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Performance Optimization of Solar Photovoltaic System using Parabolic Trough and Fresnel Mirror Solar Concentrator

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Abstract: An attempt has been taken to design parabolic trough and Fresnel mirror solar concentrator with the purpose of optimizing the output power of a photovoltaic system for both bright sunny day and cloudy day by using a 72-cell 5W photovoltaic solar panel. The PV system's efficiency has been analyzed in terms of output voltage, current, and power of the solar panel. Accordingly, to our expectation, we observed that on a bright sunny day, the output power improvement of the solar panel is 26.81% for the parabolic trough and 17.89% for the Fresnel mirror concentrator. On a cloudy day, both concentrators improve output power by 22.3% and 14.1%, respectively. In terms of power optimization of a photovoltaic system, the following has been discerned: a solar photovoltaic concentrator system with a parabolic trough is much more effective than one with a Fresnel mirror.

Keywords: Parabolic trough concentrator, fresnel mirror concentrator, solar concentrator, photovoltaic system, power optimization

1. Introduction

Renewable energy is currently the most preferred energy source, as it provides a solution to rising energy demand while also addressing issues such as environmental pollution, reserve constraints, and energy costs. Having advantages like endless supply and nearly low environmental impacts, renewable energy like solar energy has become the major focus of interest to the researchers and have been utilized and studied comprehensively more and more for a long time [1] [2]. The reserves of fossil fuels, including coal, fuel oil, and natural gas, are dwindling on a regular basis on our planet, and as a result, solar energy, i.e., solar photovoltaic systems, are becoming a very effective alternative for electrical power generation to meet the regular energy demand [3].

The sun radiates roughly 166 PW of energy, of which 85 PW reaches our planet. To meet our planet's current power consumption of 15 TW, this power can be turned into electrical energy using the solar cell. As a matter of fact, solar power is clearly more than 500 times our current energy consumption [4]. While solar energy is widely distributed, at irradiance levels of 500-1000 W/m^2, it is available to us in both scattered and direct forms. If somehow the intensity of radiation to a solar cell is increased, the output power of the solar cell can also be improved [5]. A solar concentrator plays this role by collecting both scattered and direct solar irradiation. Concentrators use refractive lenses or reflective mirrors to focus sunlight onto a smaller area of the photovoltaic (PV) solar cell, and PV concentrating systems are more advantageous than flat plate systems because they require fewer PV cells to produce the same amount of power [6]. Since solar cell is manufactured using semiconductor materials, their properties allow solar cells to work more efficiently under focused light [7]-[9]. During the manufacturing process of the solar cell multiple other elements like annealing temperature, pressure etc. can have a significant influence on the photovoltaic system performance [10]-[13].

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In this study, we have investigated the performance of a photovoltaic system using a parabolic trough and a Fresnel mirror solar concentrator for both bright sunny day and cloudy day. Although due to the effect of irradiance there can be significant changes in the output voltage or current of the PV system that has been observed by researchers [14] [15], the novelty of this research paper is that it aims to present a concise, clear, and concise demonstration of an improved photovoltaic solar concentrator system with experimental results that have been achieved practically. The changes in the output power of the PV system using solar concentrator might be helpful to describe the opportunities of advance research, and possible further improvements on PV solar system using solar concentrator.

2. Materials

2.1 Photovoltaic (PV) System

A solar photovoltaic system is made up of one or more solar panels, an inverter, and other electrical and mechanical components that generate electricity using the sun's energy. PV systems come in a variety of sizes, ranging from small rooftop systems to massive utility-scale power plants [16]. When sunlight strikes a solar panel fabricated with semiconductor materials in the form of packets of energy called photons, the photovoltaic effect generates electrical current in a load connected to the panel. Solar cells are normally connected in series in a PV panel, with each cell's normal voltage remaining around 0.5 V while generating maximum power. Nevertheless, it is dependent on the temperature and level of illumination of the PV panel. The higher the light intensity, the more electricity flow will be generated [17].

