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POWER OUTPUT LOSSES IN SOLAR CELLS WHEN CHARACTERISED BY OPTIMAL RESISTIVE LOAD METHOD

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Abstract - The current and voltage of a solar cell can be measured by optimal load method. However, this method does not automatically adjust the load to ensure maximum power output as solar irradiance varies, hence power output losses. This study investigated the losses in power output that occur in solar cell when characterised by optimal load method. This was done by exposing the solar cell at different illumination intensities (between 300 and 1,000 W/m^2 in the interval of 100 W/m^2) and measuring current and voltage using Keithley Source-meter as well as optimal load (102 mΩ) method. From current and voltage, maximum power output of the solar cell for both methods were calculated and compared. It was found that the power output calculated from optimal load method (102 mΩ) were in good agreement with those from Keithley 2340 Source-meter only between 500 to 700 W/m^2. As a result, the solar cell lost between 1.3 to 33.4% of its maximum power when illumination intensities were outside the operating range of the optimal resistive load. Conversely, when a resistive load of 45 mΩ (which is not optimal) was used, the solar cell lost between 0.8 to 81.4% of its maximum power at various illumination intensities.

Keywords: Maximum power output, optimal resistive load method, data acquisition system, illumination intensity.

1. INTRODUCTION

The electrical behaviour of a photovoltaic (PV) cell or module is determined by measuring current and voltage. The main reason is that most important parameters such as short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), current at maximum power point (I_{MPP}), voltage at maximum power point (V_{MPP}) and power output at maximum power point (P_{MPP}) can be extracted from the current against voltage (*I–V*) curve [1, 2]. The basic principle to obtain *I–V* curve is to control the current supplied by the photovoltaic cell or module between open-circuit voltage and short-circuit current [1, 3]. The current and voltage of a PV cell or module can be measured with data acquisition systems such as Keithley Source-meters [4, 5], I–V curve tracers [6], PV peak power measuring devices [7], PV power analysers [8], etc that continuously adjust the electrical load to achieve the maximum possible output power. However, the main disadvantage of using data acquisition systems is the high cost of these devices [9, 10].

Capacitor charging and discharging is another method found in the literature for PV cells/modules current and voltage measurements [9, 11]. This is based on the principle that when a capacitor is charged by a PV cell/module, the cell/module moves from its maximum operating range and presents a set of current and voltage values that form the *I–V* curve. However, for a PV cell/module that generate high current, the disadvantage of this method is the high power loss due to equivalent series resistance, which causes high voltage drop around the kneel of the *I–V* curve [12-14].

Using variable resistor is another method for obtaining *I–V* curve of a PV cell/module [3, 15-18]. This is achieved by varying the resistor in steps from zero to infinity in order to obtain a set of current and voltage values from short-circuit to open-circuit. However, in practical situations, a fixed resistive load is used [19-25]. This is realised by incorporating a resistive load called optimal resistance in the experimental test circuit [19, 20, 26]. The advantage of this method is that it is simple and inexpensive [20] but results in power output losses for solar radiation outside the operating range of the optimal resistive load. This is due to the fact that optimal load does not automatically adjust the load to ensure maximum power output as solar irradiance varies throughout the day. However, the literature has been silent on quantifying the power output losses in PV cells/modules when characterised by optimal resistive load method.

Therefore, the present study aimed at determining the power output losses of a mono-crystalline solar cell at various illumination intensities when current and voltage were measured by optimal resistive load method. This was done by comparing maximum power of the solar cell calculated from Keithley Source-meter and optimal resistive load method measurements.

2. MATERIALS AND METHODS

2.1. Solar cell used in this study

The solar cell used in this study was mono-crystalline purchased from Blue-Sky Technology (China) [27]. The solar cell was fabricated by soldering connecting wire to positive and negative terminals.

