EXPERIMENTAL STUDY OF SOLAR RADIATION AUGMENTATION ON PHOTOVOLTAIC MODULES

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Abstract. *The initial capital cost of the photovoltaic cells and modules has always been a major barrier for the widespread use of the technology all over the world and in Latin America specifically. The general idea of reducing the initial capital costs of PV systems by producing more power out of the same module is appealing by itself.*
As it is known, by increasing the incident solar radiation falling on a PV module, the PV module's power output will increase according to the inherent characteristics of the PV cells. However, an increment in the radiation level may increase the temperature of the cells that, in turn, would diminish the efficiency and power output of PV cells.
The objective of this experiment was to evaluate in the field the performance of photovoltaic modules when the incident solar radiation is augmented by means of planar reflectors and up to which extent the temperature increase offsets the increment in the power output of the PV module. In the process, the effect of the reflectors' geometry on the performance of the module was studied in terms of two of the main geometric parameters. The experiment has yielded promising results considering both the increase in power output obtained and the simplicity and low cost of the system studied.

Keywords. *photovoltaic modules performance, planar reflectors, solar radiation augmentation, temperature effect, PV system cost*

1. Introduction

The initial capital cost of the photovoltaic (PV) cells and modules has always been a major barrier for the widespread use of the technology all over the world and in Latin America specifically (United Nation Development Programme, 2000). The general idea of reducing the initial capital costs of PV systems by producing more power out of the same PV module is appealing by itself. It is well known that by increasing the incident solar radiation falling on a PV module, the PV module's power output will increase according to the inherent characteristics of the PV cells. However, an increment in the radiation level may increase the temperature of the PV modules that, in turn, would diminish the efficiency and power output of the PV cells (López Araujo, 1995 e Radziemska, 2002).

Solar radiation concentrating devices have been developed mainly for solar thermal applications such as space and water heating (Tabor, 1966 e Pucar, 2002). In solar thermal applications, the temperature increase of the solar collector represents a temperature increase in the working fluid which is, in turn, the ultimate goal of this type of solar collectors.

Experiments attempting to increase the power output per unit of area of PV cells are more recent (Uematsu, 2001). These experiments have usually dealt with high-concentration lenses to concentrate solar radiation on PV cells specifically designed for these applications (Miñano, 1995, Yoshioka, 2003 e Wennerberg, 2000). In these cases, resultant issues such as intense heat radiation from the PV cells may arise because the cells temperature can reach high values that cannot be neglected whatsoever. In theses systems, the PV cells, or modules, also require an accurate sun-tracking device that can be costly. Thus, the high-concentration lenses, the special PV cells and the sun-tracking device can eventually offset the economic benefits of reducing the surface area of the PV module (or the number of PV modules). The complexity and expensiveness of high-concentration systems have encouraged in the last few years the development of a different type of concentrating systems that do not required neither sophisticated tracking systems nor concentrating lenses and that can be used with commercially available PV modules.

Several experiments, such as the one carried out by Matsushima et al., use commercial PV modules and low-concentration planar reflectors (Matsushima, 2003). Matsushima's experiment achieved power output increments of 50% with respect to conventional PV modules without radiation augmentation even though in this case the entire system (i.e. PV modules and planar reflectors) was fixed on the ground.

In the experiment presented in this paper, the performance of a sun-tracking photovoltaic module when the incident solar radiation falling on it is augmented by means of aluminium planar reflectors was evaluated. The experiment also assessed up to which extent the temperature increase offsets the increment in the power output of the PV module (Radziemska, 2003). In the process, the effect of the reflectors' geometry on the performance of the module was studied in terms of two of the main geometric parameters.

The results show the power output increment of the PV module with planar reflectors attached with respect to the power output of the PV module without reflectors for six different reflectors' geometries. The results also show the incidence of the temperature increase due to the augmented radiation.

2. Experiment set up

The experiment set up consisted of two 48-Wp (peak power) photovoltaic modules mounted at a given tilt angle on a single-axe sun-tracking device that allowed the modules to face the sun at all times. One of the modules was used as a reference (reference module), receiving unaltered direct and diffuse solar radiation from the sky. For the other module (testing module), the incident solar radiation was increased by attaching two aluminium planar reflectors along the longest sides of the testing module. A third module at the same tilt angle was installed and fixed on the ground for comparison purposes. The tilt angle was chosen to be the optimum for the location (Olavarría, Argentina, is located at 36º south latitude) and the time of the year when experiment was performed (i.e. fall and winter). The electronic circuit and other components of the sun-tracking device were developed at our Department of Electromechanical Engineering (Blanco, 1998).

