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EXPERIMENTAL INVESTIGATION OF CONCENTRATED PHOTOVOLTAIC SYSTEM

FAIZAN E MUSTAFA[1], M. FAISAL KHAN[2], KH.S. KARIMOV[3,4]

Key words: Concentrated photovoltaic (CPV), Monocrystalline, Compound parabolic concentrator (CPC), Photovoltaic system

Concentrated photovoltaic (CPV) technology is becoming one of the core photovoltaic (PV) technologies over past few decades as it increases the output of PV module. Different models of CPV technology are available in literature but there is still room for a simple system that can easily be implemented. In this paper, a CPV system is presented which is the integration of PV module and compound parabolic concentrator (CPC). Proposed system is experimentally investigated in this research work to describe the electrical performance. Experimental results are measured (without tracking the sun) in winter season using CPC of concentration ratio (*C*) 3.3, where it is observed that electrical power of proposed system increases 29.7 % at maximum as compared to PV module, which is 6.7 % more than that of published results. This work can be used to increase the output electrical power of PV modules which are already installed for domestic and commercial purposes.

1. INTRODUCTION

The prospect of every country depends on using energy resources for economic and social development. Over the last twenty years, world has changed significantly because of great advancement in electronic technologies. Human life is highly affected by the machines and electronic devices which run on mainly electricity. One cannot imagine human life without electricity in today's world. With the increase in population and electricity demand, use of alternative energy resources is the need of hour.

There are mainly two types of energy resources; renewable and non-renewable. Sources like coal, oil, radioactive material (which once used cannot be recycled for further consumption) are included in non-renewable energy resources while renewable energy resources include solar, wind, biomass etc. which can be used again and again. Later ones are becoming the most important alternative energy resources as non-renewable energy resources cause greenhouse effects and environmental hazards due to emission of carbon. Furthermore, all these fossil fuels are becoming short due to their excess usage, so it is very important to use renewable energy resources to fulfill human being needs.

The most prime, abundant, permanent, environment friendly and clean renewable energy resource is solar energy which is readily available on daily basis in the form of sunlight. Sun releases 166 PW every day, but only 85 PW comes to the surface of earth [1]. If 0.1 % of 85 PW is converted into electricity by use of PV system with an efficiency of 10 %, it could be sufficient enough to fulfill energy demands of whole earth [1].

PV module converts solar radiations into electricity due to photoelectric effect. It can supply energy without any moving or noisy part and has low maintenance cost. Number of research papers has been published till to date regarding PV technology and still more to come [2–4]. At present, despite current economic situations of most developing countries, use of PV technology is very limited due to high initial cost and low electrical output.

To overcome these limitations, CPV technology is used. In CPV technology, sunlight is concentrated on small size PV cells by using low cost solar concentrators [5, 6]. Although these systems are low cost than non-concentrated PV systems and have low efficiency, but the amount of output electrical power are usually higher.

Solar concentrators are devices which concentrate solar radiations to small area of PV cell. Researchers have introduced a wide variety of solar concentrators. These are differentiated from one another on basis of optical characteristics *i.e.*, concentration ratio, focal shape, distribution of illumination and optical standard. It is important to know that mainly solar concentrators are classified on basis of concentration ratio *C* which is sub-classified as higher, medium and lower. Solar concentrators having concentration ratio *C* greater than 100 requires two-axis tracking and usually classified as high concentration ratio concentrators. Medium concentrator systems have concentration ratio between 10 and 100 which are classified as parabolic trough concentrators and Fresnal lens concentrators. Usually most of these medium size concentrators also require tracking. Low concentrator systems have concentration ratio less than 10. It includes different types of concentrators like V-trough concentrator, CPC, halographic concentrators, fluorescent concentrator and quantum dot concentrator. These concentrators generally do not require any tracking mechanism. Among these concentrators, number of research papers is available related to CPC and more to come in near future to optimize the use of CPC. A good research work related to optimization of CPC is presented in 2015 by Yurchenko [7].

This paper is organized in six sections. In Section 2, a detailed literature review related to research work on CPC with PV systems is discussed, along with contribution of proposed research work. Section 3 explains the design of 2D symmetric compound parabolic concentrator. Section 4 discusses the experimental setup used for proposed work along with results. In Section 5, comparison of proposed work with published work is presented. Conclusions of proposed system are summarized in Section 6.

