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# A Compact Mathematical Modelling for Performance Evaluation of PV Module considering Single-Diode M odel

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## Abstract

**Objective:** To develop closed-form relation between current and voltage of PV module based on single-diode equivalent circuit under valid approximation. **Methods:** The behaviour of PV module under various operational conditions can be easily and accurately determined when the intrinsic parameters like series resistance, shunt resistance, photo current and ideality factor are accurately modelled. Therefore, it is required to develop a mathematical model that must be compact and accurate to provide new insights into the electrical performance of the module faster. This paper presents a simple, compact, and precise mathematical model of these intrinsic parameters which enable high-speed and accurate predictions of the electrical characteristics of the commercially available PV module. **Findings:** The proposed model shows an excellent matching with experimental results only for $V<V_{oc}$. Terminal current degrades and takes negative value when voltage is larger than $V_{oc}$. The proposed model is applicable to Si-based crystalline and polycrystalline PV modules when $R_s<1\ \Omega$ and $V\leq V_{oc}$. As series resistance increases, ideality factor takes negative value. This observation reflects that increase in $R_s$ over years degrades the performance of the module. From analysis it was observed that larger open circuit voltage and short circuit current are desirable for larger photocurrent in PV module. Larger Ns results in lower series resistance which ultimately increases the terminal current and enhance the overall module performance whereas larger dark current reduces the terminal current which further degrades the performance of the cell. **Novelty:** The compact closed form of analytical validated model for current-voltage characteristics to predict the behavior of PV module accurately within limited computation time. The proposed models of five intrinsic parameters enable high-speed accurate prediction of the electrical characteristics of the commercial module.

**Keywords:** Solar Cell; Photo Voltaic Module; Mathematical Models; Standard Test Conditions; Single Diode Model

## 1 Introduction

Modeling and simulation of PV modules is essential at the predesign stage in better understanding of its performance and characteristics. The current-voltage characteristics of the photovoltaic module is characterized by its nonlinear implicit equation that would be hard to solved numerically. Since, modeling of PV cell involves the estimation of the current-voltage characteristics curve to evaluate the performance of the commercial cell under various environmental conditions, therefore, the developed characteristics equation should be accurate, compact, and simple for effective use in predicting the behaviour of PV cell accurately with less computational time. A single diode model of a solar system has been studied for decades because it gives simple and reliable analysis of the current-voltage characteristics of solar cells[1–3]. The model requires thorough and careful computation of five unknown parameters, photo current ($I_{ph}$), dark current ($I_0$), ideality factor ($\eta$), series resistance ($R_s$) and shunt resistance ($R_{sh}$), to determine the current in the PV module. Exponential non-linearity of the current equation in the single diode model causes many problems for evaluating these parameters. Several techniques were proposed by researchers to determine these five intrinsic unknown parameters based on the equivalent circuit model. Among them numerical and analytical methods[4,5] are the traditional techniques. The analytical approach relies heavily on the data for short-circuit current, maximum power point voltage ($V_m$), maximum power point current ($I_m$), open-circuit voltage ($V_{oc}$). The values of these parameters are provided by manufacturer's at STC (standard test conditions) or NOC (nominal operating conditions). Numerical methods are based on iterative algorithms for fitting simulated I-V curves into experimental data. This technique is time consuming[6]. The simplest and comprehensive approach takes arbitrary value of ideality factor and determines other parameters by adjusting the curve at $I_{sc}$, $P_m$ and $V_{oc}$ points. An accurate and fast convergence method of extracting the unknown parameters by first analysing the ideality factor and setting it as the primary parameter and obtaining the shunt/series resistances through a repetitive process was reported in ref.[7]. This method is not economical in terms of time. Other available models are, normalized root mean-square deviation (NRMSD)[8], Newton-Raphson algorithm[9] and Lambert W Function[10]. These methods have complex implementation procedures and relatively low calculation speed that require more computing power. From above discussion, it is evident that determining values of these five parameters is a challenging task. Considering these challenges, it is required to develop a model for each parameter individually to make analysis faster and easier. The compact analytical validated models are necessary to predict the behavior of PV module accurately within limited computation time.

In this paper we have proposed compact mathematical models for $I_{Ph}$, $\eta$, $R_s$ and $R_{sh}$ based on single diode equivalent circuit which is further utilised to derive closed form relation of I-V characteristics of the PV module. The proposed models have been simulated using MATLAB and the results were compared to published results in literature. This paper is organized as follows: section II describes the methodology whereas section III presents simulation results and discussion to show the validity and importance of the developed models. Finally, section IV concludes the paper.

