Anti-Reflecting Coating to Improve the Performance of Polycrystalline Photovoltaic Module

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Abstract. Photovoltaic performance module (PV) is affected by surface temperature panel, which can reduce output efficiency represented by output power and internal parasitic resistance. Series resistance ($R_s$) and shunt resistance ($R_{sh}$) are needed to determine the characteristics and performance of PV modules for long-term operations. In this work, an anti-reflecting coating (AR layer) has been used to improve the efficiency of solar cells and to determine the stability of the parasitic resistance $R_s$ and $R_{sh}$. A 10Watt Visero Polycrystalline PV module coated with AR layer is irradiated using direct sunlight, and using an artificial light of 500W halogen lamp at various temperature ranges from 30 °C to 60 °C. $R_s$ and $R_{sh}$ are determined based on the current-voltage curve using three parameters; short circuit current, open-circuit voltage, and the maximum power point generated for the Lambert-W calculation. Results show an increase of 11% output power using AR coated module, while the internal resistance $R_s$ increases for 13% and $R_{sh}$ decreases by 0.54%. For non-coated PV, $R_s$ increased significantly for 165% and $R_{sh}$ decreased by 7.4%. Furthermore, the temperature also affects the open-circuit voltage for 8.6% lower and increase the output power for 6.7%. The results show the series $R_s$ and shunt resistance $R_{sh}$ values depend on the PV module temperature.

1. Introduction
Photovoltaic Module (PV) can convert solar energy into electrical energy consisting of array solar cells. PV cells are generally made of silicon that can absorb solar radiation energy well. Many parameters affect the performance of solar modules, including air mass, wind speed, environment, solar cell surface temperature, as well as the characteristics of solar cell material [1]. Temperature is one of the critical factors that influence the performance of PV modules, where an increase in temperature causes the voltage produced by solar panels to decrease [2].

The effect of temperature on the efficiency of multicrystalline type solar panels has been done by [3] have measured changes in Voc value due to temperature changes, but in this study it will also affect temperature changes in $Rs$ and $R_{sh}$ values. by simulating light bulbs as a substitute source for the natural light. However, the internal resistances are not analyzed, so it cannot see the performance of a PV panel. Furthermore, [4] observed the effect of temperature on the voltage and current generated by the PV module, where the parameters I-V were measured manually resulted in an inaccurate measurement. Current-voltage characteristic of PV module by various sunlight intensity using filter cover on the surface of the PV module has been carried out by [5] to determine the parasitic internal resistivity value at room temperature. I-V characterization of PV module using direct solar radiation at a specific temperature has been carried out by [6] increased efficiency of PV modules with water cooling methods has been carried out by [7] to analyze the parasitic internal resistivity using the Lambert-W function. Therefore the heat on the PV module is not constant because the magnitude of the sun's intensity is affected by wind speed Changes in the efficiency of the PV
module due to surface temperature has also been carried out by [8] based on current-voltage characteristic without determines the internal parasitic resistance.

In contrast, Habeeb [9] have conducted research using cooling pipes to increase the current and voltage in the PV module. The effect of temperature on the surface of the polycrystalline PV module which is illuminated by sunlight has been carried out by [10] which discuss the impact of temperature on the surface of the PV module using a halogen lamp light source. Therefore needs to improve the efficiency of the available PV module using anti-reflecting (AR) coating and observed the internal resistance simultaneously.

In this research, the polycrystalline Visero PV module has been characterized at various temperatures with an exposure time of ± 1 minute by giving an anti-reflective coating layer. Measurements are made in direct solar light and use artificial light to observe the performance of the PV module and determine the internal resistance of the cell due to the influence of surface temperature. The data is acquired automatically using the Arduino Uno-based INA 219 sensor. Current-voltage characteristic at various surface temperature was then analyzed using the Lambert-W Function to determine the parasitic resistance Rs and Rsh as well as the efficiency factor of the PV module.

