Chapter 6
Concentrated Photovoltaic (CPV) for Rooftop—Compact System Approach

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Abstract The single-junction-based conventional PV panels are dominating almost the entire photovoltaic market. In addition, they can only offer a limited solar conversion efficiency due to limitations of the band gap of their single pn-junction. On the other hand, third-generation multi-junction solar cell offers the highest solar energy conversion efficiency as their multiple pn-junctions can absorb a larger portion of solar spectrum. Despite such high potential, their share in current photovoltaic market is still negligible, even though, they have been used in form of concentrated photovoltaic (CPV) systems to reduce the use of expensive solar cell material. The main reason for such low market share is due to the gigantic design of commercial PV system which is only suitable to install in the open desert regions, thereby limiting its customers and application scope. In this chapter, a compact CPV system design is discussed with the motivation for its rooftop application and installation. Moreover, the long-term performance of CPV is also compared with conventional PV system in tropical conditions to highlight its potential in low solar energy areas.

Keywords Long-term CPV potential · CPV · Concentrated photovoltaic
Compact · Solar tracker · Multi-junction cell

6.1 Background

The global ambient temperature is reaching a drastic limit rapidly, due to emissions from excessive use of fossil fuel based systems, which will have irreversible impact on our planet. Such situation demands change in our energy needs to be shifted to sustainable resources (Desideri and Campana 2014; Shahzad et al. 2018a, b;

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Desideri et al. 2013; Ng et al. 2017). Many renewable energy resources, such as wind, biomass, geothermal have been reported to sustainably fulfill a part of our energy needs. However, none of the energy sources has potential greater than the solar radiations hitting the earth surface, which is many times higher than our global energy needs (Solanki et al. 2009; IPCC 2012). The only need is to capture it efficiently and effectively.

Due to low energy density and quality of received solar radiations, they have to be converted into a high-grade energy form such as electricity, and photovoltaic system or solar cell provides the best and most simple method of sunlight to electricity conversion (Burhan et al. 2016a, b, c, d, e, 2017a). As mentioned before, the most important factor regarding the sustainability of any renewable energy sources is that how efficiently its potential is captured. In the current market trend of photovoltaic systems, first and second generations of solar cells, comprising of monocrystalline, polycrystalline and thin film, are contributing to 99% of the total installed capacity. However, due to their material characteristics of single-junction-based semiconductor, they offer very low solar energy conversion efficiency. This is because of the fact that they respond to a certain portion of solar radiations, depending upon the band gap of the pn-junction (Green et al. 2015; Burhan et al. 2017b). On the other hand, the third generation solar cells are based upon multi-junction solar cells, offering highest efficiency of 46% so far (National Renewable Energy Laboratory (NREL) 2016). The main reason for such high efficiency is their material characteristics which are based upon a stack of multiple pn-junction of the semiconductor material. Each junction is designed to have a certain band gap such that they can respond to a certain portion of solar spectrum. As a result, whole solar spectrum is absorbed from short wavelength of ultraviolet radiations to the large wavelength infrared radiations (Cherucheril et al. 2011). Despite higher efficiency, multi-junction solar cells are still unable to make the prominent contribution in the photovoltaic market.

The multi-junction solar cells still cannot be fabricated as flat panels like conventional single-junction solar cells, because of high cost of material. Therefore, concentrated photovoltaic (CPV) concept is used which utilizes low-cost concentrators to concentrate solar radiations to an intensity of 500–1000 times onto a small area of cell. This reduces the use of expensive solar cell material with low-cost optical material (Mathur et al. 1990; Muhammad et al. 2016). The concentrated photovoltaic system was firstly developed in 1976 at National Sandia Laboratories. Later, many system design prototypes were developed to be installed in different locations across the globe (Sala et al. 1979; Claverie et al. 1980; Giuffrida et al. 1980; Salim and Eugenio 1990). The CPV system evolved in many phases, i.e., from development of high performance multi-junction solar cells (Garboushian et al. 1996; Shahzad et al. 2018c; Tsadka et al. 2009; Singh and Liburdy 1993; Clemens 1997; Walter and John 1994; Burhan et al. 2018a; Burhan 2015) to the compact solar concentrators for cost-effective fabrication and system assembly (Burhan et al. 2018b; Garboushian et al. 2007; David and Stephen 2007). However, till now, the concentrated photovoltaic systems are aimed to install in open deserts field due to their operational needs as they can only respond to solar beam radiations. Therefore, these systems are commercially available in gigantic design which can only be installed in open field conditions, with limited applications and customers. As CPV system requires highly accurate solar tracking to capture solar beam radiations (McConnell 2008), therefore, multiple CPV modules are mounted onto a gigantic tracker to lower the need of sophisticated tracking units.

If installations trends of conventional single-junction PV panels are notice, then it can be seen that large number rooftop units contribute to a significant share of overall installed capacity which is targeted to be increased to 40–50% (Burhan et al. 2018c). On the other hand, there is no such provision available for the concentrated photovoltaic system, which makes their share negligible in the market due to such limited applications and customers. Due to their current commercial design, their production potential is still utilized despite their highest energy conversion efficiency. Therefore, compact CPV design is needed, which can remove all such installation related restrictions to boost their market potential and application scope, especially for rooftop installation. However, as mentioned before, the CPV system requires very sophisticated and highly accurate solar tracking units, therefore, it is not that simple to have compact CPV system design. With such compact design, more number of sophisticated tracking units will be needed, which will increase the overall cost of the system. This chapter discuss the design and development of compact CPV system with cost-effective and highly accurate solar tracking methodology and sensor. Detailed operations methodologies and construction design are discussed for such compact CPV system development which will also be able to be installed for rooftop operation.

