An Effective Solar Photovoltaic Module Parameter Estimation Technique for Single-Diode Model

M Premkumar1*, R Sowmya2, S Umashankar3, and J Pradeep4

1 Department of EEE, GMR Institute of Technology, Rajam, Andhra Pradesh, India
2 Department of EEE, National Institute of Technology, Tiruchirapalli, Tamil Nadu, India
3 Renewable Energy Laboratory, Prince Sultan University, Riyadh, Saudi Arabia
4 Junior Engineer, Rajasthan Rajya Vidyut Prasaran Nigam, Sikar, Rajasthan, India

Abstract. This paper presents a simplified parameter estimation procedure for a photovoltaic (PV) single diode model (SDM). Based on an iterative method, the module parameters are estimated for the SDM using the information from the datasheet. The five parameters of the SDM are estimated based on the datasheet using two steps. In the first step, the best ideality factor, \( n \), value is determined, and in the next step, the value of the shunt resistance, \( R_{sh} \), can be calculated to increase its accuracy. For validating the performance of the estimated parameters, a model that considers the difference in the solar irradiance and the temperature. In the standard testing conditions (STC), the proposed procedure shows the best results relative to other methods. The optimization of the parameters, such as \( n \), \( R_{sh} \), and series resistance, \( R_{se} \), allows the minimum error between the values obtained from the proposed technique and datasheet.

1. Introduction
Suitable modelling circuit and estimation of optimum parameters of PV panels are serious subject matter for various applications, such as design, simulation, performance assessment under different environmental conditions, efficiency assessment, and PV system control [1-3]. It is helpful also for the operation of PV systems, the testing and development of the maximum power point tracking (MPPT) techniques [4], the progress of fault detection approaches, the power forecasting, the calculation of losses, and the reproduction of the PV simulator references as a function of temperature and irradiation differences in real-time in commercial PV inverter testing [5]. The curves, such as voltage (V) - current (I) and power (P) - V, generally characterize the PV cells. The manufacturers give the specification of the PV module at STC, such as open-circuit voltage (\( V_{oc} \)), short-circuit current (\( I_{sc} \)), and maximum power point (MPP), i.e., maximum power (\( P_{mpp} \)), maximum current (\( I_{mpp} \)), and maximum voltage (\( V_{mpp} \)). Few manufacturers provide the values of the short-circuit current (\( \alpha_{sc} \)) temperature coefficient and the open-circuit voltage (\( \beta_{vc} \)) temperature coefficient. The parameters in the datasheet cannot represent the PV cell or module behavior, because these are not foreseen in most electric models already in use. Hence, the parameters for the different PV models must be extracted from the datasheet [6].

The electrical equivalent of the PV cell is traditionally represented by an ideal current source and a diode with no hint of shunt resistance (\( R_{sh} \)) and the series resistance (\( R_{se} \)). Different studies on the development of PV cell models have been presented. These models, however, have different complexity levels. These differences depend on the diode numbers used, the infinite or finite value of \( R_{sh} \), the variable or fixed diode-ideality factor, \( n \) and various algorithms used to determine the necessary
parameters. In the scientific community, the assessment among the PV cell models is an essential topic of research [7]. The electrical equivalent model of the SDM has the parameters, such as diodes saturation current \( I_{sd} \), photocurrent \( I_{ph} \), diode ideality-factor \( n \), and \( R_{sh} \) and \( R_{se} \) resistances. Nevertheless, the manufacturers of PV modules neither provide these parameters explicitly nor entirely. As a result, electrical PV cell modeling and parameter extraction methods are based on various aspects, for instance, complexity, photovoltaics technology, accuracy, and the speed of estimation [8]. The field of PV cell modeling and parameter estimation is based on numerous research publications. There are several essential investigations on the simulation and estimation of parameters of PV cells are carried out in [9]. The PV cell model, such as SDM, double-diode model, and three diode models, are discussed in the literature. The authors also covered analytical and soft computing approaches and analytical methods for the estimation of parameters. In the review [10], the hybrid method between the analytical and soft computing approaches was recommended. The numerical, analytical, graphical, and heuristic methods are used mainly to extract the photovoltaic cell parameters.

The primary objective of this paper is to present a simplified five parameter assessment method for the SDM of the multi-crystalline PV panel. The presented process uses an iterative method that differs from the optimization-based estimation of the parameters, such as \( n \), \( R_{se} \), and \( R_{sh} \). The presented method has two iterative steps to estimate the model parameters, beginning with the datasheet of the supplier. The results obtained by the presented method are compared with a few literature methods. In addition, electrical models have been used to obtain the V-I characteristics in light of the variation in irradiance and temperature.