The aluminium planar reflectors (with reflectivity coefficients of 0.74) simply reflect the radiation from the sun increasing the overall radiation received by the testing PV module. The structure supporting the aluminium reflectors allowed changing the angle α between the PV module and the reflectors from 105º to 125º. The reflectors' width, in turn, could be extended from 0.25 m to 0.50 m as shown in Fig. (1). Thus, these two critical geometric parameters could be controlled and adjusted during the experiment.

Keeping in mind the goal of reducing initial capital cost of the system, both the sun-tracking device and the planar reflectors supporting structure were developed for simplicity and low initial and operation and maintenance costs.

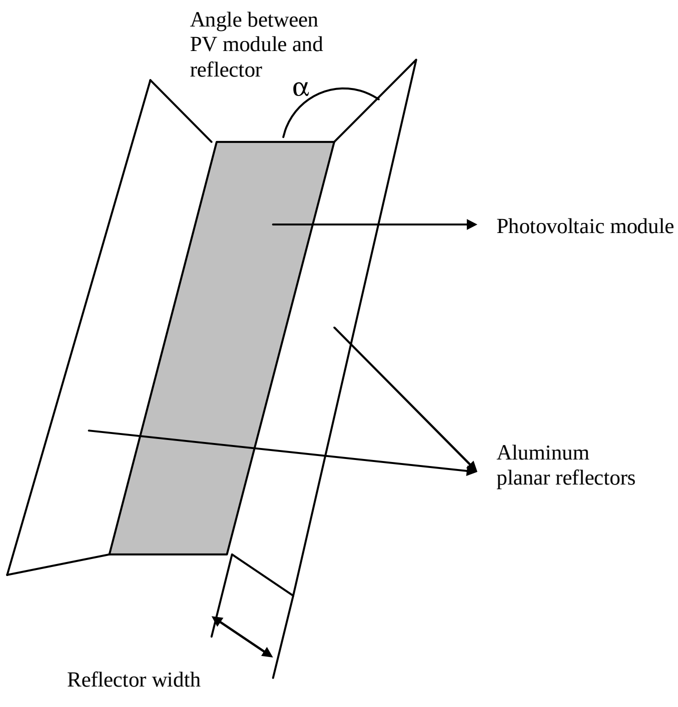

Figure 1. Geometry of the PV module and aluminium planar reflectors

The sun tracker with the testing and reference modules was installed along with the planar reflectors supporting structure in an open site at the college's campus. Figure (2) shows the installation.

Figure 2. Testing module (left) and reference module (right) mounted on the sun tracker at College of Engineering of the UNCPBA campus in Olavarría, Argentina.

In order to assess the effect of temperature on the performance of the module, the testing module was cooled down during part of the experiment by using air fans until it reached the same temperature of the reference module. For this purpose, thermo resistors were attached to the modules and an electronic control loop was developed and installed to start up and shut down the air fans automatically.

The power output (i.e. current and voltage) and temperature signals from the three PV modules were collected during 4 months, varying the angle between module and aluminium reflectors for different panel widths during the experiment. As mentioned above, this feature of the supporting structure allowed studying the relative geometry of the reflectors with respect to the module. The data acquisition system used during the experiment was also developed at our Department of Electromechanical Engineering.

The following section describes the mathematical models used to represent the behaviour of the PV modules.

3. Photovoltaic generator characteristics and models

The behaviour of a PV cell can be represented by a equivalent circuit that consists of a constant current generator delivering a current I_L (so called the light current) into a network of impedances, which includes a diode, an intrinsic series resistance R_s, an intrinsic shunt resistance R_{sh}, and a load resistance R_L as shown in Fig. (3) (Angrist, 1976; Duffie, 1991 e López Araujo, 1995).

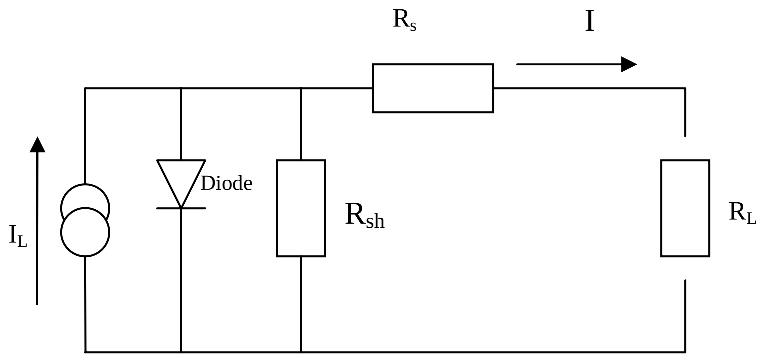

Figure 3. Equivalent circuit of a photovoltaic cell

The mathematical model that represents the equivalent circuit of a PV cell is then (Ahmad, 2003):

$$I = I_L - I_o \cdot \{\exp[\frac{e \cdot (V + I \cdot R_s)}{m \cdot k \cdot T}] - 1\} - \frac{V + I \cdot R_s}{R_{sh}} \quad (1)$$