6.2 Compact Solar Tracking Unit Design for CPV

Owing to the need of large number of tracking units for the compact CPV system design; low cost, simple but highly accurate tracking units are needed for its feasible and economical operation. There are many systems and techniques discussed in the literature regarding design and operation of solar tracking systems for conventional PV systems. These conventional solar tracking units range from fixed speed single axis systems to the two-axis controlled systems. However, if concentrated photovoltaic systems are considered, there are very few studies discussing the tracking requirements of CPV. It must be noted that the solar tracking units required and designed for conventional PV systems cannot be used for CPV due to their poor tracking accuracy of 10–12°. CPV system demands tracking accuracy of order 0.1–0.3°. In addition, the solar tracking units for CPV cannot only rely on the passive tracking methodologies, due to high accuracy requirements. As passively tracked solar tracker can incur error due to mechanical backlash and wind disturbance related problems, therefore, tracking accuracy can only be insured through feedback from solar tracking sensor. Such hybrid tracking can only work for concentrated photovoltaic system. A detailed design of compact solar tracking unit for CPV application with proposed hybrid tracking algorithm and tracking sensor is discussed in this section.

6.2.1 Passive/Astronomical Solar Tracking

The solar radiations hitting earth's surface change their incident angle throughout the day, due to its continuous motion around the sun. However, such motion follows a certain profile which can be easily and accurately traced through predefined astronomical models of solar geometry. With known information of date, time, latitude, and longitude, the position of sun can be determined through these defined models, at any location throughout the globe. The position of sun is defined by two planer angle, i.e., azimuth and zenith, presented in the horizontal plane and the vertical plane, respectively. The azimuth angle is reference from the south. On the other hand, zenith is reference from horizontal surface with movement in vertical plane. Such tracking methodology, based upon predefined solar coordinates from reference planes, obtained from solar astronomical models, is called as astronomical tracking. As it does not have any feedback regarding actual position of the tracker, instead of calculated motion from reference plane, therefore, it is also called as passive tracking. As per the solar geometry model, azimuth "θ_{az}" and zenith "θ_z" angles are given by Eqs. (6.1) and (6.2a) or (6.2b), respectively.

$$\theta_z = \cos^{-1}\{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega\} \tag{6.1}$$

If $\omega < 0$,

$$\theta_{az} = 90 + \cos^{-1}\left\{\frac{\sin\delta - \sin(90-\theta_z)\sin\phi}{\cos(90-\theta_z)\cos\phi}\right\} \tag{6.2a}$$

If $\omega > 0$,

$$\theta_{az} = 360 - \left[90 + \cos^{-1}\left\{\frac{\sin\delta - \sin(90-\theta_z)\sin\phi}{\cos(90-\theta_z)\cos\phi}\right\}\right] \tag{6.2b}$$

where "ω", "δ", and "ϕ" are hour angle, declination angle and latitude respectively, as explained in detailed in Oh et al. (2015).

6.2.2 Master–Slave Configuration for CPV Field

To implement the defined astronomical or passive solar tracking strategy and to compute the tracking angles through mentioned solar geometry model, a control circuit is needed which also control the motion of the tracker in two axis as per given instructions or pulses. On the other hand, for compact CPV field configuration, larger number of tracking units are needed and so as these sophisticated and expensive control box. Therefore, for cost-effective operation, a master–slave configuration is presented in which control box of single master tracking unit is equipped with all required electronic modules which are expensive and sophisticated, and needed to get the necessary real-time data to implement astronomical tracking methodology. However, when the computations are done by the master tracker, the required information of solar position in form of azimuth and zenith angles is transmitted to the slave tracker which only have transceiver module to receive and implement the received information. As a result, most of expensive modules are save from slave tracker control circuit, as shown in Fig. 6.1, reducing the overall capital cost of the CPV field.

A wireless communication protocol of Zigbee network is utilized for such configuration, in which radio frequency waves are used for data transmission. As per Zigbee network, illustrated in Fig. 6.1, the master tracker acts as coordinator "C" which creates its own network of communication. However, rest of the trackers in the field acts as slave which join the created communication network as router "R" or end devices "ED" as per their communication preferences. The router can receive and further transmits the information. However, end devices only act as receiver and normally, the devices in the last circle of the zigbee network act as end devices. The number and address to each of the tracking unit in the zigbee network are defined by Eqs. (6.3) and (6.4), as explained in Farahani (2011). Such wireless communication is very important for compact CPV field configuration which can be easily set up at rooftop of multiple and distant residential or commercial buildings, without any need of horizontal level ground.

$$\mathrm{C}_{skip} = 1 + C_m(L_m - d - 1) \quad \text{if } R_m = 1, \text{for } d < L_m \tag{6.3}$$

$$\mathrm{C}_{skip} = \frac{1 + C_m - R_m - \left(C_m R_m^{(L_m - d - 1)}\right)}{1 - R_m}, \text{otherwise, for } d < L_m \tag{6.4}$$

6.2.3 Development of Solar Feedback Sensor

As explained before, to achieve high level accuracy of solar tracking for concentrated photovoltaic system, hybrid solar tracking algorithm is needed in which the accurate position of the solar tracker is ensured through real-time solar position feedback from solar tracking sensor. Therefore, the sensor is of prime importance here which must also have very high accuracy and sensitivity but at low cost due to the need of large number of solar tracking units for compact CPV field.