The paper is organized as follows: The SDM of the PV module is discussed in Section 2, section 3 presents the simplified five-parameter extraction technique, while section 4 presents results in comparison with other approaches. Lastly, Section 5 concludes the paper.

2. Single-diode PV model of the module
The electrical equivalent circuit of the PV module describes its physical characteristics. The single-diode PV model is being used in many of the fields, specifically to describe the characteristics of the PV module [11]. There are several PV cells connected in parallel \( N_p \) or series \( N_s \) in the PV module, and the equivalent circuit structure of the SDM is depicted in Fig. 1, which includes photocurrent \( I_{ph} \), shunt resistor current \( I_{sh} \), and the diode current \( I_d \). Furthermore, the total PV current \( I_{pv} \) of the cell is given in Eq. (1).

\[
I_{pv} = I_{ph} + I_{sh} - I_d
\]  

(1)

Based on the Shockley equation, the diode current, \( I_d \), is written and given in Eq. 2, and the shunt resistance current, \( I_{sh} \), is presented in Eq. 3. The thermal voltage, \( V_t \), of the PV module is given in Eq. 4.

\[
I_d = I_{sd}\left[\exp\left(\frac{V_{pv} + I_{pv}R_{se}}{V_t}\right) - 1\right]
\]  

(2)

\[
I_{sh} = \frac{V_{pv} + I_{pv}R_{se}}{R_{sh}}
\]  

(3)

\[
V_t = \frac{knT}{q}
\]  

(4)

Where, \( q \) represented the electron charge and is equal to \( 1.602*10^{-19} \) C, \( I_{sd} \) represents the saturation current, \( n \) represents the ideality factor, \( T \) symbolized the absolute temperature in Kelvin, the output voltage is denoted by \( V_{pv} \), \( k \) represents the Boltzmann constant and is equal to \( 1.3806*10^{-23} \) J/K. Based on the above-said equations, Eq. 1 is rewritten as follows.
Figure 1. Electrical equivalent circuit of the PV module.

\[ I_{pv} = I_{ph} - I_{sd} \left[ \exp \left( \frac{V_{pv} + I_{pv}R_{se}}{V_t} \right) - 1 \right] + \frac{V_{pv} + I_{pv}R_{se}}{R_{sh}} \]  

Eq. 5 is expanded to the PV module by considering the series-connected PV cells \((N_s)\) to form the module as follows and assume \(N_p\) is equal to 1. The thermal voltage for the module is given in Eq. 7.

\[ I_{pv} = I_{ph} - I_{sd} \left[ \exp \left( \frac{V_{pv} + N_sI_{pv}R_{se}}{V_t} \right) - 1 \right] + \frac{V_{pv} + I_{pv}R_{se}N_s}{R_{sh}N_s} \]  

\[ V_t = \frac{k n T N_s}{q} \]  

3. Proposed Estimation Technique

The suggested method of estimating the parameters of the SDM involves two iterative phases. The first phase is the calculation of the global value of \(n\). During this iterative process, the effect of the shunt resistor is ignored, and the \(R_{se}\) value is also determined. The \(R_{sh}\) value is then pulled out in phase 2, using the value from step 1. The presented method is simulated using MATLAB software.

3.1. Phase-I

During this step, Eq. 6 is rewritten by considering the zero effects due to the shunt resistance as Eq. 7. The operating conditions, such as open-circuit and short-circuit, is applied to Eq. 7 and the equations for the four unknown parameters, such as \(I_{ph}, I_{sd}, n,\) and \(R_{se}\). During short-circuit, the value of \(V_{pv}\) is equal to zero, and the value of \(I_{pv}\) is equal to the short-circuit current, \(I_{sc}\). Therefore, Eq. 6 rewritten as follows.

\[ I_{sc} = I_{ph} - I_{sd} \left[ \exp \left( \frac{N_sI_{sc}R_{se}}{V_t} \right) - 1 \right] \]  

Now, by considering the open-circuit test condition, Eq. 6 is rewritten as follows by assuming the value of \(V_{pv}\) is equal to the open-circuit voltage, \(V_{oc}\), and the value of \(I_{pv}\) is equal to zero.

\[ I_{ph} = I_{sd} \left[ \exp \left( \frac{V_{oc}}{V_t} \right) - 1 \right] \]  