## 2 Methodology

### 2.1 Mathematical Modelling for Current-Voltage Characteristics

Figure 1 shows the single diode circuit that consists of shunt resistance $R_{sh}$ and series resistance $R_s$. The series resistance $R_s$ takes care of ohmic losses inside different regions of solar cell and assumed to be zero in an ideal case whereas the shunt resistance ($R_{sh}$) represents the resistance offered to the leakage path of the current flow and is assumed to be infinite for ideal case[11]. $I_{Ph,}$ I and V represent photocurrent, the terminal current and voltage, whereas $I_D$ and $I_{sh}$ represent the diode current and shunt current respectively.

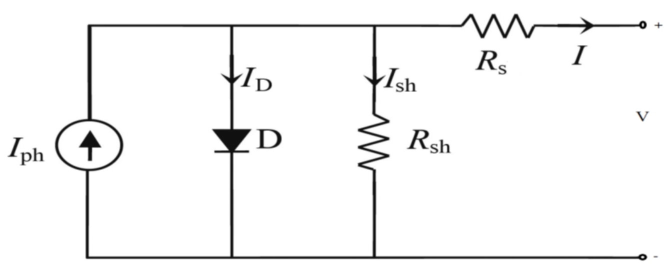



**Fig 1.** Single Diode Model

The characteristics equation of the five-parameter model is generated from Kirchhoff's current law (KCL) in Figure 1 and expressed as

$$I = I_{ph} - I_0 \left\{ \exp\left(\frac{V_D}{\eta V_{Th}}\right) - 1 \right\} - \frac{V}{R_{Sh}} \tag{1a}$$

After solving equation 1(a), we get

$$I = \left(\frac{R_{sh}}{R_S + R_{sh}}\right) \left[ I_{ph} - I_0 \left\{ \exp\left(\frac{IR_S}{\eta V_{Th}}\right) \exp\left(\frac{V}{\eta V_{Th}}\right) - 1 \right\} - \frac{V}{R_{Sh}} \right] \tag{1b}$$

Equation 1(b) is an implicit and transcendental equation that would normally require a numerical solution to obtain the five parameters. However, numerical methods are susceptible to convergence and initialization difficulties. *Assuming* $\frac{IR_s}{\eta V_{Th}} \ll 1$ (because $R_s$ is very-2 small) equation 1(b) reduces as

$$I = \left[ I_{ph} + I_0 \left\{ 1 - \exp\left(\frac{V}{\eta V_{Th}}\right) \right\} - \frac{V}{R_{Sh}} \right] / \left[ \left(\frac{R_S + R_{Sh}}{R_{Sh}}\right) + I_0 \frac{R_S}{\eta V_{Th}} \exp\left(\frac{V}{\eta V_{Th}}\right) \right] \tag{1c}$$

Equation 1(c) gives compact and closed form of mathematical relation between current and voltage of the PV cell. This equation can evaluate the electrical performance accurately and faster. For ideal conditions ($R_s$=0 and $R_{sh}$=∞), equation 1(c) reduces to $I = \left(I_{ph} + I_0 \left(1 - exp\left(\frac{V}{\eta V_{Th}}\right)\right\}\right]$

This expression predicts that in ideal condition, the terminal current I depends exponentially on the terminal voltage V, which contradicts the observation that ideally current I is independent of terminal voltage. The expression 1(c) also shows that the values of five parameters are essential for designing, sizing, and measuring the performance of the PV systems.

## 2.2 Modelling for Ideality factor ($\eta$)

Ideality factor is an important electrical parameter in the description of the solar cell's behaviour and provides the valuable information about the charge transportation and recombination process in the cell. Consider two cases.

**Case1: Open circuit**: In this case, I=0 and V=$V_{oc}$, under this condition, equation 1(a) reduces to

$$V_{oc} = R_{sh} \left[ I_{ph} + I_0 \left\{ 1 - \exp\left(\frac{V_{oc}}{\eta V_{Th}}\right) \right\} \right] \tag{2a}$$

**Case 2: Short Circuit**: V=0 and I=$I_{sc}$, under this condition, equation 1(a) reduces to

$$I_{sc} = \left(\frac{R_{sh}}{R_s + R_{Sh}}\right) \left[ I_{ph} + I_o \left\{ 1 - \exp\left\{\frac{I_{sc} R_S}{\eta V_{Th}}\right\} \right\} \right] \tag{2b}$$

After solving equation 2(a), without any approximation, we have,

$$\eta = \left(\frac{V_{oc}}{V_{Th}}\right) \left[ \ln \left( \frac{I_{ph} + I_0 - \frac{V_{oc}}{R_{Sh}}}{I_0} \right) \right]^{-1} \tag{3a}$$