2.2. Determination of optimal load resistance

To determine the optimal load resistance ($R_{optimal}$) for the mono-crystalline solar cell fabricated in section 2.1, a method recommended by Rao and Padmanabhan [28] was adapted. This involved exposing solar cell to different illumination intensities (300, 400, 500, 600, 700, 800, 900 and 1,000 W/m^2) from the solar simulator. The solar simulator was set to illuminate the solar cell at normal incidence angle as shown in Fig. 1. The illumination intensity on the surface of test unit (where the solar cell was placed) was measured by CM4 high temperature pyranometer with an error of ± 20 W/m^2 at 1000 W/m^2 [29]. To ensure that the temperature of the solar cell was same for each experimental test, the cell was cooled by using a fan before the next experiment begins. Data-logger (DL2e model) was used to measure ambient and real surface temperature of the solar cell. On the other hand, Keithley 2430 Source-meter was used to measure current and voltage of the solar cell [4]. For each level of illumination intensity, current against voltage curve was plotted and P_{MPP} as well as resistive load were extracted. To determine optimal resistive load at each illumination level, a relationship between maximum power output and resistive load was plotted as shown in Fig. 2. From this figure, optimal resistive loads were extracted and presented in Table 1.

Fig. 1. Solar simulator set-up to illuminate the solar cell at normal incidence angle

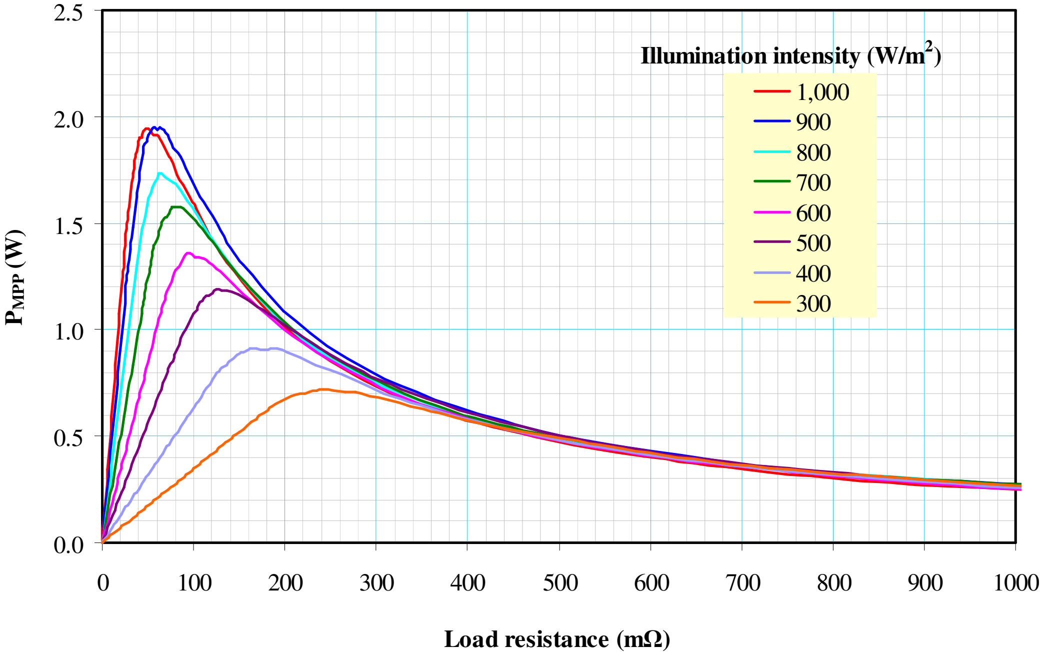

Fig. 2. Variation of maximum power output of a solar cell as a function of illumination intensity and load resistance

Table 1. Variation of optimal load resistance of a mono-crystalline solar cell as a function of illumination intensity

Illumination intensity (W/m^2)	Optimal load resistance, R_{optimal} (mΩ)
300	242
400	169
500	125
600	96
700	75
800	65
900	58
1,000	50

As illustrated in Table 1, the optimal load resistance varied significantly with illumination intensities. This means that a particularly resistive load value, which is optimal at a certain intensity level, is not the optimal value to a similar cell at different illumination level. Based on the definition of optimal resistive load which is the ratio of the voltage at P_{MPP} to the current at P_{MPP} [20], a value of 102 mΩ was obtained. To investigate the effect of measuring current and voltage of a solar by using a resistive load which is not the optimal value, resistance value of 45 mΩ was also used in the experimental test as explained in section 2.3.2.

