1 **Chapter 5**
2 **Concentrated Photovoltaic (CPV): From Deserts to Rooftops**
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8 **Abstract.** The current photovoltaic market is completely domi-
9 nated by the conventional single junction PV panels, despite the
10 fact that the highest energy efficiency of multi-junction solar
11 cells is in the form of concentrated photovoltaic (CPV) system.
12 CPV technology has faced many challenges of reliability and per-
13 formance since its conception. However, despite much im-
14 provement in design and reliability, CPV technology is still un-
15 able to gain the attention of customers and energy planners with
16 its high-performance potential. Due to its response to only solar
17 beam radiations, CPV systems are believed to be only suitable to
18 operate in clear sky weather conditions. That's why the current
19 gigantic CPV systems are only designed to be installed in open
20 desert regions. It is still lacking the same application scope
21 which the conventional PV is experiencing. With the aim to
22 boost its market potential, in this chapter, a compact CPV design
23 is discussed with low cost but highly accurate performance, to
24 be targeted to install at the rooftop of commercial and residen-
25 tial building in the urban region. In addition, the performance of
26 CPV system is also evaluated and compared with the different
27 conventional PV system in the tropical weather condition with
28 low beam radiation availability.

29 **Keywords:** Concentrated Photovoltaic, Electrical Rating, CPV,
30 Long Term Performance, Solar Tracker, MJC.

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1 **1 Background**

2 The photovoltaic market is based upon three generation of solar cells [1-3]. If
 3 first- and second-generation solar cells are considered first, then it can be
 4 seen that they are fabricated using a single pn-junction of semiconductor
 5 material [4]. Due to certain bandgap of pn-junctions, they can only respond
 6 to certain to a certain portion of the solar spectrum and convert it into elec-
 7 tricity [5,6]. The remaining portion of the solar spectrum is just converted
 8 into heat. On the other hand, the third-generation solar cells are based upon
 9 multi-junction cells in which the multiple pn-junctions of different band gaps
 10 are sliced together. Each of the pn-junctions respond to a certain portion of
 11 solar spectrum and in the presence of these multiple pn-junctions, a larger
 12 portion of solar spectrum is absorbed and converted into electricity while a
 13 small portion is released as heat loss [7,8]. In order to keep this loss mini-
 14 mum, the bandgap of a pn-junction is selected such that it covers the whole
 15 solar spectrum with minimum difference between consecutive junctions. If
 16 the bandgap is higher than a large portion of received radiations is lost as
 17 heat [9]. Currently, a highest efficiency of 46% has been reported for multi-
 18 junction solar cells [10,11]. However, these third-generation multi-junction
 19 solar cells are expensive to fabricate due to high material cost. Therefore, to
 20 be used cost effectively, concentrated photovoltaic (CPV) concept is used in
 21 which solar radiations are concentrated onto a small area of solar cell using
 22 low cost concentrators. As a result, expensive solar cell material is replaced
 23 with low cost solar concentrators [12,13].

24 The first CPV system was developed in 1976 by National Sandia Laborato-
 25 ries with 1kW capacity. A satisfactory performance was observed from the
 26 prototype which later led to development of several prototypes of 0.5-1kW
 27 capacity in multiple countries. In 1981, another pre-industrial prototype of
 28 CPV system was installed in Saudi Arabia with capacity of 350kW. There were
 29 many performance degradation issues of this plant were observed due to
 30 high operation temperature of the cell, despite its satisfactory performance.
 31 Spectrum splitting was also used to increase the reliability of the CPV plant.
 32 However, these efforts could not help in the commercialization of CPV tech-
 33 nology [14,15]. The main reason for this was the use of silicon based conven-
 34 tional single junction solar cells which are not suitable to operate under high
 35 concentration and as a result, showed poor reliability. After that, much of
 36 the efforts were focused on to the development of reliable solar cell which
 37 could show reliable performance under high concentration and temperature
 38 [16]. When multi-junction solar cells were introduced into the photovoltaic
 39 market then this problem was solved as they can operate under high tem-

perature with high efficiency due to absorbance of larger portion of the solar spectrum. They also showed satisfactory field performance and long term reliability, with minimal degradation issues.