There are many studies available in literature regarding design and working principle of solar tracking sensor for conventional PV system (Luque-Heredia et al. 2007), e.g., shadow rod, wedge shape and quadrant designs. Although, they are workable for conventional PV tracking their accuracy is not as per CPV tracking requirements (Yao et al. 2014). In addition, the response of optical sensor employed in such solar tracking sensor configuration is not steady and uniform under same light intensity. For CPV tracking, there is only one commercial solar tracking

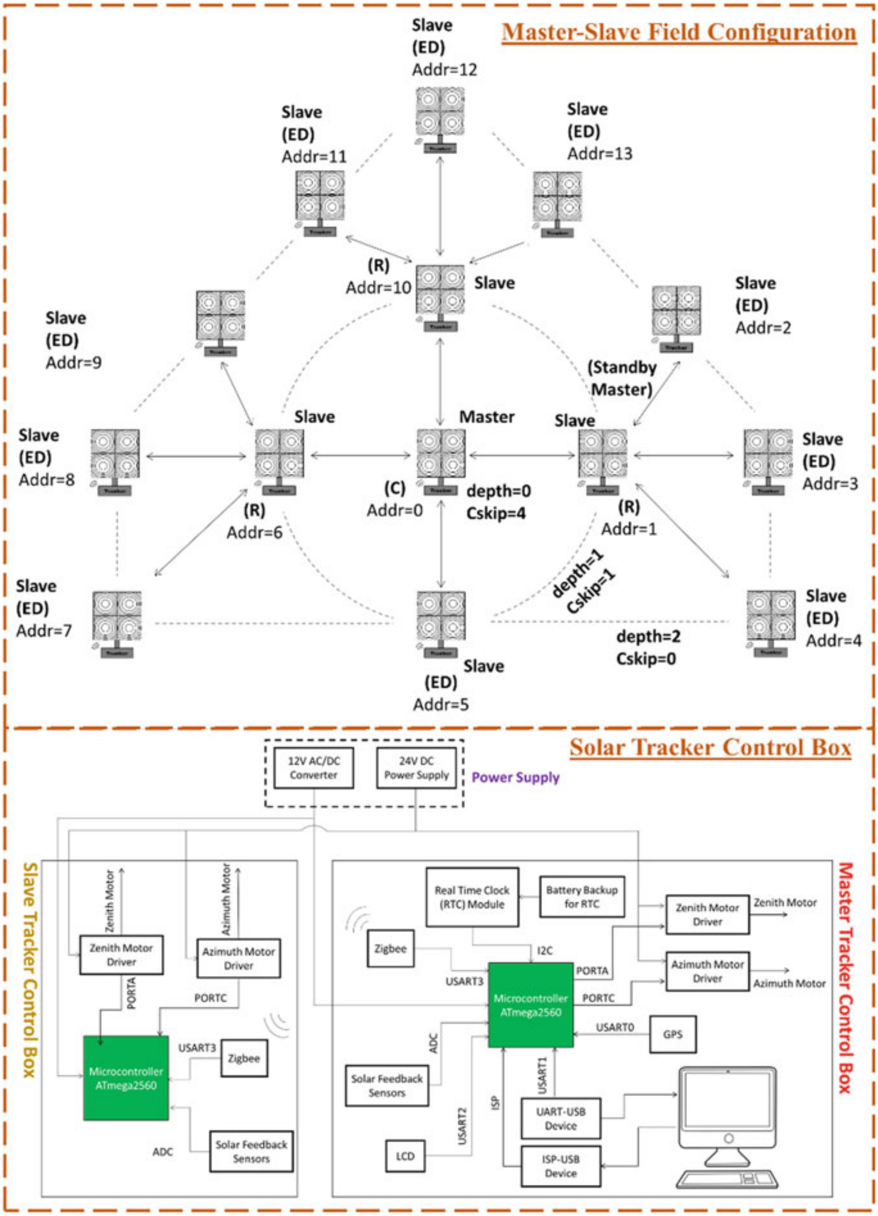

Fig. 6.1 Master slave configuration and control box for compact CPV field

sensor available which utilizes highly accurate position sensitive diode (PSD) (Luque-Heredia et al. 2006; Xu et al. 2013). Though such sensor can provide the solar tracking feedback in the range of CPV requirements, however, due to its high cost, it is not suitable to be used for compact CPV field configuration. In addition, larger number of such tracking sensor will be needed for compact CPV as compared to conventional configuration, thereby, increasing overall capital cost of the system. Therefore, a simple solar tracking sensor is needed at fraction of the cost of its commercial alternative, but with same accuracy and sensitivity response, so that overall cost of the system is not affected by it.