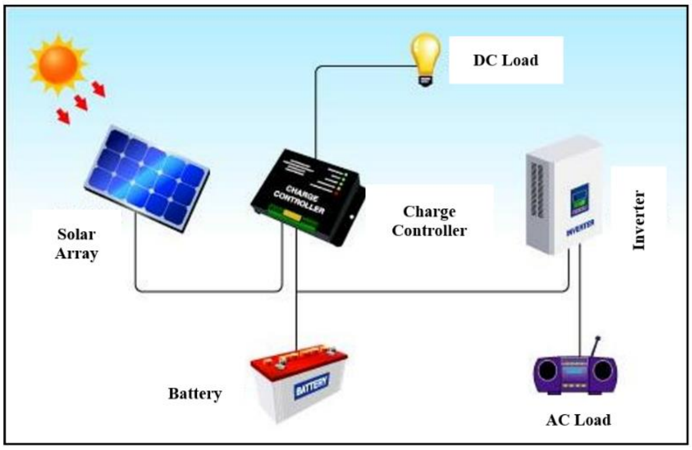


Fig. 1 - Photovoltaic (PV) system [18]

Depending on the energy requirements, several PV panels of various sizes and power outputs are available at a reasonable price. For example, the 1-1.2 m² panels (typically 72 solar cells) that delivers around 200 W can be used in home applications, 80 W panels for the modules in street-lighting, and the 12 W to 24 W panels can be used for solar lanterns [19] [20]. In this study, we have used a 5 W PV panel (72 solar cells). The short circuit current (I_{sc}) and open circuit voltage (V_{oc}) for the panel are 0.29 A and 17.2 V respectively.

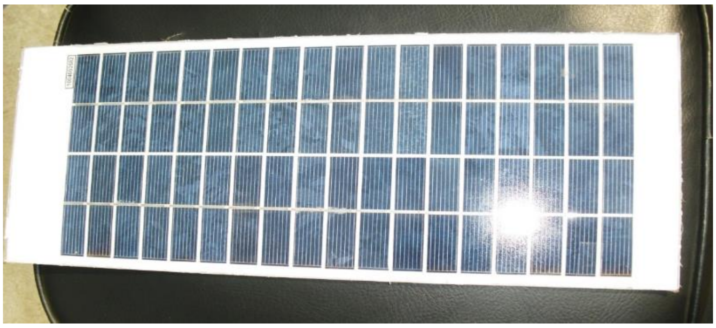


Fig. 2 - A 72-cell 5 W photovoltaic solar panel

2.2 Solar Concentrator

A solar concentrator is a system that concentrates solar energy in general. It collects sunlight from a large area and concentrates it on a smaller area of the photovoltaic solar cell. Solar concentrators are used in photovoltaic solar systems to enhance the efficiency of the photovoltaic system [21] [22]. Fig. 3 illustrates the core idea of using a solar concentrator in PV cells. It explains how a solar concentrator can concentrate a significant amount of sunlight into a smaller area of the PV cell.

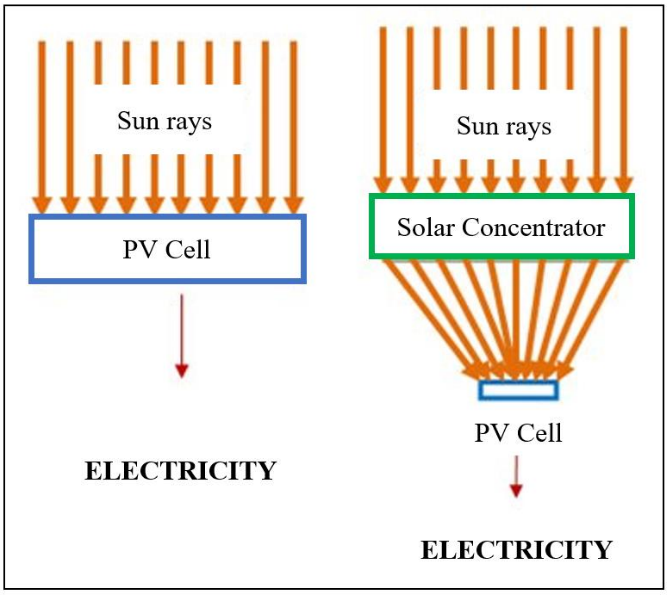


Fig. 3 - Conceptual representation of solar concentrator in PV system [23].

