Parasitic resistance calculation of PV module at various irradiance based on three condition Lambert-W

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Abstract. Serial and parallel parasitic resistances of the photovoltaic (PV) module are needed to determine the characteristics and performance of the module. Its values are constant for a long period operation. Characterization of PV modules using direct irradiation of sunlight is rather difficult to obtain constant radiation under a clear sky condition and the measurement should be taken in a short time period less than 5 minutes. In this work, Rs and Rsh values were determined by characterizing PV module at various levels of sunlight intensity and modeled after Lambert-W function. A Solarland SLP100S-12 monocrystalline 100Wp photovoltaic module was illuminated at different intensity 100%, 75%, 50%, and 25% using filters covered the PV module surface. Based on the measured I-U curves, three important parameters are generated for the Lambert-W calculation: short-circuit current (Isc), open-circuit voltage (Uoc), and also the current-voltage at the Maximum Power Point (Imp, Ump). The calculated values were 0.63Ω ± 0.027 for Rs and 93.2Ω ± 0.588 for Rsh and relative constant for filter variation which are not influenced by the intensity of the sun.

1. Introduction
Solar cells are one important component in photovoltaic (PV) systems that convert sunlight into electrical energy. The electrical performance of PV modules can be explained by the characteristics of the current-voltage (I-U) curve which shows the material properties and module output. However, light intensity to the earth fluctuates due to environmental influences such as temperature variations or clear sky index making it difficult to characterize the PV module with constant intensity [1,2].

Simplified PV module characterization using a single diode model has been carried out by [3], which investigates the I-U data of the manufacturer's data sheets and experimental data. All solar module parameters, including short circuit current (Isc), open-circuit voltage (Uoc), fill factor and efficiency change due to various light intensity, while the parasitic value of the series and parallel resistance alter over a long period. However, these parasitic resistances can also depreciate the efficiency of the module resulting in the degradation of the output power [4].

To determine the Rs and Rsh, an I-U curve of the polycrystalline PV modules characterized under dark current conditions is extracted based on the Lambert-W function model. Nevertheless the Rs and Rsh is determined only based on certain intensities [5]. The Lambert-W function has been recognized in the solution of scientific and technical problems in operating numerical calculations especially for analysis and calculation of Rs and Rsh parameters [6].

The various intensity of light for the determination of Rs has been done by [7] using a single exponential function by using an infinite Rsh assumption. These assumptions may not be accurate
2. Method

2.1. Light Irradiation
PV modules are generally characterized by the Standard Test Condition (STC) with an input radiation of 1000 W/m² and a module cell temperature of 25°C. The effect of radiation on the almost linear PV power output expressed by equation (1), where $P_{\text{max}}$ is the measured power, $P_{\text{STC}}$ is the maximum power and $G$ is the plane irradiance constant [9].

$$P_{\text{max}} = G \cdot \frac{P_{\text{STC}}}{1000 \text{W/m}^2}$$

(1)

Short circuit currents increase linearly with respect to intensity, but in the diode model for ideal solar cells without $R_s$ and $R_{sh}$, the open circuit voltage increases logarithmically with radiation, according to equation (2).

$$U_{oc} = \frac{k_B T_c}{q} \ln \left( \frac{I_{sc}}{I_0} + 1 \right)$$

(2)

Where $k_B$ is the Boltzmann constant, $T_c$ is cell temperature, $q$ is electron charge, $I_0$ is saturation current. The $I_{sc}$ decreases linearly to the radiation factor and the efficiency of the PV module is also lower due to decreasing of $U_{oc}$ with $I_{sc}$.

