ICMIEE18-229

Development of Surface Mounted concentrator for Photovoltaic solar cell

Md Anwar Hossain[1], YiHong Zhang[12]*
[1]College of Information Science & Technology, Donghua University, Shanghai, P. R. China
[2]State key University, Ministry of Education, P. R. China

ABSTRACT

This paper will provide a design of Surface Mounted concentrated photovoltaic (SMCPV) at low cost. First work on finding the best and suitable concentrator that can increase the efficiency of PV cell near about 20% of its traditional efficiency. At the accurate combination point of concentrator and PV cell, the focus point is set behind the PV cell. As the distance between concentrator and PV cell is X, the focus of concentrator is 4X to ensure close contact between concentrator and PV cell and prevent from burning cell sections. To ensure the targeted result, the optical modeling of this system and performance analysis through experimental tests has done. The experimental validation allows concluding that, high accurately controlled application of SMCPV is very important since the big density of the solar radiation leads to important losses of system efficiency or system failure. On the other hand, it is found that the external factors can affect the final results which include the optical and geometrical properties of the concentrators, the absorptivity as well as the weather conditions (especially the wind speed and clouds). Thus, the paper aims to present the advantages and benefits of this technology.

Keywords: Renewable Energy Resources, Solar Concentrator, Surface Mounted Solar Concentrator, Improved Solar Cell.

1. INTRODUCTION

The photovoltaic industry is growing rapidly today. Even though photovoltaic (PV) technology offers great potential in terms of supplying the world's energy needs, its current contribution to the world is still limited. The main factor is related to the high initial cost of building the system. However solar energy is one of the most economic and freely available energy sources in today's world [1-2].

The development of photovoltaic (PV) concentrator innovation started adequately in 1976 at national Sandia laboratories. This early work was the first line of solution related to solar cell and concentration system. Utilizing optics such as mirror or lenses to concentrate sunlight radiation is the basic purpose of Photovoltaic (PV) concentrator [3].

Now days, the use of cost-efficient concentrating optics that severally diminish the cell area is the standard of concentration photovoltaic (CPV), taking into consideration the utilization of more cost efficiency, high-efficiency cells and possibly a leveled cost of electricity competitive with concentrated solar oriented power and standard flat-plate photovoltaic (PV) technology in certain sunny zones with high direct normal irradiance (DNI) [4].

For SMCPV systems to be cost-effective, the complete cost of the optics, assembly and mechanical tracking must not exceed the cost savings gained from using small area PV cells. Solar ray tracing programs was used to find new types of solar lens concentrator to save the cost by reducing the area of PV cells [5].

For many years in the field of the concentrator, the Fresnel lens is being used. Despite the simplicity and uniform illumination on a cell of this concept, due to its low acceptance concentration product, their application is still a big challenge to low concentrations.

For traditional Fresnel concentrator, however, the proposed model for the focal length of SMCPVs will be enlarged with the geometric concentration [6]. Such a module will also be of interest when solar energy utilization is in higher demand. To date, such an SMCPV module has not yet been experimentally demonstrated. In this study, we proposed this concept using a prototype Fresnel lens based SMCPV module with an additional low-cost solar cell.

2. CONCENTRATOR GEOMETRY

The concentration ratio is used to describe the intensity of energy concentration achieved by a given collector.

The geometrical concentration ratio (CR_g) of a solar concentrator over a typical absorber surface is calculated as the ratio of the entrance aperture area(A_a) to that area of the absorber (A_r) which is capable of collecting all the radiation reflected from the concentrator and which takes part in the emission of thermal radiation at the absorber temperature [7].

$$CR_g = \frac{A_a}{A_r} \quad (1)$$

The aberration-free solar image height was calculated using 2 f tan θ where f is the lens focal length and θ is the acceptance half-angle. Lens element has its own two-dimensional geometric concentration defined by, [8].

$$C_{lens} = \frac{1}{(2Ftan\theta)^2} \quad (2)$$

The lens aperture to image area is expressed in terms of the lens focal length to diameter ratio, or F-number, and acceptance half-angle.