2.3 Parabolic Trough Concentrator

The parabolic trough solar concentrator (PTSC) is one of the most widely used and simplest solar power concentrating techniques. It comprises of a parabolic-shaped reflector iron frame with mirrors inside that start concentrating solar radiation at a focal point [24] [25]. PTC has the potential to increase the overall efficiency of a PV system. Researchers have discussed several techniques for improving the performance of a PV system using a parabolic trough concentrator [26]. The conceptual structure of the parabolic trough solar concentrator is demonstrated in Fig. 4.

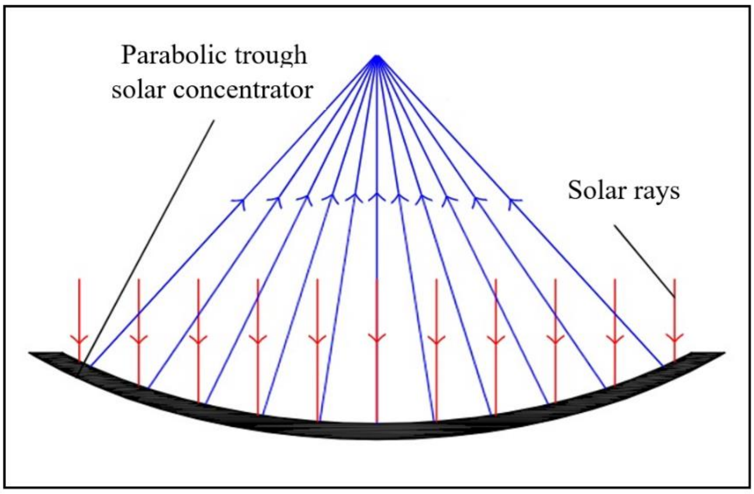


Fig. 4 - Conceptual representation of parabolic trough solar concentrator in a PV system

2.4 Fresnel Mirror Concentrator

The Fresnel mirror solar concentrator (FMSC) is constructed up of multiple small, narrow, and plain mirror sheets that focus light over to a receiver located along the reflector's focal line. This concentrator is typically supported by a flat base frame. A line focusing concentrator system is another name for it. When the sun's rays strike the Fresnel mirror strips, they are reflected back to the receiver. Flat mirrors are designed in such a way that they have a larger reflective surface area in the very same amount of space compared to parabolic reflector that allows more solar energy to be captured. Additionally, they cost a lot less than cylindrical parabolic trough concentrators [27] [28]. Fig. 5 demonstrates the conceptual structure of the Fresnel mirror solar concentrator.

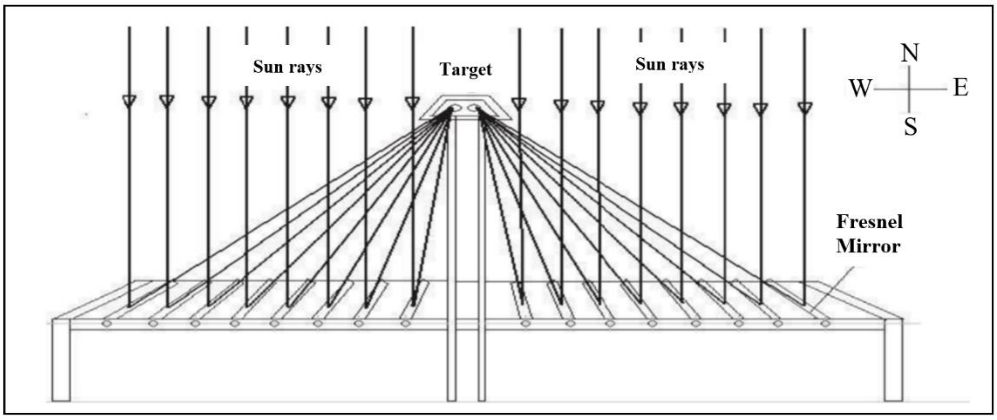


Fig. 5 - Conceptual representation of Fresnel mirror solar concentrator in a PV system

