An Improved Mathematical Model Derivation Based on Circuitry Approach for Crystalline Silicon Photovoltaic Module

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Abstract. This paper revises the five-parameter model, an approach that contributes the fundamental knowledge on performing accurate mathematical modelling for most of the commercially-available photovoltaic cells. However, such model can be further improved in order to increase the modelling accuracy while reducing the required modelling parameters at the same time. Improvement is made through formula derivation for photo-generated current and diode saturation current, while the remaining parameters (series resistance, shunt resistance, and diode ideality factor) remained un-managed for the parameterisation procedure. The derivations presented in this paper are direct, yet such procedures are frequently overlooked by others. The comparison between conventional and proposed modelling methods is presented. The methodology of this work is presented through MATLAB script demonstrated on the measured field data for 70W mono- and poly-crystalline silicon photovoltaic modules. The performed methodology justifies that formula derivation can be applied for photo-generated and diode saturation current parameters that originated from five-parameter model. Such approach simplifies the works of parameterising the theoretical model matches with the experimental I-V curve. Generally, the work of this paper contributes to the mathematical modelling of photovoltaic module, simulation of experimental I-V curve result, and interactive education tool.

1. Introduction
Over the year, the role of renewable energy becomes increasingly important through the power generation aspect as it enhances the flexibility to energy sourcing while reducing the dependence on fossil fuel-based energy generation [1]. The photovoltaic (PV) system, which is categorised under renewable energy, refers to the solar power generation technology which sources energy from the sunlight and converts into electricity form. Solar energy considered as a promising alternative to replace the non-renewable energy source due to its abundant existence in nature. Through such aspect, solar energy possesses high growing rate amongst all of the renewable energy including ocean wave, wind, hydro, and biomass [2]. This scenario also reflects the increase of PV system worldwide [3]. Regardless of their relatively high installation and operative cost of PV system during its initial development stage, such aspect is progressively overcome by lower-cost-focused research over the years [3-5].

Most of the conducted research applies the similar approach on modelling the PV system through mathematical or circuitry means, with the sole concern on allowing the designer to optimize the performance of the PV system [6]. Through mathematical modelling perspective, the most prominent work is presented by [7], which conclude the five required parameters to model the I-V curve of PV cell. This five-parameter model is crucial as the parameters of photo-generated current ($I_{ph}$), diode saturation current ($I_s$), diode ideality factor ($A$), shunt ($R_{sh}$) and series ($R_s$) resistance are required for I-
V curve analysis but these are usually not provided in manufacture’s datasheet [7, 8]. However, the five-parameter model can be further simplified to ease the parameterisation of I-V curve. Presented in [1], the five-parameter model is simplified by deriving $I_{ph}$, $I_o$ and $R_s$ parameter, and thus the I-V curve is parameterised with remaining $A$ and $R_{sh}$ parameter. However, the methodology shown in [1] lacks convincing statements as two different derived equations for $I_o$ parameter are used at the same time. Such methodology is indirectly debated by [9] stating that both derived equations presented the duplicated function. Besides, the modelling accuracy for the derived five-parameter model can be improved as well, through another derivation approach that will be proposed in this paper. As a continuation of the research outcomes, the I-V curve of PV module could be parameterised with the remaining $A$, $R_s$ and $R_{sh}$ parameter. Nonetheless, applied works of this paper also describe the reason for amending the algorithmic parameterisation approach applied in [10].

To converge the researches result and adopted into the work of this paper, it serves the purpose to model a PV module through the mathematical approach. The I-V characteristic curve of PV module is described by the lumped parameter equivalence, in which the total model parameter reflects the internal mechanism of PV module [11]. The objective of the work is to develop a more accurate general mathematical model for crystalline silicon PV module in order to evaluate the long-term performance. Nonetheless, the comparison between proposed and conventional model is presented in this paper, justifying that improvement of modelling accuracy can be achieved through the application of the proposed model.