From Eq. 8 and Eq. 9, the expression for the diode saturation current, \(I_{sd}\) is as follows.
\[ I_{sd} = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{V_t}\right) - 1} - \exp\left(\frac{N_s I_{sc} R_{se}}{V_t}\right) - 1 \]  

(10)

The output power during this iterative process is written as follows.

\[ P_{pv} = V_{pv} \ast \left( I_{ph} - I_{sd} \left[ \exp\left(\frac{V_{pv} + N_s I_{pv} R_{se}}{V_t}\right) - 1 \right] \right) \]  

(11)

Differentiate Eq. 11 with respect to \( V_{pv} \) and equate it to zero to derive the expression for \( R_{se} \).

\[ \frac{dP_{pv}}{dV_{pv}} = \left( I_{ph} - I_{sd} \left[ \exp\left(\frac{V_{pv} + N_s I_{pv} R_{se}}{V_t}\right) - 1 \right] \right) + V_{pv} \left( -\frac{I_{sd}}{V_t} \left[ \exp\left(\frac{V_{pv} + N_s I_{pv} R_{se}}{V_t}\right) \right] \right) = 0 \]  

(12)

By replacing \( V_{pv} \) and \( I_{ph} \) as \( V_{mpp} \) and \( I_{mpp} \) in Eq. 12, the expression for the \( R_{se} \) is written as follows.

\[ R_{se} = \left\{ V_t \ln \left[ \frac{I_{ph} - I_{sd}}{I_{sd} V_t + V_{mpp}} \right] - V_{mpp} \right\} \frac{1}{I_{mpp} N_s} \]  

(13)

Substitute Eq. 9 and Eq. 10 in Eq. 13, and the expression for the \( R_{se} \) is rewritten as follows.

\[ R_{se} = \frac{V_{oc}}{I_{mpp} N_s} + \frac{V_t}{I_{mpp} N_s} \ln \left[ \frac{V_t}{V_t + V_{mpp}} \right] - \frac{V_{mpp}}{I_{mpp} N_s} \]  

(14)

The value of the diode ideality factor taken from 1 to 2 on an iterative basis to estimate the other parameters by comparing the voltage value given by the manufacturer at the MPP. The variation of the value of \( n \) affects the thermal voltage, and hence the value of \( R_{se} \). The maximum power voltage can be obtained by using Eq. 6, and replacing \( I_{pv}=I_{mpp} \) and \( V_{pv}=V_{mpp} \) and with the highest voltage. The expression for the maximum output voltage is as follows.

\[ V_{mpp} = V_t \ln \left( \frac{I_{ph} - I_{sd}}{I_{sd}} \right) + V_t - I_{mpp} N_s R_{se} \]  

(15)

The initial definition of the parameter, \( n \) is provided by the proposed algorithm, which is equal to 1 and the tolerance for the measured voltage of 0.1 \( V_{max} \). The number of iterations is selected as 5000. \( V_t \), and \( R_{se} \) values are then calculated with the ideality factor, \( n=1 \), and started with iterations. When the newly estimated maximum voltage is lower than the theoretical voltage, the value of \( n \) is incremented by 0.01; otherwise, it is decremented by 0.01. For the new ideality factor, \( n \), the values, such as \( I_{ph} \), \( I_{sd} \), and \( V_{mpp} \) are recalculated using Eq. 9, Eq. 10, and Eq. 15, respectively. The algorithm continuously runs till the maximum iteration or the error is less than the specified tolerance. Lastly, the \( R_{se} \) value is updated with the estimated diode ideality factor.

3.2. Phase-II

The PV model without the effect of \( R_{sh} \) is, unfortunately, not accurate, and the MPP with the updated values of \( R_{se} \) and \( n \) does not correspond with the value stated by the manufacturer. Therefore, the value of \( R_{sh} \) is introduced to increase accuracy. A similar procedure is followed in step 2, but the estimated parameter is \( R_{sh} \) using the updated values of \( R_{se} \) and \( n \). The presented technique provides an initial \( R_{sh} \) estimate, which can be obtained using the expression below.

\[ P_{mpp} = V_{mpp} \ast \left( I_{ph} - I_{sd} \left[ \exp\left(\frac{V_{mpp} + N_s I_{mpp} R_{se}}{V_t}\right) - 1 \right] + V_{mpp} + \frac{I_{mpp} R_{se} N_s}{R_{sh} N_s} \right) \]  

(16)
From Eq. 16, the expression for the $R_{sh}$ is derived as follows.