A simple schematic of proposed solar tracking sensor, for CPV application, is shown in Fig. 6.2. The proposed configuration is based upon a twin lens collimator which provides a collimated and concentrated beam at the center of photo-sensors array. Parallel solar rays, after being refracted through convex–concave lens collimator, become parallel but as a concentrated beam which creates a bright spot at the center of photo-sensors array. The focal point of both lenses must coincide for better collimated effect. Therefore, the rays become parallel after being refracted through concave lens. The proposed solar tracking sensor configuration works in such a way that the when the sensor position is aligned with solar position then the solar radiations parallel to the collimator axis creates a bright spot at the center of the photo-sensor array. When tracking error is induced, received solar radiation deviates from collimator axis, causing the bright spot to move from its center position. The deviation of bright spot from its center position depends upon the angular deviation of solar radiation from the collimator axis. When this angular deviation increases from a certain limit, the concentrated spot hits any sensor of the photo-sensors array. The feedback of photo-sensors is given to the microcontroller of the control box, which translated its analogue signal to digital value, using ADC (analogue to digital converter). The microcontroller processes the feedback signal in such a way that it moves tracker to bring back bright spot at the center of photo-sensor array.

The feedback from photo-sensors to microcontroller works in binary mode, i.e., high or low. The concentrated radiations falling onto the photo-sensor are higher than its saturation limit. When bright spot hits any of the photo-sensor, a high feedback signal is given to the microcontroller. Depending upon the position of the photo-sensor, giving high feedback signal, the direction of tracker movement is decided to bring back the bright spot in between photo-sensors array. As long as bright spot remains within photo-sensor array, the feedback signal to microcontroller is low, indicating that the tracker is operating within defined tracking accuracy. This depicts that the distance between photo-sensor array and the bright spot defines the tracking error limit, higher the distance, lower the tracking accuracy. Therefore, based upon the relationship between the deviation of the parallel rays from collimator axis and corresponding deviation of bright spot from its center position, the distance between photo-sensors array and bright spot is adjusted. However, thickness "b_t" of collimated beam also need to be considered while selecting photo-sensors spacing. As far as, the concentrated bright spot remains within the photo-sensors array, the tracker is ensured to be operated with required

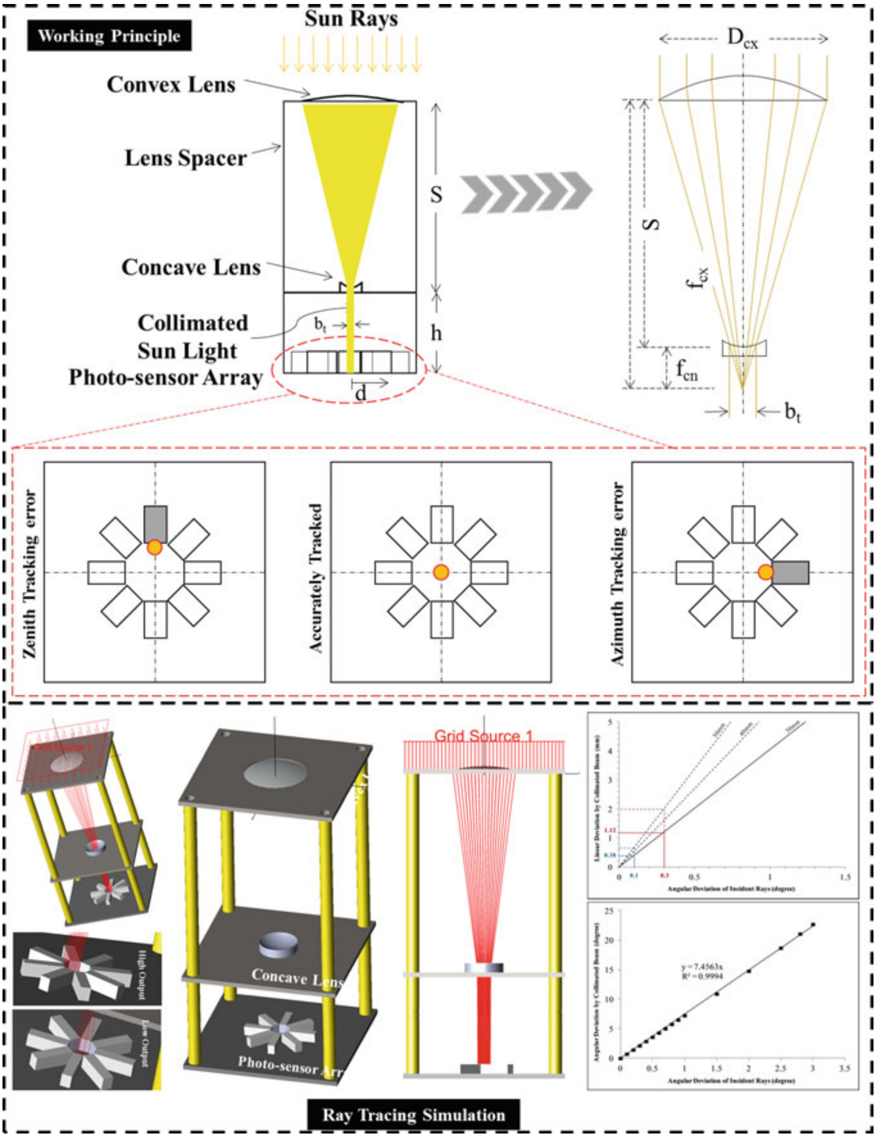

Fig. 6.2 Collimator based solar tracking sensor schematic and ray tracing simulation

tracking accuracy. If the diameter of primary convex lens is "D_{cx}" and the focal lengths of convex and concave lenses are "f_{cx}" and "f_{cn}", respectively, then the thickness "b_t" of collimated beam and the distance "S" between collimated lenses can be found mathematically by using Eqs. (6.5) and (6.6).

$$S = f_{cx} + (-f_{cn}) \tag{6.5}$$

$$b_t = \frac{D_{cx}}{f_{cx}} \cdot f_{cn} \tag{6.6}$$

It must be noted that the focal length of concave lens is negative. Therefore, the distance between the collimated lenses is actually the sum of their focal lengths, in which one component is negative.