2.2. Internal Parasitic Resistance
The parasitic internal resistance arises from contact between solar cells in the PV module which has relative constant value. This can be slightly varies and changes over a long period of operation.
A figure 1 show an increase in $R_s$ and a decrease in $R_{sh}$ which causes the curve drift downwards and denotes a decrease in the maximum output power of the module. A significant increase of $R_s$ causes a leakage of current, while a decrease of $R_{sh}$ implies a voltage drop [10]. Figure 2 shows the equivalent circuit of a single diode solar cell equation model expressed in equation (3).

$$I = I_{pv} - I_0 \left[ \exp \left( \frac{U + I \cdot R_s}{a \cdot U_T} \right) - 1 \right] - \frac{U + I \cdot R_s}{R_{sh}}$$  \hspace{1cm} (3)$$

![Figure 2. Model of a single diode solar cell circuit](image)

PV module work like diodes optimally when exposed to direct sunlight, but when the intensity of light on the module surface decreases, the PV module does not work optimum, which is called dark currents condition. Solar cells in the equivalent circuit model have inherent $R_s$ and $R_{sh}$ parasitic resistance due to cell contact between cells in the PV module.

2.3. The I-U Curve Extraction Based on Three Conditions and Lambert-W function

The measured I-U curve under solar irradiation produces three point conditions for the determination of internal parasitic resistance, namely $I_{sc}$, $U_{oc}$ and Maximum Power Point (MPP). Short circuit current is the maximum current that occurs when the load resistance is very low ($R_L \approx 0$). The maximum current value is equal to the amount of current produced by solar cells from the excitation of photons in an ideal cell ($I_{sc} = I_{max}$). Open circuit voltage ($U_{oc}$) is the maximum voltage that occurs when no current passes through the solar cell, while the maximum power in the solar cell is obtained at the operating point of maximum output power. The $I_{sc}$ condition produces $I_{pv}$ photovoltaic current which is proportional to the sun’s intensity as in equation (4).

$$I_{pv} = \frac{R_{sh} + R_s}{R_{sh}} I_{sc}$$ \hspace{1cm} (4)$$

The $U_{oc}$ conditions produce equation (5) based on equation (3) of the solar cell model.

$$0 = I_{pv} - I_0 \left[ \exp \left( \frac{U_{oc}}{a \cdot U_T} \right) - 1 \right] - \frac{U_{oc}}{R_{sh}}$$ \hspace{1cm} (5)$$

With $U_T$ is the thermal voltage that satisfies equation (6).

$$U_T = \frac{n k B T}{q}$$ \hspace{1cm} (6)$$

Equation (6) is simplified to produce saturation current $I_0$ in equation (7).

$$I_0 = \frac{(R_{sh} + R_s) I_{sc} - U_{oc}}{R_{sh} \left[ \exp \left( \frac{U_{oc}}{a \cdot U_T} \right) - 1 \right]}$$ \hspace{1cm} (7)$$

The MPP condition arises when the maximum rated power output produces the current point and the voltage at maximum power produces equation (8).
Based on these 3 points, $Rs$ and $Rsh$ values can be calculated using the Lambert-W function and various mathematical operations implicitly with. The Lambert-W function is also called the Omega function, which is an inverse relation of an exponential function [12].

$$f(x) = x \cdot \exp(x)$$

Equation (9) is an inverse relation function producing a Lambert-W function with some use of mathematical operations and modifications to produce equation (10).

$$x = W(f(x))$$

The $Rs$ and $Rsh$ are a function of the current, voltage and temperature at certain intensities which are solved using the Lambert-W function. Calculations are made using the Mathcad and Mathlab software based on modification, addition, and subtraction of mathematical operations.

