Improvement of Pv Systems Power Output Using Sun-Tracking Techniques

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ABSTRACT

The amount of power produced by a photovoltaic (PV) or solar panel depends on the amount of sunlight to which it is exposed. As the sun's position changes throughout the day, the PV panel must be adjusted so that it is always aimed directly at the sun and, as a result, produces the maximum possible power. A sun-tracking system tracks the motion of the sun across the sky and moves the PV panel to face directly at the sun and thereby ensuring that maximum amount of sunlight strikes the panel throughout the day. Sun-tracked PV systems are more efficient than fixed PV systems and are capable of enhancing productivity. In this paper different types of sun-tracking systems are reviewed and their energy gains are discussed.

KEYWORDS: Solar energy, PV systems, Sun-trackers, Maximum power, Environment

I. INTRODUCTION

The increasing demand for energy, the continuous reduction in existing sources of fossil fuels and the growing concern regarding environment pollution, have pushed mankind to explore new technologies for the production of electrical energy using renewable sources, such as solar energy, wind energy, etc. Among the renewable energy sources solar energy affords great potential for conversion into electric power, able to ensure an important part of the electrical energy needs of the planet [1].The sun is regarded as a good source of energy for its consistency and cleanliness, unlike other kinds of energy such as coal, oil, and derivations of oil that pollute the atmosphere and the environment. Most scientists, because of the abundance of sunshine capable of satisfying our energy needs in the years ahead, emphasize the importance of solar energy. It is clean, renewable, and plentiful throughout the world. In addition, energy needs and costs have increased in recent years and nature continues to suffer damage during energy production [1].Solar photovoltaic (PV) technology is a very attractive renewable energy option for clean energy generation, but has limited use due to its high cost. The cost has slightly increased in recent years to a point that is still quite high compared to the cost of other conventional power generation technologies, as well as non-conventional technology such as wind energy technology [2]. The power generated by a PV system is highly dependent on weather conditions. During cloudy periods and at night, a PV system would not generate any significant power. Concepts related to the solar energy have constantly been under heavy research and development. The amount of power produced by a solar system depends on the amount of sunlight to which it is exposed. As the sun's position changes throughout the day, the solar system must be adjusted so that it is always aimed precisely at the sun and, as a result, produces the maximum possible power. In order to ensure maximum power output from PV cells, the sunlight's angle of incidence needs to be constantly perpendicular to the solar panel[2]. This requires constant tracking of the sun's apparent daytime motion, and hence develops an automated sun tracking system which carries the solar panel and positions it in such a way that direct sunlight is always focused on the PV cells. A tracking mechanism must be reliable and able to follow the sun with a certain degree of accuracy, return the collector to its original position at the end of the day or during the night, and also track during periods of cloud cover. Regarding movement capability, two main types of sun trackers exist[2]:

- One axis trackers,
- Two axes trackers

Single-axis-tracking systems are considerably cheaper and easier to construct, but their efficiency is lower than that of two axes sun-tracking systems. Since PV power output is always non-linear in shape, there is the need to maximize the power that is being transferred to the load. High efficiency can be achieved by controlling the PV unit to operate at its maximum power extraction. In automatic sun tracker systems, the solar panels are made to track the movement of the sun. Hence, a tracking mechanism (mechanical device) that requires constant tracking of the sun's apparent daytime motion, and hence develops an automated sun tracking system which carries the solar panel and positions it in such a way that direct sunlight is always focused on the PV cells for maximum efficiency. A comparison between fixed and sun-tracked solar stills shows that sun-tracking increases productivity by over 32% [3]. For increasing sun power generation efficiency, the techniques of sun-tracking have been surveyed for maximizing solar system output.