2.3. Experimental test procedure

In this study, power output loss of the solar cell was determined by comparing the maximum power output of the cell calculated from current and voltage measured by Keithley Source-meter and optimal resistive load method.

2.3.1. Maximum power output from Keithley 2430 Source-meter measurements

In this study, current and voltage of the solar cell fabricated in section 2.1 were measured by using automatic data acquisition system (Keithley 2400 Source-meter). The solar cell was exposed to different illumination intensities (300, 400, 500, 600, 700, 800, 900 and 1,000 W/m^2) from the solar simulator. The solar simulator was set to illuminate the solar cell at normal incidence angle as shown in Fig. 1. To ensure that the temperature of the solar cell was the same at the beginning of each experimental test, the cell was allowed to cool by using a fan before the next experiment begins. For each illumination intensity level, short-circuit current, open-circuit voltage and instantaneous current and voltage were recorded. From the current and voltage measurements, the *I–V* characteristics of the solar cell at each level of illumination intensity were plotted. These curves were used to extract power at maximum power point.

2.3.2. Maximum power output from optimal resistive load method measurements

The current and voltage of the solar cell fabricated in section 2.1 were also measured by using optimal resistive load method. This was achieved by incorporating a fixed optimal resistive load (R_{optimal}) with value of 102 mΩ in the circuit diagram shown in Fig.3. The test unit (Fig. 3) was exposed to different illumination intensities (300, 400, 500, 600, 700, 800, 900 and 1,000 W/m^2) from the solar simulator. At each illumination intensity level, current and voltage from the solar cell were recorded manually by using Fluke 115 AC/DC digital multimeter [30]. The solar cell was cooled by using a fan before the next experiment begins. Then, the value of R_{optimal} in Fig. 3 was replaced with load value of 45 mΩ and similar experiments were carried out. From current and voltage measurements, maximum power output at each level of illumination intensity was calculated.

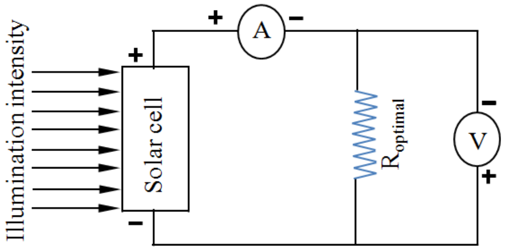

Fig. 3. Circuit diagram for measuring current and voltage of a solar cell by fixed resistive load method [26]

3. RESULTS AND DISCUSSIONS

3.1. I–V characteristics and maximum power output

Fig. 4 shows the I–V characteristics of the solar cell at different illumination intensities and P_{MPP} calculated from current and voltage measured by Keithley Source-meter as well as fixed resistive loads method. It can be seen that with optimal resistive load of 102 mΩ, the power output increases but at lower and higher illumination intensities the line passes far away from the kneel of the I–V curves. This indicates that the power output is independent of illumination intensity at these points. On the other hand, the line for 45 mΩ load also intersects with the I–V curves very far from the kneel, expect at higher illumination intensities. This also indicates that the power output was independent of illumination intensity hence very low maximum power output as compared to that calculated from Keithley Source-meter.