2. Derivation of Mathematical Model

Many modelling methods exist to describe the behaviour of the PV system. The available modelling method could be categorised through either circuitry or mathematical mean. Among these two, the electrical equivalent circuit-based model is considered the popular method to simulate the behaviours of the PV cell. This statement is supported by the reason which circuitry model possesses the advantages of available electrical simulation software, such as PSpice and Proteus. With a proper model applied, the performance of PV cell, module, or even array can be predicted accurately through simulations [12]. As per today, the available circuitry modelling for PV module categorised into three, which are the double-diode model, single-diode $R_s$ and $R_p$ model [8]. The commonly used model is the single-diode $R_p$ model, as shown in Figure 1.

![Figure 1. Single-diode equivalent circuit $R_p$ model of PV cell](image)

Due to simplicity, the single-diode $R_p$ model is widely used to model a PV module [13], same reason is applied to justify the application of this model into this paper. As shown in Figure 1, the single-diode $R_p$ model consisted of the current source connected in parallel to a PN junction diode and a shunt resistor, while connected in series to a resistor that leads to the terminal output. The current source models the irradiance current generated by the photon carriers that sourced from the sun; the diode models the electron-hole recombination between the PN junctions, thus representing the diode saturation current of PV cell. Lastly the shunt and series resistance models the leakage current of the diode and internal resistance of the PV module respectively.

Applied with Kirchhoff’s Current Law, the mathematical model for single diode $R_p$ model can be derived to determine the PV cell’s terminal current through Equation (1), where $I_{ph}$ is the photo-generated current which varies linearly to the irradiance level of the sunlight; $I_D$ is the current flowing
through the parallel diode, which resulting the non-linear characteristic of I-V curve; and $I_{Rs}$ is the leakage current at shunt resistor.

$$I = I_{ph} - I_D - I_{Rsh}$$

(1)

With the substitution of Shockley diode equation and also relevant variables, the complete mathematical model of photovoltaic module is obtained as Equation (2), where $I_i$ is the diode saturation current; $R_i$ is the series resistance; $R_{sh}$ is the shunt resistance; $N_i$ is number of PV cells connected in series; $V_T$ is the thermal voltage; $V$ and $I$ respectively represents the voltage and current of output terminal. The thermal voltage can be calculated using Equation (3), where $A$ is the diode ideality factor of PV cell, $k$ is the Boltzmann constant of $1.38 \times 10^{-23}$; $T$ is the PV cell’s temperature; $q$ is the electron charge constant of $1.6 \times 10^{-19}$ .

$$I = I_{ph} - I_0 \left( e^{\frac{V+IR_s}{N_iAeVT}} - 1 \right) - \frac{V+IR_s}{R_{sh}}$$

(2)

$$V_T = \frac{AkT}{q}$$

(3)

Equation (2) represents the relationship of the PV module’s terminal output current respect to different terminal output voltage value. This equation applies the physic of PN junction and generally accepted to represent the behaviour of PV cell, especially for crystalline silicon [14]. Thus, a conventional single-diode $R_p$ circuitry model is mapped to the mathematical model of Equation (2), which the equation is the foundation leads to the five-parameter model.

2.1. Five-parameter Model

In [7] and [15], the five-parameter is obtained by deriving the I-V characteristic curve general equation of Equation (2) under three conditions of short-circuit current condition $I_{sc}$, open-circuit condition $V_{oc}$ and maximum output power of current $I_{mp}$ and voltage $V_{mp}$. With such approach, both [7] and [15] conclude that a minimum of five parameters are required to model the I-V characteristic curve of PV cell, which also known as the behaviours of PV cell. The five parameters $I_{ph}$, $I_0$, $A$, $R_{sh}$, $R_i$ represents the photo-generated current, diode saturation current, diode ideality factor, shunt and series resistance respectively. It is proven in [7] and [15] that each of these five parameters does influence the characteristic of the I-V curve. The solid justification of five parameter model towards the characteristic of I-V curve is recognized by most of the publication [1, 12, 16] and further improvement for PV system is proceeded after the contribution of the five-parameter model. However, the five-parameter model can be further simplified, through the formula derivation for photo-generated current, $I_{ph}$ and diode saturation current, $I_0$.