YiHong Zhang Tel.: +86-(0)21-67792359
E-mail: zhangyh@dhu.edu.cn

2. 1 CONCENTRATOR APERTURES and COMPARISON

A ray tracing software for Complex Solar Optical Systems, ‘SolTrace’ was used to design and optimize the efficiency of the optic concentrator [9]. The analysis simulated circular, triangular, rectangular, hexagonal aperture lenses forming a focus on a slab of the PV. Ray intersection for each aperture with flat, parabolic and spherical surfaces was examined with direct normal irradiance (DNI) of 1000. Encircled energy, illumination distribution on the PV cell was included in optical efficiency calculations [10].

Table 1 Baseline parameters for the comparison study.

Sun Parameter	Target Parameter
Buie Sunshine Day 80 at solar noon Latitude 34.96 Insulation 1000 k-m^2/w	Lens facing north (no tilt) Size: 8x5 mm Aperture: Circular, Triangle, Rectangular, and Hexagonal

Table 2 Simulation runs with “Soltrace”.

Parameters/ Aperture	Circular	Triangular	Rectangular	Hexagonal
DNI	1000	1000	1000	1000
Sun ray count	32077	33561	32019	39090
Power per ray (W)	1.247	0.52797	1.60704	1.02328
Number of plotted rays	20000	20000	20000	20000
Power of plotted rays (W)	12470	10559.5	32140.8	20465.6
Peak flux	3212.27	1429.75	4184.73	2586.85
Average flux	124.7	52.7973	160.704	102.328

Table 3 Specification of the test for SMCPV system.

Parameters	Value
Irradiation power source	Buie Sunshine
Irradiance (DNI)	1000
Solar cell	monocrystalline Si solar cell
Cell efficiency	18.13% at (STC)
Open-circuit voltage (*V*oc)	10.8V
Short-circuit current (*I*sc)	0.98 A (at 1000W/m2)
Module size	290 cm×190cm

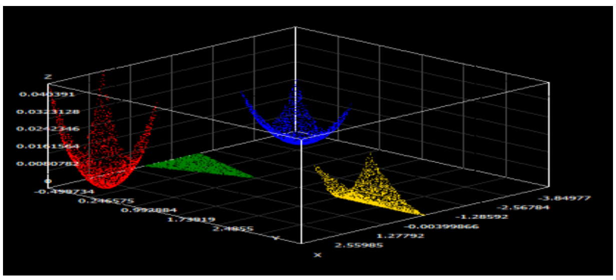

Fig.1 Ray intersection for triangular aperture with flat, parabolic and spherical surfaces

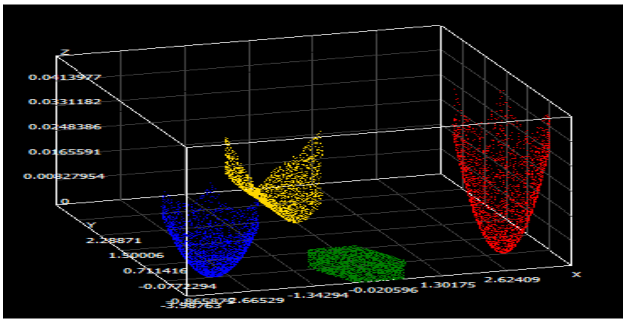

Fig.2 Ray intersection for hexagonal aperture with flat, parabolic and spherical surfaces

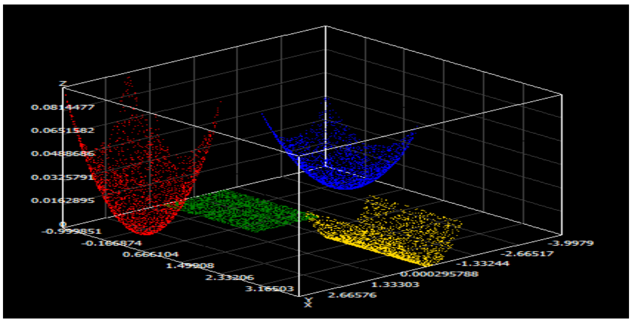

Fig.3 Ray intersection for rectangular aperture with flat, parabolic and spherical surfaces