After solving the issue for the reliability of the solar cell, attention was then paid onto development of an effective design of the concentrating assembly for CPV. For the initial designs of CPV plants, a larger size of concentrating reflectors was used in form of parabolic dishes [17,18]. These designs were utilizing a point concentration concept in which solar cells were placed at the focus point of the concentrator. Some of the systems were also developed with linear focus using linear Fresnel lens or trough. Moreover, some of the design with a common focal point were also seen in which multiple reflectors were focusing at single common point. [19-23]. All of these designs offered a very complex manufacturing process, especially for large size reflectors, which were not easy to be fabricated using cost effective fabrication techniques. In addition, high radiation flux at the cell array resulted in high heat loss which demanded liquid cooling system to effectively cool down the solar cells. To solve these manufacturing issues and high heat flux problems caused by to the use of large size concentrators, small size concentrators were used in the manufacturing of the CPV system in which single concentrator was focusing onto a single solar cell, instead of an array of the cell. Therefore, passive cooling was also effective for such system design and cost-effective manufacturing techniques, i.e. injection molding, was used for these small size concentrators [24,25]. After reducing the size of concentrators, the attention was also paid onto the compact design of the concentrating assembly by using cassegrain arrangement of reflectors [26-28]. As a result, overall height of the concentrating assembly was reduced for the compact CPV module. In addition, secondary optical elements (SOE) designs were also incorporated in the concentrating assemblies for their better response and uniform distribution of solar radiation onto the cell area.

Despite all of these efforts and research, CPV still unable to make a significant contribution in the photovoltaic market. As solar concentrators can only respond to the beam part of solar radiations, they need solar tracking to remain faced towards sun throughout their operation. The CPV systems require very high solar tracking accuracy, which is different than the conventional solar trackers used for non-concentrated photovoltaic systems. In the case of poor tracking accuracy, the power output of the CPV system can drop to zero as the focal point will be shifted off the solar cell. Such a high tracking accuracy is achieved through complex two axis solar tracker, utilizing a hybrid tracking algorithm, which is available for high cost as compared to a conventional solar tracking unit. Furthermore, as CPV can only respond to

1 beam radiations, it is also believed that they are only feasible to operate in
 2 desert region. Due to sophisticated tracking requirement, a current commer-
 3 cial CPV system is available as gigantic unit with many CPV modules mounted
 4 onto a large solar tracking system, which is only suitable to be installed in an
 5 open desert field. With such design, the CPV system application is limited to
 6 open desert fields, which is the main reason for its low market share. On the
 7 one hand, if a conventional single junction PV system is considered, their 40-
 8 50% installation [29] is aimed to be on the rooftop of commercial and resi-
 9 dential buildings in the urban region. On the other hand, there are no CPV
 10 systems available which can be installed for rooftop application, like conven-
 11 tional PV. Therefore, CPV appeared to be the technology with limited cus-
 12 tomers and application scope. In this chapter, a compact design of concen-
 13 trated photovoltaic (CPV) system is discussed with aim for its rooftop appli-
 14 cation, without compromising its tracking accuracy requirement and cost. It
 15 is not very simple to have compact CPV design due to high tracking accuracy
 16 requirement, which will increase overall system cost as a greater number of
 17 tracking units will be needed. Therefore, a cost effective but highly accurate
 18 solar tracking design is presented based upon hybrid tracking algorithm and
 19 solar tracking sensor design. Moreover, the performance potential of a CPV
 20 system is also shown in a tropical region and compared with a conventional
 21 PV as it absorbs both beam and diffuse radiations while a CPV can only re-
 22 spond to beam radiations.

23 **2 Development of Compact CPV System**

24 As mentioned, the concentrated photovoltaic (CPV) system requires a two
 25 axis solar tracking unit to capture beam radiation, to which they can respond.
 26 Therefore, in the development compact system, it is very important to dis-
 27 cuss the tracking technologies designed for CPV operation, followed by the
 28 tracking mechanical hardware, and then concentrating assembly design.