2.2. Derivation for Photo-generated Current

For simplicity, many researchers [1, 7, 9, 12] apply the concept of photo-generated current, $I_{ph}$ is equivalent to short-circuit current, $I_{sc}$ as presented in Equation (4). Besides, some researchers derive the photo-generated current to increase modelling accuracy, such as [3, 4, 16, 17]. The prominent work is presented in [16]. The photo-generated current can be calculated through Equation (5), which is the derivation from Equation (2) at open-circuit voltage condition. However, the decision of deriving the formula to obtain photo-generated current parameter would be questionable as the photo-generated current should be mapped with short-circuit current condition based on the general assumption made by researchers [1, 7, 9, 12].

$$I_{ph} \approx I_{sc}$$

(4)

$$I_{ph} = I_0 \left[ e^{\frac{V_{oc}}{N_iAeVT}} - 1 \right] + \frac{V_{oc}}{R_p}$$

(5)
In [17], a similar method is applied, in which the derivation of photo-generated current is derived based on short-circuit current condition. As in general, the assumption is made where the photo-generated current is almost equal to short-circuit current [1, 7, 9, 12], and thus the derivation for photo-generated current should be applied on short-circuit current condition of single-diode $R_p$ model, as shown in Figure 2.

![Figure 2. Single-diode $R_p$ model under short-circuit condition](image)

Under the short-circuit condition, the output terminal voltage and current value would be zero and $I_{sc}$ respectively. With these parameters substituted into Equation (2), the result is obtained as Equation (6). Thus, the derivation for the photo-generated current of Equation (7) is obtained by rearranging Equation (6) in form of photo-generated current.

$$I_{sc} = I_{ph} - I_0\left(\frac{l_{sc}R_s}{e^{V_{oc}/N_sV_T} - 1} - \frac{l_{sc}R_s}{R_{sh}}\right)$$

$$I_{ph} = I_{sc} + I_0\left(\frac{l_{sc}R_s}{e^{V_{oc}/N_sV_T} - 1} + \frac{l_{sc}R_s}{R_{sh}}\right)$$

### 2.3. Derivation for Diode Saturation Current

The same concept is applied which parameterisation of the five-parameter model can be simplified by reducing required parameters. Two popular equations are used among the researchers on deriving diode saturation current parameter. It is shown as Equation (8) [1, 3, 12, 18] and Equation (9) [1, 7, 9, 12], where $E_g$ is the bandgap energy for PV cell which can be calculated from Equation (10).

Shown in [1], which applied both of Equation (8) and Equation (9) to model the I-V curve of PV cell at operating condition, the MATLAB script provided in the publication shows that both of the equations have repeated function of determining the diode saturation current parameter at different PV cell’s temperature. This statement is supported by [9] stating that Equation (9) is the ratio of diode saturation current at different temperature. Thus, the application of Equation (8) had already catered the requirement to model PV cell or module at specific temperature. The works of applying the derived diode saturation current formula can be traced from [16] and [5], which respectively shown in Equation (11) and Equation (12). However, the derivation methodology is remained debatable as the short-circuit current parameter $I_{sc}$, open-circuit voltage parameter $V_{oc}$, and series resistance $R_s$ exist at the same equation, which such condition is physically impossible to exist on the circuitry model.

$$I_0 = \frac{l_{sc}}{e^{V_{oc}/N_sV_T} - 1}$$

$$I_0 = I_{0,ref} \times \left(\frac{T}{T_{ref}}\right)^{\frac{3}{2}} \left[\frac{E_g}{E_{g,ref}}\right] \left(\frac{E_{g,ref}}{E_g + E_{g,ref}}\right)^{-\frac{1}{2}}$$

$$\frac{E_g}{E_{g,ref}} = 1 - 0.0002677(T - T_{ref})$$

$$I_0 = \frac{l_{sc}(1+R_s/R_p)}{e^{V_{oc}/N_sV_T}}$$

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The derivation of diode saturation current formula is based on the open-circuit condition of the single-diode $R_p$ model, as shown in Figure 3. Under open-circuit condition, the output terminal voltage and current value would be $V_{oc}$ and zero respectively. With these parameters substituted into Equation (2), the result is obtained as Equation (13). Thus, the derivation for the diode-saturation current of Equation (14) is obtained by rearranging Equation (13) in form of diode-saturation current.