The proposed expression 3(a) is based on open circuit condition and predicts that $\eta$ only depends on the shunt resistance $R_{sh}$ and dark current $I_0$. At open circuit condition the voltage drop across series resistance is zero which allows a better analysis of the recombination mechanism at higher voltage. Equation 3(a) gives more accurate value of $\eta$ compared to the expression based on the short circuit condition because short circuit condition-based ideality factor equation is not closed form expression since it depends on series resistance $R_s$. The closer look of the denominator of equation 3(a) shows that the logarithm term is greatly influenced by current $I_0$ instead of $I_{sc}$ as reported in literature[12]. The ideality factor $\eta$ increases as $I_0$ increases due to increased recombination process which is undesirable. The maximum value of $\eta$ is obtained by letting $R_{sh}$=∞ in equation 3(a) which is expressed as

$$\eta_0 = \left(\frac{V_{oc}}{V_{Th}}\right) \left[ \ln \left(\frac{I_{Ph} + I_0}{I_0}\right) \right]^{-1} \tag{3b}$$

Expression 3(b) shows that the optimal ideality factor gets affected only by $I_{Ph}$ and $I_0$. Larger value of $I_{Ph}$ results lower ideality factor as desired whereas larger $I_0$ gives larger value of $\eta$ which is undesirable. The relationship between $\eta_0$ and $\eta$ is derived using equations 3(a) and 3(b) and given as,

$\eta = \eta_0 - (\frac{V_{oc}}{V_{Th}})[ln\left\{1 - \frac{V_{oc}}{R_{sh}}\frac{1}{I_{Ph}}\right\}]$

This is an important relation to estimate the ideality factor at any conditions when $R_{sh} \neq \infty$. In terms of parameters, $I_m$ (maximum terminal current) and $V_m$ (maximum terminal voltage), ideality factor is given as

$$\eta = \left[\frac{\frac{V_m - V_{oc} + I_m R_s}{V_{Th}}}{ln\left\{\frac{I_{sc} - I_m}{\left(1 + \frac{R_s}{R_{sh}}\right) I_{sc} - \frac{V_{oc}}{R_{sh}}}\right\}}\right] \tag{4}$$

The proposed analytical model (4) is not only simple but compact also compared to the models presented in [12,13]. Equation 3(a) shows the dependency of $\eta$ on $I_0$ whereas at maximum power condition ($V_m$, $I_m$) $\eta$ is independent of $I_0$ which is a major observation concluded from equation (4).

## 2.3 Mathematical Modelling for Photocurrent $I_{Ph}$

Since, photocurrent measurement/calculation is the key instrument for inspecting the properties and performance of PV cell, therefore a sufficiently accurate and compact model of photocurrent is needed. From equation 2(a) we get

$$I_{Ph} = \left(\frac{\left(1 + \frac{R_S}{R_{sh}}\right) I_{sc} + \left(\frac{V_{oc}}{R_{Sh}}\right)\alpha}{(1+\alpha)}\right) \tag{5a}$$

This expression shows that $I_{Ph}$ is solely dependent on incoming light and is independent of voltage across the cell. Substituting value of $I_0$ from [12] into equation 5(a), we get

$$I_{Ph} = \left(\frac{\left(1 + \frac{R_S}{R_{Sh}}\right) I_{SC} + \left(\frac{V_{oc}}{R_{Sh}}\right)\alpha}{(1+\alpha)}\right. \tag{5b}$$

Where

$\alpha = \left(\frac{\exp\left(\frac{I_{SC}R_S}{\eta V_{Th}}\right)}{\exp\left(\frac{V_{oc}}{\eta V_{Th}}\right)}\right)$

For ideal situation, equation 5(b) reduces to

$I_{Ph0} = \left(\frac{I_{sc}}{(1+\alpha 0)}\right)$

Where

$\alpha 0 = \left(\frac{1}{exp(\frac{V_{oc}}{\eta V_{Th}})}\right)$

This expression tells that even in ideal situation $I_{Ph} \neq I_{sc}$ as reported in ref[12] but it is smaller than the short circuit current. The approximation that $I_{Ph}=I_{sc}$ introduces error in calculation of the photocurrent. It is observed that ideally $I_{Ph}$ will be equal to $I_{sc}$ when $(V_{oc}/\eta V_{Th}) << 1$.

