Investigation of the design aspects on the performance of a LCPV system

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Abstract. This paper addresses the procedures that need to be considered when designing an optical and electrical sub-system of a low concentrator photovoltaic (LCPV) module. CPV systems make use of optical elements and solar tracking to concentrate solar flux onto a photovoltaic (PV) receiver. The performance of the concentrator module is highly dependent on the configuration and alignment of the optical elements in the system. In this study a LCPV module was constructed to satisfy a certain set of predetermined boundary conditions. This LCPV module has a geometric concentration ratio of 5.3 X. Various design considerations were taken into account to optimise the configuration of the photovoltaic receiver of the module. The LCPV module was then characterised with respect to optical design and electrical performance.

1. Introduction.

Concentrator Photovoltaics (CPV) is one of the technologies that have attracted a renewed interest due to the increased search for the use of non-fossil fuel based sources of energy to mitigate environmentally damaging effects of using fossil fuel for electricity production. CPV modules are a cost effective alternative to flat-plate photovoltaic (PV) modules since they concentrate sunlight onto small efficient solar cells [1].

In low concentration photovoltaics (LCPV), solar cells are subjected to higher irradiance levels than conventional flat-plate cells. The electrical output, and hence efficiency of a LCPV module is dependent on three factors; the amount of irradiance, uniformity of illumination across the solar cells and PV receiver temperature. These factors are interdependent and need careful consideration when deigning an LCPV module.

Three subsystems can be identified in CPV modules, namely optical, thermal and electrical. This paper discusses the design aspects and characterisation of the optical sub-system as well as electrical sub-system of a LCPV concentrator. By optimising the aperture area of the LCPV concentrator while still maintaining a uniform illumination intensity across the solar cells, the electrical performance can be maximised.

In theory it is assumed that an optical concentrator produces a perfectly uniform illumination profile, but in reality this is not the case due to a number of factors. The concentration level obtained is an average of the concentration profile impinging upon the solar cell [2]. It is important that the optical elements in the system create a uniform illumination profile across the solar receiver as far as possible. A non uniform illumination profile from an optical concentrator generates a 2 dimensional temperature gradient on the receiver surface which affects the power output of the solar receiver.

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Previous research resulted in the construction of a V-trough concentrator reaching 2.4 X concentration [3]. One of the main problems with the vertical receiver system was that the distance between the facetted reflector element and the receiver emphasized the effects of small misallignments of optical elements [4].

An initial design that had to satisfy a predetermined set of boundary conditions was introduced to improve on the V-trough concentrator system.

2. Theoretical Framework.

Due to difficulty in obtaining a uniform illumination intensity distribution in the aforementioned vertical receiver design an alternative design was sought, with an emphasis on the module cross-sectional aspect ratio that must be kept as low as possible and keeping in mind the uniformity of the intensity profile across the PV receiver.

The predetermined set of boundary conditions that had to be satisfied were:

- Module profile to have a low cross-sectional aspect ratio.
- Facetted reflector as concentrator element.
- Light incident on the receiver must be as perpindicular as possible to the incident light from the reflection facets.
- Reflector element symmetrical around receiever.
- Beams incident on opposite ends of facet to be reflected to opposite ends of the receiver.

A mathematical model was constructed in Optica 3 [5] for this design. From initial testing and prototypes it was found that a horizontal face down receiver system was the more feasible design. Figure 1 shows an illustration of the horizontal receiver design traced in Optica 3. The receiver pairs are also labeled in the figure.

