6.51E-06	7.77E-06	1.05E-05	1.41E-05	-	-	-
$R_s(\Omega)$	0.000011	0.038	0.123	0.201	-	-	-
$R_{sh}(\Omega)$	164640	2257	9608	4962	-	-	-
$I_{ph}(A)$	9.53	9.5302	9.5301	9.5304	-	-	-



(a) (b) (c)

Figure 4: A graph of Power against Voltage for (a) MSX60 (b) BP SX150 and (c) KK280P

Conclusion

A new, simple and robust method has been derived and tested to determine ideality factor (A), saturation current (I_o), photocurrent (I_{ph}), series resistance (R_s) and shunt resistance (R_{sh}) of a single diode equivalent circuit for modeling a photovoltaic solar system based on the data sheet values. This new algorithm gave output power of 59.56 ± 0.29W for MSX60, 150.13 ± 0.13W for BP SX150 and 280.36 ± 0.33W for KK280P.

The output power generated from the new algorithm agrees with the value available from the modules' data catalog within 0.5 percent error at the maximum power point. The new approach can be used for quick evaluation of a PV array prior to implementation of maximum power point tracking techniques. The straightforward mathematical analysis of a PV array based on manufacturers' data reported in this paper makes it possible to easily analyze and design a PV plant prior to its implementation.

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