2. Research materials and methods

2.1. Characteristics and Performance Parameters of Photovoltaic Modules

Solar cells have a characteristic curve that shows the relationship between the current with the output voltage (IV), as shown in Figure 1. The current and voltage curves measured under normal irradiation conditions consist of three performance parameter points namely current short circuit (short circuit current), open-circuit voltage (open circuit voltage), and maximum power point (MPP).

Based on Fig. 1, a solar cell equation model can be written as follows:

\[
I = I_{pv} - I_0 \left( \frac{V + I \cdot R_s}{a \cdot V_T} \right) - \frac{V + I \cdot R_s}{R_{sh}}
\]  

(1)

The parameters used to determine the performance of a PV module are short circuit current, open circuit voltage and voltage at maximum power, which is derived from on equation (1) [1].

a. Short circuit current (Isc) is Isc is the current short circuit, the current through a solar cell when the voltage on the solar cell is equal to zero (Voc = 0), or
\[ I_{sc} = I_{pv} - I_0 \left[ \exp \left( \frac{I_{sc} \cdot R_s}{a \cdot V_T} \right) - 1 \right] - \frac{I \cdot R_s}{R_{sh}} \]  

(2)

b. Open circuit voltage (Voc) is the maximum voltage of a solar cell that occurs when the current of a solar cell is equal to zero (Isc = 0) or a non-load circuit. Based on equation (1) the equation (3) is obtained.

\[ 0 = I_{pv} - I_0 \left[ \exp \left( \frac{V_{oc}}{a \cdot V_T} \right) - 1 \right] - \frac{V_{oc}}{R_{sh}} \]  

(3)

c. Maximum power point (MPP) is a condition where the maximum value of the output is obtained.

\[ I_{mp} = I_{pv} - I_0 \left[ \exp \left( \frac{I_{sc} \cdot R_s}{a \cdot V_T} \right) - 1 \right] - \frac{V_{mp} + I \cdot R_s}{R_{sh}} \]  

(4)

2.2. Effect of Temperature on Current-Voltage Characteristics

The temperature has an important role in the characteristics of I-V produced by PV modules. The PV module will produce optimal currents and voltages if the surface of the solar panel is directly facing the light source (without obstructions). Changes in the environment temperature very quickly can also disrupt the output power generated by the PV module. The PV module will work optimally at 25°C. The higher the temperature of the solar panel will have an impact on the output voltage produced by the solar panel. The electrical voltage generated by the PV module can be formulated as follows.

\[ P_{pv} = P_{pv, stc} \cdot f_{pv} \cdot f_{temp} \left( \frac{I_T}{I_{T, stc}} \right) \]  

(5)

\[ f_{temp} = [1 + a_T(T_C - T_{c, stc})] \]  

(6)

\[ T_C = T_a + I_T \frac{(T_{c, NOCT} - T_{a, NOCT})}{I_{T, NOCT}} \left(1 + \frac{nc}{T_a} \right) \]  

(7)

2.3. Lambert-W function

The Lambert-W function, also known as the Omega function [11], is an inverse of \( x \) \( \exp (x) \) where \( \exp (x) \) is an exponent function, which can be written as follows

\[ x = W(x, \exp (x)) \]  

(8)

The Lambert-W function is used to determine the parasitic internal resistivity values of series resistance and shunt resistance by modifying the equation (2) to (4) of IV characteristic, the value of Rs is obtained by equation (9) as follows:

\[ \frac{a \cdot V_T V_{mp} \left( 2 I_{mp} - I_{sc} \right)}{(V_{mp} I_{sc} + V_{oc} (I_{mp} - I_{sc})) (V_{mp} - I_{mp} R_s) - a \cdot V_T (V_{mp} I_{sc} - V_{oc} I_{mp})} = \exp \left( \frac{V_{mp} + I_{mp} \cdot R_s}{a \cdot V_T} \right) \]  

(9)