29 **2.1 Development of Solar Tracking Technique**

30 In order to ensure better tracking accuracy, a hybrid tracking algorithm
 31 which utilizes the advantages of both passive and active tracking strategies is
 32 important. Only one method cannot ensure accuracy due to their limitations.
 33 However, in hybrid tracking strategy, one method compensates for the limi-
 34 tations of the other one. The details of each of tracking strategy is further
 35 discussed as following.

2.1.1 Astronomical Tracking

Due to rotation of earth around its own axis and the around the sun, the sun appears to constantly move during the diurnal period. Owing to this rotational motion, the angle of incidence of solar beam radiations with the earth surface is changing throughout the day. However, the movement of the sun is in a certain path which can be easily predicted with accuracy, at any time and part of the world, through a solar geometry model. The movement takes place in two axes of rotation and it is defined by two corresponding angles i.e. azimuth and zenith angles, as shown in Fig. 1. The azimuth angle defines the position of the sun in the horizontal plane, with reference from South. The zenith angle is defined in the vertical plane, with reference from the horizontal plane. The zenith and azimuth angles can be calculated as per given equations (1) and (2), respectively.

$$\theta_z = \cos^{-1} \{ \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \} \quad (1)$$

If $\omega < 0$,

$$\theta_{az} = 90 + \cos^{-1} \left\{ \frac{\sin \delta - \sin(90 - \theta_z) \sin \phi}{\cos(90 - \theta_z) \cos \phi} \right\} \quad (2a)$$

If $\omega > 0$,

$$\theta_{az} = 360 - \left[90 + \cos^{-1} \left\{ \frac{\sin \delta - \sin(90 - \theta_z) \sin \phi}{\cos(90 - \theta_z) \cos \phi} \right\} \right] \quad (2b)$$

The value of these two angles depends upon declination angle ' δ ', hour angle ' ω ', latitude ' ϕ ', longitude, date and time of the local position which are discussed in detail in [30].

22

23 **Fig.1.** Solar Position in Two Angular Planes.

24 In order to implement the discussed passive tracking algorithm, some of the
 25 real time information related local position of the tracker is needed i.e. date,
 26 time, latitude and longitude. To obtain such real time data, sophisticated

1 electronic modules of RTC (Real Time Clock) and GPS (Global Positioning Sys-
 2 tem) are needed for each tracking unit. In addition, a control circuit and cod-
 3 ing algorithm are also needed to extract the useful information out of the
 4 raw data received from such electronic modules. With increased number of
 5 tracking units needed for a compact CPV field, the multiple units of these
 6 electronic modules will increase the overall system cost and the computa-
 7 tional requirement of the system. Therefore, to cost effectively implement
 8 the passive tracking strategy for the compact CPV system design, master
 9 slave configuration is adopted, in which there is only one master tracker
 10 which is equipped with such sophisticated electronic modules and the neces-
 11 sary computational algorithm. After getting and processing the received raw
 12 data, the useful information of azimuth and zenith angles is transmitted to
 13 the slave trackers which just implement the received instructions. As a result,
 14 the need of extra electronic modules can be eliminated for the implementa-
 15 tion of passive tracking strategy in compact CPV design, which not only re-
 16 sults in the reduced system cost but also make control of the system simpler
 17 as only one unit is now responsible for all of the computation and data han-
 18 dling responsibilities. The rest of the tracking units are just implementing the
 19 received solar position coordinates.

20 To implement the master slave configuration, a wireless communication
 21 protocol of Zigbee network is considered in which the master tracker acts as
 22 coordinator 'C' of Zigbee network by creating its own communication net-
 23 work. The slave trackers join the network of coordinate with whom they
 24 would like to establish a communication link. The graphical representation of
 25 Zigbee network is given in Fig. 2. The slave trackers acts as router 'R' or end
 26 node 'ED' in the Zigbee network, depending upon their mode of operation
 27 either transceiver or receiver, respectively. Each slave has its own address
 28 with which it registers with the network of coordinate. The number to each
 29 of the slave unit in Zigbee is assigned through following equations (3) and (4)
 30 [31].

$$31 \quad Cskip = 1 + C_m(L_m - d - 1) \quad \text{if } R_m = 1, \quad \text{for, } d < L_m \quad (3)$$

$$32 \quad Cskip = \frac{1 + C_m - R_m - (C_m R_m^{(L_m - d - 1)})}{1 - R_m}, \quad \text{otherwise, for, } d < L_m \quad (4)$$

Fig.2. Compact CPV Field arrangement with Master Slave Configuration.

