New analytical expressions of photovoltaic solar module physical parameters: Effects of module temperature and incident solar irradiance

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Abstract. In this work, we present three methods to extract model physical parameters of a photovoltaic solar module modelled by a single-diode electronic circuit. The model physical parameters we are looking for are photocurrent \( I_{ph} \), saturation current \( I_s \), ideality factor \( \eta \), series resistance \( R_s \) and shunt conductance \( G_p \). The first method is based on exact solution of module characteristic equation, the second one uses exact expression of dynamic conductance and the third one makes use of exact expression of the integral of translated current-voltage characteristics \( (I-I_{sc}) \). In all these extraction methods, we achieve numerical fitting of experimental data of output current, differential conductance and area under translated characteristics with suitable analytical expressions to get model physical parameters at standard test conditions (STC). Then, we assume these values as initial conditions and derive exact analytical expressions reporting effects of module temperature and incident solar irradiance on photocurrent, saturation current and ideality factor using temperature coefficients as well as irradiance coefficients extracted from module manufacturer datasheet. We examine new analytical expressions of model physical parameters in the case of Shell SQ80 photovoltaic solar module at arbitrary operating conditions of module temperature and solar irradiance. We evidence good agreement between experimental characteristics and forecasted analytical characteristics generated by new analytical expressions.

1. Introduction

Today, global energy demand is steadily increasing cause energy needs in developed economies such as USA, Europe, Japan and newly emerging countries such as India, China, Brazil, Russia and South Africa grow continuously. Unfortunately, global fossil origin fuel reserves have reached the phase of overexploitation and even in some cases depletion. In addition, geopolitical instabilities in Middle East and Arabian Persian Gulf about nuclear program of Iran make the supply of world oil market uncertain in medium term. Otherwise, heavy and unreasonable burning of fossil origin fuels such as oil, natural gas and coal leads to a regular increase of water vapor, methane, carbon dioxide and nitrogen dioxide contents in the atmosphere. Because of anthropogenic emissions coming from deforestation and combustion of fossil fuels, our planet Earth is facing major environmental challenges such as air pollution and global warming. This causes a general climate disorder engendering melting of polar ice, rising of sea levels, severe droughts and catastrophic floods. Nowadays, the use of clean and sustainable energies is the alternative solution capable of giving adequate answers to all these crucial questions. Solar energy as a source of clean and sustainable energy available everywhere is able to meet the growing energy needs of all humanity. It is free from all geopolitical issues. It is also independent of the issue of transportation, supply since we harvest sunlight and produce electricity locally. With its components: solar thermal, concentrated solar power and solar photovoltaic, Sun is hope for all inhabitants of our planet.

In the present paper, we focus on solar photovoltaic topics. More precisely, our interest will be in all devices that convert incident solar irradiation into electricity such as photovoltaic solar cells, modules and arrays. The issue we are tackling in this work is the investigation of effects of module
temperature and incident solar irradiance on model physical parameters of photovoltaic solar module. Indeed, module temperature as well as incident solar irradiance vary throughout a sunny day. Temperature and irradiance are maximum at solar midday and minimum at sunrise and sunset [1]. Thus, it is very important to predict evolving of model physical parameters throughout a sunny day in order to guess variations of current-voltage characteristics and to predict accurately maximum power point coordinates, optimal load resistance value, fill factor and module efficiency.

In the literature, majority of papers dealing with this topic consider photocurrent as a bilinear function of T and G [2–4], saturation current as exponential function of T and quasi-constant function of G [2,5,6], ideality factor often as independent function on T and G [4,5] and rarely as a linear function of T [2,7]. Recently, El Achouby et al. [8,9] considered series resistance and parallel conductance as independent functions on solar irradiance and module temperature, determined numerically and analytically variations of photocurrent, saturation current and ideality factor versus G and T and gave sets of I=f(V) and P=f(V) characteristics for G=1000W/m² and different values of module temperature and T=25°C and different values of solar irradiance. Zaimi et al. [10] considered all model-physical parameters as dependent functions on solar irradiance and module temperature and determined numerically their values for solar module operating under non-standard conditions. In the present work, we consider that photocurrent, saturation current and ideality factor are all dependent on T and G. We assume that series resistance and shunt conductance are independent on T and G.