[1] Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, District Swabi, Pakistan, E-mail: faizanemustafa449@gmail.com
[2] Hamdard Institute of Engineering and Technology, Faculty of Engineering Sciences and Technology, Hamdard University, Karachi, Pakistan
[3] Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, District Swabi, Pakistan
[4] Physical Technical Institute of Academy of Science, RudakiAve. 33, Dushanbe, Tajikistan

2. LITERATURE REVIEW

CPC is the non-imaging type of concentrator as no image of sun is received at receiver. It gathers large amount of sunlight due to its large surface area and concentrates them to the receiver. It has a simple geometry which is divided into three parts, an entrance aperture, exit aperture and two parabolic segments. In 1974, the schematic structure of CPC and its properties were first discussed by Winston [8]. In literature, two commonly used designs of CPC are available *i.e.*, 2D linear design and 3D rotational symmetrical design. A 2D design of CPC consists of two rectangular entrance and exit apertures as shown in Fig. 1. A 3D design is produced by rotating a 2D CPC around its optical axis which forms a circular entrance and exit aperture. It is very important to mention that concentrator can be made by choosing any reflective materials.

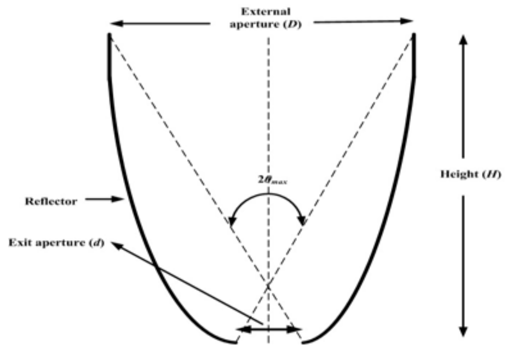

Fig. 1 – Schematic structure of compound parabolic concentrator (CPC).

In 1976, Winston also discussed CPC made of dielectric material [9]. Ronnelid investigated large size CPC collector and compared it with flat plate PV systems in 1996 [10]. He used 2D symmetrical reflective CPC with exit aperture 14.4 cm, 1.53 concentration gain, height of 12 cm and 35° half acceptance angle. He concluded that annual energy outcome increase by 2.6 % than conventional non-concentrated system. In 2000, Wennerberg used CPC with conventional silicon PV module and by varying concentration ratio from 1 to 4, studied its electrical performance [11]. In 2006, Mallick experimentally investigated asymmetrical compound parabolic concentrator (ACPC) and compared results with non-concentrating systems [12]. He observed that electrical performance of ACPC increased by 62 % as compared to simple PV system. In 2007, Mallick also discussed the optical losses up to 15 % in ACPC [13]. In 2009, an ACPC with polycrystalline silicon solar cells was investigated by Jinshe [14]. He concluded that electrical power of PV module is increased by 2.13 times using concentration ratio of 2.46. In 2009, Yang et al. also experimentally studied symmetrical CPC with polycrystalline silicon PV module and perceived that electrical power of PV module increased two times [15]. In 2010, Benitez discussed about the importance of concentration-acceptance product (CAP) formula [16]. He described that the performance of any concentrator of 2D or 3D can be estimated by CAP formulae. In 2011, symmetric and asymmetric CPC were explained by Norton [17]. In 2012, Pei experimentally investigated the performance of effect of coating on solid dielectric CPC [18]. He used the 2D symmetrical dielectric CPC with 2.41 concentration ratio, 1 cm exit aperture, 2.7 cm height and 36.8° acceptance angle. In 2013, a new novel type of 3D reflective cross compound parabolic concentrator (CCPC) was discussed by Mammo [19]. He explained that his design is capable of increasing electrical power by three times. In 2014, Siti Hawa Abu-Bakar *et al.* discussed 3D dielectric CCPC with 1.616 cm height, 3.61 concentration gain, exit aperture of 1 cm by 1 cm and CAP of 1.09 [20]. This design increases electrical output by 2.67 times as compared to non-concentrating PV module.

In 2014, Bahaidarah investigated four systems; flat PV system with cooling, PV-CPC system with cooling, flat PV system without cooling and PV-CPC system without cooling. He numerically and experimentally investigated these systems and compared with each other [21].

Bahaidarah's PV-CPC system was based on concentration ratio of 2.3 which should be greater than 2.5 according to Markvart [22]. This suggestion of concentration ratio is being used in research work (presented in this paper) and experimental investigation of polycrystalline PV module with 2D symmetric, hollow and non-dielectric CPC is presented. A brief part of proposed work has been published in [23].