The PV Solar Cell

Covering 0.16% of the land on earth with 10% efficient solar conversion systems would provide 20 TW of power, nearly twice the world's consumption rate of fossil energy [4]. Directly converting sunlight to electricity is accomplished via PV solar cells. The birth of the modern era of PV solar cells occurred in 1954, when D. Chapin, C. Fuller, and G. Pearson at Bell Labs demonstrated solar cells based on p–n junctions in single Silicon crystals with efficiencies of 5–6% [4]. Peak watt (Wp) rating is the power produced by a solar module illuminated under the standard conditions; 1000 W/m^2 solar intensity, at 25^0C ambient temperature, and a spectrum related to sunlight passing through the atmosphere when the sun is at a 42^o elevation from the horizon. Because of day/night and time-of-day variations in insolation and cloud cover, the average electrical power produced by a solar cell over a year is about 20% of its Wp rating [5].

Astronomy

The earth revolves around the sun in an elliptical orbit with the sun as one of the foci. The plane of this orbit is called the ecliptic. The time taken for the earth to complete this orbit defines a year. The relative position of the sun and earth is conveniently represented by means of the celestial sphere around the earth. The equatorial plane intersects the celestial sphere in the celestial equator, and the polar axis in the celestial poles. The earth motion round the sun is then pictured by apparent motion of the sun in the elliptic which is tilted at 23.45^o with respect to the celestial equator. The angle between the line joining the centers of the sun and the earth and its projection on the equatorial plane is called the solar declination angle (δ). This angle is zero at the venal (20/21 march) and autumnal (22/23 September) positions [6]. Calculating the sun's approximate path requires one to first find the declination. The declination is the angle of deviation of the sun from directly above the equator. Reference [6], evaluated a plot of declination(deg) versus day of the year for a geographical area with Latitude 10^o N (Precisely, the University of Nigeria, Nsukka). The declination angle is computed with the formula.

$$\delta(d) = 23.45\,\deg(\sin)\left[\left(\frac{360}{365}\right)(d-81)\,deg\right] \qquad 2.1$$

The plot is shown below in fig.2.1.

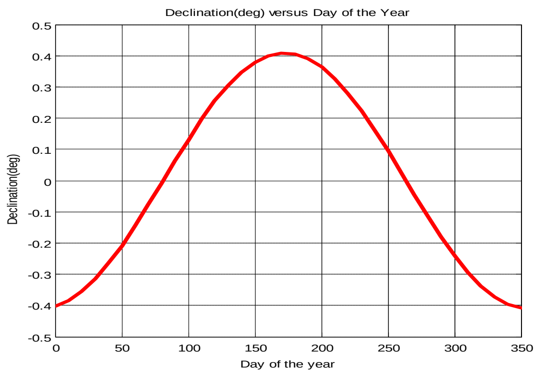

Fig:2.1 : Declination (deg) verses Day of the year[6]

Positive angles from Fig: 2.1 are considered north of the equator and negative angles are considered south of the equator. These results are only approximate, however, since the year is not exactly 365 days long.

The earth itself rotates at the rate of one revolution per day around the polar axis. The daily rotation of the earth is depicted by the rotation of the celestial sphere about the polar axis, and the instantaneous position of the sun is described by the hour angle (ω), the angle between the meridian passing through the sun and the meridian of the site. The hour angle is zero at solar noon and increases toward the east. For observers on the earth's surface at a location with geographical latitude (φ), a convenient coordinate system is defined by a vertical line at the site which intersects the celestial sphere in two points, the zenith and the nadir, and subtends the angle φ with the polar axis (Fig. 2.2). The great circle perpendicular to the vertical axis is the horizon [7].