## 2.4 Mathematical Modelling for Parasitic Resistance (Rs and Rsh)

Parasitic resistances $R_s$ and $R_{sh}$ play an important role to decide the performance of the solar module correctly. These resistances affect the slope of the I-V characteristics which ultimately affects the fill factor as well as efficiency of the cell. A compact analytical model for these resistances is essential to evaluate the performance and degradation of the cell in outdoor environment. Researchers have mostly calculated the value of $R_s$ and $R_{sh}$ by approximating the reciprocal of the slope of the

I-V curve at the open circuit and short-circuit-points[14]. In this paper, we have proposed the mathematical expressions for $R_{sh}$ and $R_s$ by considering maximum power point technique and assuming maximum power remains constant with voltage at $V_m$.

At maximum power point

$$\frac{\mathrm{dI}}{dv}\left(I_m, V_m\right) = -\frac{I_m}{V_m} \tag{6a}$$

Differentiating equation 1(a) we have

$\frac{I_m}{V_m} = \left(\frac{R_{sh}}{R_{sh}+R_s}\right)\left[-I_0 \exp\left(\frac{IR_s+V}{\eta V_{Th}}\right)\left\{\frac{\mathrm{dI}}{\mathrm{dV}}\mathrm{R_s}+1\right\}\left(\frac{1}{\eta V_{Th}}\right) - \frac{1}{R_{sh}}\right]$

Substituting (dI/dV)=$I_m$/$V_m$ in above equation and after simplification, we get

$\left(\frac{I_m}{V_m}R_s - 1\right] = (I_0\alpha_{11} - \frac{I_m}{V_m})R_{sh}$

Where $I_0 = \frac{(R_{sh}+R_s)I_{sc}-V_{oc}}{R_{sh}[-\frac{I_{sc}R_s}{\eta V_{Th}}+\left(1-exp\left(\frac{V_{oc}}{\eta V_{Th}}\right)\right)]}$

$$\alpha_{11} = exp\left(\frac{IR_s+V_m}{\eta V_{Th}}\right)(1-\frac{I_m}{V_m}R_s)(\frac{1}{\eta V_{Th}})$$

After solving we finally get

$$R_{sh} = \frac{\beta\left(R_s I_{sc} - V_{oc}\right) - \alpha_{12}}{\left(\frac{I_m}{V_m}\right) - \left(I_{sc}\right)\beta} \tag{6b}$$

Where,

$\alpha_{12} = (\frac{I_m}{V_m}R_s - 1), \beta = \frac{\alpha_{11}}{\alpha_{14}}, \alpha_{14} = -\frac{I_{sc}R_s}{\eta V_{Th}}$+(1-exp$\frac{V_{oc}}{\eta V_{Th}}$)

Equation 6(b) is simple and compact.

To derive the analytical expression for series resistance $R_s$, we used following boundary condition (BC) $\frac{dP}{dV}\left(I_m,\, V_m\right) = 0$

Since, P=V*I and using relations 1(a) and above boundary condition, we get

$$I_0\left[1-\exp\left(\frac{I_m R_S + V_m}{\eta V_{Th}}\right)\left(\frac{V_m}{\eta V_{Th}}\right)\right] = \frac{2V_m}{R_{Sh}} - I_{Ph} \tag{7a}$$

Assuming $\frac{V_m}{\eta V_{Th}} \gg 1$, $\frac{I_m R_s+V_m}{\eta V_{Th}} \approx \frac{V_m}{\eta V_{Th}}$ (since $R_s$ is very-2 small) and $(1-\exp\left(\frac{V_m}{\eta V_{Th}}\right)\left(\frac{V_m}{\eta V_{Th}}\right)) = \beta_{11},$ equation 7(a) reduces to

$I_0\beta_{11} = \frac{2V_m}{R_{sh}} - I_{Ph}$

Substituting the values of $I_{Ph}$ and $I_0$ in above equation, we get

$\frac{\beta_{11}\left[\left(\frac{R_S+R_{Sh}}{R_{Sh}}\right)I_{sc} - \frac{V_{oc}}{R_{Sh}}\right]}{\left(\frac{I_{sc}R_S}{\eta V_{Th}}+\beta_{12}\right)} = \frac{2V_m}{R_{sh}} - \left[\left(\frac{R_{Sh}+R_S}{R_{sh}}\right)I_{sc} + I_0\left\{\frac{I_{Sc}R_S}{\eta V_{Th}}\right\}\right]\}$

This equation is solved by making an approximation that $\frac{I_{sc}R_s}{\eta V_{Th}} \ll 1$, and $(\frac{R_s+R_{sh}}{R_{sh}}) \approx (\frac{R_s}{R_{sh}})$ which results.

$$R_s = \frac{\gamma_{11}}{2}\left[-1 \pm \sqrt{1+\frac{4\gamma_{12}}{\gamma_{11}^2}}\right] \tag{7b}$$