Where,

e: electron charge [C]
I: current delivered by the cell [A]

I_L: light current [A]
I_o: saturation or dark current [A]
k: Boltzmann's constant [J/K]
m: curve fitting parameter
R_s: series resistance [ohm]
R_{sh}: shunt resistance [ohm]
T: absolute temperature of the cell [K]
V: voltage at the load [V]

The curve fitting parameter m, the series resistance R_s and the shunt resistance R_{sh} were determined based on the I-V curve given in the technical specifications of the PV modules used in the experiment.

The influence of the temperature on the PV cell characteristics can be seen in the open circuit voltage expression that follows:

$$V_{oc} = \frac{E_{go}}{k \cdot T} - \frac{k \cdot T}{e} \cdot \ln\left(\frac{K_a \cdot T^3}{I_L}\right) \tag{2}$$

Where,

E_{go}: material band gap energy [J]
K_a: constant [A/K^3]
V_{oc}: open circuit voltage [V]
In Eq. (2) **ln** is the natural log and k, T, e and I_L are the same variables already described for Eq. (1).

Values for the material band gap energy E_{go} and for the constant K_a were also determined, although indirectly, from the technical specifications of the PV modules.

In all cases the light current I_L was assumed to be proportional to the solar radiation and set equal to the short circuit current I_{sc} when the circuit was open.

4. Methodology

In order to calculate the power output of all three modules, the short circuit current I_{sc} for each module was measured by means of a small (i.e. 0.1 ohm) shunt resistance connected to the modules' terminals. The open circuit voltage V_{oc} was measured by opening the circuit cyclically with a given period of time by means of a relay. Both I_{sc} and V_{oc} signals were acquired alternatively every second along with the temperature T signal coming from the thermo resistors.

The signals were collected for a wide range of solar radiation levels and for three different angles between planar reflectors and testing module (i.e. 125º, 115º and 105º) combined with two different planar reflector widths (i.e. 0.25 m and 0.50 m). Thus six different data sets were obtained and processed.

Once the signals were converted to current, voltage and temperature values respectively they were introduced into the mathematical model of the PV module described above and developed in the Engineering Equation Solver (EES) software package. EES allowed calculating the maximum power output of each module as a function of the I_{sc}, V_{oc} and temperature T for a given planar reflector geometry.

In order to assured that readings from all three modules were the same for a given solar radiation, at the beginning of the experiment the modules were fixed exactly at the same position (i.e. tilt and azimuth angles) and the I_{sc}, V_{oc} and temperature T signals were acquired. Then correction factors were determined to adjust the modules' outputs and make them equal to each other.

Once the Eq. (1) and Eq. (2) were introduced in EES, the saturation current I_o was calculated for each value of I_{sc}, V_{oc} and temperature T collected through the acquisition system and later adjusted with the correction factors. Then, by using EES maximization built-in function, the maximum power output (i.e. P_{max}=V_{max}.I_{max}) of the PV module was calculated for each set of I_{sc}, V_{oc} and temperature T measured in the field. The procedure was repeated for all three PV modules installed and for the six different geometric configurations of the planar reflectors. The figures in the following section show the results obtained in this experiment.

To assess the effect of temperature on the PV module, two methods were used. First, the testing module was cooled down to the temperature of the reference module during part of the experiment by means of air fans. Then, the new power output data points were compared with the power output when the module was working at the temperature it reached naturally with the planar reflector attached. The second method used the mathematical model of the PV module built on EES. In this case the testing module model was run using the temperature of the reference module. The results are shown in Fig. (8).

5. Results

The results of the experiment are summarized in this section in the form of two graphs showing the power output calculated from data measured and collected from the field and two additional graphs showing the average power output increase for the six different reflectors' geometries with respect to both the reference module and the module fixed on the ground. A fifth graph shows the effect of temperature on the testing module power output calculated from actual data and from the mathematical model as explained in section 4. Methodology.

Figure (4) shows the power output of the of the testing PV module with planar reflectors attached as a function of a wide range solar radiation levels (represented here for the short circuit current I_{sc} of the reference PV module) for 3 different angles between reflectors and module. The actual power output of the reference module is also shown for comparison purposes. In Fig. (4) reflector width was set at 0.25 m.