After general introduction object of this section, we lay in the second section the foundations of our work. We present three different methods to extract physical parameters of equivalent electronic circuit modelling behavior of a photovoltaic solar module built by series mounting of a given number of solar cells. We derive new analytical expressions describing variations of model physical parameters versus module temperature and incident solar irradiance. In the third section, we investigate the case of Shell SQ80 solar module and present results of our achievements. We extract its physical parameters at STC. We determine analytical expressions of photocurrent, saturation current and ideality factor at given temperature and irradiance. We carry out an estimate of accuracy for each model physical parameter extraction method by comparing optimized characteristics to experimental characteristics at standard test conditions (STC) (T=25°C, G=1000W/m²). Then we achieve an evaluation of precision for analytical expressions modelling variation of physical parameters against temperature and irradiance by comparing predicted characteristics to experimental characteristics at arbitrary operating conditions of temperature and irradiance. In the last section, we close our paper with general conclusion.

2. Theoretical framework

2.1. Photovoltaic solar module fundamental equations

In this paper, we model photovoltaic solar module by single-diode equivalent electronic circuit with five physical parameters (see figure 1):

![Figure 1. Electronic circuit modelling a photovoltaic solar module [11]](image-url)
The characteristic equation of single-diode equivalent electronic circuit writes [11–15]:

\[ I = I_{ph} - I_s \left[ \exp \left( \frac{V + I R_s}{N_s \eta V_{th}} \right) - 1 \right] - G_p \left( V + I R_s \right) \]  \hspace{1cm} (2.1)

Where \( I_{ph} \) is the photocurrent, \( I_s \) is the diode saturation current, \( \eta \) is the ideality factor, \( R_s \) is the series resistance and \( G_p=1/R_{sh} \) is the shunt conductance, it is the reciprocal of parallel resistance \( R_{sh} \). \( V_{th} = k_B T / q \) is the thermal voltage, it is the energy quanta corresponding to thermodynamic agitation within semiconductor. \( k_B \) is Boltzmann constant, \( q \) is elementary charge, \( N_s \) is the number of cells mounted in series to build photovoltaic solar module and \( T \) is the module temperature. In the following, we give module key equations at cardinal points.

At open-circuit point, photovoltaic solar module voltage \( V_{oc} \) corresponding to an output current \( I=0 \) is expressed as follows:

\[ 0 = I_{ph} - I_s \left[ \exp \left( \frac{V_{oc}}{N_s \eta V_{th}} \right) - 1 \right] - G_p V_{oc} \]  \hspace{1cm} (2.2)

At short-circuit point, photovoltaic solar module current \( I_{sc} \) corresponding to an output voltage \( V=0 \) is given by:

\[ I_{sc} = I_{ph} - I_s \left[ \exp \left( \frac{R I_{sc}}{N_s \eta V_{th}} \right) - 1 \right] - G_p R_s I_{sc} \]  \hspace{1cm} (2.3)

At maximum power point, photovoltaic solar module current \( I_{mpp} \) and voltage \( V_{mpp} \) are linked via the following equation:

\[ I_{mpp} = I_{ph} - I_s \left[ \exp \left( \frac{V_{mpp} + R_s I_{mpp}}{N_s \eta V_{th}} \right) - 1 \right] - G_p \left( V_{mpp} + R_s I_{mpp} \right) \]  \hspace{1cm} (2.4)

2.2. Numerical extraction of model physical parameters

In this subsection, we use three different methods to determine physical parameters of single-diode equivalent electronic circuit describing behavior of photovoltaic solar module operating at standard test conditions (STC) (G=1000 W/m², \( T=25^\circ \text{C} \)). The methods of extraction are fully analytic. They rely on mathematical calculations where no approximation is used. They do not use initial guess values of model physical parameters to trigger iterations.

According to the first method, we determine analytical solution of photovoltaic module characteristic equation (see equation (2.1)), giving output current versus output voltage and model physical parameters:

\[ I(V) = -\frac{\eta N_s V_{sh}}{R_s} \text{W} \left( \frac{R I_s}{\eta N_s V_{th}(1+G_p R_s)} \exp \left( \frac{R (I_{ph} + I_s) + V}{\eta N_s V_{th}(1+G_p R_s)} \right) \right) + \frac{I_{ph} + I_s - G_p V}{1+G_p R_s} \]  \hspace{1cm} (2.5)