3. DESIGN OF COMPOUND PARABOLIC CONCENTRATOR

The design of 2D symmetric, reflective and hollow CPC with PV module is discussed in this section. It consists of two reflective parabolic segments with external and exit apertures, as shown in Fig. 1. These segments are placed at a certain angle called acceptance angle (θ_{max}). Solar radiations are accepted within acceptance angle. Major parameters of the proposed design of CPC are height (*H*), exit aperture (*d*), external aperture (*D*) and acceptance angle (θ_{max}) which can easily be understood by Fig. 1 [24].

As CPC receives sunlight, some rays of sunlight directly go to surface of solar cell while some rays are reflected from the walls of reflector of CPC. It should be noted that the reflector of proposed CPC is manufactured using highly reflective stainless steel sheets in this research work. CPC accepts all incoming solar radiations which are within the acceptance angle while all other radiations are not used. PV module is attached with rectangular exit aperture of CPC.

CPC is being designed in this paper using following equations [25]:

$$C = \frac{D}{d}, \tag{1}$$

$$C = \frac{1}{\sin \theta_{max}}. \tag{2}$$

So the dimensions of CPC are calculated to be 0.40 m exit aperture (*d*), 1.32 m entrance aperture (*D*), 17.63° maximum acceptance angle (θ_{max}) and the length of steel sheets is taken as 1.95 m. The concentration ratio *C* is 3.3 in this research work by keeping in view that as per [22], it should be greater than 2.5 for static concentrators.

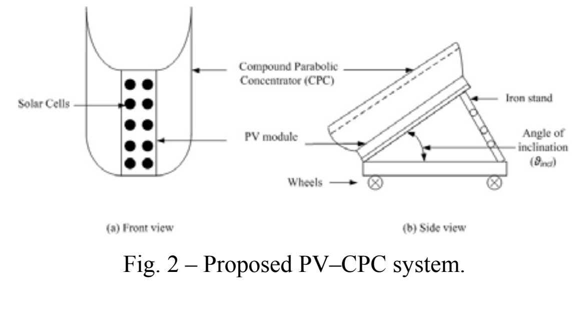

Fig. 2 – Proposed PV–CPC system.

4. EXPERIMENTAL SETUP AND RESULTS

This section explains the experimental setup of proposed system along with the experimental results which have been measured at Ghulam Ishaq Khan Institute of Engineering Sciences & Technology Pakistan during winter season. PV module (ARCO-ASI 16–2300, power 37 W) is interconnected with CPC by using iron stand and inclined at certain inclination angle (θ_{incl}). Different views of proposed system are shown in Fig. 2 for better understanding, while experimental setup's photograph is shown in Fig. 3.

Proposed setup is placed at an angle of 45° using standard relation of angle of inclination (θ_{incl}) of PV module [25],

$$\theta_{incl} = L_P \pm 11^\circ , \quad (3)$$

where L_P is the latitude of experiment's site (and it is 34° for Ghulam Ishaq Khan Institute).

Normal solar radiation under which experiments have been performed varied from 600 W/m^2 to 890 W/m^2. During the experiments on each sunny day, short circuit (I_{SC}) current, open circuit voltage (V_{OC}), maximum voltage (V_{max}), maximum current (I_{max}), ambient temperature (T_{amb}), temperature of PV module (T_{PV}) and light intensity (G_{PV}) have been measured. It should be noted that two systems (PV-CPC and PV module) are installed at same location and same angle, for measurements of fair comparison.

Figure 4 shows light intensities of both systems where it is observed that sunlight is maximum during middle of day and is minimum at start and end of the day for conventional PV module. Due to presence of CPC in other system, light intensity is more than its counterpart from 10:30 am to 1 pm, while for rest of time, it is lesser due to shadowing by CPC. By comparing both plots, it is found that light intensity is increased to maximum 32 % due to use of CPC.

Due to more sunlight, increase in temperature is obvious. It is observed in Fig. 5 that temperature of PV system varies from 30.1°C to 35°C and then reduces to 28.3°C in later part of the day, while PV-CPC system's temperature increases from 16.8°C to 43.3°C and then it ends up at 26.7°C. So, maximum increase in temperature is found to be 28.1 %.