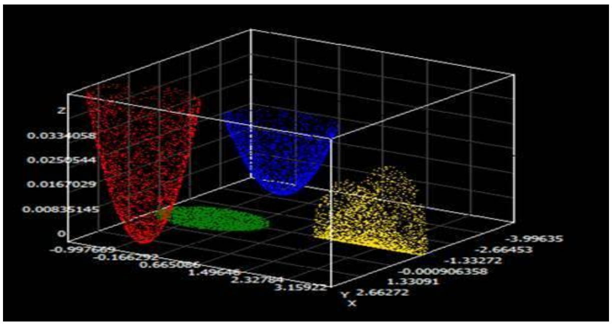

Fig.4 Ray intersection for circular aperture with flat, parabolic and spherical surfaces

3. PROPOSED SMCPV MODEL

The SMCPV optics constitute a typical design problem that contains both the bundle coupling problem for obtaining maximum acceptance-concentration product and the prescribed irradiance to obtain uniform irradiance distribution on the solar cell area [11]. The solar cell is adhered at the bottom of the lens directly, making it simple to seal against moisture and prevent misalignment. Figure 5 shows the cross-sectional sketch of this compound Fresnel-R concentrator for SMCPV system. The design method includes two parts: design of Fresnel lens with the close setup of base photovoltaic (PV) cell and design of secondary or extended PV cells of SMCPV system. This design also includes two parts: design of the outer saw teeth of Fresnel lens that work by total internal reflection and design of the inner saw teeth that work by refraction.

3.1. PROPOSED MODEL DESIGN

A crystalline silicon solar cell with an extended rectangular module also might be installed onto a Fresnel-lens SMCPV module. In this configuration, incident direct solar radiation is concentrated by the Fresnel lens onto direct contact solar cell module. The Si solar cell does not capture total radiation of the concentrating rays. Incident diffuse and reflected solar radiation through the Fresnel lens is then captured by the extended Si solar cell. The Si solar cell was encapsulated by EVA with a glass cover. With both base PV cell module and extended PV cell module in order to keep them safe from heat damage heatsink is being used.

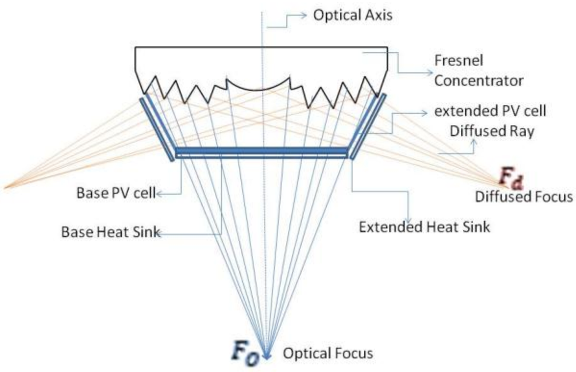

Fig.5 Compound Fresnel-R concentrator for SMCPV system.

The proposed system shows the optical configurations of an SMCPV module for harvesting diffuse solar radiation through an additional low-cost cell, as described in a patent document [12]. To overcome Optical aberration photovoltaic (PV) cell should set as close as possible. The geometrical concentration ratio for the low-cost cell should be close to unity in order to fully capture diffuse radiation and for maximum acceptance angle. For a given acceptance angle θ, for a point-focus concentrator, the maximum concentration possible, C_{max} is given by,

$$C_{max} = \frac{n^2}{\sin\theta} \qquad (3)$$

Where n is the refractive index of the medium in which the receiver is immersed [13]. In practice, real concentrators either have a lower than ideal concentration for a given acceptance or they have a lower than ideal acceptance angle for a given concentration. This can be summarized in the expression $CAP = \sqrt{C}\sin\theta \leq n$ (4)

This defines a quantity concentration acceptance product (CAP), which must be smaller than the refractive index of the medium in which the receiver is immersed. The Concentration Acceptance Product is a consequence of the conservation of etendue. The higher the CAP, the closer the concentrator is to the maximum possible in concentration and acceptance angle [14].

Test modules based on Fresnel lenses are easily fabricated by installing an additional low-cost cell. Although the proposed module in this study is a single-lens module, a practical multiple-lens-array module could in principle be constructed according to the schematic.