For wireless data transmission and communication, radio frequency waves are used by a Zigbee network. As the communication is through wireless means, such master slave configuration of CPV field can be set up at the rooftop of multiple buildings, without a need for any horizontal level adjustment.

2.1.2 Active Tracking

The passive tracking strategy relies on the pre-defined angles and the reference position of the tracker. With wind disturbance and mechanical backlash, the accuracy of such tracking methodology is compromised. Therefore, to ensure tracking accuracy, the real time position of the sun is also obtained through solar tracking sensor in an active tracking strategy. In this methodology, the feedback regarding actual current position of the sun is provided. The photo-sensors are arranged in certain position such that their feedback pattern determines the position of the sun. The main working principle of simple active tracking is explained in Fig. 3.

(b)

Fig.3. Basic Algorithm for Active Tracking.

In the simple form, the planar view of solar feedback is divided into four quadrants and each quadrant has its own photo-sensor. However, two opposite quadrants are paired together and each pair represents one axis of tracking. By comparing the output of photo-sensors in each pair, the position of the sun is determined for each axis. When the tracker is accurately facing the sun, the position of the sun is right at the centre of solar feedback sensor and the output of all four feedback sensors is equal. However, if sun is inclined towards 'signal 1' or 'zenith +', its output goes high as compared to its opposite 'signal 2' sensor. Therefore, by comparing their signal output, the position of the sun is adjusted such that their output signals become equal again.

This is the simplest solar feedback sensor configuration which is normally used for the conventional PV system tracking. In order to detect the movement of sun and to create difference in the output value of these photo-sensors as a result of solar movement, many designs have been studied in literature comprising of shadow rod, wedge shape and pin hole collimator design. Out of all these, the shadow rod design is a popular design in which a long rod is placed in the centre of four photo-sensors. With the movement of sun, if it is not tracked accurately, a shadow is created on one of the sensors in the pair, as shown in Fig. 4.

Fig.4. Shadow Rod Design of Solar Feedback Sensor.

These type of solar feedback sensors are only suitable for conventional PV tracking as they offer very poor sensitivity and tracking accuracy. In addition, they often utilize CdS based phot-sensors which offer non-uniform output under same light intensity. As per equation (5), if the angular deviation ' θ_a ' of shadow casted by this rod is plotted against height of the rod, then it can be seen from Fig. 5 that for tracking accuracy of $0.1-0.3^\circ$ as per the need of CPV system, the required of this shadow rod is around 1-2m which is an impractical design for field operation.

$$CH = \frac{SD}{\tan \theta_a} \quad (5)$$

The solar tracking literature is stuffed with such designs of feedback sensors but they are only good for conventional PV systems and do not have capability to meet the CPV tracking requirement. The only feedback sensor available commercially for CPV tracking is based upon a position sensitive diode (PSD) sensor [32]. However, the high cost of such sensor does not go well with the idea of compact as larger number of tracking units will need more number of such sensors and, as a result, the overall cost of the system will be higher than the conventional system of same capacity. Therefore, for a cost effective solar feedback sensor, an optical collimator based design is presented in the next section which utilizes the concept of optics to increase the sensitivity of the sensor to detect tracking errors with high accuracy. In addition, concentrated radiation will be used in the discussed design which will bypass the non-uniform output of photo-sensors as they will always be operated at a light intensity higher than their saturation limit.

Fig.5. Different Heights of Shadow Rod for required Offset Angle.