\( W(x) \) is LambertW function, it is the analytic solution of transcendental equation \( w(x)e^{w(x)}=x \). In order to extract five model physical parameters according to the present method, we achieve a numerical fitting of \( I=f(V) \) experimental characteristics to equation (2.5) via Statistics [NonlinearFit] (SNF) package [16] of Maple computer algebra software [17].
Following the second method, we derive an analytical expression of module differential conductance \( G_{\text{dyn}} \) from equation (2.1) [18–21]:

\[
G_{\text{dyn}}(I,V) = \left( \frac{I - I_{\text{ph}} - I_s + G_p V + G_p I R_s - G_p N \eta V_{\text{th}}}{(1 - I_{\text{ph}} - I_s + G_p V + G_p I R_s - G_p N \eta V_{\text{th}}) R_s - N \eta V_{\text{th}}} \right)
\]

(2.6)

Which leads to an expression linking output current \( I \) and output voltage \( V \) to the five physical parameters. Then we achieve a two-dimensional fitting of differential conductance experimental data to analytical equation (2.6) via Statistics [NonlinearFit] package of Maple computer algebra software.

According to the third method, we calculate Co-Content function \( CC(I, V) \) which is defined as the area under \((I(V)-I_{sc})\) translated characteristics:

\[
CC(I, V) = \int_V^{I_{sc}} (I(V) - I_{sc}) dV
\]

(2.7)

Where

\[
\begin{align*}
& a_1 = \frac{N \eta V_{\text{th}}}{R_s} \\
& a_2 = \frac{R_s I_s}{N \eta V_{\text{th}} (1 + G_p R_s)} \\
& a_3 = R_s (I_{\text{ph}} + I_s) \\
& a_4 = N \eta V_{\text{th}} (1 + G_p R_s) \\
& a_5 = -\frac{G_p}{1 + G_p R_s} \\
& a_6 = \frac{I_{\text{ph}} + I_s}{1 + G_p R_s} - I_{sc}
\end{align*}
\]

To determine five model physical parameters, we carry out two-dimensional fitting of Co-Content function \( CC(I, V) \) experimental values to analytical equation (2.7) using Statistics [NonlinearFit] package of Maple computer algebra software.

2.3 Effects of module temperature and incident solar irradiance on model physical parameters

Model physical parameters of photovoltaic solar module are very sensitive to variations of temperature \( T \) and global incident solar irradiance \( G \). Thus, it is crucial to be able to guess physical parameters evolving versus \( T \) and \( G \) variables in order to foresee changes occurring in current-voltage characteristics and to guess its maximum power point \((P_{\text{mpp}})\), optimal load resistance \((R_{\text{mpp}})\), Fill Factor and module efficiency.

Thereafter, and for the purpose of simplicity, we assume that series resistance \( R_s \) and parallel conductance \( G_p \) are independent of \( T \) and \( G \). Therefore, we consider that changes of \( T \) and \( G \) throughout a sunny day only affect photocurrent \( I_{\text{ph}} \), saturation current \( I_s \) and ideality factor \( \eta \).

In the majority of works concerned with this topic, scholars assume that open-circuit voltage \( V_{oc} \) and short-circuit current \( I_{sc} \) vary linearly with temperature from standard temperature \( T_{STC} \) equal to 25°C and at fixed global irradiance equal to 1000W/m² [1, 2, 4-6]:

\[
\begin{align*}
V_{oc}(T) &= V_{oc}(T_{STC}) + K_v (T - T_{STC}) \\
I_{sc}(T) &= I_{sc}(T_{STC}) + K_i (T - T_{STC})
\end{align*}
\]

(2.8)

(2.9)

Where \( V_{oc}(T_{STC}) \) and \( I_{sc}(T_{STC}) \) are open-circuit voltage and short-circuit current for a given illumination and for the reference temperature \( T_{STC} \) equal to 25°C. \( K_v \) is the temperature coefficient of open-circuit voltage \((\text{V/°C})\). \( K_i \) is the temperature coefficient of short-circuit current \((\text{A/°C})\).
In this study, we suggest for the first time in the literature two affine expressions to model effect of global incident irradiance on open-circuit voltage and short-circuit current:

\[ V_{oc}(G) = V_{oc}(G_{STC}) + \alpha_v (G - G_{STC}) \]  \hspace{1cm} (2.10)

\[ I_{sc}(G) = I_{sc}(G_{STC}) + \alpha_i (G - G_{STC}) \]  \hspace{1cm} (2.11)

Where \( V_{oc}(G_{STC}) \) and \( I_{sc}(G_{STC}) \) are open-circuit voltage and short-circuit current for a given module temperature and under reference irradiance \( G_{STC} \) equal to 1000Wm\(^{-2}\). \( \alpha_v = dV_{oc}/dG \) is the irradiance coefficient of open-circuit voltage (V/m\(^2\)/W). \( \alpha_i = dI_{sc}/dG \) is the irradiance coefficient of short-circuit current (A/m\(^2\)/W). In the present work, \( \alpha_v \) and \( \alpha_i \) are extracted from module manufacturer datasheet.