3.2 PROPOSED SMCPV SYSTEM EXPERIMENT

To verify the effectiveness of the SMCPV system proposed in this study, a power-measurement test was performed using a non-commercial Fresnel lens. Table 3 lists the specifications of the test used in this study. The test consists of a polycrystalline Si solar cell with a conversion efficiency of 20%, a sunny day with an illumination intensity of 1,388W/m^2 was an irradiation source. For current - voltage measurement, a Keithly-616 digital electrometer, Tektronics CDM 250 multimeter and a dual Farnel LT30/2 (-3 to 3) V power supply were used. We measured Open circuit voltage V_{OC} and short circuit current I_{SC} to calculate the fill factor (FF) and the efficiency (η%) of the proposed SMCPV model using the relations [15].

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \qquad (5)$$

$$P_{max} = I_{sc} V_{oc} FF \qquad (6)$$

$$\eta = \frac{FF I_{sc} V_{OC}}{P_{in}}\% \qquad (7)$$

Where V_m is maximum voltage and I_m is maximum current, and P_{max} represents the maximum power output of the solar cell. The current voltage characteristics for the PV were measured with and without concentrator by using the electric circuit shown in Figure-6.

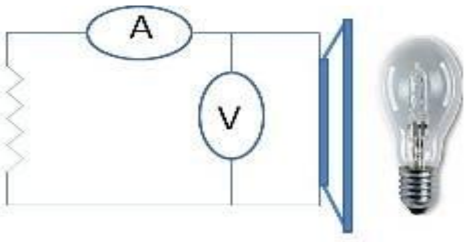

Fig.6 Electrical diagram represent I-V characteristic measurements circuit.

4. RESULTS and DISCUSSION

The analysis of concentrators for solar power has been investigated using simulation software ‘Soltrace’ along with theoretical studies. The analysis is done for four different types of apertures and three different types of surfaces. It has been found that; concentrator is a most important role for any CPV system.

Proposed SMCPV system is a most effective system for tradition photovoltaic solar cell for general use. And some test has been done using the best aperture for Fresnel lens for proposed SMCPV model.

Analyzing test data shows the improvement of the efficiency of the solar cell system.

4.1 Concentrator lens aperture

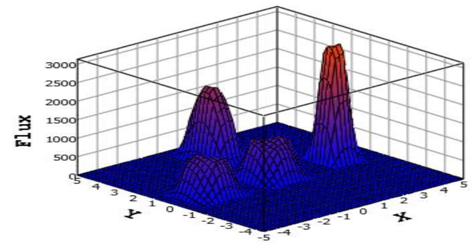

Fig.7 Surface plot of the flux density of circular aperture

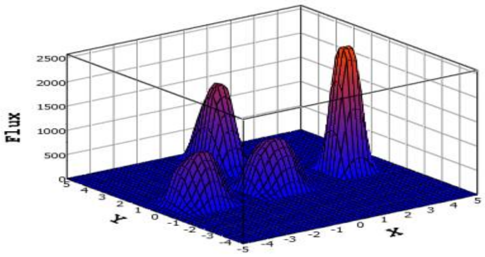

Fig.8 Surface plot of the flux density of hexagonal aperture

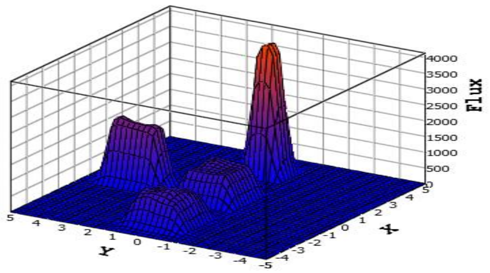

Fig.9 Surface plot of the flux density of rectangular aperture

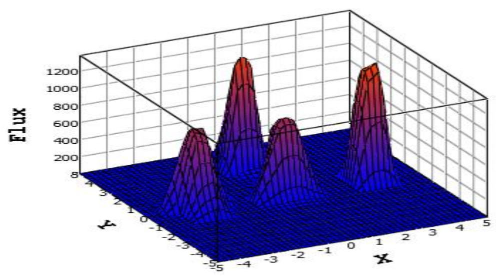

Fig.10 Surface plot of the flux density of triangular aperture

Table 4 Investigated the flux density of the concentrator.