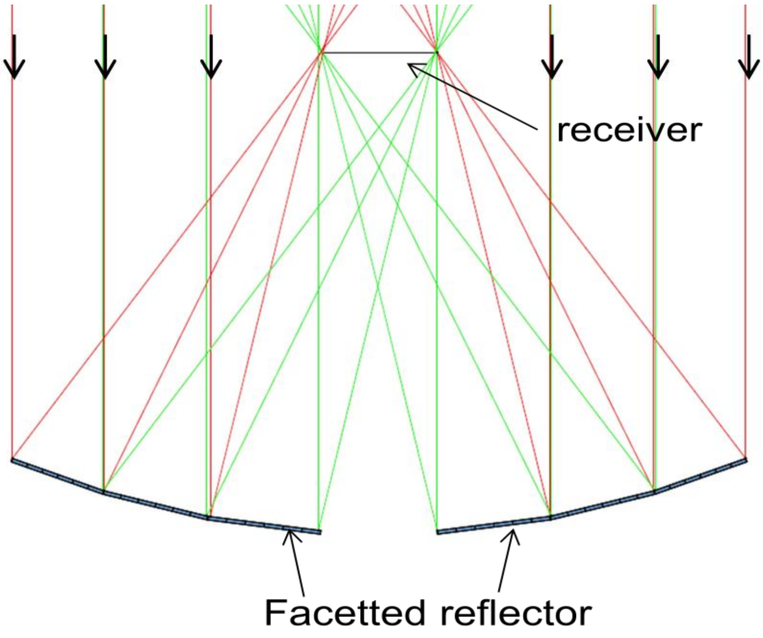


Figure 1: Illustration of horizontal receiver design with ray tracing

3. Experimental.

A horizontal receiver LCPV prototype module was constructed and characterised with respect to optical and electrical performance. For optical characterisation the intensity profiles were obtained by investigating the contribution of each facet pair and compared to the theoretical contribution. Verification of illumination intensity and uniformity on the receiver plane was done by making use photography and image analysis using Image J software [6]. Image J analysis software also facilitated the extractof line scans from the intensity profiles.

For electrical characterisation various cell string configurations used as the PV receiver for the concentrator system were evaluated. These include 3, 4, 6 and 8 cell string receivers. The cell material was cut to ensure that the total area of cell material remained constant.Electrical output parameters were measured at 1 sun (1000 W/m2) and under concentration using an Agilent Current-Voltage (I-V) tracer.

4. Results and Discussions

4.1. Optical characterisation

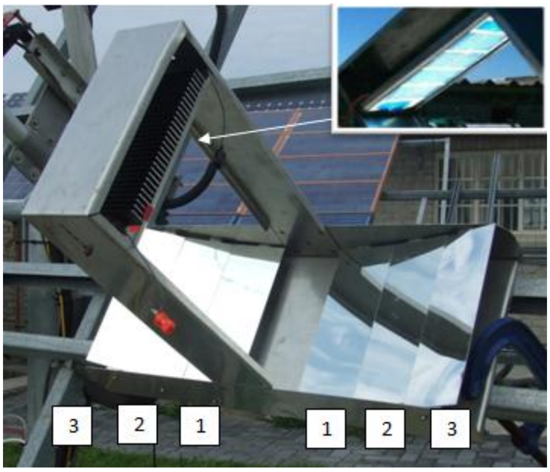


Figure 2. Photograph of horizontal receiver concentrator system.

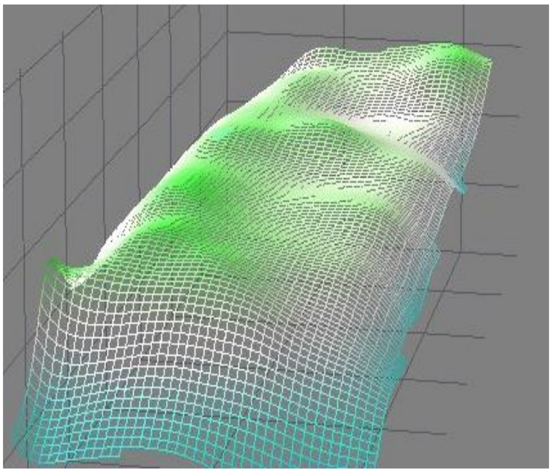


Figure 3. Intensity profile obtained from LCPV module.

Figure 2 shows a photograph of the horizontal receiver LCPV module. The inset in the figure shows the PV receiver under concentrated illumination. A typical illumination profile such as that seen in the inset was recorded and is shown in figure 3. This type of profile was used to evaluate the optical performance of the respective reflector pairs (1; 2 and 3) as illustrated in figure 1. The effective concentration for each pair is listed in table 1 and typical line scans extracted from an intensity profile map, like that shown in figure 3, are shown in figure 4.