2.1.2.1 Solar Feedback Sensor for Compact CPV

Fig. 6 shows the simple schematic of the solar feedback sensor which is based upon a double lens collimator design and photo-sensor array. The collimator is based upon the pair of convex and concave lenses. The solar radiations parallel to the collimator axis experience converging and diverging effects when they pass through convex and concave lenses, respectively, and a concentrated collimated beam is generated after concave lens which falls at the center of photo-sensor array. The working principle of the feedback sensor is such that, when the tracker is accurately facing the sun, the concentrated collimated beam is right at the center of photo-sensor array. With induced tracking error, the incident radiations are no longer parallel to the collimator axis and, as a result, the collimated beam also shifts from its center point. If the tracking error exceeds the required tracking error limit, then the collimated beam hits any of the photo-sensor in the array. The feedback from all of the photo-sensors is recorded all the time. When the collimated beam interacts with any of the photo-sensors, it gives high output and, depending upon the position of the sensor with high feedback, the position of the tracker is adjusted such that the collimated beam again comes at the center of photo-sensor array. As long as the collimated beam remains in between photo-sensor array, the trackers are considered to be operated with the required tracking accuracy. Due to concentrating beam interacting with the photo-sensor, its output is always at maximum, and that is why it operates in binary mode of either high or low value. This step completely elimi-

notes the chance of error which may rise due to non-uniform output of photo-sensors.

Fig.6. Design and Working Principle of Double Lens Collimator Based Solar Feedback Sensor.

As mentioned before, sensitivity and accuracy of the feedback sensor are the main concern in the CPV application. Before analyzing these aspects, it is important to see the important design parameters of the proposed configuration. By knowing the diameter of convex ' D_{cx} ' lens, as the size of main receiver, and the focal points of both convex ' f_{cx} ' and concave lenses ' f_{cn} ', the lens spacing and the thickness of collimated beam are given by equations (6) and (7), respectively.

$$S = f_{cx} + (-f_{cn}) \quad (6)$$

$$b_t = \frac{D_{cx}}{f_{cx}} \cdot f_{cn} \quad (7)$$

It is important to note here that the lens spacing is basically the sum of focal lengths of both lenses. However, a minus sign appears with concave lenses is due to their negative focal length.

To investigate the sensitivity of the discussed configuration, the raytracing simulation is shown in Fig. 7 for designs values of $f_{cx}=80\text{mm}$, $D_{cx}=20\text{mm}$ and $f_{cn}=-12\text{mm}$. From the results, it can be seen that with 1° angular deviation in

collimated beam, a 7.4° deviation (same as the slope of the graph) is recorded in the collimated beam. This shows that the proposed configuration has shown an excellent sensitivity of 7.4 for the given design parameters. On the other hand, such sensitivity can also be defined in terms of linear translation of collimated beam which can be increased by increasing the distance 'h' between optical collimator and the photo-sensors array. It can be seen that the feedback sensor can even detect the tracking errors as low as 0.1° . Hence, the proposed configuration of solar feedback sensor provides a cost effective and highly accurate solar tracking option for the compact CPV field design.

Fig.7. (a) Accuracy and (b) Sensitivity of Double Lens Collimator Based Solar Feedback Sensor.

2.2 Hybrid Tracking Algorithm

After development of each tracking strategy, the next step is their implementation which is done through a tracking algorithm. The tracking algorithm for the compact CPV design is a hybrid scheme, which is based upon both passive and active tracking strategies. However, astronomical tracking strategy is utilized as the primary tracking methodology. In the master tracker, from the received and processed information of date, time, latitude, and longitude, the azimuth and zenith angles are calculated. Based upon the actual position of the tracker and the calculated values of sun position, the trackers are moved in steps until the difference between sun position and the tracker position is within the required error limit. At this stage, the calculated zenith and azimuth angles are also transmitted to the slave trackers which also follow the same strategy. After completion of the passive tracking loop, the optical tracking method is activated and the feedback from the photo-sensors array is evaluated. As all of the trackers in the field are equipped with the solar feedback, they are independent in this tracking loop. In addi-

tion, the effect of mechanical backlash and the wind disturbance is different for each tracker. If any of the tracker received high feedback from the solar feedback sensor, then its position is adjusted accordingly and the main loop starts again with the passive tracking. Such algorithm is repeated is again and again during diurnal period. After sunset, all of the trackers return to their reference position and start their operation again after sunrise.