Rs is determined by modifying equation (9).
and Shunt's internal resistance value as follows:

$$R_{sh} = \frac{(V_{mp} - I_{mp} R_s) \| V_{mp} - R_s (I_{sc} - I_{mp}) - aV_T)}{(V_{mp} - I_{mp} R_s) \| I_{sc} - I_{mp}) - aV_T I_{mp}}$$

(11)

2.4. Anti-Reflecting Coating

Anti-reflecting (AR) coating is a layer on the surface of the PV module made from an anti-reflection material to improve the efficiency of the solar cell. The anti-reflection layer is used to reduce the light waves reflected by the surface of the solar cell so that the light energy falling on the surface of the solar cell can be transmitted and absorbed as much as possible by the solar cell to be converted into electrical energy [12]. The AR coating on the solar cells helps increase the amount of light absorbed into the cells and needed because the reflection of silicon PV cells is more than 30%

2.5. Diagram Block of I-V Characteristic Research

The PV module used in this work was a 10 Watt of Visero PV Module which has 16 solar cells connected in series and parallel. Table 1 shows the module specification.

### Table 1. Polycrystalline PV module of data specifications.

| Specifications parameter   | Unit | VISERO Polycrystalline |
|---------------------------|------|------------------------|
| Output power, Pmax        | Wp   | 10                     |
| Efficiency, $\eta$        | %    | 14.7                   |
| Open circuit voltage, Voc | V    | 21                     |
| Saturation current, Isc   | A    | 0.64                   |
| Voltage in Pmax, Vmp      | V    | 17.5                   |
| Current in Pmax, Imp      | A    | 0.571                  |
| Number of cells, n        | -    | 16                     |
| Dimension ( p x l x t)    | mm$^3$ | 354 x 251 x 18       |

The PV module was characterized using a commercial anti-reflective coatings Glass Tint Film 3M with 35% transparency made of polyethylene terephthalate (PET), which can reject 20% heat and 99% UV. This AR coating covered the surface of the PV module and was measured using direct irradiation from sunlight at a constant temperature of 30°C. This experiment aim is to determine the improvement of PV efficiency using AR coating as well as the internal resistance using Lambert-W model. The temperature influence on the PV characteristic was observed by characterizing the PV module in an adiabatic chamber at various temperature of 40°C, 50°C, and 60°C. The AR coating is not able to withstand surface temperatures above 40°C, therefore the measurements are made using an artificial light source in the temperature room. The temperature measurement method relies on several assumptions for accurate results, namely the value of Isc is inversely proportional to the value of Voc, which is influenced by the surface temperature of the PV panel. The use of coatings can reduce the heat, reaching the surface of the PV panel [12].
Figure 2 shows the setup of the experiment using an acquisition module enables fast and accurate data capture. The measurement of the I-V curve in each condition of the surface temperature should be less than 5 minutes to avoid the changes in lamp intensity as a factor causing errors in measurement (Kunz, 2000). Current and voltage are measured in real-time by the data acquisition module based on the INA219 current sensor and the ATMEGA328 microcontroller that has been integrated and the load resistance PHYWE SE6 rheostat varied from 0 Ω – 100 Ω, the I-V data is displayed on a PC in Word format [13]. Current and voltage are measured using a data acquisition module based on the INA219 current sensor integrated with ATMEGA328 microcontroller, and the load resistance of the PHYWE SE6 rheostat varies from 0 Ω - 100 Ω. While I-V data is displayed on a PC in Word format.

3. Result and Discussion

Figure 3a shows the current-voltage curve of the coated PV module and without AR coating, which shows a significant increase in the output current using AR coating. The measurement was made in the same surface temperature. Figure 3b shows the measurement of the PV module illuminated by a 500 Watt halogen lamp with a various surface temperature of 40 °C, 50 °C and 60 °C.