3. Methodology

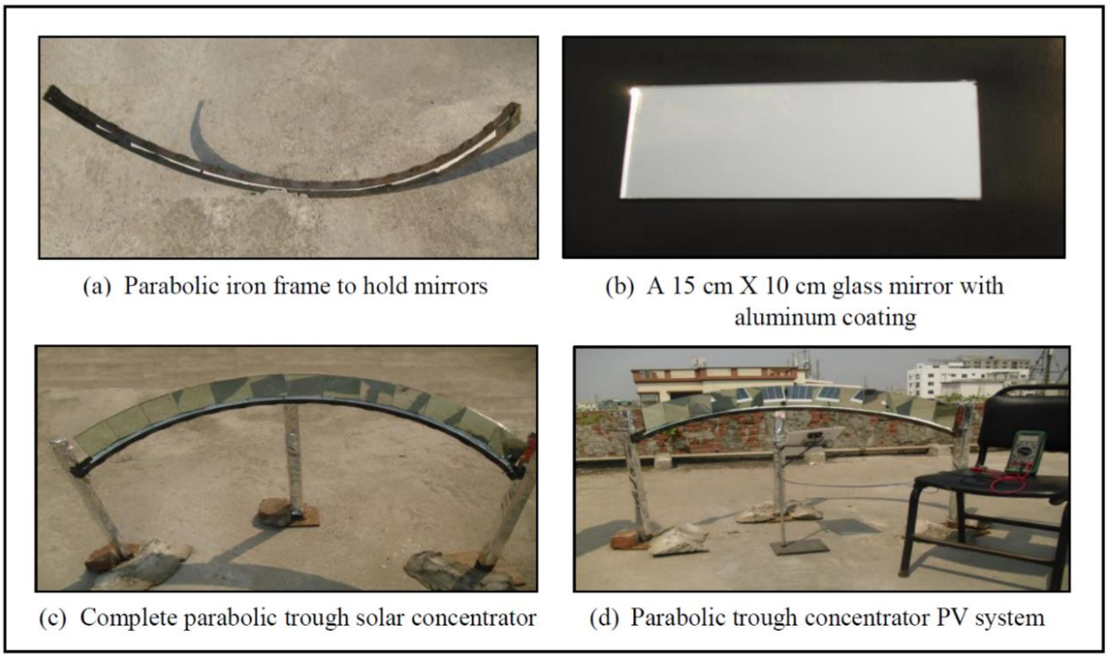
3.1 Photovoltaic (PV) System without Solar Concentrator

In order to set a standard for comparison with parabolic trough and Fresnel mirror solar concentrator photovoltaic systems, a photovoltaic system without any solar concentrator was designed and the output data from the solar panel was recorded in direct irradiation sun condition for both bright sunny day and cloudy day.

Fig. 6 - Photovoltaic system without solar concentrator

3.2 Design and Construction of Parabolic Trough Concentrator PV System

The parabolic trough concentrator's fundamental design is created using two sections of parabolic-shaped iron sheet, each measuring 125 cm in length, to hold the reflecting mirrors (Fig. 7a). The PTC was built with thirteen reflecting mirrors, each measuring 15 cm in length and 10 cm in width (Fig. 7b). For a thickness of 4 mm glass with aluminum coating, the reflectivity of these local mirrors is around 50%. The height of the concentrator set up was 1.25 meters with a downward mirror angle of 23^{o} with the aim to focus the sun beams directly on the solar panel, allowing the solar panel to be readily struck (Fig. 7c). Finally, by placing the PV panel at a distance of 1 meter from the concentrator at the height of 1 meter from the ground we constructed the complete PTC photovoltaic system with the goal of observing the effect on the PV system's performance under direct irradiation sun conditions for both bright sunny day and cloudy day (Fig. 7d).