Besides tracking error limit, another important feature of solar tracking sensor is its sensitivity to tracking error. Due to high tracking accuracy, it is very important to have high sensitivity, so that even a small tracking error can be detected by the sensor. To investigate the sensitivity of proposed solar tracking sensor configuration, the optical simulation of a prototype is conducted with components details as f_{cx} = 80 mm, D_{cx} = 20 mm, and f_{cn} = −12 mm. The raytracing simulation results, performed using Tracepro, are shown in Fig. 6.2. The performance graphs show the response of sensor in terms of linear deviation of concentrated bright spot and angular deviation of collimated beam against incident radiations. It can be seen that even for 0.1° incident ray deviation, there is a significant linear deviation of bright spot. Moreover, from angular deviation of collimated beam graph, it can be seen that there is 7.4° deviation in collimated beam for one-degree deviation in incident radiations, which also represents the slope of the graph. For the mentioned configuration, a sensitivity of 7.4° is offered by the solar tracking sensor. On the other hand, such sensitivity can be further increased by increasing distance between concave lens and photo-sensors array. Thus, simple, highly sensitive and accurate solar tracking sensor is proposed and designed, which has tracking accuracy and sensitivity of 0.1°. In addition, as the radiations interacting with photo-sensors are higher than their saturation limit, therefore, ordinary photo-sensors can be used without worrying about their nonuniform response at same intensity.

6.2.4 Development of Tracking Algorithm for CPV Field

After designing the solar tracking algorithms, the next step is the development of solar tracking algorithm which is used by the microcontroller to implement the solar tracking methodologies. In the proposed compact CPV tracking system, a hybrid tracking algorithm (passive/astronomical + active/optical) is developed using C-language programming and CodevisionAVR compiler. In the developed hybrid algorithm, astronomical/passive tracking methodology (Oh et al. 2015) is executed first, which acts as the main primary tracking methodology. The actual position of the tracker is compared with the calculated position of the sun. If the difference between actual position and calculated value is greater than the required tracking limit, then the tracker is rotated either in azimuth and zenith direction, accordingly. When such difference is within the acceptable range then the tracker is stopped or it remains stationary. When execution of astronomical method is completed, then the optical/active tracking method is implemented to ensure the tracking accuracy. During optical tracking execution, the feedback from solar tracking sensor is obtained. If high feedback signal is obtained from any of the sensor then the tracker is adjusted accordingly, till a low feedback signal is obtained and the loop starts again with the astronomical tracking.

The hybrid tracking algorithm, as explained above, is shown in Fig. 6.3. At the start of the loop, the data from RTC (Real Time Clock) and GPS (Global Positioning System) modules is obtained and sorted to get local date, time, latitude, and longitude which are transmitted continuously through Zigbee to the slave trackers. Such communication is time independent and whenever a new data set is received by the slave tracker, it is replaced with old value. However, the slave tracker does not have any movement unless difference between actual solar position of the tracker and the received coordinates is greater than the tracking accuracy, even though the data transmission is always happening in the background. When there is time of sunset, the solar tracker returns to its initial reference position, i.e., horizontal module while facing south. The operation starts again when there is time for sunrise.