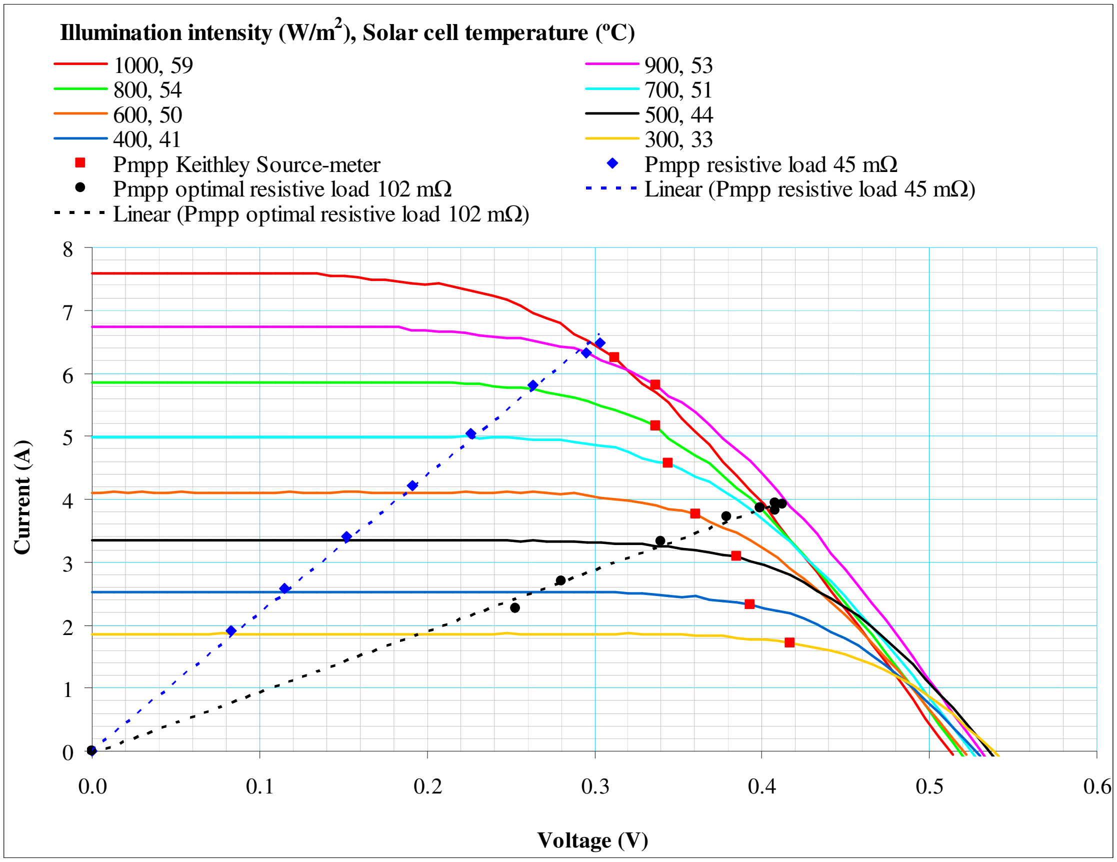

Fig. 4. The I–V curves of the solar cell at different illumination intensities and comparison of maximum power output calculated from Keithley Source-meter and fixed resistive loads method measurements

3.2. Power output losses due to fixed resistive load method

To clearly illustrate the relationship between maximum power output and illumination intensity, a graph of maximum power output against illumination intensity for each value of resistive load was plotted and compared with maximum power output calculated from Keithley 2340 Source-meter measurements as illustrated in Figs. 5 and 6. It can be seen that in both figures, maximum power output calculated from Keithley 2340 Source-meter measurements were linear with illumination intensities because the device automatically adjusts the load as the illumination intensity varies. However, due to higher cell temperatures at higher illumination intensities, there was a slightly fall in maximum power output calculated from Keithley 2340 Source-meter measurements. In contrast, the maximum power output calculated from optimal resistive load of 102 mΩ (Fig. 5) were in good agreement with those from Keithley 2340 Source-meter only in the illumination intensity operating range of the optimal load (500 to 700 W/m²). Below 500 W/m², the power output were non-linear and less than the values from Keithley 2400 Source-meter. On the other hand, above 700 W/m² the power output were almost constant in spite of the increase in illumination intensities. For example, while there was about a 43% increases in illumination intensity from 700 W/m² to 1,000 W/m², the power output increased only by about 5%. This means that the illumination intensities above 700 W/m² did not contribute significantly to the power output generated. This is due to the fact that the optimal resistive load value (102 mΩ) does not automatically adjust the load as the illumination intensities varies. As a result, there were losses in maximum power output when compared with that from Keithley 2340 Source-meter.