(a) Parabolic iron frame to hold mirrors

(b) A 15 cm X 10 cm glass mirror with aluminum coating

(c) Complete parabolic trough solar concentrator

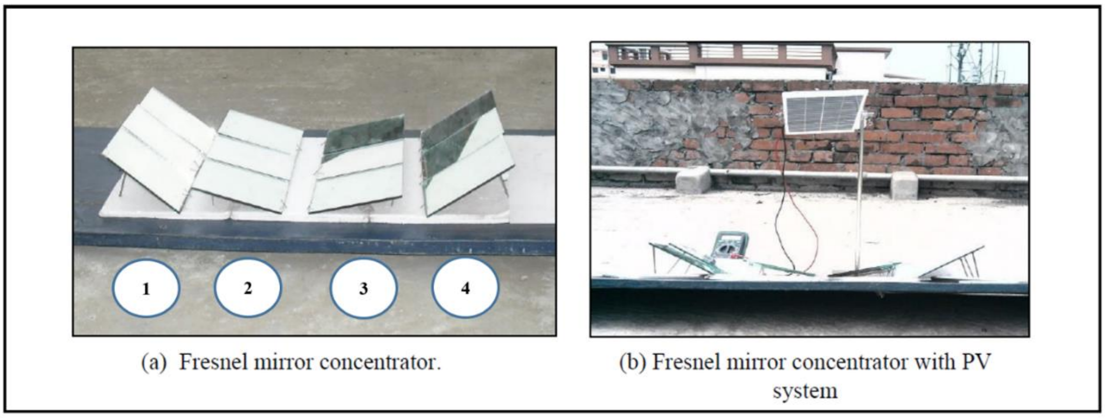
(d) Parabolic trough concentrator PV system

Fig. 7 - Construction of parabolic trough concentrator

3.3 Design and Construction of Fresnel Mirror Concentrator PV System

Fig. 8a represents the cross-sectional structure of the Fresnel mirror concentrator design. It's made up of long, narrow flat mirrors all of which are the same size and fixed on a flat base. Each constituent mirror element's tilt is controlled so that reflected sun rays illuminate a common focus on the PV panel. Sunrays that strike the center of each mirror and incident normally on the aperture plane reach the panel after reflection. The FMC is mainly composed of mirrors with lengths and widths of 15 and 10 cm, respectively.

A total of four rows are used in the Fresnel mirror concentrator's construction. Three mirror pieces make up one row. The plane iron frame that holds the flat mirror plates were kept at an angle of 20º with the ground. The angles for the mirror rows 1, 2, 3 and 4 (from left side in the figure) with the plane iron frame were 154º, 167º, 16º and 33º respectively. Ultimately, we constructed the entire FMC photovoltaic system with the goal of observing the PV system's improved performance under direct irradiation sun conditions on both bright sunny day and cloudy day (Fig. 8b).



(a) Fresnel mirror concentrator.

(b) Fresnel mirror concentrator with PV system

Fig. 8 - Construction of Fresnel mirror concentrator

4. Result and Discussion

The experiment was conducted in Dhanmondi, Dhaka, Bangladesh (23.7461ºN, 90.3742 ºE) on 15th March for bright sunny day, and on 10th May for cloudy day respectively. All the relevant data were collected on the day of experiment. To observe the effect of solar concentrator on the performance of the PV system, we measured the output voltage, current, and power of the PV panel separately at a regular interval of 30 minutes using a digital multi-meter from 9.00 AM to 4.00 PM Bangladesh Standard Time (BST) for both bright sunny day and cloudy day under three different PV system configurations as follows:

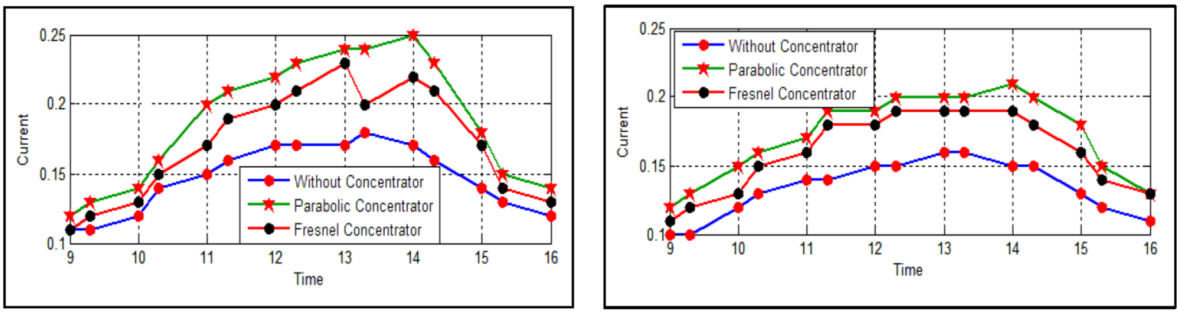
- Without solar concentrator
- With parabolic trough concentrator
- With Fresnel mirror concentrator