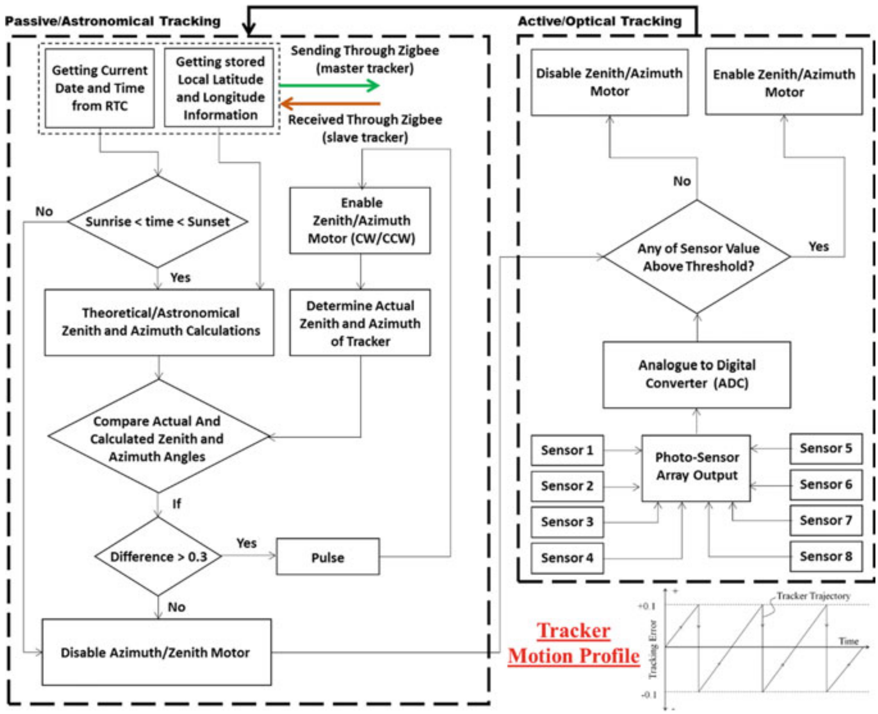

Fig. 6.3 Hybrid solar tracking algorithm for compact CPV field

6.3 Development of CPV System

As per tracking methodology and design discussed, a compact CPV system prototype is developed for CPV field at the rooftop, as shown in Fig. 6.4. The shown system is consisting of four compact CPV units in which there is one master tracker with three slave trackers. Each CPV unit is also equipped with the proposed solar tracking sensor for CPV, for which the developed prototype is shown in Fig. 6.4. It can be seen that there is a perfect bright spot at the center of photo-sensors array, which verifies the proposed design and configuration. It must be noted that four developed CPV system are also equipped with four different types of CPV concentrating assemblies, refractive and reflective both, to analyze their performance. However, only the performance of Fresnel lens based CPV unit will be discussed here as other systems design are not under the scope of current discussion.

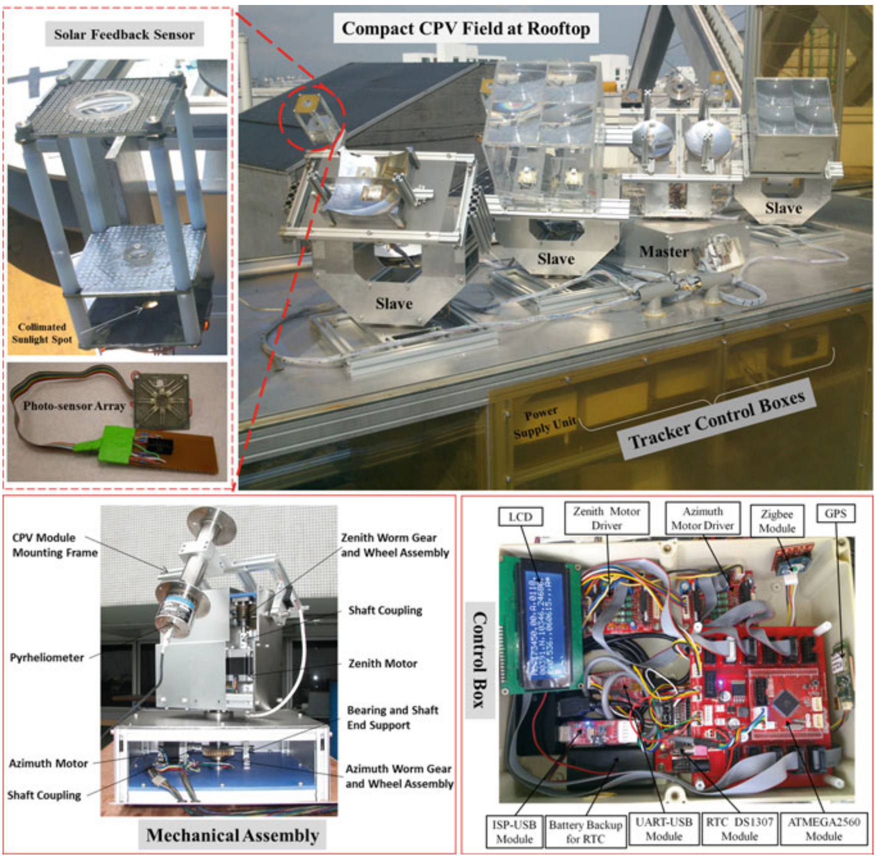

Fig. 6.4 Experimental prototype of compact CPV field for rooftop operation

The Fresnel lens based CPV systems are using primary concentrator as Fresnel lens. The CPV unit consists of two parts: CPV module and solar tracker. The construction of CPV module is such that the incident solar radiations, after being refracted from Fresnel lens, are converged and focused at its focal point which is placed at the inlet aperture of secondary optical element, known as homogenizer. The homogenizer rod further guides and uniformly distributes radiations at its outlet aperture where multi-junction solar cell (MJC) InGaP/InGaAs/Ge is placed. The heat spreader and heat sink are place at the back side of the MJC for heat dissipation during operation so that the cell temperature remain with optimum limits.

The solar tracking unit also consists of two parts: control box and mechanical system. The developed control box of CPV prototype is also shown in Fig. 6.4, based upon Atmega2560 microcontroller. It also contains power supply, Zigbee transceivers, and motor drivers. The mechanical system of solar tracker further consists of two parts; support structure with top frame where CPV module is mounted, and mechanical drive. The mechanical drive is constructed using motors and gear assembly, for physical movement of the solar tracker. The motor receives signal from motor drivers which receive instructions from microcontroller. The gear assembly contains worm gear and wheel. Each of the tracking unit has two gear assemblies, on for each axis tracking, i.e., azimuth and zenith. In the developed prototype of CPV system, the zenith and azimuth gear assemblies have gear ratio of 60 and 40, respectively. However, motor drivers have capability of further reduction of motor step in 16 steps. Therefore, as per the Eq. (6.7), the overall step size of 0.001875° and 0.0028125° can be obtained for zenith and azimuth drives, respectively.

$$\text{Tracker Movement/Step} = \frac{\text{Motor Step}}{\text{Driver Step} \times \text{Gear Ratio}} \tag{6.7}$$