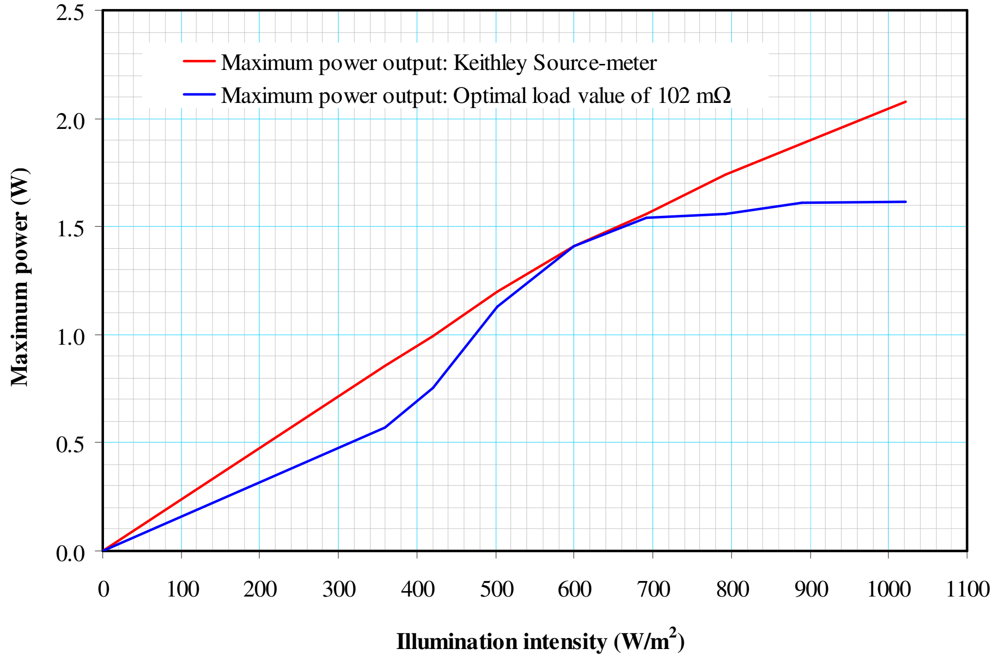

Fig. 5. Comparison of maximum power output of mono-crystalline solar cell when characterised by Keithley 2340 Source-meter and optimal resistive load of 102 mΩ