2.3 Drive and Control Assembly

So far, the discussion is based upon the solar tracking strategy and methodology. However, to implement such methodology, a mechanical drive and control assemblies are needed. The control assembly is based upon the electrical circuit which is based upon the microcontroller, Zigbee transceivers and the motor drivers, along with the electronic modules required to obtain the time, date, and position coordinates for passive tracking. However, these electronic modules are only required for the master tracker. The control circuit for master and slave trackers are shown in Fig. 8.

Fig.8. Comparison of Control Boxes for Master and Slave Trackers.

Fig.9. Mechanical Drive of Two Axis Solar Tracker.

The hybrid tracking algorithm is stored in the microcontroller using C-programming. The tracking instructions from the microcontrollers are needed to be translated in to the physical movement of the tracker, which is implemented through mechanical drive assembly. The mechanical drive assembly consists of stepper motors and a gear assembly. There is a separate mechanical drive assembly for each tracking axis. The motor drivers operate the stepper motors after receiving the required signal from the microcontroller. The gear assembly, consisting of a worm gear and wheel, divides the motor movement into further small steps for fine controlled movement. In order to find the final step movement of the mechanical drive per step movement of the stepper motor, equation (8) can be considered.

$$\text{Tracker Movement/Step} = \frac{\text{Motor Step}}{\text{Driver Step} \times \text{Gear Ratio}} \quad (8)$$

The mechanical drive is supported by mechanical structure which also provides space to mount the CPV modules. The physical representation of mechanical drive is given in Fig. 9.

2.4 Concentrating Assembly and CPV System

The concentrating assembly is the component of the CPV, using multi-junction solar cell, on which the performance of the system relies. For compact CPV system design, a single stage refractive concentrating assembly provides the most simple and effective solution, as shown in Fig. 10. Fresnel lens is used as the main receiver, which concentrates beam solar radiations at the inlet aperture of the glass homogenizer. The homogenizer further guides and uniformly distributes radiations over its outlet aperture where

multi-junction solar cell is placed. The back surface of MJC is pasted with a heat spreader and heat sink to effectively reject heat loss and to keep the cell temperature within optimum operating limit. It must be noted that the height and side angle of homogenizer must be designed such that the rays can propagate towards its outlet aperture. Otherwise, there is a chance that the refracted rays can be reflected backward to the inlet aperture through total internal reflection.

Fig.10. Single Sage Concentrating Assembly for CPV using Fresnel Lens.

Based upon the discussed tracking methodology, hybrid tracking algorithm, drive and control assembly, and single stage concentrating assembly, the prototype of developed compact CPV system is shown in Fig. 11. The CPV modules is mounted onto a two-axis solar tracking unit. A triple junction In-GaP/InGaAs/Ge based solar cell is used, for which PMMA based Fresnel lens is concentrating solar radiations with a geometric concentration ratio of $\times 476$. The homogenizer is a glass prism rod made of quartz material. For the control box of the tracking unit, a ATmega2560 microcontroller is used in which the hybrid tracking algorithm, written in C-programming and compiled with CodevisionAVR, is installed. The shown control box is for the master tracker. However, such CPV units be re-produced as slaves which will have a much simple control box, consisting of microcontroller, wireless transceiver module, and motor driver only. The concentrated bright spot in the center of photo-sensors array verifies the discussed design of solar feedback sensor. Such compact CPV systems can be anywhere in the urban region for rooftop application.

Fig.11. Compact CPV Unit.

3 CPV performance in Tropical Urban Region

As mentioned at the start of this chapter, it is commonly believed that the CPV is only capable of feasible operation in the desert region with clear sky conditions as they can only respond to beam radiation. On the other hand, the conventional PV can respond to both beam and diffuse solar radiations. Despite the highest energy conversion efficiency, CPV is unable to make in the photovoltaic market. This shows that it is not the system efficiency, but the total energy output of the system in which customers and energy planners are interested. However, none of the study has been conducted to verify the misconception of such inferior performance of CPV in the tropical conditions. In order to compare the performances of CPV and conventional PV, both systems were operated long term under tropical weather conditions of Singapore, at the rooftop of a building. The production of the system is monitored for one year, in terms of its energy output and the comparison parameter, which has been used here is defined in equation (9) as electrical rating in kWh/m²/year. Based upon this total energy output and the average energy efficiency, instead of instantaneous (input/output) energy efficiency, is the best way to present the long-term production potential of a system, as shown in equation (9).