In the case where \( T \) and \( G \) vary at the same time, we model open-circuit voltage and short-circuit current by two-dimensional affine equations:

\[ V_{oc}(T,G) = V_{oc}(T_{STC},G_{STC}) + K_v (T - T_{STC}) + \alpha_v (G - G_{STC}) \]  \hspace{1cm} (2.12)

\[ I_{sc}(T,G) = I_{sc}(T_{STC},G_{STC}) + K_i (T - T_{STC}) + \alpha_i (G - G_{STC}) \]  \hspace{1cm} (2.13)

In all references in literature devoted to this subject, ideality factor is considered as constant, photocurrent \( I_{ph} \) is explicitly dependent on module temperature and solar irradiance while saturation current \( I_s \) is explicitly dependent on temperature and implicitly dependent on irradiance. At STC, the saturation current \( I_s \) is given by [5,24,25]:

\[ I_s(T) = DT^3 \exp\left(-\frac{qE_s}{\eta_{STC}k_BT}\right) \]  \hspace{1cm} (2.14)

Where \( E_s \) is the semiconductor band gap energy equal to 1.12eV for crystalline silicon at 25°C. \( D \) is a real constant, which depends on diffusion process within the module. At STC, the analytical expression of \( D \) is determined from equation (2.14):

\[ D = \frac{I_s(T_{STC})}{T_{STC}^3 \exp\left(-qE_s/\eta_{STC}k_BT_{STC}\right)} \]  \hspace{1cm} (2.15)

In the present paper, we consider that ideality factor is dependent on both module temperature and incident solar irradiance. We then generalize the writing of equation (2.14) to arbitrary operating conditions of \( T \) and \( G \). The new expression of saturation current becomes:

\[ I_s(T,G) = DT^3 \exp\left(-\frac{qE_s}{\eta(T,G)k_BT}\right) \]  \hspace{1cm} (2.16)

2.4. New analytical expressions modelling effects of module temperature and incident solar irradiance on physical parameters

2.4.1. Expression of photocurrent \( I_{ph} \)

By neglecting excess minority carrier’s diffusion current within the module in equation (2.3), we lead to the following analytical expression of photocurrent \( I_{ph} \) versus module temperature and incident solar irradiance:

\[ I_{ph}(T,G) = I_{ph}(T_{STC},G_{STC}) + K_p \left(1 + G_p R_s\right)(T - T_{STC}) + \alpha_p \left(1 + G_p R_s\right)(G - G_{STC}) \]  \hspace{1cm} (2.17)
2.4.2. Expression of ideality factor $\eta$

In equation (2.2), we neglect thermal agitation current with regard to minority carrier’s diffusion current and lead to an equation containing ideality factor and quantities depending on both module temperature and incident solar irradiance:

$$0 = I_{ph}(T,G) - I_s(T,G) \exp\left(\frac{V_{oc}(T,G)}{\eta(T,G)N_sV_{th}(T)}\right) - G_pV_{oc}(T,G)$$

(2.18)

Analytical resolution of equation (2.18) leads to exact expression of ideality factor versus module temperature and incident solar irradiance [8]:

$$\eta(T,G) = \frac{N_sE_s - V_{oc}(T,G)}{\ln\left(-DT^3/(G_pV_{oc}(T,G) - I_{ph}(T,G)\right)N_sV_{th}}$$

(2.19)

2.4.3. Expression of saturation current $I_s$

By plugging equation (2.19) into equation (2.16), we obtain a new analytical expression of saturation current against module temperature and incident solar irradiance:

$$I_s(T,G) = DT^3 \exp\left(-\left(\frac{N_sE_s - V_{oc}(T,G)}{\ln\left(-DT^3/(G_pV_{oc}(T,G) - I_{ph}(T,G)\right)N_s}\right)\right)$$

(2.20)