Aperture	Most Flux density
Circular	3200
Triangular	1350
Rectangular	4050
Hexagonal	2600

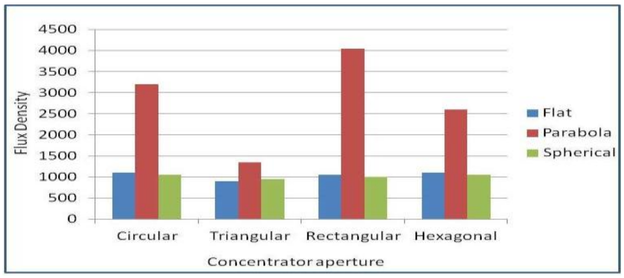

Fig.11 Comparison study for different aperture with different surface

The concentrator lens is approximated in SolTrace using 4 aperture and three types of surfaces (flat, parabolic, spherical) total 12 types of surfaces since SolTrace can only plot flux maps for surfaces and cylinders, but not spheres. Figure 7-10 shows examined flux maps of these surfaces. Figure 11 is representing the comparison of different types of concentrator aperture with a different surface. In SolTrace, specularity errors in the range of 0 to 15 mrad are investigated and slope errors in the range of 0 to 15 mrad are considered, to determine the effect on the performance of the receiver. According to SolTrace, this is an optical error range of 0 to 33.5 mrad.

A tracking error range of 0° to 3° is also considered. The concentrator surface is modeled with a reflectivity of 85%. A direct normal irradiance of 1000 W/m^2 and a pillbox sun shape are assumed in the analysis. The optimized receiver using entropy generation minimization has concentrator diameter of 5x8 mm. This receiver geometry was investigated in SolTrace. Examined data is shown in Table 4. Analyzing these data indicates rectangular aperture the best concentrator.

4.2 PROPOSED SMCPV MODEL TEST

The FF is the parameter which, in conjunction with V_{OC} and I_{SC} , determines the P_{max} from a PV solar cell (equation 5). Since I_{SC}, V_{OC} and FF are used directly in characterizing the performance of the PV modules and are defined as equation 6, improvement of output power i.e. P_{max} of a PV module is depended on the improvement of I_{SC} , V_{OC} and FF. Data comparing include and exclude of concentrator indicates the improvement of I_{SC},V_{OC}, FF, maximum output power P_{max} , and the efficiency (η) by significant amount (table-5). There is Δη = 26.61% improvement in the efficiency of SMCPV with concentrator (here the efficiency (η) is calculated by equation 7). By analyzing data's of table 5, we conclude that there is an improvement in PV module by using the proposed system. Another way is, it is also reduction of cost, by reducing the high cost of Si material, proposed SMCPV can be used for traditional household appliances. Figure 12 represents the current-voltage characteristics curve of PV cell without and with the new concentrators. This figure shows the improvement in solar cell performance.

Table 5 Performance parameters for PV cell without and with a concentrator (930 DNI).

Parameters	Without concentrator	With Concentrator	Improvement %
Isc in A	0.98	1.23	25.55
Voc in V	10.80	11.10	2.8
Pmax in W	8.012	10.144	26.61
FF	0.757	0.743	
η%	18.13	21.63	17.81

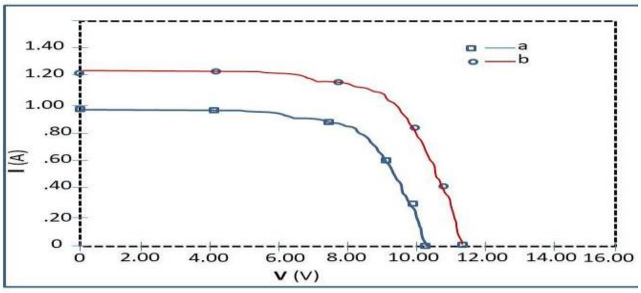

Fig.12 The current-voltage characteristics for PV Si cell without (a) and with (b) Fresnel lens.