Where,

$\gamma_{11} = \frac{\beta_{11} - \frac{V_{oc}}{\eta V_{Th}} - \frac{2V_m}{\eta V_{Th}} + \beta_{12}}{\frac{2I_{sc}}{\eta V_{Th}}}$

and

$\gamma_{12} = \frac{(V_{oc}\beta_{11} - 2V_m\beta_{12})\eta V_{Th}}{2I_{sc}^2}$,

and $\beta_{12} = exp\left(\frac{V_{oc}}{\eta V_{Th}}\right) - 1$

The analytical expression of $R_s$ is quadratic in nature. While deriving the analytical models we observed that the four parameters ($I_{Ph}$, $I_0$, $R_s$ and $R_{sh}$) depends on ideality factor whereas ideality factor depends on $R_s$ and $R_{sh}$. Therefore, once value of ideality factor is known, all other parameters can be easily calculated to evaluate the electrical performance of the module.

To determine ideality factor $\eta$ we have assumed that initially $R_s$=0 Ω and $R_{sh}$=$R_{sh0}$ where the mathematical expression for $R_{sho}$ is given as.

$$R_{sh0} = \frac{1+\left(\frac{(V_m+V_{oc})*Ns}{V_m}\right)}{\left(\frac{I_m}{V_m}\right)-\left(\frac{I_{sc}}{V_m-V_{oc}}\right)}$$

The whole methodology adopted in this paper for analysing current-voltage characteristics of the module is given in Figure 2 .

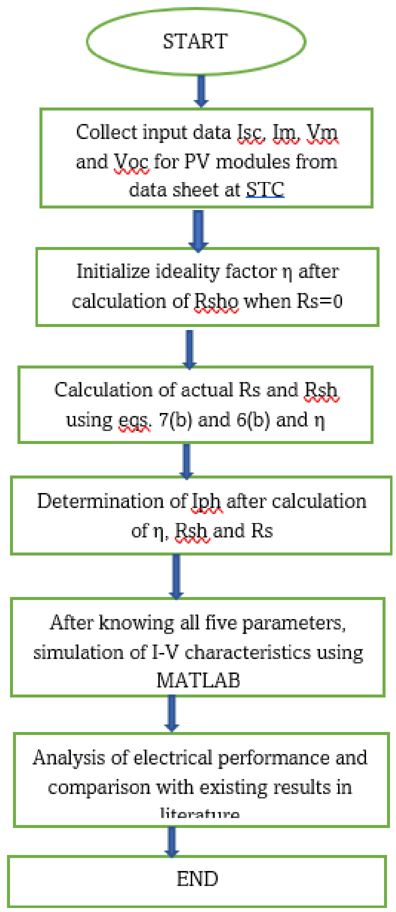



**Fig 2.** Flow Chart for the Proposed Methodology

## 3 Results and Discussion

The I-V characteristics has been numerically calculated using MATLAB for various PV modules after replacing $\eta$*$V_{Th}$ by $N_s$*$\eta$*$V_{Th}$, where $N_s$ is the number of series connected cells. The values of the parameters $I_{sc}$, $V_{oc}$, $I_m$, $V_m$ were taken from data sheet provided by manufacturer at STC ($T_r$=298 K, $G_r$=1000 W/m$^2$) (Table 1 ). For comparison purpose, we have chosen the same values of the various parameters as provided in the literature.

We have compared the simulated results of the parameters $\eta$, $R_s$ and $R_{sh}$ with the published and experimental results available in the literature[14–17] for various solar modules at STC (Table 2 ) with good agreement for $\eta$ and $R_s$. Table 2 results confirm the validity of the proposed analytical models of the parameters $\eta$, $R_s$ and $R_{sh}$.

Figure 3 shows that the ideality factor falls with increase in $R_{sho}$. Larger $R_{sho}$ results in lower ideality factor due to controlled leakage current which increases the efficiency of the cell by reducing the recombination rate. During simulation, it is observed that ideality factor $\eta$ takes negative value for larger value of $R_s$, which is a serious concern because as $R_s$ increases over years

**Table 1.** Electrical Performance under STC

| Type of solar Module | Open circuit voltage $V_{oc}$ (V) | Short circuit current $I_{sc}$ (A) | Maximum Power Voltage $V_m$ (V) | Maximum Power Current $I_m$ (A) | Number of series connected cell |
|---|---|---|---|---|---|
| KC200GT | 32.9 | 8.21 | 26.3 | 7.61 | 54 |
| SQ80 PV | 21.8 | 4.85 | 17.5 | 4.58 | 72 |
| STM-40/36 | 21.02 | 1.663 | 16.98 | 1.50 | 36 |
| STM-120/36 | 19.21 | 7.48 | 14.93 | 6.83 | 36 |
| Photowatt-PWP 201 | 16.778 | 1.030 | 12.649 | 0.912 | 36 |