The experimental configurations were prepared first and kept at a suitable arrangement so that authors could attain all the required data simultaneously within 1 minute for all three arrangements so that the deviations in irradiance can be neglected. For example, all system configurations were kept side by side at suitable distances at 9 a.m. in order to measure the output voltage, current and power of the systems within 1 minute. Same procedures were applied for all the measured data.

The output current, voltage, and power are always greater in the PV system with solar concentrator than the PV system without solar concentrator for a specific period of time for both bright sunny day and cloudy day as shown in Fig. 9, Fig. 10 and Fig. 11. Even though, output values of the parabolic trough concentrator system are greater than the Fresnel mirror concentrator system. Figures also suggest that the output has increased from 9.00 AM to 2.00 PM, and decreased from 2.30 PM to 4.00 PM.

4.1 Output Current of the PV System

The PV system's computed output current on a bright sunny day at 2 PM without solar concentrator, with parabolic trough concentrator, and with Fresnel mirror concentrator are 0.17A, 0.25A, and 0.22A respectively as shown in Fig. 9(a). It is observed that infliction of solar concentrator increases PV system’s output current on a bright sunny day.



(b) For a bright sunny day. (a) For a cloudy day.

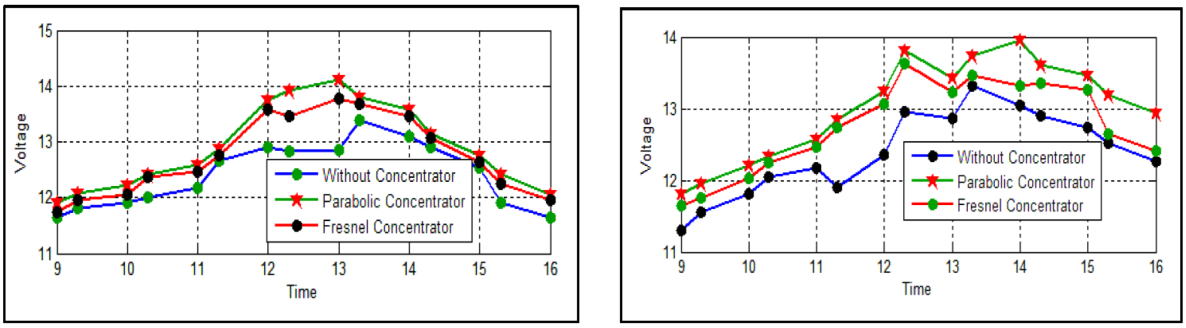
Fig. 9 - Output current of the PV system

Again, PV system's computed output current on a cloudy day at 2 PM without solar concentrator, with parabolic trough concentrator, and with Fresnel mirror concentrator are 0.15A, 0.21A, and 0.19A respectively as shown in Fig. 9(b). It is witnessed that infliction of solar concentrator increases PV system’s output current on a cloudy day as well.

4.2 Output Voltage of the PV System

The PV system's measured output voltage on a bright sunny day at 2 PM without solar concentrator, with parabolic trough concentrator, and with Fresnel mirror concentrator are 13.10V, 13.78V, and 13.46V respectively as shown in Fig. 10(a). It is witnessed that the use of solar concentrator increases PV system's output voltage on a bright sunny day.

Once again, PV system's measured output voltage on a cloudy day at 2 PM without solar concentrator, with parabolic trough concentrator, and with Fresnel mirror concentrator are 13.05V, 13.96V, and 13.32V respectively as shown in Fig. 10(b). It is witnessed that use of solar concentrator increases PV system's output voltage on a cloudy day also.