CONCLUSION

The optical properties of used Fresnel lens were measured using simulation software "Soltrace". The Fresnel lens was used practically to concentrate sunlight components on the solar cell. The electrical output parameters of the used solar cell were measured practically where the used Fresnel lens was found to increase the electrical output power from the solar cell which was related to the action of used Fresnel lens and properties of the used solar cell. An increase in the output power is observed about 29.01% of total output. The proposed SMCPV system is designed for direct normal irradiance, diffused light and reflected light from base PV cell. Focus length is set behind the solar PV cell to mount the concentrator on the base PV cell and the improved characteristic with concentrator was found. Our future work will include the cost analysis of the proposed model. Our primary focus will be on details electrical parameter experiment of SMCPV.

ACKNOWLEDGMENT

The authors gratefully acknowledge the constant encouragement of administration of Donghua University, and very good research environment. Thanks to supervisor for inspirational supervision. This work is supported by the Fundamental Research Funding for the Central Universities of Ministry of Education of China, Project Number: [18D110408] and the Special Project Funding for the Shanghai Municipal Commission of Economy and Information Civil-Military Inosculation Project "Big Data Management System of UAVs", Project Number: [JMRH-2018-1042].

REFERENCES

[1] Nowak S, the IEA PVPS Programme: Towards Sustainable Global Deployment of PV". *Proceedings 20th European Photovoltaic Solar Energy Conference, June 6-10, 2005, Barcelona, Spain.* Volume III of 3, pp. 2827.

[2] R. Singh, and Y.R. Sood, "Transmission tariff for restructured Indian power sector with special consideration to the promotion of renewable energy sources", *The IEEE Conference TENCON-2009*, pp. 1-7, 2009.

[3] Reis A.M., Coleman N.T., Marshall M.W., Lehman P.A. Comparison of PV Module Performance before and after 11-Years of Field Exposure, *The Proceedings of the 29th IEEE Photovoltaics Specialists Conference, New Orleans, Louisiana* May, 2002.

[4] Mehrdad khamooshi, hanasalati, fuategelioglu, alihooshy arfaghiri, judytarabishi, and saeedbabadi," a review of solar photovoltaic concentrators",*international journal of photo energy*, 2014, pp: 17.

[5] Al-Hamdani, Ali H., Al-Ani S.K. and Blawa B.D. Performance of two - stages solar concentrator. *Journal of Um-Salama for science.* 1(2): 317-320.

[6] R. Leutz and A. Suzuki, Nonimaging Fresnel Lenses: Design and Performance of Solar Concentrators, Springer Series in Optical Sciences, *Springer, New York, NY, USA*, 2001.

[7] Jason H. Karp, Eric J. Tremblay and Joseph E. Ford. 2010. Planar micro-optic solar concentrator. *Optics express.* 18(2): 1122-1133.

[8] Rabl A. Active solar collectors and their applications. *Oxford university press, New York, USA*.1985.

[9] Tim Wendelin and Aron Dobos. October 2013. SolTrace: A Ray-Tracing Code for Complex Solar Optical systems. *Technical Report. NREL/TP-5500-59163. Prepared under Task No. ST11.3070.*

[10] M. Thirugn anasam bandam, S. Iniyan, and R. Goic, "A review of solar thermal technologies," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 312–322, 2010

[11] Garcia, P., Ferriere, A., and Bezian, J-J, "Codes for solar flux calculation dedicated to central receiver system applications: A comparative review," *Solar Energy 82(3)*, 189-197 (2013).

[12] L. W. James, "Use of refractive secondaries in photovoltaic concentrators," *Tech. Rep. SAND89-7029, Sandia National Laboratories, Alburquerque, NM, USA*, 1989.

[13] P. Benitez, J. C. Minano, and R. Alvarez, Photovoltaic concentrator with auxiliary cells collecting diffuse radiation, *US patent application publication,Pub. No.: US* 2010/0126556 A1 (2010).

[14] Chaves, Julio (2015). Introduction to Non-imaging Optics, Second Edition. *CRC Press.* ISBN 978-1482206739.

[15] Tuzun S.O. Altindal and T. S. Mammadov. 2006. Electrical characterization of novel Si solar cells. *Thin Solid Films.* 511-512, pp. 258-264.