3. Results and discussions

In Table I, we give all technical settings of Shell SQ80 photovoltaic solar module as given in manufacturer datasheet.

| Parameters | Estimated values |
|------------|-----------------|
| $I_{ph}$ (A) | 4.8500056431 | 4.8500165894 | 4.8500146358 |
| $I_s (10^{-8} \text{ A})$ | 2.0462947584 | 2.5215848057 | 2.0324189480 |
| $\eta$ | 1.2243484559 | 1.2343158965 | 1.2212970838 |
| $R_s (\Omega)$ | 0.3399880892 | 0.3193999322 | 0.3365411991 |
| $G_p (\Omega^{-1})$ | 0.000253586 | 0.0002735582 | 0.0002278270 |

In Figure 2, we plot experimental current-voltage characteristics as well as optimized characteristics obtained via all methods of extraction at standard test conditions (STC) corresponding...
to a module temperature equal to 25°C and a solar spectrum AM1.5G which is equivalent to an incident solar irradiance equal to 1000W/m².

![Graph](image)

**Figure 2.** Experimental and optimized $I=f(V)$ characteristics of Shell SQ80 solar module at standard test conditions ($G=1000W/m^2$, $T=25°C$).

To do assessment of analytical expressions predicting values of model physical parameters $I_{ph}$, $I_s$ and $\eta$ for module temperature and incident solar irradiance different from those corresponding to standard test conditions, we draw current-voltage and power-voltage characteristics for $T=25°C$, $G=200$, 400, 600, 800, 1000 Wm⁻², and for $G=1000Wm^{-2}$, $T=20$, 30, 40, 50, 60°C. To do so, we use equations (2.17), (2.19) and (2.20) while keeping $R_s$ and $G_p$ constant. Then we compare obtained curves to experimental data available in manufacturer datasheet and corresponding to identical operating conditions.

3.2. **Influence of incident solar irradiance** In Figures 3, we plot current-voltage $I=f(V)$ (a) and power-voltage $P=f(V)$ (b) characteristics of Shell SQ80 solar module for different irradiance intensities $G$ and a module temperature $T$ equal to 25°C. Dots correspond to experimental values coming from datasheet and solid lines correspond to predicted characteristics obtained assuming $R_s$ and $G_p$ constant and using analytical expressions of output current (equation 2.5), photocurrent $I_{ph}(T,G)$ (equation 2.17), ideality factor $\eta(T,G)$ (equation 2.19) and saturation current $I_s(T,G)$ (equation 2.20). We note that there is a very good agreement between forecasted analytic characteristics and experimental characteristics.

![Graphs](image)

**Figure 3.** Experimental (dots) and predicted (solid lines) $I=f(V)$ (a) and $P=f(V)$ (b) characteristics of Shell SQ80 photovoltaic solar module at reference module temperature and different irradiance values.
3.3. Influence of module temperature

In Figures 4, current-voltage $I=f(V)$ (a) and power-voltage $P=f(V)$ (b) characteristics of Shell SQ80 photovoltaic solar module are drawn for different module temperatures $T$ and a given intensity of incident solar irradiance $G$ equal to 1000 Wm$^{-2}$. Experimental values from datasheet correspond to dots and forecasted characteristics obtained assuming $R_s$ and $G_p$ constant, and using analytical expressions of output current (equation 2.5), photocurrent $I_{ph}(T,G)$ (equation 2.17), ideality factor $\eta(T,G)$ (equation 2.19) and saturation current $I_s(T,G)$ (equation 2.20) correspond to solid lines. One can notice that experimental data and foreseen characteristics are in good agreement.

![Figure 4](image)

**Figure 4.** Experimental (dots) and forecasted (solid lines) $I=f(V)$ (a) and $P=f(V)$ (b) characteristics of Shell SQ80 photovoltaic solar module at reference incident solar irradiance and different module temperature values.