In Fig. 3b, it can be seen that the Voc has decreased significantly at a surface temperature of 60 °C or 14.48 V. This results obtained agrees as stated in [14] that Voc is influenced by the surface temperature of the PV module.
The I-V curves were simulated using Lambert-W function based on the three conditions I-V values, as depicted in Eq. (2)-(4). Figure 4a shows the effect of AR coating on the PV module performance measured at 30°C resulted in a slight difference of parasitic resistances. For coated PV module, Rs increases for 13% and Rsh decreases for 0.54% compared with non-coated PV module. Furthermore, the AR coating increases also the Isc current and output power for 8.6% and 11% respectively, as shown in Fig. 4b. Reflective layer on the AR coating improves more incident light targets on the solar cell. Parameters extracted based on the three conditions of the Lambert W function are shown in Table 2. Based on table 2, it can be understood the Rs and Rsh is inversely proportional to the influence of temperature on the surface of the PV module.

**Figure 4.** Effect of AR coating on the performance of the PV module (a) parasitic resistance and (b) short circuit current and output power, measured at 30°C

**Table 2.** PV module performance with AR coating

| Temperature (°C) | AR Layer | Isc (A) | Voc (V) | MPP P (W) | Rs (Ω) | Rsh (Ω) |
|-----------------|----------|--------|--------|-----------|--------|--------|
| 30              | coating  | 0.377  | 17.99  | 0.349     | 15.32  | 5.35   | 0.020  | 11.10 |
|                 | non coating | 0.347 | 16.90  | 0.317     | 15.22  | 4.82   | 0.023  | 11.04 |

Figure 5 shows the non-coated PV performance at a various temperature from 40°C to 60°C, which affects the parasitic resistance significantly; 165% increase for Rs and 7.4% decrease for Rsh. In a long time operation, photovoltaic performance can decrease due to direct sunlight exposure resulted in various surface temperature, and humidity, which involves an internal resistance variation. The increase in surface temperature will increase the Rs value and inversely to the Rsh, since the polycrystalline PV module made from the semiconductor, which agrees with [6]. In Table 3, it appears that the open-circuit voltage Voc and the output power P decrease for 8.6% and 6.7% respectively, which is agrees with the research in [15].

**Table 3.** Non-coated PV module at various temperature

| Temperature (°C) | AR Layer | Isc (A) | Voc (V) | MPP P (W) | Rs (Ω) | Rsh (Ω) |
|-----------------|----------|--------|--------|-----------|--------|--------|
| 40              | non coating | 0.238 | 15.84  | 0.224     | 14.69  | 3.29   | 0.025  | 10.9  |
| 50              | non coating | 0.239 | 15.10  | 0.226     | 14.20  | 3.21   | 0.045  | 10.3  |
| 60              | non coating | 0.255 | 14.48  | 0.235     | 13.08  | 3.07   | 0.069  | 10.1  |
7 Figure 5. Values of (a) Rs, Rsh for temperature variations and (b) output performance

The Rs and Rsh are also influenced by environmental factors such as rain, dust, and even corrosion on the series and parallel connection between cells that causes a periodic increase in parasitic resistance value. Therefore, this parameter Rs and Rsh must be monitored regularly to observe the degradation of output. The use of coating has shown a more stable module surface temperature, thus preventing changes in the Rs and Rsh value, which causes deterioration of the PV output power in the long time operation.

4. Conclusion
The photovoltaic module performance has been improved using an anti-reflective coating when exposed to sunlight. Results show that there is an increase of 11% of output power, while the internal resistance Rs increases for 13% and Rsh decreases by 0.54%. Since temperature affects the whole PV performance, for the experiment with various temperature on the non-coated PV surface, Rs increased significantly for 165% and Rsh decreased by 7.4%. The surface temperature will affect not only the parasitic resistances but also the open-circuit voltage and the output power, which decreases 8.6% for Voc and increases 6.7% for output power. The results show the series Rs and shunt resistance Rsh values depend on the PV module temperature. The use of an anti-reflective coating does not have a significant effect on changes of internal resistance, which allows the determination of the Rsh and Rs values in each condition. Furthermore, the AR coating increases the efficiency of the PV module in producing output power.

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