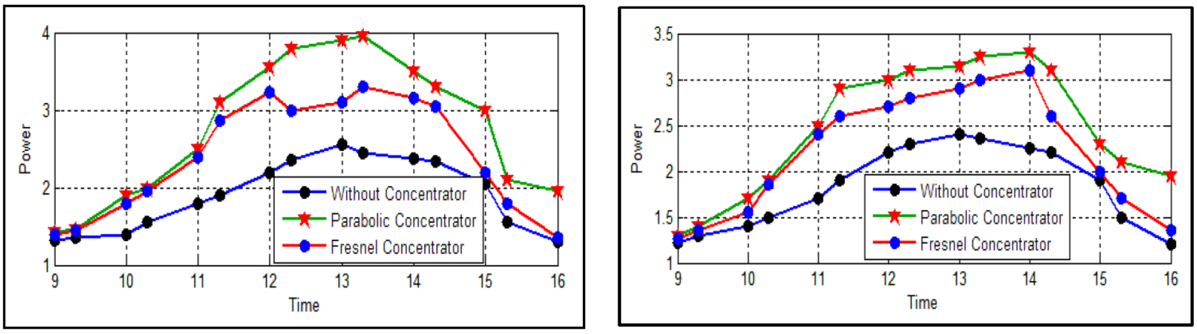


(a) For a bright sunny day. (b) For a cloudy day.

Fig. 10 - Output voltage of the PV system

4.3 Output Power of the PV System

The PV system's calculated output power on a bright sunny day at 2 PM without solar concentrator, with parabolic trough concentrator, and with Fresnel mirror concentrator are 2.38W, 3.50W, and 3.15W respectively as shown in Fig. 11(a). It is countersigned that application of solar concentrator increases PV system's output power on a bright sunny day.



(b) For a bright sunny day. (b) For a cloudy day.

Fig. 11 - Output power of the PV system

The PV system's calculated output power on a cloudy day at 2 PM without solar concentrator, with parabolic trough concentrator, and with Fresnel mirror concentrator are 2.25 W, 3.30 W, and 3.10 W respectively as shown in Fig. 11(b). Therefore, it is examined that application of solar concentrator increases PV system's output power on a cloudy day too.

The average output voltage, current and power have been calculated using following equations,

$$V_{avg} = \frac{\sum V_i}{n} \tag{1}$$

$$I_{avg} = \frac{\sum I_i}{n} \tag{2}$$

$$P_{avg} = \frac{\sum P_i}{n} \tag{3}$$

where V_i, I_i, and P_i represents measured voltage, current, power at different time, and n represents total no. of observations.

In summary, the authors found that using both parabolic trough and Fresnel mirror concentrator optimizes the output performance of a solar PV system on both sunny and cloudy days.

Table 1 - Comparison of the output voltage, current and power of PV system on a bright sunny day

Types of PV system	Average output voltage (V)	Average output current (A)	Average output power (W)
Without solar concentrator	14.42	0.14	2.02
With parabolic trough concentrator	14.52	0.19	2.76
With Fresnel solar concentrator	14.47	0.17	2.46

Table 2 - Comparison of the output voltage, current and power of PV system on a cloudy day

Types of PV system	Average output voltage (V)	Average output current (A)	Average output power (W)
Without solar concentrator	12.13	0.15	1.82
With parabolic trough concentrator	13.66	0.18	2.46
With Fresnel solar concentrator	13.37	0.16	2.14

5. Conclusion

Solar concentrators both parabolic trough and Fresnel mirror can offer a good deal to increase the solar photovoltaic system’s output power. With a view of studying the possible power optimization of photovoltaic system using solar concentrators this research has been performed, and the parabolic trough concentrator offered an output power improvement of 26.81% for a bright sunny day and 22.3% for a cloudy day respectively. On the other hand, using the Fresnel mirror concentrator we attained a power improvement of 17.89% for a bright sunny day and 14.2% for a cloudy day as well. Although we have been expecting more improvements in the output power, this study was limited by the panel temperature. As a matter of fact, monitoring PV system’s output power with a water spray system in the panel could be a good way to reduce panel temperature for future research.

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