6.4 Field Testing and Analysis

In order to analyze the performance of developed compact CPV unit, in terms of its tracking accuracy and efficiency/power production, an outdoor field operation was conducted at the rooftop of Engineering-EA building of National University of Singapore (NUS), in tropical weather conditions. First of all, the performance of developed solar tracking system was investigated for the whole day operation and the comparison of calculated solar coordinates was made with the solar position data obtained from US Naval Observatory (Astronomical Applications Department of the U.S. Naval Observatory 2015); one of the oldest scientific agency which provides data related to date, time, and position for navigation. Figure 6.5 shows the graphs for error between calculated azimuth and zenith values with the data obtained from US Naval Observatory. The comparison is made for coordinates of 1.229°N latitude and 103.771°E longitude, and date January 1, 2015. From the

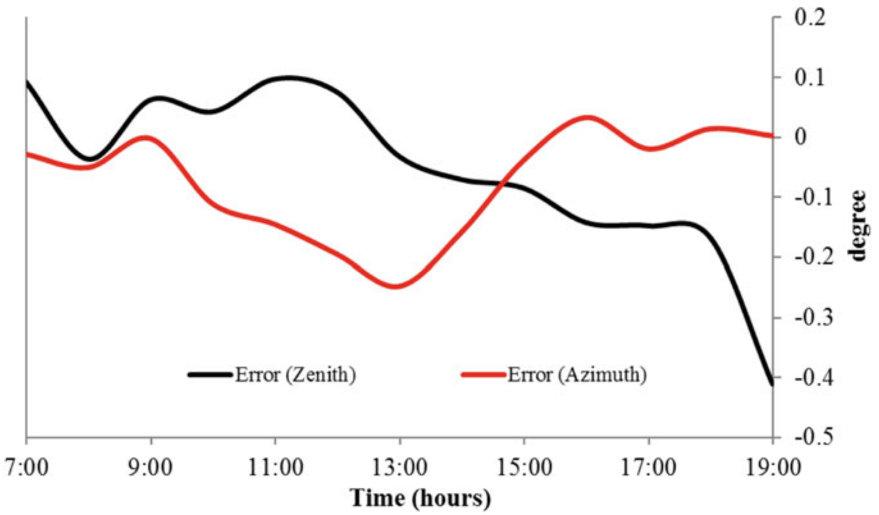

Fig. 6.5 Calculated and actual solar position angles comparison

graph, it can be seen that the graphs of both calculated and obtained values are overlapping. Therefore, from the difference of these position coordinates, it is evident that for most of the time, the tracking error is with ±0.1°. However, maximum error for azimuth and zenith axis are −0.225° and −0.4°, respectively.

To analyze CPV system performance and production, under tropical weather conditions, it was operated under field conditions of Singapore. Figure 6.6 shows