Table 1. Theoretical and experimental contribution of each facet pair.

Facet Pair	Measured Concentration	Theoretical Concentration
First	1.96	1.96
Second	1.65	1.84
Third	1.52	1.68

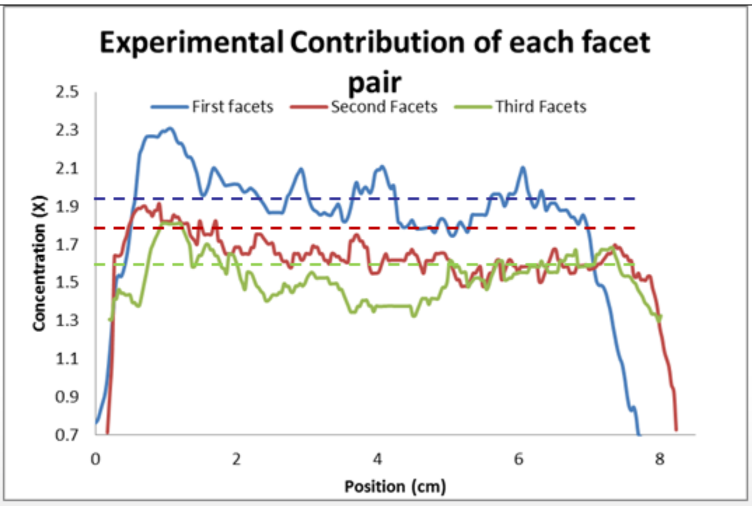


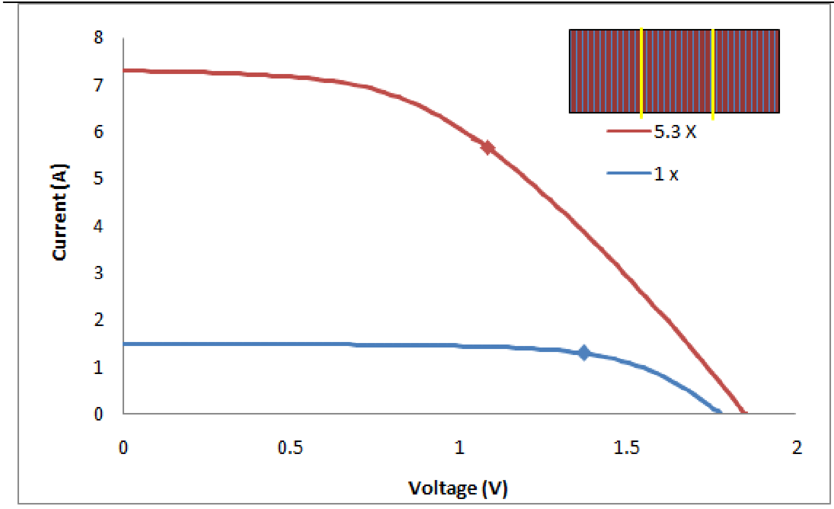
Figure 4. Line scans obtained from intensity profiles of each facet pair.

From the data it can be seen that the contributions closely resemble the expected theoretical values. The reasons for the second and third facet pair not reaching the expected contribution are due to lensing effects of the facets as well as some illumination missing the receiver. Although the illumination profile uniformity is much improved for this design, compared to the vertical receiver system, further optimization is required.

4.2. Electrical characterisation

The different cell string configurations were tested in the concentrator systemand the I-V characteristics measured under one-sun and concentration are shown in in figures 5, 6, 7 and 8. The performance parameters are also listed in the figures. Also shown in each figure is a schematic of the PV receiver, illustrating the number of cells and the fact that the total effective receiver area remains constant.