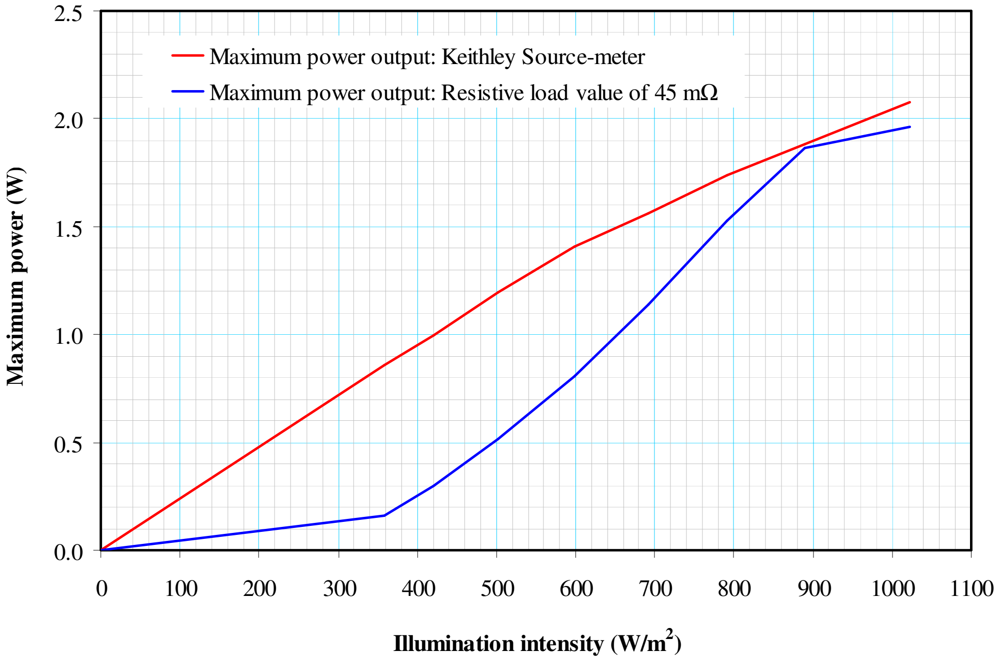

Fig. 6. Comparison of maximum power output of mono-crystalline solar cell when characterised by Keithley 2340 Source-meter and resistive load of 45 mΩ

Table 2 shows the losses in P_{MPP} of the solar cell at each illumination intensity level due to optimal load of 102 mΩ. It can be seen that power output losses were greater at lower and higher illumination intensities than in the operating range of the optimal load (500 to 700 W/m^2). The reason is that resistive load method is only optimal to a range of illumination intensities. In practical situation, this translates to low power output and hence high cost for solar system installation (since many solar panels are required). Therefore, charactering solar cells or PV modules by optimal resistive load method should be avoided.

Table 2. Power output losses of the solar cell when current and voltage were measured by optimal load of 102 mΩ

Illumination intensity (W/m^2)	P_{MPP} (W) calculated from Keithley Source-meter measurements	P_{MPP} (W) calculated from optimal resistive load (102 mΩ) measurements	P_{MPP} loss (%)
300	0.8583	0.5718	33.4
400	0.9950	0.7560	24.0
500	1.1958	1.1322	5.3
600	1.4089	1.4089	0.0
700	1.5597	1.5401	1.3
800	1.7419	1.5586	10.5
900	1.8832	1.6075	14.6
1,000	2.0765	1.6150	22.2

Fig. 6 shows that when current and voltage of the solar cell were measured by resistive load of 45 mΩ, there was a larger divergence of maximum power output as compared to that from Keithley 2340 Source-meter, except at higher illumination intensities (900 W/m^2 and above). The reason is that with smaller resistive loads than the optimal value, the solar cell behaves as a constant current source (almost equal to the short-circuit current, independent of the voltage) which in turn causes non-linear relationship between irradiance and output power [20]. This causes high losses in maximum power output as shown in Table 3. For example, the solar cell lose about 81% of its maximum power output at 300 W/m^2 as compared to about 33% at the same illumination intensity when characterised by optimal load value (Table 2). Since high solar radiation occurs at solar noon, in practical situation, this is translated to high power output losses before and after solar noon.

Table 3. Power output losses of the solar cell when voltage and current were measured by resistive load of 45 mΩ

Illumination intensity (W/m^2)	P_{MPP} (W) calculated from Keithley Source-meter measurements	P_{MPP} (W) calculated from resistive load (45 mΩ) measurements	P_{MPP} loss (%)
300	0.8583	0.1594	81.4
400	0.9950	0.2979	70.1
500	1.1958	0.5168	56.8
600	1.4089	0.8041	42.9
700	1.5597	1.1413	26.8
800	1.7419	1.5280	12.3
900	1.8832	1.8674	0.8
1,000	2.0765	1.9634	5.5

5. CONCLUSIONS

This study investigated the losses in power output that occur in mono-crystalline solar cell when characterised by optimal resistive load method. It was found that the maximum power output calculated from optimal load method (102 mΩ) were in good agreement with those from Keithley 2340 Source-meter only in the illumination intensity operating range of the optimal load (500 to 700 W/m^2). As a result, the solar cell lost between 1.3 to 33.4% of its maximum power when illumination intensities were outside the operating range of the optimal load. In practical situation, this translates to low power output and hence high cost of solar system installation (since many solar panels are required). On the contrary, when a resistive load of 45 mΩ (which is not optimal) was used, the solar cell lost between 0.8 to 81.4% of its maximum power at various illumination intensities. Since high solar radiation occurs at solar noon, in practical situation, this is translated to high power output losses before and after solar noon. Therefore, charactering solar cells or PV modules by fixed resistive load method should be avoided.

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