$$I_0 \approx (I_{sc} - V_{ac} + l_{sc} R_s) e^{-V_{ac} R_s R_{sh}}$$  \hspace{1cm} (12)$$

$$I_0 = I_{sc} - I_0 \left( e^{V_{oc} R_s} - 1 \right) - \frac{V_{ac} R_{sh}}{R_{sh}}$$  \hspace{1cm} (13)$$

$$I_0 = \frac{I_{sc} V_{ac} R_{sh}}{e^{V_{oc} R_s} - 1}$$  \hspace{1cm} (14)$$

Comparing Equation (2) and Equation (13), the photo-generated current variable is changed to short-circuit current variable during the derivation. Such assumption is required as the derivation procedure for Equation (6) requires the diode saturation current parameter while Equation (13) requires the photo-generated current parameter. Assumption of photo-generated current equal to short-circuit current is required to avoid such recursive loop.

2.4. Algorithmic parameterisation for $A$, $R_s$, and $R_{sh}$

The five-parameter model is simplified through the derivation of photo-generated and diode saturation current parameters. This simplified five-parameter model can also use to determine the behaviours of PV cell or module, as presented through the work of [3, 5, 9, 10]. All of these works have the similarities, which the algorithmic parameterisation for $A$, $R_s$ and $R_{sh}$ parameters requires unique mathematical derivation approaches. However, the mathematical approach from [7] is applied for the work presented in this paper and the algorithmic parameterisation of the simplified five-parameter model is implemented by taking inspiration from [3, 5, 9, 10] without justifying their mathematical approach.

Both [10] and [18] give a strong reference for the work of this paper. [18] uses the optimization algorithm for the five parameter model while [10] applies algorithmic parameterisation through the simplified five-parameter model of the remaining $A$, $R_s$ and $R_{sh}$ parameters. [10] states that both ideality factor $A$ and shunt resistance $R_{sh}$ have an effect on the series resistance $R_s$. With such idea, the algorithmic parameterisation in [10] is executed through the sequence of $A$, to $R_s$, and to $R_{sh}$. The algorithmic parameterisation continues until minimum error is achieved. To apply this algorithm into the work published in this paper, the algorithm is amended into the sequence of $R_s$, to $A$, and to $R_{sh}$. This algorithm represents the idea that characteristic change of I-V curve under the influence of $R_s$ parameter is adjusted with the following changes of $A$ and $R_{sh}$ parameters. This statement is justified through Equation (2), which the changes of $R_s$ parameter will affect both diode saturation and shunt resistance leakage current, and the counter-feedback can be applied respectively with the change of $A$ and $R_{sh}$ parameters.

The algorithmic parameterisation methodology shown in Figure 4 is applied on both conventional and proposed model through MATLAB script, as shown in Figure 5.
Applying the simplified five-parameter model, the algorithm can be applied to characterise the commercially available PV module today. This algorithm is tested with the field measurement data obtained for both mono- and poly- crystalline silicon PV module. Comparison is made between the field measurement data with the I-V curve generated by the mathematical model of Equation (2). The algorithmic parameterisation result of mono- or poly- crystalline silicon PV module consider obtained when the minimum possible Mean Absolute Percentage Error (MAPE) achieved. MAPE is chosen due to its robustness and suitability of measuring the data point distance between two graphical models, as stated in [19]. Equation (15) shows the MAPE equation, which $I$ is the data point for terminal output current value of PV module; and $n$ is the total number of data point to model the I-V curve.