$$\eta_{avg} = \frac{\text{Electrical Rating}}{\text{Solar Input}} = \frac{\left[\left(\sum_{i=1}^t \frac{(V_{CPV} \cdot I_{CPV})_i - (V_{CPV} \cdot I_{CPV})_{i-1}}{2 \times A_c} \right) \cdot S \right] \times \frac{365}{m}}{\left[\left(\sum_{i=1}^t \frac{(Ir)_i - (Ir)_{i-1}}{2} \right) \cdot S \right] \times \frac{365}{m}} \quad (9)$$

Where parameter 'S' represents the interval for data scanning, 'm' represents the total number of days for which the performance of the system was monitored. For the presented results, the scanning interval is 1 second.

First, in order to thoroughly discuss the performance potential of CPV system, the maximum instantaneous efficiency of the developed CPV system is shown in Fig. 12. It can be seen that system showed maximum efficiency of 28% which is based upon the electrical output of the system over the solar energy input in form of beam radiations only. Such efficiency of the system is irrespective of the working conditions. That is why it is not a true representative of system field potential, which can vary as per operating location conditions. Moreover, it can also be seen that efficiency of the system is fluctuating with change in the received beam radiations, expressed as direct normal irradiance (DNI). Therefore, in order to truly analyze the true performance potential of the system, in terms of its energy output, the electrical ratings of developed CPV system and different types of conventional PV systems under tropical weather conditions are shown in Fig. 13 for one year of operation.

Fig.12. Maximum Instantaneous Efficiency of CPV.

It can be seen that the energy output of the CPV system is almost twice the output of the conventional PV. However, for such weather conditions, it is important to mention here that only 66% of the solar year was received as the beam radiations, out of 1700 kWh/m²/year. Despite such low beam radiation ration, the CPV system showed that it produced double the power of the conventional PV which was responding to 100% of the available solar

1 energy. In terms of efficiency, if we can plot the average annual efficiency of
 2 each photovoltaic system, as per equation (9), we can see that the CPV sys-
 3 tem showed an average efficiency of 14.1% while the maximum efficiency
 4 showed by a conventional PV is only 7.5%. It must be noted that that these
 5 efficiency values are calculated by global horizontal irradiance (GHI) as solar
 6 energy input, includes both beam and diffuse radiations. However, if conven-
 7 tional method of CPV efficiency calculation followed, which only considers
 8 beam radiations as solar energy input, an average annual efficiency of 22%
 9 can be achieved. These results show that the CPV technology has immense
 10 production potential in the current photovoltaic market, even in a tropical
 11 region. However, the only need is to increase its application scope and cus-
 12 tomers with simple low cost system, as discussed in this chapter.
 13

14
 15 **Fig.13.** Comparison of Long-Term Field Performance of CPV with Conven-
 16 tional PV under Tropical Weather Conditions.

17 4 Summary of Chapter

18 Concentrated photovoltaic (CPV) system has appeared to be one of those
 19 technologies with less customers and market share, despite much research
 20 and the highest energy efficiency. Such limited application is because of its
 21 complex, gigantic design and the fallacy of their feasibility only in desert re-
 22 gions. In this chapter, a compact CPV design is discussed with cost effective
 23 and highly accurate solar tracking, for its application at the rooftops of com-
 24 mercial or residential buildings. A hybrid tracking algorithm is explained

which utilizes both active and passive solar tracking strategies. The cost-effective implementation of passive tracking for compact CPV design is made through use of master slave configuration in which only one master tracker extracts and processes the required data. However, the rest of the tracking units only follow the instruction received. On the other hand, for highly accurate real time tracking accuracy feedback, a double lens collimator-based feedback sensor is discussed which uses the optical design to increase the sensitivity and accuracy of tracking error detection.

To analyze the performance potential of a CPV in a tropical urban region, the long-term energy output of the system is recorded for one-year operation and compared with conventional PV operating in the same conditions. With only 66% beam radiations availability, the CPV system produced twice the power output of the conventional PV. It can be seen that with such production potential and the simple system design, the application scope of the CPV system can be increased with great market potential.

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