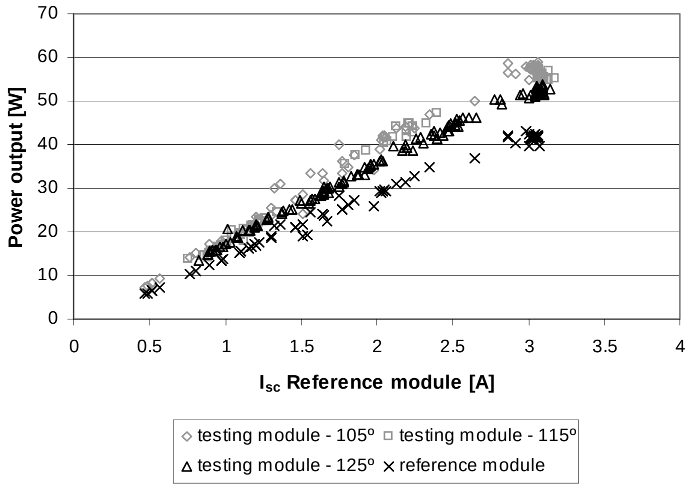

Figure 4. Actual power output of the testing module (with planar reflectors) vs. short circuit current of reference module for 3 different angles between reflectors and PV module. Reflector width 0.25 m.

Figure (5) also shows the power output of the of the testing PV module with planar reflectors attached as a function of the solar radiation (as before represented for the short circuit current I_{sc} of the reference PV module) for 3 different angles between reflectors and module. The actual power output of the reference module is also shown for comparison purposes. In Fig. (5) reflector width was doubled and set at 0.50 m.

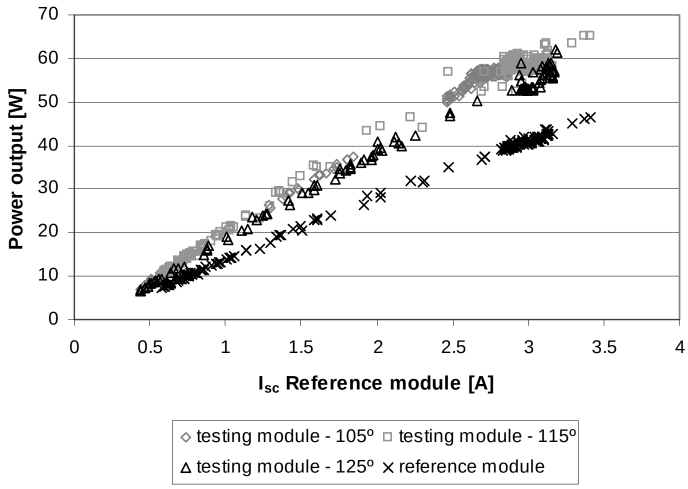

Figure 5. Actual power output of the testing module (with planar reflectors) vs. short circuit current of reference module for 3 different angles between reflectors and PV module. Reflector width 0.50 m.

Figure (6) summarized the results obtained by showing the weighted average of the testing module power output increment; that is, taking into account the number of data points for different solar radiation ranges. In this figure, the testing module power output increment is shown as a percentage of the reference module power output. Figure (6) shows the power output increment for 6 different reflectors' geometries.

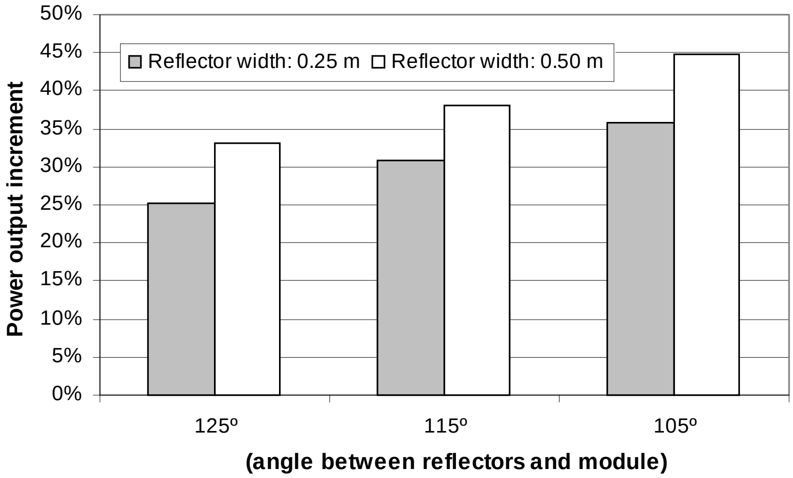

Figure 6. Power output increment of the testing module (with planar reflectors) as a percentage of the reference module power output for 3 different angles between reflectors and module and 2 different reflector widths.