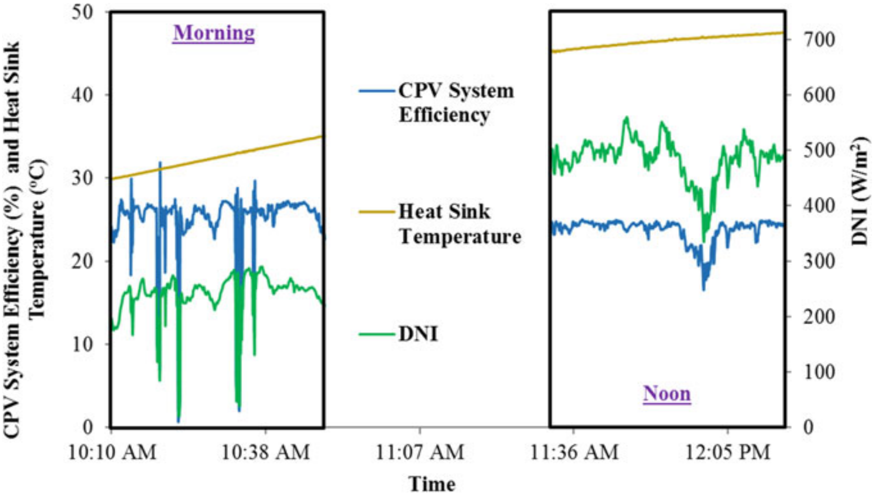

Fig. 6.6 Maximum efficiency curve for CPV module

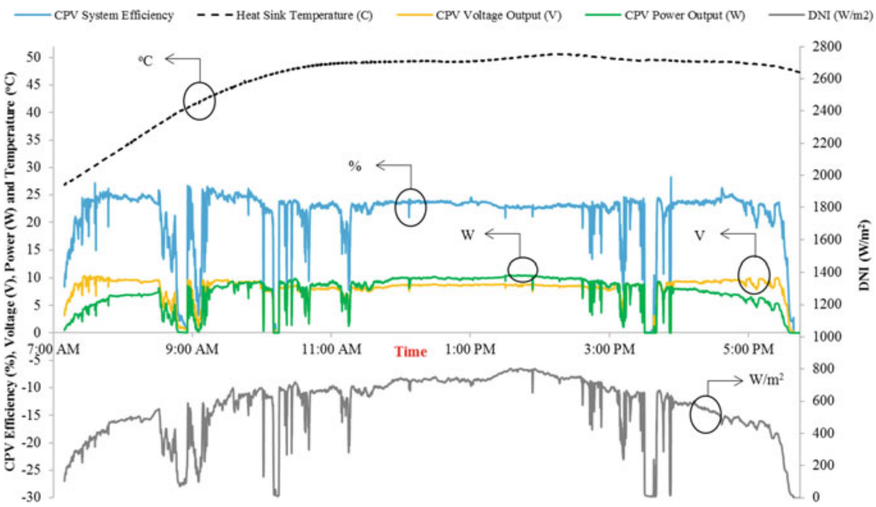

Fig. 6.7 Field performance curves of CPV system

the maximum CPV system efficiency. It can be clearly seen that the maximum efficiency of 28% is recorded during daytime. However, the system efficiency drops to 25–26% during the noon period. To understand such efficiency variations, the system performance curves, for whole day operation are shown in Fig. 6.7. The efficiency value seems to increase with increase in direct normal irradiance (DNI) in the morning. However, when DNI increases further, the efficiency of the system decreases. Such drop in efficiency can be attributed to cell temperature increment which can be predicted from heat sink temperature as shown in Fig. 6.7. With increase in DNI, the concentration at the cell area increases, which also increases the heat loss, causing an increase in cell temperature and decrease in its efficiency. On the other hand, in the afternoon, with drop in DNI, the heat sink temperature also decreases with increase in efficiency. However, after certain drop in DNI, the efficiency also starts to drop as the concentration at cell area decrease. If we look at the power out curve, it varies in proportion to the received DNI.

As mentioned before, the concentrated photovoltaic (CPV) system are normally considered to be feasible in open desert field, from performance point of view, as they only absorb beam radiations. As the main motivation of this study is the development of compact CPV unit which is targeted to be installed on the rooftops of urban regions. Therefore, to analyze the performance of CPV system in tropical weather conditions, the performance of the CPV and different types of conventional PV systems (Monocrystalline of size 6.86 m^2 with efficiency of 17.2% at STC, Polycrystalline of size 19.4 m^2 with efficiency of 16.2% at STC, and Thin Film-CIS of size 21.27 m^2 with efficiency of 17% at STC) were analyzed for one period in terms of their energy output, presented in Fig. 6.8 as kWh/m^2/year (Burhan et al. 2017c). As CPV only absorbs beam radiations while conventional PV can respond to both, diffuse and beam radiations. Therefore, to access their performance

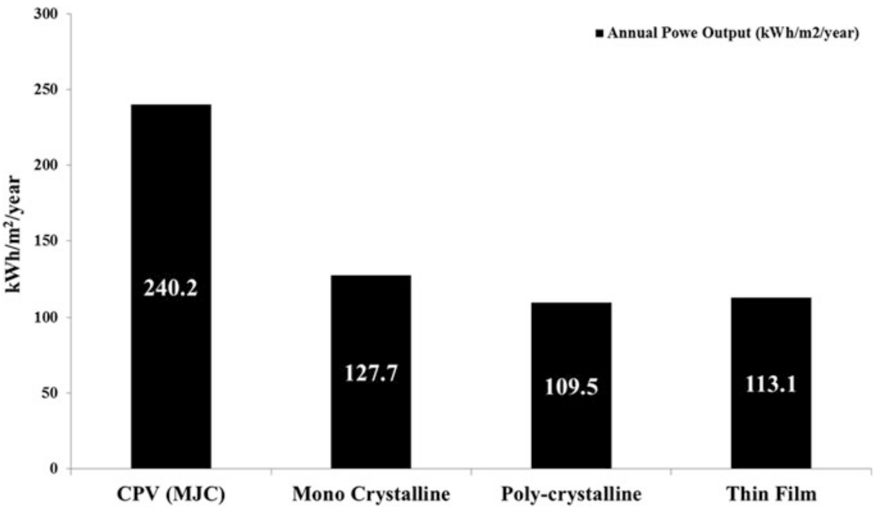

Fig. 6.8 Long-tem energy production potential of photovoltaic systems under tropical weather conditions

feasibility, efficiency is not an appropriate parameter of comparison. At the end, it is the total energy produced, which is supplied to the customer. In such scenario, energy output is the true performance indicator which is used here. The long-term energy output of all types of photovoltaic systems is analyzed under conditions of Singapore, as shown in Fig. 6.8. It can be seen that the energy output of photovoltaic system is almost two times higher than the conventional PV. Such double production is observed in weather conditions where only 66% of total received solar energy was in form of beam radiations. It shows that CPV not only has great production potential in desert field but it is also feasible to be installed in urban region, which justifies the concept of compact CPV for rooftop operation as discussed in this chapter.

6.5 Summary of Chapter

Despite highest energy efficiency, third-generation multi-junction solar cells are still unable to make significant in the photovoltaic market. Their cost-effective use in the form of concentrated photovoltaic (CPV) is also unable to boost their market share due to limited market and customers of current gigantic CPV units. A novel design of compact CPV system is developed and discussed for efficient and cost-effective rooftop operation of MJC, in urban region. By keeping in mind the need of large number of solar trackers, a master–slave control technique is proposed for cost-effective operation compact CPV field tracking. Moreover, to ensure high accuracy need of CPV tracking unit, a solar tracking sensor which is optically sensitive, is designed, analyzed, developed, and tested for field operation. The proposed sensor is a unique design of its own type with fraction of the cost of commercial unit. The proposed design made it possible to have high accurate two-axis solar tracking with extreme low cost. The simple construction and algorithm of compact CPV will boost its customers and share in photovoltaic market. Moreover, the double energy production of CPV system, even in tropical weather, will also negate the general perspective that CPV system is only feasible to operate in open desert conditions.

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