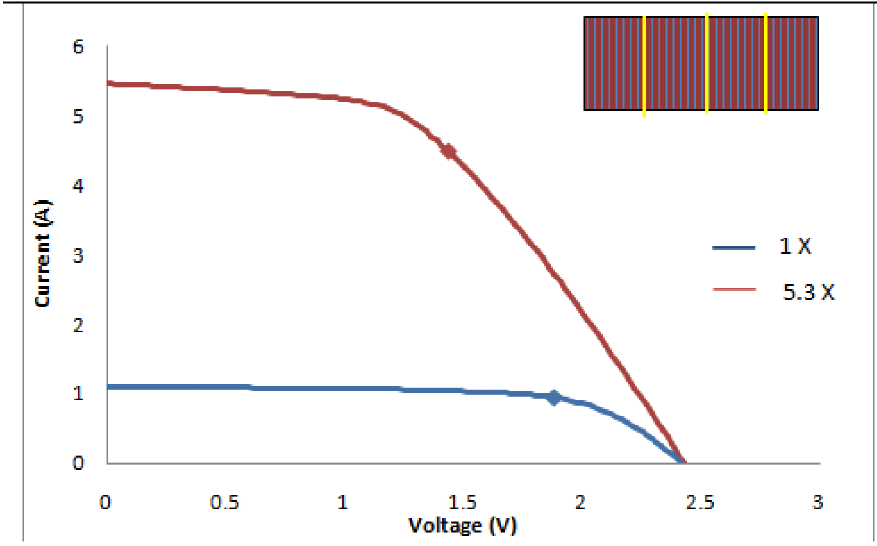
3 cell string



	X = 1	X = 5.3
Isc	1.49 A	7.30 A
Voc	1.78 V	1.84 V
Imp	1.29 A	5.67 A
Vmp	1.37 V	1.08 V
Pmax	1.77 W	6.14 W
Temp	34.4^{0}C	31.0 ^{0}C
Series Resistance	0.042 Ω	

Figure 5. I-V characteristic of 3 cell string configuration with electrical parameters.

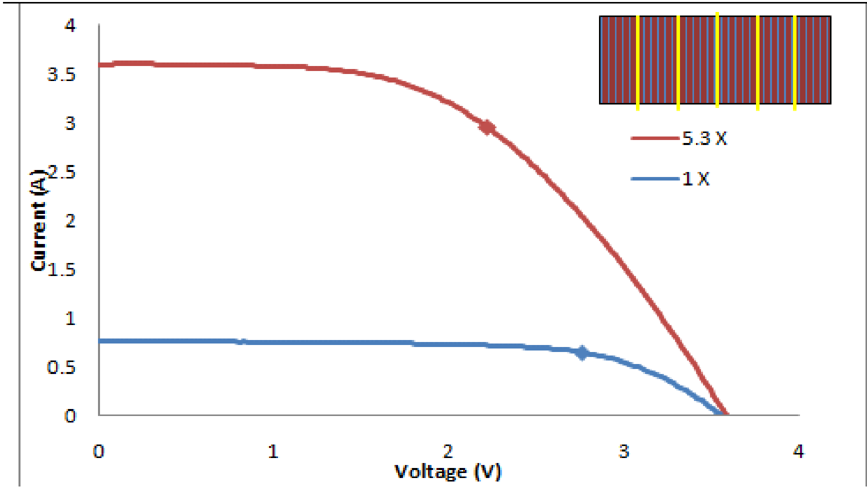
4 cell string



	X = 1	X = 5.3
Isc	1.10 A	5.50 A
Voc	2.42 V	2.43 V
Imp	0.94 A	4.49 A
Vmp	1.88 V	1.43 V
Pmax	1.78 W	6.45 W
Temp	28^{o}C	32 ^{o}C
Series Resistance	0.04 Ω	

Figure 6. I-V characteristic of 4 cell string configuration with electrical parameters.