**Table 2.** Comparison results for $\eta$, $R_s$ and $R_{sh}$

| Module Type | Ideality Factor $\eta$ | | | Series Resistance ($R_s$) $\Omega$ | | | Shunt Resistance ($R_{sh}$) $\Omega$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Reported | Proposed | Absolute error | Reported | Proposed | Absolute error | Proposed | Reported | Absolute error |
| KK280P [15] | 1.72293 | 1.6958 | 0.02713 | 0.27686 | 0.3123 | -0.03544 | 190.645 | 189.1763 | 1.4687 |
| JAP60SO1 [15] | 1.54662 | 1.5272 | 0.01942 | 0.21724 | 0.19111 | 0.02613 | 501.121 | 490.5887 | 10.5323 |
| REC245E [15] | 1.912 | 1.5945 | 0.3175 | 0.26557 | 0.2068 | 0.0561 | 2094.48 | 2104.541 | -10.061 |
| TSM295 [16] | 2.621 | 1.980 | 0.64 | 0.3283 | 0.29068 | 0.03762 | 275.394 | 272.4439 | 2.9501 |
| BPMX-120 [17] | 1.3976 | 1.4121 | -0.0145 | 0.4728 | 0.5358 | -0.063 | 1365.8 | 1374.56 | -8.76 |
| KC200GT [14] | 1.08317 | 1.08285 | 0.00032 | 0.27077 | 0.2621 | 0.00867 | 124 | 124 | 0 |

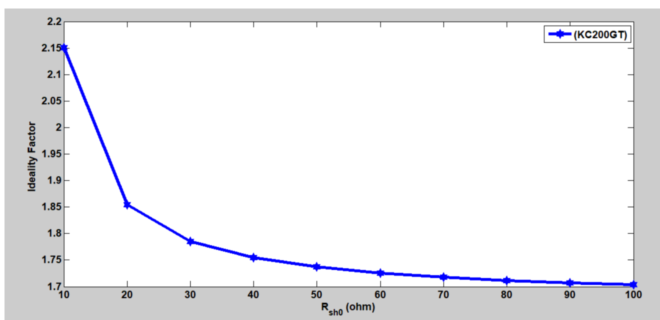



**Fig 3.** Variation of ideality factor ($\eta$) with $R_{sho}$ when $R_s$=0 Ω for KC200GT module

the performance of the cell degrades. The degraded performance of the cell reduces the capacity of PV system.

Figure 4 shows that series resistance$R_s$ does not depend upon $V_{oc}$ significantly and larger value of Ns results in lower series resistance which is an essential requirement to enhance the performance of the module. Figure 5 shows that beyond the critical value of $V_{oc}$, photocurrent remains constant irrespective of $I_{sc}$.

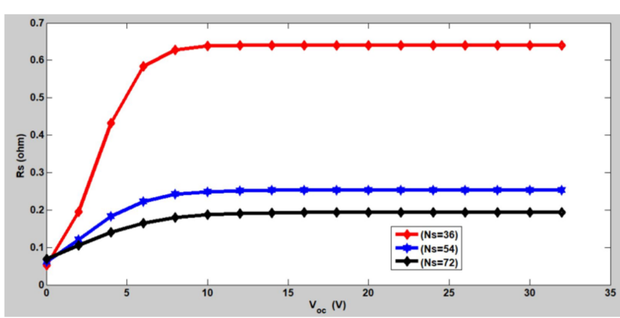



**Fig 4.** $R_s$ versus $V_{oc}$ for different $N_s$ value

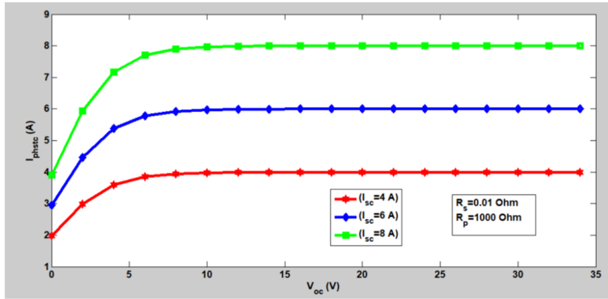
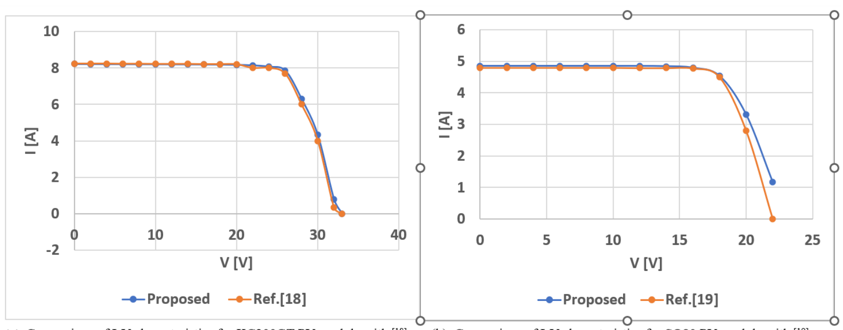