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{I_{\text{Measured}} - I_{\text{calculated}}}{I_{\text{Measured}}} \right| \times 100\% \quad (15)$$

### 3. Result and Discussion

The application of the simplified five-parameter model is tested on mono- and poly- crystalline silicon PV module of unknown specification. The measured specifications for mono- and poly- crystalline silicon PV modules are presented in [20] and the data is summarised into Table 1. The number of PV cells should be included in Equation (2) as the parameterisation procedure executed in this paper is applied on PV module instead of PV cell.
Table 1. Measured specification of mono- and poly- crystalline PV module

| Measured Specification of PV Module | Mono-crystalline | Poly-crystalline |
|------------------------------------|-----------------|-----------------|
| Measured maximum power (Pmax)      | 69.52W          | 69.54W          |
| Maximum power voltage (Vmp)        | 15.48V          | 15.08V          |
| Maximum power current (Imp)        | 4.49A           | 4.61A           |
| Open-circuit voltage (Voc)         | 20.27V          | 19.99V          |
| Short-circuit current (Isc)        | 5.00A           | 5.10A           |
| Number of cell in series           | 36              | 36              |

The field measurement data is obtained for both of the PV module models and imported through MATLAB script to compare with the mathematical modelling of Equation (2) individually. The original MATLAB script and field measurement data are obtained from [20] as well, with some amendment. The final parameterisation result is obtained when the mathematical model could match to the measured I-V data with lowest MAPE value as possible. The conventional model refers photo-generated current $I_{ph}$ and diode saturation current $I_o$ parameter are based on Equation (4) and Equation (8) respectively, while the proposed three-parameter model refers the photo-generated current $I_{ph}$ and diode saturation current $I_o$ parameter are based on Equation (7) and Equation (14) respectively. Comparison between the conventional and proposed model is made through the same field measured data, indicating that both data are influenced by irradiance and temperature factors under the same level, thus these effects towards the PV module is not investigated for the work presented in this paper. The comparison of both models is presented in Figure 6 to Figure 9. The algorithmic parameterisation is applied based on Figure 4 to match both measured and modelled I-V curve until the MAPE value from Equation (15) no longer be reduced. The essential analytic parameters are then extracted from the modelled I-V curve, summarised as Table 2 and Table 3. All of the improved MAPE results throughout the iteration are recorded and plotted, as shown in Figure 10.

Interpret the result obtained for Figure 6 to Figure 9, the proposed model shows the better result on matching both measured and modelled I-V curve, especially at the near open-circuit condition. This result is apparent at the mono-crystalline silicon PV module as referred to Figure 6 and Figure 7. This statement is supported by [2] stating that there is denser data distribution after the maximum power point of P-V curve. However, the near open-circuit voltage of the I-V curve presented in Figure 6 and Figure 7 does not show a smooth curve like Figure 8 and Figure 9. This is due to the inaccurate series resistance value is introduced at the result of Figure 6 and Figure 7, as this parameter will result in a significant effect on the slope of the near open-circuit voltage data point. However, these series resistance parameter can no longer be managed as it is the best result obtained from the algorithm shown in Figure 4. Such inaccuracy is obtained because the error induced from the non-smooth region of I-V curve generated at near open-circuit voltage data point is compensated at another region of I-V curve, such as the I-V curve slope at maximum power point or short-circuit current region. However, a hypothesis can be made which reducing the step-size on $R_s$ parameterisation might able to eliminate this phenomenon.

Table 2. Parameterisation result comparison between mono- crystalline silicon PV modules applied with both conventional and proposed three-parameter modelling

| Parameterisation Result | Mono-crystalline silicon PV Module |
|-------------------------|-----------------------------------|
|                         | Conventional Model | Proposed Model |
| Diode Ideality Factor(A) | 1.52                  | 1.53           |
| Series Resistance ($R_s$) | 0.28 Ω               | 0.27 Ω         |
| Shunt Resistance ($R_a$)  | 248 Ω                | 124 Ω          |
Table 3. Parameterisation result comparison between poly-crystalline silicon PV modules applied with both conventional and proposed three-parameter modelling

| Parameterisation Result | Poly-crystalline silicon PV Module |
|-------------------------|-----------------------------------|
|                         | Conventional Model | Proposed Model |
| Diode Ideality Factor (A) | 1.30 | 1.27 |
| Series Resistance (R_s)  | 0.34 Ω | 0.35 Ω |
| Shunt Resistance (R_sh)  | 248 Ω | 164 Ω |
| Mean Absolute Percentage Error (MAPE) | 1.2786% | 1.0041% |
| Total number of iteration | 176 | 196 |