$$R_{sh} = \frac{V_{mpp} \left( V_{mpp} + I_{mpp} R_{se} N_s \right)}{\left\{ V_{mpp} \left( I_{ph} - I_{sd} \left[ \exp \left( \frac{V_{mpp} + N_s I_{mpp} R_{se}}{V_t} \right) - 1 \right] \right) - P_{mpp} \right\} N_s} \tag{17}$$

As similar, the expressions for the updated values of diode saturation current, $I_{sd}$, and the photocurrent, $I_{ph}$, is derived from Eq. 6 by considering the open-circuit and short-circuit conditions.

$$I_{sd} = \frac{I_{sc} \left( 1 + \frac{R_{se}}{R_{sh}} \right) - \frac{V_{oc}}{R_{sh}} \left[ \exp \left( \frac{V_{oc}}{V_t} \right) - 1 \right]}{\left[ \exp \left( \frac{V_{oc}}{V_t} \right) - 1 \right] - \left[ \exp \left( \frac{N_s I_{sc} R_{se}}{V_t} \right) - 1 \right]} \tag{18}$$

$$I_{ph} = I_{sd} \left[ \exp \left( \frac{V_{oc}}{V_t} \right) - 1 \right] + \frac{V_{oc}}{R_{sh}} \tag{19}$$

As discussed earlier, an initial estimate of the $R_{sh}$ is needed in step 2. By considering the values of $n$, $R_{se}$, and $I_{ph}$, the value of $R_{sh}$ is calculated using Eq. 17. In step 2, the tolerance is 0.001 A, and the number of iterations is equal to 5000. The updated $I_{sd}$ and $I_{ph}$ values are calculated using Eq. 18-19 with the initial estimation of $R_{sh}$. The method consists of locating the current at the maximum power conditions in Eq. 6 with $V_{pv} = V_{mpp}$. The calculated power is compared with the maximum power provided by the supplier, and the value of $R_{sh}$ is updated. If the value is below the expected current, the $R_{sh}$ value is incremented by a factor, $0.1 \times \text{current iterations}$, otherwise decremented by a factor, $0.1 \times \text{current iterations}$. The error is compared with the acceptable tolerance. This process is repeated until the error exceeds the desired threshold or the maximum number of iterations.

The accuracy of the PV model is evaluated by finding the value of the root mean square error (RMSE). The expression for finding the value of RMSE is given as follows.

$$RMSE = \sqrt{\frac{1}{M} \sum_{j=1}^{M} (I_{exp,j} - I_{sim,j})^2} \tag{20}$$

Where, $I_{sim,j}$ denotes the simulated value of the current and $I_{exp,j}$ denotes the measured value of the current. Along with the value of RMSE, the other performance metrics, such as the absolute error (AE) and relative error also calculated as per the following equations.

$$RE_i = \frac{I_{exp} - I_{sim}}{I_{exp}} \tag{21}$$

$$AE_i = \left| \frac{I_{exp} - I_{sim}}{I_{exp}} \right| \tag{22}$$

4. Results and Discussions

The presented parameter estimation approach was realized by utilizing the SDM equations in the MATLAB software. The method was selected to test the Kyocera KC200GT module with 54 series-connected PV cells. The specifications of the PV module are shown in Table 1.

The various output data phases of the presented technique for the Kyocera KC200GT PV module is shown in Fig. 2. Fig. 2 illustrates the V-I and P-V characteristics of the PV module by considering the three cases, such as without the effect of $R_{sh}$, with the effect of the $R_{sh}$, and the proposed technique by considering the effect of $R_{sh}$. From Fig. 2, it is noticed that the model by considering the
effect of $R_{sh}$ shows a better result, and matches the datasheet results. Therefore, it is decided to consider the presented equations from Eq. 9 - Eq. 19 to model the proposed technique.

**Table 1.** Electrical specifications of Kyocera KC200GT PV module.

| S. No. | Name of the parameters        | Specifications |
|-------|-------------------------------|----------------|
| 1     | Maximum output voltage, $V_{mpp}$ | 26.3 V         |
| 2     | Maximum output current, $I_{mpp}$ | 7.61 A         |
| 3     | Open circuit voltage, $V_{oc}$  | 32.9 V         |
| 4     | Short circuit current, $I_{sc}$ | 8.21 A         |
| 5     | Temperature coefficient at $V_{oc}$ | 0.0138 V/°C |
| 6     | Temperature coefficient at $I_{sc}$ | -0.123 A/°C |
| 7     | Number of series cells, $N_s$    | 54             |

![Figure 2.](image) Various output phases of the presented method, (a) V-I characteristics, (b) P-V characteristics.
The PV module behavior is simulated by a model defined by Eq. 6 for the STC, i.e., 1000 W/m$^2$ solar irradiance and 25 °C temperature. The V-I characteristics of the Kyocera KC200GT PV module with respect to STC is illustrated in Fig. 3.