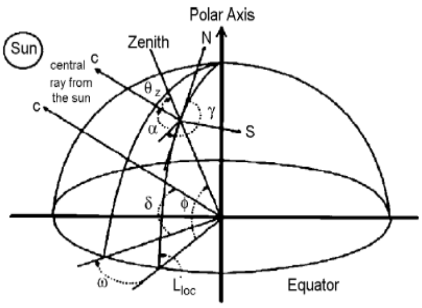

Fig 2.2. Schematic representation of the solar angles [7]

The latitude (φ) of a point or location is the angle made by the radial line joining the location to the center of the earth with the projection of the line on the equatorial plane. The earth's axis of rotation intersects the earth's surface at 90^o latitude (North Pole) and -90^o latitude (South Pole). Any location on the surface of the earth then can be defined by the intersection of a longitude angle and a latitude angle. The solar altitude angle (α) is defined as the vertical angle between the projection of sun's rays on the horizontal plane and direction of sun's rays passing through the point, as shown in Fig. 1. As an alternative, the sun's altitude may be described in terms of the solar zenith angle (θ_z) which is a vertical angle between sun's rays and a line perpendicular to the horizontal plane through the point

$$(\theta_z = 90 - \alpha) \tag{2.2}$$

Solar azimuth angle (γ) is the horizontal angle measured from south (in the northern hemisphere) to the horizontal projection of the sun's rays [7].

Radiation on Inclined and Tracking Surfaces

The solar radiation data are usually given in the form of global radiation on a horizontal surface and PV panels are usually positioned at an angle to the horizontal plane; therefore, the energy input to the PV system must be calculated accordingly. The calculation proceeds in three steps. In the first step, the data for the site are used to determine the diffuse and beam components of the global irradiation on the horizontal plane. This is carried out by using the extra-terrestrial daily irradiation, B_0 as a reference and calculating the ratio $K_T = G/B_0$, known as the clearness index where G is the daily global irradiation on a horizontal plane (usually the monthly mean), and K_T describes the average attenuation of solar radiation by the atmosphere at a given site during a given month. In the second step, the diffuse irradiation is obtained using the empirical rule that the diffuse fraction D/G of the global radiation is a universal function of the clearness index K_T (D is the monthly mean daily diffuse irradiation on a horizontal plane in W/m2). Since B = G - D, this procedure determines both the diffuse and beam irradiation on the horizontal plane (B is daily beam irradiation on a horizontal plane). In the third step, the appropriate angular dependence of each component is used to determine the diffuse and beam irradiation on the inclined surface. With allowance for the reflectivity of the surrounding area, the albedo can also be determined. The total daily irradiation on the inclined surface is then obtained by adding the three components [7]. Sun is moving across the sky during the day. In the case of fixed solar collectors, the projection of the collector area on the plane, which is perpendicular to the radiation direction, is given by function cosine of the angle of incidence (Fig. 2.3).

The higher the angle of incidence θ, the lower is the power. Theoretical calculation of the extracted energy in case of using tracking collectors is carried out by assuming that the maximum radiation intensity I = 1100Wm^{-2} is falling on the area which is oriented perpendicularly to the direction of radiation.

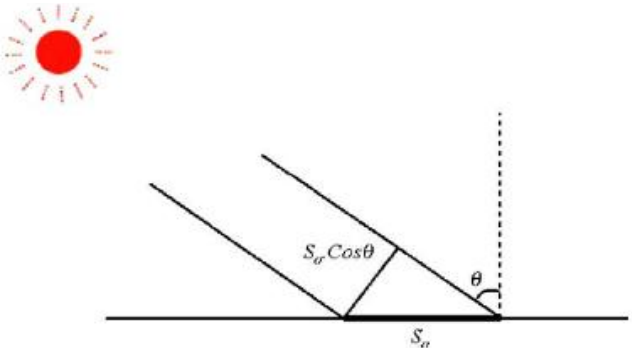

Fig. 2.3 Angle of incidence θ of the solar radiation [7].

Taking the day length t = 12, h = 43,200 s, intensity of the tracking collector which is always optimally oriented facing the sun is compared to that of a fixed collector which is oriented perpendicularly to the direction of radiation only at noon. The sun rays reaching the earth surface go through the thick layer of atmosphere. As we deviate from the noon, the solar insolation on the surface is weakened.

Fig. 2.4 shows the dependence of the energy lost on the maximum tracking angle in comparison to that of an ideal tracking.

It is clear that in tracking angles beyond +/-60^o no considerable energy gain is obtained.