**Fig 5.** Variation of$I_{Ph}$ versus $V_{oc}$ for different $I_{sc}$

To show the validity of the proposed closed form current-voltage equation (which is derived using minimal approximation), we have compared the numerically calculated value of current at various terminal voltage for the KC200GT with ref[18] (Figure 6 (a)) and the Shell SQ80 PV modules with[19] results (Figure 6 (b)). The proposed model shows an excellent matching with[18] results. For terminal voltage larger than open circuit voltage, terminal current degrades for KC200GT. The proposed model is simple, compact and closed form, whereas the ref[18] model is based on an iterative method that is time-consuming. The numerically calculated results of equation 1(c) show an excellent matching with ref[19] results for $V<V_{oc}$ and a slight difference for larger terminal voltage is due to negligence of material properties in the proposed model (Figure 6 (b)). The values of parameters of $R_s$, $R_{sh}$, $I_{ph}$, $I_0$ and $\eta$, taken from different published papers, are given in Table 3 .



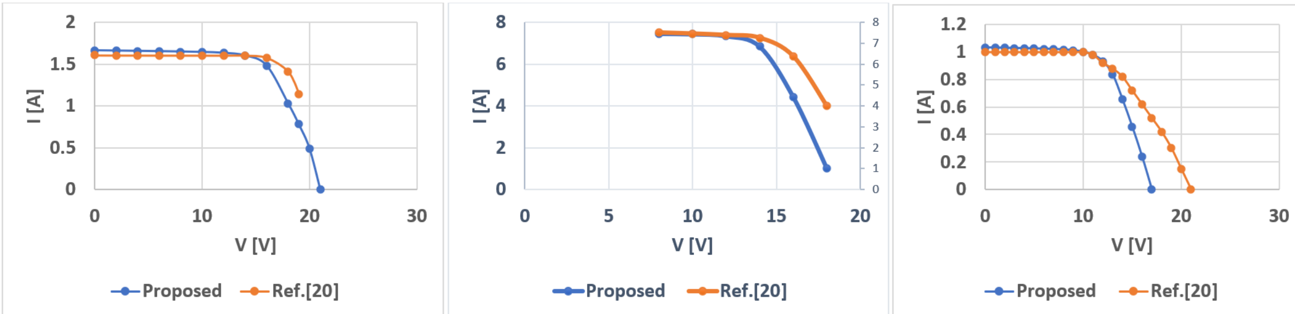

(a): Comparison of I-V characteristics for KC200GT PV module with [18] (b): Comparison of I-V characteristics for SQ80 PV module with [19]

**Fig 6.** Comparison of current-voltage characteristics

**Table 3.** Values of various parameters obtained from literature

| PV module | $R_s$ (Ω) | $R_{sh}$ (Ω) | $I_{ph}$ (A) | $\eta$ | $I_0$ x10$^{-6}$ A |
|---|---|---|---|---|---|
| STM-40/36 [20] | 0.1617 | 573.51 | 1.663469 | 1.5100579 | 1.58333 |
| STM-120/36 [20] | 0.17585 | 360.22 | 7.4836 | 1.20897 | 1.2367 |
| Photowatt-PWP201 [20] | 1.2210 | 716.54024 | 1.03345 | 1.03345 | 2.9484 |
| KC200GT [18] | 0.2187 | 712.83 (1/0.00002535) | 8.2174 4.85 | 1.34 | 1.667x10$^{-1}$ |
| Shell SQ 80 PV [19] | 0.339988 | | | 1.2243 | 2.0463x10$^{-2}$ |

Figure 7 compares I-V characteristics obtained using the proposed mathematical model with experimental findings of various PV modules as reported in the ref[20]. Our numerically calculated values show an excellent matching with the experimental values, except at higher terminal voltages due to negligence of temperature effect in the model that drastically affect the performance of the module. For all the solar module, terminal current degrades drastically and takes negative value when terminal voltage is larger than open circuit voltage ($V_{oc}$). For Photowatt-PWP 201 solar module case, the difference is larger at higher terminal voltage due to larger series resistance. This result confirms that the proposed model is valid only for lower series resistance ($R_s$<1 Ω) and V≤ $V_{oc}$.