Interpreting the result summarised in Table 2 and 3, the proposed model able to further reduce the MAPE error for both mono- and poly-crystalline silicon PV module models. Although the conventional and proposed model extracts the three parameters into different results, the proposed model considered to possess higher modelling accuracy as it able reaches to a lower MAPE value. For both of the crystalline silicon PV module model, the proposed model requires a higher number of iteration to complete the algorithmic parameterisation compared to the conventional model, which the result is shown in Figure 10. This reflects that the proposed model is able to continue the algorithmic parameterisation which already terminated by the conventional model at the pre-mature state of the parameterisation for the I-V curve fitting. As the trade-off of higher modelling accuracy, the parameterisation of the proposed model will show higher MAPE value at the initial stage of parameterisation compared to conventional model. However, the proposed model able to achieve lower MAPE value as the iteration of parameterisation proceeds.

**Figure 6.** Algorithmic parameterisation for I-V characteristic curve fitting applied on mono-crystalline silicon PV module (Conventional Model)
Figure 7. Algorithmic parameterisation for I-V characteristic curve fitting applied on mono-crystalline silicon PV module (Proposed Model)

Figure 8. Algorithmic parameterisation for I-V characteristic curve fitting applied on poly-crystalline silicon PV module (Conventional Model)

Figure 9. Algorithmic parameterisation for I-V characteristic curve fitting applied on poly-crystalline silicon PV module (Proposed Model)
Figure 10. Comparison of iterative MAPE succession between conventional and proposed model applied in (a) mono-crystalline silicon PV module; (b) poly-crystalline silicon PV module

Since the formula derivation of the proposed model is introduced with a higher degree of resemblance towards the single-diode $R_p$ model, thus a finer adjustment of the three parameters are required in order to obtain the modelled I-V curve with lowest possible MAPE value, and this explains the higher number of iterations required for the proposed model. Comparing Equation (8) and Equation (14), the derivations of these two formulas indirectly state that the single-diode $R_p$ model possesses higher modelling accuracy compared to the single-diode $R_s$ model. Equation (8) omitted the open-circuit voltage to shunt resistance ratio as compared to Equation (14), this related to the assumption of single-diode $R_s$ circuit modelling on considering shunt resistance with infinite value. Considering this aspect, it is predicted that a much accurate algorithmic parameterisation result can be obtained by applying the same derivation methodology on the double-diode model.

To summarize the result, the proposed three-parameter model is proven to be valid on performing the algorithmic parameterisation curve fitting between the measured and modelled I-V curve. The proposed three-parameter model increases the modelling accuracy and simplified the parameterisation procedure as compared to the conventional five-parameter model. By introducing a higher resemblance of circuitry elements to derive the proposed model, the error between measured and modelled I-V curve could be reduced. Overall, the proposed model does improve the modelling accuracy for crystalline silicon PV module model.

4. Conclusion
To conclude the work presented in this paper, the commonly used five-parameter model consisted of $I_{ph}$, $I_o$, $A$, $R_s$ and $R_{sh}$ parameters can be simplified into a five-parameter model that consisted of diode ideality factor ($A$), series ($R_s$) and shunt ($R_{sh}$) resistance with derived photo-generated ($I_{ph}$) and diode saturation ($I_o$) current parameters. It proves that the proposed three-parameter model does improve the modelling accuracy of crystalline silicon PV module’s I-V characteristic curve. The modelling accuracy is determined by the minimum difference can be achieved between the field measured and mathematically modelled I-V characteristic curve. Comparison between the proposed three-parameter and conventional five-parameter model is made, showing that the proposed three-parameter model able to improve the modelling accuracy of I-V characteristic curve through a higher number of iteration for algorithmic parameterisation. A better overview of the connection between the circuitry and mathematical modelling of PV cell/module is presented. The work presented also indirectly proves that the single-diode $R_p$ model possesses higher modelling accuracy than the single-diode $R_s$ model, based on the derivation methodology of the proposed and conventional model. The MATLAB scripts entitled
PV Module’s I-V Characteristic Curve Fitting Tools used for the data presentation in this paper are made available by the author at Mathworks official MATLAB Central File Exchange [21].

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