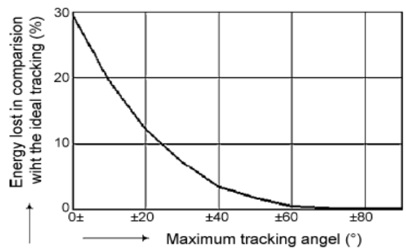

Fig.2.4 Energy lost in dependence of the maximum tracking angle in comparison with the ideal tracking [7].

Oladiran[8] assessed the mean global radiation captured by flat surfaces inclined at f-10^o, f, and f+10^o (f as latitude), while tilting the surface from 0^o to 75^o at 15^{o}intervals azimuthally for three zones in Nigeria. The mean total solar flux captured by three collector inclinations and six surface azimuth angles was calculated theoretically and a computer program was written. For graphic presentation, a data file was created for each run of the program. The total radiation per day of year, the mean monthly radiation and mean annual radiation for three zones were evaluated. Oladiran concluded that for all azimuth angles, an inclination angle equal to f produces the best all-year-round performance.

II. SUN-TRACKERS

Solar tracking can be implemented by using one-axis, and for higher accuracy, two-axis sun-tracking systems. For a two-axis sun-tracking system, two types are known as: polar (equatorial) tracking and azimuth/elevation (altitude–azimuth) tracking. The solar tracker, a device that keeps PV or photo-thermal panels in an optimum position perpendicular to the solar radiation during daylight hours, increases the collected energy. The first tracker introduced by Finster in 1962, was completely mechanical. One year later, Saavedra presented a mechanism with an automatic electronic control, which was used to orient an Eppleypyrheliometer [9]. Trackers need not point directly at the sun to be effective. If the aim is off by 10^o, the output is still 98.5% of that of the full-tracking maximum. In the cloudiest, haziest locations the gain in annual output from trackers can be in the low 20% range. In a generally good area, annual gains between 30 and 40% are typical. The gain in any given day may vary from almost zero to nearly 100% [10].

The presence of a solar tracker is not essential for the operation of a solar panel, but without it, performance is reduced. Although solar trackers can boost energy gain of PV arrays, in their installation some problems such as cost, reliability, energy consumption, maintenance and performance must be considered.

All tracking systems have all/some of the following characteristics

- Single column structure or of parallel console type.
- One or two moving motors.
- Light sensing device.
- Autonomous or auxiliary energy supply.
- Light following or moving according to the calendar.
- Continuous or step-wise movement.
- Tracking all year or all year except winter.
- Orientation adjustment with/without the tilt angle adjustment.

Several methods of sun following have been surveyed and evaluated to keep the solar panels, solar concentrators, telescopes or other solar systems perpendicular to the sun beam. An ideal tracker would allow the PV cell to accurately point towards the sun, compensating for both changes in the altitude angle of the sun (throughout the day), latitudinal offset of the sun (during seasonal changes) and changes in azimuth angle. Sun-tracking methods are usually classified into three categories: methods of tracker mount, methods of drives, and methods of control [11].

Methods of Tracker Mount

Single Axis Solar Trackers

Single axis solar trackers can either have a horizontal or a vertical axle. The horizontal type is used in tropical regions where the sun gets very high at noon, but the days are short. The vertical type is used in high latitudes where the sun does not get very high, but summer days can be very long. The single axis tracking system is the simplest and most commonly used.

Double Axis Solar Trackers

Double axis solar trackers have both a horizontal and a vertical axle and so can track the Sun's apparent motion exactly anywhere in the World. This type of system is used to control astronomical telescopes, and so there is plenty of software available to automatically predict and track the motion of the sun across the sky. The dual axis tracking system is also used for concentrating a solar reflector toward the concentrator on heliostat systems.