(a): STM-40/36 solar moule (b): STM-120/36 solar module (c): Photowatt-PWP 201 solar module

**Fig 7.** Comparison of Current-Voltage characteristics with experimental results for various PV modules

Table 4 (a) explains the symbol and abbreviations whereas Table 4 (b)gives the comparison of various techniques used to model the five intrinsic parameters as well as I-V characteristics the PV module with proposed models which is simple, compact and less time consuming. The proposed I-V characteristics is not transcendental in nature as reported in literature.

**Table 4.** Comparison amongavailable techniques

| Different Methods | Comparison |
|---|---|
| Numerical methods [1] | Depend on initial values to initiate the process and suffers from convergence problems and usually uses non-linear optimization techniques, such as: Newton–Raphson methods (NRM), conductivity method (CM) or the Levenberg–Marquardt (LM) algorithm. The major disadvantage is that the large number of unknown parameters complicates the extraction's procedure, and the approach is scarifying thebaccuracy.<br>Lambert W function is used in literature for solving transcendental I-V characteristics analytically which necessitates several approximations/relaxations as the mathematical relation between currents and voltages is nonlinear, affecting the model's accuracy. |
| Analytical methods [6] | These methods require simplifications or approximations of the expressions used which has a significant impact on the solution's accuracy. |
| Deterministic and metaheuristic algorithms [21] | Due to their reliance on gradient information and sensitivity to initial points, deterministic algorithms are unreliable. Moreover, because of their nonlinearity, these classical algorithms also have trouble capturing local optima in the nonconvex space the equivalent PV circuits created. The result may be an inaccurate estimation of parameters and, consequently, a failure to track the maximum power point |
| Traditional PV module maximum power point detection technology [17] | This method can guarantee the accuracy of the fitting curve through a large amount of experimental data, in practice, the accuracy of the fitting curve is poor (less than 10%) because of the inaccuracy of the sampling data itself or the unreasonable sampling point. As a result, there is a certain deviation between the calculated maximum power point and the real maximum power point, and the output power of PV module cannot be maximized.<br>At the same time, when the Newton iterative method is used to solve the extreme value of the polynomial, the algorithm is not convergent because the selection of the initial value is not suitable, or the target deviation and the step length are not correct. Thus, it makes the maximum power point detection fail. |
| Evolutionary algorithm (EA) [21] | This technique requires a huge amount of data for training and processing work, which needs a large computer memory space. Acquiring these datasets itself is a difficult job. EAs are not able to predict the accurate output if the fitness function is not appropriate which is required to decide prior to the processing work. |
| Proposed Models | Developed models are simple and compact. Current-voltage characteristics is not transcendental in nature, but closed form and numerical calculation takes less time. The main limitation of our proposed models is that it fails beyond $V \leq Voc$. |

## 4 Conclusion

This work presents a closed form relationship between the current and voltage of a PV module which will be a valuable design tool for PV system designers. The analytical models of ideality factor, series resistance, shunt resistance, and dark current show a good agreement with the results available in literature. These models can evaluate the performance of PV modules faster and accurately. The simulated results of the proposed model of I-V characteristics show an excellent matching with experimental data for various solar modules. The terminal current degrades and takes negative value for terminal voltage larger than open circuit voltage. As series resistance increases, ideality factor takes negative value which reflects that increase in series resistance over years degrades the performance of the module. The larger open circuit voltage and short circuit current are desirable for the larger performance of the module whereas larger dark current reduces the terminal current which degrades the performance of the cell.

## 5 Abbreviations

| Abbreviation/Symbol | Explanation |
|---|---|
| PV | Photovoltaic |
| Rs | Series resistance (Ω) |
| Rsh | Shunt resistance (Ω) |
| Rsh0 | Shunt resistance when Rs=0 (Ω) |
| Voc | Open circuit voltage (V) |
| Isc | Short circuit current (A) |
| Vm | Maximum power voltage (V) |
| Im | Maximum Power current (A) |
| IPh | Photo current (A) |
| V | Terminal voltage (V) |
| I | Terminal current (A) |
| $\eta$ | Ideality factor |
| Ns | Number of series connected cells |
| I0 | Dark current (A) |
| VD | Diode voltage (V) |
| STC | Standard test condition |
| NOC | Normal operating condition |
| VTH | Thermal voltage (V) |

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