3.4. Accuracy and error calculation

We define absolute error $\epsilon_{\text{absolute}}$ as the difference between experimental and computational values of output current:

$$
\epsilon_{\text{absolute}} = |I_{\text{exp}} - I_{\text{cal}}|
$$

(3.1)

We may do a finer analysis of error by calculating normalized root mean squared error (NRMSE). We define NRMSE as square root of mean quadratic errors to mean experimental values ratio [27]:

$$
\text{NRMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (I_{\text{exp}}^i - I_{\text{cal}}^i)^2} / \sqrt{\frac{1}{N} \sum_{i=1}^{N} I_{\text{exp}}^i}
$$

(3.2)

At the beginning, we evaluate accuracy of physical parameters extraction methods in case of Shell SQ80 photovoltaic solar module functioning under standard test conditions. In Figure 5, we plot absolute error of output current versus output voltage for all methods of extraction presented above. We remark that absolute error is negligible for output voltage values lying between 0 and $V_{\text{mp}}$ which correspond to output current values lying between $I_{\text{sc}}$ and $I_{\text{mp}}$. For output voltage values lying between $V_{\text{mp}}$ and $V_{\text{oc}}$, output current values decreases exponentially between $I_{\text{mp}}$ and 0 and absolute error increases while remaining below 0.11 A. On the other hand, the reader can easily remark that SNF method achieving numerical fit of $I=f(V)$ experimental characteristics to equation (2.5) (method I) ensures best accuracy while accuracies of methods achieving numerical fit of $G_{\text{dyn}}$ (method II) and $CC(I,V)$ (method III) are approximately the same.
Figure 5. Absolute error of output current against output voltage for methods of extraction of physical parameters in case of Shell SQ80 photovoltaic solar module operating under standard test conditions.

Now, we tackle evaluation of accuracy of analytical model established to forecast $I=f(V)$ characteristics for Shell SQ80 solar module operating under arbitrary conditions of incident solar irradiance and module temperature. We remind the reader that this analytical model is founded on analytical expressions of $I_{ph}$, $\eta$ and $I_s$ while and it considers $R_s$ and $G_p$ constant.

In Figure 6, we present absolute error of output current versus output voltage for different values of irradiance and reference value of module temperature $T=25^\circ C$ (a). We also present absolute error of output current versus output voltage for different values of module temperature and reference value of solar irradiance equal to 1000Wm$^{-2}$ (b).

Figure 6. Absolute error of current versus voltage for mathematical model derived to predict $I=f(V)$ characteristics in case of Shell SQ80 photovoltaic solar module for different values of incident irradiance and reference value of module temperature $T=25^\circ C$ (a) and for different values of module temperature and reference value of incident solar irradiance $G=1000$ Wm$^{-2}$ (b).

In the following histograms, we present NRMSE of mathematical model derived to predict $I=f(V)$ characteristics in case of Shell SQ80 solar module for different solar irradiance values and reference module temperature (a) as well as for different module temperature values and reference solar irradiance (b). Established mathematical model is based on analytical expressions of physical parameters $I_{ph}(T,G)$, $I_s(T,G)$ and $\eta(T,G)$, it uses as boundary conditions the values of photocurrent,
saturation current and ideality factor corresponding to STC, determined via the three methods of extraction and gathered in Table II.

Figure 7. NRMSE of output current corresponding to mathematical model derived to predict current-voltage characteristics in case of Shell SQ80 photovoltaic solar module for different solar irradiance values and reference module temperature (a) and for different module temperature values and reference solar irradiance (b). Mathematical model is founded on analytical expressions of physical parameters $I_{ph}(T,G)$, $I_s(T,G)$ and $\eta(T,G)$ and uses as boundary conditions values of photocurrent, saturation current and ideality factor corresponding to STC and determined via the three methods of extraction.

4. Conclusion
In this study, we present three methods to determine physical parameters of single-diode electronic circuit modelling photovoltaic solar module operating under standard test conditions (STC) (G=1000 Wm$^{-2}$ and T=25°C). The first method extracts physical parameters via one-dimension statistical nonlinear fit of experimental current-voltage characteristics to exact solution of characteristic equation. The second and third methods determine physical parameters by means of two-dimension statistical nonlinear fit of experimental values of differential conductance and co-content function to respective analytic expressions. We show that optimized characteristics generated using physical parameters coming from methods of extraction and experimental characteristics are in good agreement. We assume that series resistance and shunt conductance are independent on module temperature and incident solar irradiance. We consider values of model physical parameters obtained at STC as boundary conditions and establish analytical equations modelling variations of photocurrent, saturation current and ideality factor versus module temperature and incident solar irradiance. We derive mathematical model capable to predict current-voltage characteristics, power-voltage characteristics, maximum power point and fill factor for arbitrary operating conditions of temperature and irradiance. We emphasize that forecasted characteristics coming from mathematical model for given values of module temperature and incident solar irradiance are in good accordance with experimental characteristics.

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