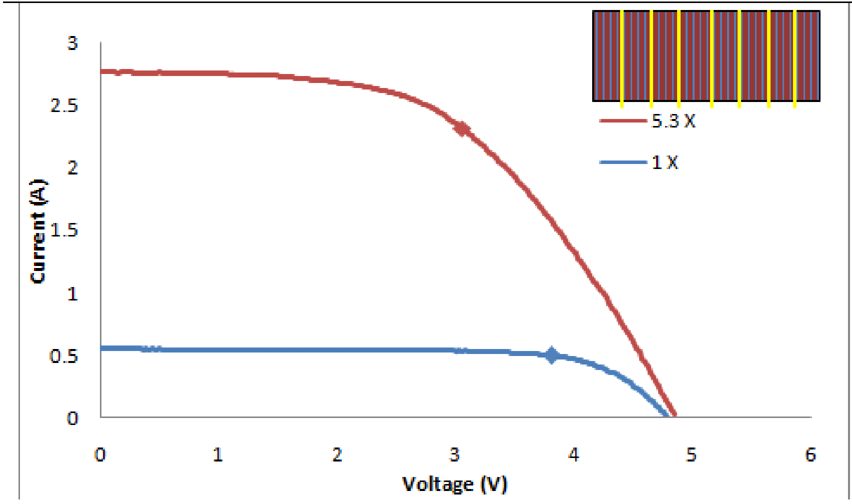
6 cell string



	X = 1	X = 5.3
Isc	0.75 A	3.58 A
Voc	3.55 V	3.57 V
Imp	0.65 A	2.95 A
Vmp	2.72 V	2.21 V
Pmax	1.77 W	6.54 W
Temp	29°C	32 °C
Series Resistance	0.07 Ω	

Figure 7. I-V characteristic of 6 cell string configuration with electrical parameters.

8 cell string



	X = 1	X = 5.3
Isc	0.55 A	2.76 A
Voc	4.79 V	4.84 V
Imp	0.49 A	2.31 A
Vmp	3.81 V	3.05 V
Pmax	1.89 W	7.07 W
Temp	26°C	32 °C
Series Resistance	0.048 Ω	

Figure 8. I-V characteristic of 8 cell string configuration with electrical parameters.

Table 2, shown below, illustrates the concentration factors achieved on short circuit current with each cell string configuration using the LCPV module.

Table 2. Concentration factors obtained for each cell string configuration.

PV receiver	Concentration Factor ($Isc_{(Concentration)}/Isc_{(one\text{-}sun)}$)
3	4.90
4	5.01
6	4.80
8	5.01

From the results it can be seen that the highest concentration factors were obtained for the 4 and 8 cell string configurations reaching 5.01 X concentration. The 3 and 6 cell string configuration reached concentration factors of 4.8 and 4.9 respectively. Theoretically 5.3 X was expected due to the geometrical concentration factor of the LCPV module, but this does not take into account optical losses and misallignment of optical elements. A comparison was made of the fillfactor as well as maximum power of each receiver under one-sun conditions as well as under concentration.

These 4 different cell string configurations were used to obtain the optimal receiver for a LCPV module. Figure 10 illustrates the different fill factors obtained for each cell string configuration. Figure 9 illustrates the maximum power obtained from each cell string configuration.

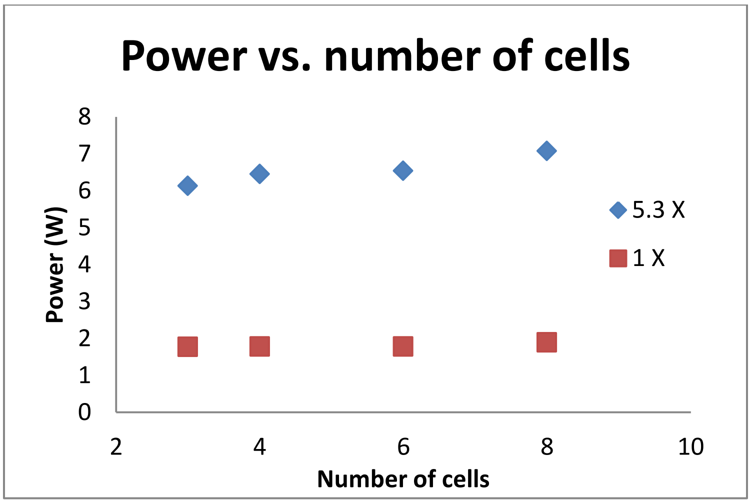


Figure 9. Relationship between Pmax and the number of cells in the string configuration.