2.4. Experiment Set-Up

The PV module used in this work is 100 Wp monocrystalline Solarland-SLP100S-12 that has 72 solar cells connected in series and parallel. The module specification parameters are shown in Table 1.

| Specifications parameter | Unit | Solarland SLP100S-12 |
|--------------------------|------|----------------------|
| Output power, $P_{max}$  | Wp   | 100                  |
| Efficiency, $\eta$      | %    | 14.7                 |
| Open circuit voltage, $U_{oc}$ | V    | 21.6                 |
| Saturation current, $I_{sc}$ | A   | 6.39                 |
| Voltage in $P_{max}$, $U_{mp}$ | V    | 17.2                 |
| Current in $P_{max}$, $I_{mp}$ | A   | 5.81                 |
| Ideal diode factor, $\alpha$ | -    | 1.5                  |

PV modules were characterized at various levels of direct irradiation with varying intensities of 100%, 75%, 25% and 25% prepared by filters made from double-layer polyethylene that cover the entire PV module surface. The filter shading method relies on several assumptions for accurate results, i.e. $I_{sc}$ values are proportional to the light intensity and the temperature of the cell must be stable, where $U_{oc}$ is affected by temperature and shading can reduce cell temperature [9].

Figure 3 shows the measurement set up of PV module I-U curves in each filter condition and short interval exposure, which is briefly made to avoid changes in solar intensity [13]. Current and voltage were measured in real-time by the data acquisition module (DAQ) based on the INA219 current sensor integrated with ATMEGA328 microcontroller, while a load resistance from PHYWE SE6 Rheostat 100W was connected to PV. The recorded I-U data was displayed on a PC in Excel format.
3. Result and Discussion

Figure 4 in (a) shows the results of I-U measurement in real time with a variation of irradiation, where the \(Isc\) values are proportional to the solar radiation intensity. While in figure (b), the increase in the percentage of the module filter affects the intensity of the module to decrease and the maximum output power in the form of the Maximum Power Point (MPP) value shifts downward.

![Figure 4](image)

**Figure 4.** (a) Measurement results of I-U and (b) P-R\(_L\) PV modules with direct illumination.

The extraction values of the I-U curve based on three conditions and the Lambert-W function per filter variation are shown in Table 2.

| No | Parameter | Intensity (%) |
|----|-----------|--------------|
|    |            | 100 | 75  | 50  | 25  |
| 1  | \(Isc\) (A) | 2.42 | 2.05 | 1.76 | 1.44 |
| 2  | \(Uoc\) (V) | 20.5 | 20.2 | 19.8 | 19.1 |
| 3  | \(Imp\) (A) | 2.15 | 1.92 | 1.65 | 1.29 |
| 4  | \(Ump\) (V) | 16.4 | 15.2 | 14.8 | 15.7 |
| 5  | \(Pmax\) (W) | 35.3 | 29.1 | 24.6 | 20.2 |

The calculated parasitic resistances show the relative constant value of 0.63\(\Omega\) ±0.027 for \(Rs\) and 93.2\(\Omega\) ± 0.588 for \(Rsh\). Figure 5 shows the \(Rs\) and \(Rsh\) values calculated based on the Lambert-W function, which shows a slight deviation for each intensity of 9.5% for \(Rs\) and 1.3% for \(Rsh\).

Based on figure 5, the \(Rs\) and \(Rsh\) are not influenced by the intensity of the sun and agreed with [7]. Changes in the value of \(Rs\) and \(Rsh\) are also influenced by environmental factors such as rain, humidity, dirt on the module due to exposure to heat and rain as well as corrosion on the connection between cells which increases the parasitic resistance. Using smart monitoring, the value of \(Rs\) and \(Rsh\) can be monitored routinely to see the occurrence of output degradation.
4. Conclusion

Determination of the $Rs$ and $Rsh$ values on the solar panel using the Lambert-W function has been carried out at various levels of light intensity. The parameters of $Rs$ and $Rsh$ in each filter variation have a constant value with a deviation of $0.63\Omega \pm 0.027$ for $Rs$ and $93.2\Omega \pm 0.588$ for $Rsh$. The results show that the $Rs$ and $Rsh$ are not affected by the light intensity which is enabling the determination of $Rsh$ values and $Rs$ for certain conditions.

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Figure 5. Value of $Rs$ and $Rsh$ at various irradiance