![Experimental and Estimated Characteristics](image1)

**Figure 3.** Characteristics of the Kyocera KC200GT PV module at STC, (a) V-I curve, (b) P-V curve.

The performance comparison of the presented technique and other techniques, such as Nayak [13], Silva [12], and Hejri [14], is presented in Table 2. The accuracy of all methods is assessed by the RMSE, AE, and RE values. The presented technique shows, among comparative approaches in the STC,
the best results for RMSE, AE, and RE. The values of RMSE, AE, and RE are 1.985E-03, 5.471E-03, and 3.698E-03, respectively. Table 4 presents the estimated parameters of the Kyocera KC200GT PV module, as a thorough study, via the presented technique at different solar irradiance and temperature values. The assessment metrics, such as RMSE, AE, and RE for all methods, including the proposed method is shown in the bar chart as follows for a better understanding. According to the above discussions, it is concluded that the presented technique which utilizes Eq. 6 gives the excellent performance at STC as compared with the conventional analytical techniques.

Table 2. Performance Comparison for the Kyocera KC200GT PV module at STC.

| Technique | Parameters | Metrics |
|-----------|------------|---------|
|           | $I_{ph}$ (A) | $I_{sd}$ (µA) | $n$ | $R_{sh}$ (Ω) | $R_{se}$ (Ω) | RMSE  | AE       | RE       |
| [12]      | 8.193      | 0.0003   | 1.000 | 171.2   | 0.2710   | 0.19   | 9.245E-2 | 9.988E-2 |
| [13]      | 8.193      | 0.0358   | 1.241 | 599.9   | 0.1984   | 0.15   | 4.878E-2 | 6.547E-2 |
| [14]      | 8.160      | 0.1501   | 1.340 | 951.9   | 0.1800   | 0.11   | 1.326E-2 | 2.147E-2 |
| Proposed  | 8.201      | 0.1781   | 1.334 | 951.93  | 0.2201   | 1.985E-3 | 5.471E-3 | 3.698E-3 |

The presented technique displays good outcomes in STC when compared to the methods discussed in the literature. Besides, the SDM for the extraction of V-I and P-V curves is normally used in the STC. However, a suitable model must be used to have accurate V-I and P-V curves which approach the expected values.

Table 3. Estimated parameters of the Kyocera KC200GT PV module at different temperature and solar irradiance.

| Temperature (°C) | Solar Irradiance (W/m²) | Parameters | $I_{ph}$ (A) | $I_{sd}$ (µA) | $n$ | $R_{sh}$ (Ω) | $R_{se}$ (Ω) |
|------------------|-------------------------|------------|--------------|---------------|-----|--------------|--------------|
|                  | 200                     |            | 1.592        | 0.0352        | 1.239 | 4389.36      | 1.0014      |
|                  | 400                     |            | 3.285        | 0.0692        | 1.277 | 2273.58      | 0.5179      |
|                  | 600                     |            | 4.939        | 0.1035        | 1.308 | 1545.87      | 0.3478      |
| 25 °C            | 800                     |            | 6.568        | 0.1388        | 1.317 | 1169.55      | 0.2688      |
|                  | 1000                    |            | 8.201        | 0.1781        | 1.334 | 951.93       | 0.2201      |
|                  | 1000                    |            | 8.288        | 0.0558        | 1.048 | 1351.22      | 0.3077      |

Figure 4. Bar chart of the metrics for all algorithms.
5. Conclusions
This paper presents a simplified parameter estimation technique for the SDM. The presented technique is based on two phases of iteration to estimate the parameters of the SDM. The technique was well-defined with all the necessary equations and simulated through MATLAB software. The commercial Kyocera KC200GT PV module is used for functional testing, and the outcomes of the presented technique are compared with the other methods. The assessment metrics, such as RMSE, AE, and RE, are employed to confirm the accuracy of the proposed technique. The error values were calculated for the PV module under STC. To conclude, when compared to other approaches, decent outcomes were realized. In fact, the RMSE, AE, and RE respectively in STC were equal to 1.985E-3, 5.471E-3, and 3.698E-3, and these values are better than other approaches.

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