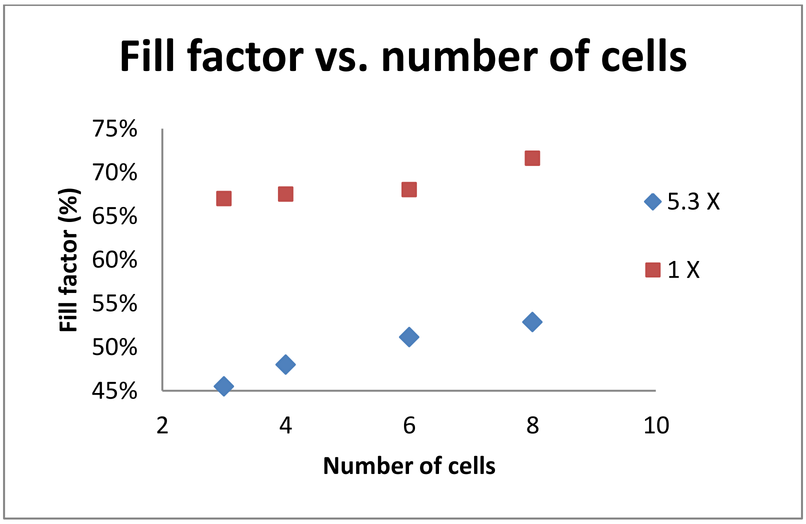


Figure 10. Relationship between fill factor and the number of cells in the string configuration.

From figure 10 it can be seen that the cell string configuration with the most cells connected in series obtained the highest fill factor. As the cell sizes increased and the number of cells connected in series decreased so did the fill factor decrease, this was observed under one-sun as well as under concentrated illumination. Figure 9 shows that the 8 cell string configuration obtained the best maximum power. The results illustrate that low current-high voltage cells yield a higher power and fill factor under one-sun and under concentration. Low current-high voltage receivers that yield better electrical performance is more ideal in a LCPV system. One of the reasons for them being more suiteable for LCPV purposes is that under concentration the current increases drastically, which in effect will lead to increase in resistive losses. These resistive losses decreases maximum power as well as fill factor obtained from the concentrator system.

5. Conclusions

A Horizontal receiver LCPV module was constructed to improve on previous prototype designs that were constructed, such as the V-trough concentrator [3] and vertical receiver LCPV module [4]. The results illustrate the feasibility of the optical design and that it can be used to improve on the V-trough concentrator design as well as the vertical receiver LCPV module. An optical characterization was done on the LCPV module by investigating the illumination profile of the module as well as contributions of each reflection facet pair. Optical losses and misalignment of optical elements lead to a reduction in concentration levels and thus performance. The optical losses and misallignment of optical elements also cause non-uniformities in the illumination profile of the LCPV module. These non-uniformities in the illumination profile caused by optical misallignments can lead to cell mismatch in the PV reciever, which will cause loss in electrical performance of the module.

Various string configurations and cell matching techniques were implemented under the electrical characterization of the LCPV module. Theoretically a geometric concentration factor of 5.3 X was expected, where experimentally close to 5 X were obtained with each PV receiver. It is important to note that this theoretical geometrical concentration factor does not account for optical losses of the reflective material etc. It was found that higher fill factors and maximum power can be obtained by using low current-high voltage cell string configurations when the total PV receiver area is kept constant.

6. References

[1] A. Luque and S. Hegedus 2008 *Handbook of Photovoltaic Science and Engineering* (Wiley-VCH).

[2] A. Luque and V. Andreev 2007 *Concentrator Photovoltaics* (Springer-Verlag, Berlin Heidelberg).

[3] B.A. Butler, E.E. van Dyk and F.J. Vorster 2010 *Investigation of Low Concentration Photovoltaic Modules and Systems* (MSc dissertation NMMU Port Elizabeth).

[4] M.A. Benecke E.E. van Dyk and F.J. Vorster 2012 *Optical design of low concentrator photovoltaic modules* (1st SASEC Conference 2012 paper)

[5] *Wolfram, MathematicaOptica 3.0*, http://www.opticasoftware.com/store/index.php, 31/10/2011

[6] *Image J*, http://rsbweb.nih.gov/ij/, 10/11/2011.