Figure (7) also shows the weighted average of the testing module power output increment although in this case as a percentage of the power output of the module fixed on the ground. As before, the power output increments are shown for 3 different angles between reflectors and module and 2 different reflector widths.

Figure 7. Power output increment of the testing module (with planar reflectors) as a percentage of the power output of the module fixed on the ground for 3 different angles between reflectors and module and 2 different reflector widths.

Figures (4), (5), (6) and (7) show the power output of the testing module working at the temperature it reached naturally with the planar reflectors attached. Figure (8) shows the percentage of the testing module power output drop as a function of the temperature increase. The power output drop was calculated from actual data by comparing the power output of the testing module working at its "natural" temperature and the power output of the same module working at the temperature of the reference module. Figure (8) also shows the percentage of testing module power output drop calculated from the mathematical model built in EES, as explained in section 4. Methodology.

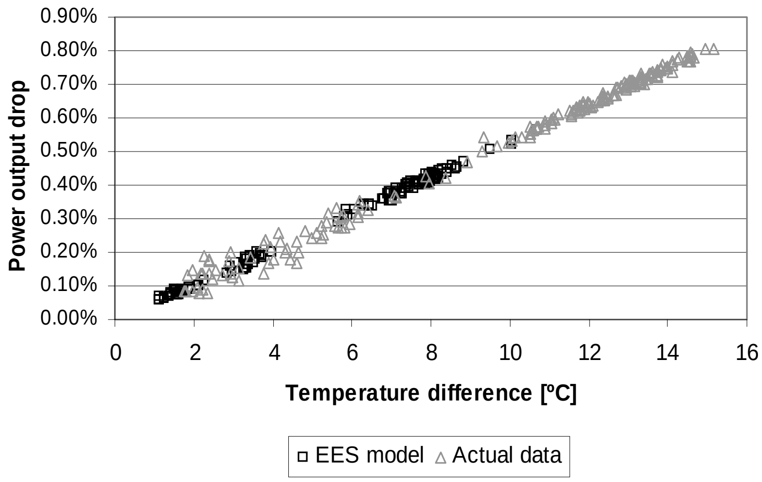

Figure 8. Power output drop as a function of temperature increase calculated from both actual data and mathematical model.

6. Discussion

The first conclusion that can be drawn from the collected data as shown in Figures (4) and (5) is that the planar reflectors are more effective for high levels of solar radiation. As it was expected, the variation in power output increment is proportional to the solar radiation level.

With respect to the planar reflectors' geometry, Figures (4) and (5) show some obvious conclusions such as the effect of the aluminium planar reflector width on the power output (Duffie, 1991). In average for all 3 angles between reflector and module and for all levels of solar radiation, when the planar reflector width is doubled approximately a 9% increase in power output is achieved. This result could be an important input for a life cycle cost analysis of the system. From the same Figures (4) and (5) and more conclusively from Figures (6) and (7), it can be seen that an angle α between planar reflector and PV module of 105 degrees yields the maximum power output increment. In average for all levels of solar radiation and for this angle α, the power output increment reaches 45% with respect to the reference module and 75% with respect to the module fixed on the ground. This result is in the same order of magnitude of Matsushima's, although in our case the power output increment is even higher due to the sun-tracking system that optimizes the effectiveness of the reflectors on the PV module.

Finally, it can be seen that the effect of temperature increase on the performance of the testing module is very small; in all cases the power output drop was less than 1%. This figure does not agree with Radziemska's, who calculated a power output drop of 0.65% for each degree C of temperature increase (Radziemska, 2003). In our case the power output drop per degree C is only one tenth of that figure. The difference could be explained for the time of the year and the absolute ambient and module temperature at which the experiments were realized (López Araujo, 1995). To shed light on this issue data should be collected over the whole year. This difference, however, does not affect the main body of collected data and the results discussed above.

7. Conclusion

An average power output increment of 75% was achieved from a sun-tracking PV module when aluminium planar reflectors were used to augment the incident solar radiation falling on it with respect to the power output of a PV module fixed on the ground. The result can be considered very promising in regard of the ultimate goal of reducing photovoltaic systems initial capital costs. Considering that both the sun-tracking device and the reflectors' materials used in this experiment were design and chosen for simplicity and low costs, the introduction of these elements in a PV system can significantly reduce initial capital costs by reducing the number of PV modules required.

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