In Fig. 6, electrical power of both systems is shown where PV-CPC system produces more electrical power than its counterpart from 11 am to 13:30 pm due to more light intensity while rest of the time, it is lesser because of shadowing of CPC. This result shows that output electrical power by PV-CPC system reaches to maximum 24.29 W while non-concentrate PV system produces 18.72 W at that time under same conditions i.e., maximum increase of 29.7 % is obtained using proposed system.

Fig. 3 – Experimental setup of proposed system.

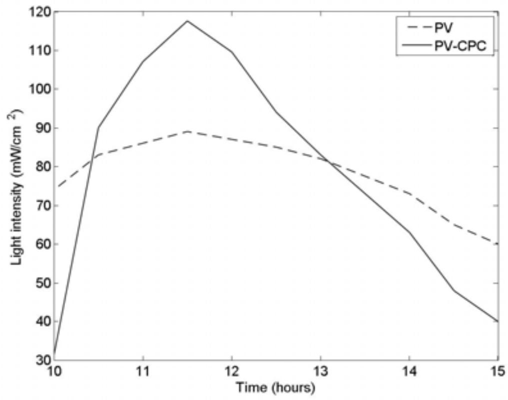

Fig. 4 – Comparison of light intensities of both systems, comprises of one day experimental results.

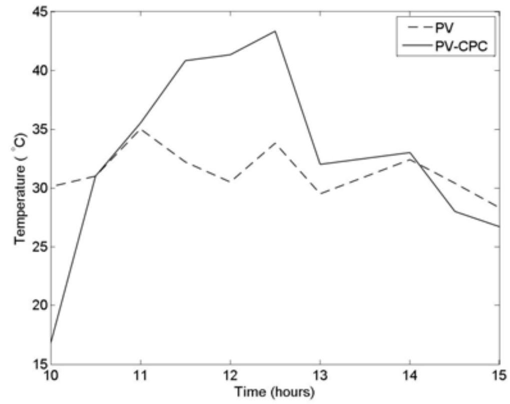

Fig. 5 – Comparison of temperatures of both systems, comprises of one day experimental results.

5. COMPARISON OF PROPOSED WORK WITH PUBLISHED WORK

This section discusses the comparison of proposed work with Bahaidarah *et al.*'s research work [21]. In that research work, Bahaidarah used CPC of concentration ratio 2.3 with PV module and the system achieved maximum increase of 23 % in electrical power, while in proposed research work, CPC of concentration ratio 3.3 is used and the system produced 29.7 % maximum increase in electrical power i.e., 6.7 % more than that of [21]. The comparison of both research works is summarized in Table 1.

6. CONCLUSIONS

PV system is a hot topic of research for past so many years, but its low output electrical power is always an issue. To overcome this problem, PV module integrated with pair of CPC is presented in this paper. In order to find out effectiveness of CPC, a PV module is also investigated along with proposed system. The design of CPC is optimized and the concentration ratio of 3.3 is being used. Experimental results have been measured in winter season and 29.7 % maximum increase in electrical power is achieved using proposed PV–CPC system which is 6.7 % more than published results. Due to simplicity of proposed system, any PV module can be easily integrated with proposed design of CPC in order to increase its electrical power. As future work, further optimization in height of CPC is suggested for additional improvement in outputs of proposed system.

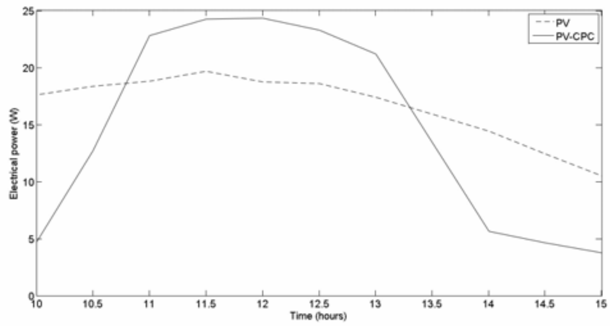

Fig. 6 – Comparison of electrical power of both systems, comprises of two days experimental results.

Table 1

Comparison of proposed research work with Bahaidarah's research work [21]

Parameters	Bahaidarah's work [21]	Proposed work
CPC Type	2D symmetric, reflective, hollow and unglazed	2D symmetric, reflective and hollow
Concentration ratio	2.3	3.3
Orientation of setup	South-North	South-North
Dimensions of setup	Smaller	Larger
PV module	Silicon monocrystalline PV module	Silicon polycrystalline PV module
Maximum increase in electrical power	23 %	29.7 %
Experimental investigation month (season)	February (Winter)	November (Winter)

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