3.2 Methods Of Drive

Active Trackers

Active Trackers use motors and gear trains to direct the tracker as commanded by a controller responding to the solar direction. Light-sensing trackers typically have two photo-sensors, such as photodiodes, configured differentially so that they output a null when receiving the same light flux. Mechanically, they should be omnidirectional (i.e. flat) and are aimed 90 degrees apart. This will cause the steepest part of their cosine transfer functions to balance at the steepest part, which translates into maximum sensitivity.

Passive Trackers

Passive Trackers use a low boiling point compressed gas fluid that is driven to one side or the other (by solar heat creating gas pressure) to cause the tracker to move in response to an imbalance.

Chronological Tracker

Chronological Tracker counteracts the earth's rotation by turning at an equal rate as the earth, but in the opposite direction. Actually the rates are not quite equal, because as the earth goes around the sun, the position of the sun changes with respect to the earth by 360° every year or 365.24 days.

Methods Of Control

Closed-loop Types of Sun Tracking Systems

Closed-loop types of sun tracking systems are based on feedback control principles. In these systems, a number of inputs are transferred to a controller from sensors which detect relevant parameters induced by the sun, manipulated in the controller and then yield outputs (i.e. sensor-based).

Open-loop Types of Sun Tracking Systems

An open-loop type of controller computes its input into a system using only the current state and the algorithm of the system and without using feedback to determine if its input has achieved the desired goal (i.e. algorithm-based). The system is simpler and cheaper than the closed-loop type of sun-tracking systems. It does not observe the output of the processes that it is controlling. Consequently, an open-loop system cannot correct any errors so that it could make and may not compensate for disturbances in the system.

III. ENERGY GAIN IN TRACKING SYSTEMS

In 1986, Akhmedyarov *et al*. [12] first increased the output power of a solar photoelectric station in Kazakhstan from 357W to 500W by integrating the station with an automatic sun tracking system. Several years later, Maish [13] developed a control system called Solar Tracker to provide sun tracking, night and emergency storage, communication, and manual drive control functions for one and two axis solar trackers in a low-cost, user-friendly package. The control algorithm used a six-degree self alignment routine and a self-adjusting motor actuation time in order to improve both the pointing accuracy and the system reliability. The experimental results showed that the control system enabled a full-day pointing accuracy of better than +/-0.1^o to be achieved Khalifa and Al-Mutawalli [14], developed a two-axis sun tracking system to enhance the thermal performance of a compound parabolic concentrator. The system was designed to track the sun's position every three to four minutes in the horizontal plane and every four to five minutes in the vertical plane. The tracking system was comprised of two identical sub-systems, one for each axis, with each sub-system consisting of two adjacent photo-transistors separated by a partition of a certain height. In the tracking operation, the difference in the voltage signals of the two photo-transistors was amplified and used as a command signal to drive the collector around the corresponding axis until the voltage difference reduced to zero, indicating that the sun's rays were once again normal to the collector surface. It was shown that the tracking system had a power consumption of just 0.5Whr and yielded an improvement of around 75% in the collected solar energy, compared to a fixed collector of equivalent dimensions.Mumba [15], developed a manual solar tracking system for a PV powered grain drier working in two positions. A 12 V, 0.42 A, DC suction fan powered with PV was placed in the air inlet. To improve collector module efficiency, the sun was tracked +/-30^o from the horizontal. Mumba investigated the performance under four cases: PV fan-off without sun-tracking, PV fan-on without sun-tracking, PV fan-off with sun-tracking and PV fan-on with sun-tracking. In the sun tracking cases the collector module angled manually eastward at 8.00 a.m. and westward at 2.00 p.m. while the collector module was tilted 15^o from the horizontal to match the sun's elevation. It was concluded that from uniform air temperature point of view, the fan-on sun-tracking case was the best, giving a temperature of 60^{o}C. From uniform energy gain point of view, the sun-tracking cases performed superior to that of non-tracking ones. It was concluded that a solar air heater with manual sun-tracking facility can improve the thermal efficiency up to 80%.

Abdallah [16] investigated the respective effects of four different electro-mechanical sun-tracking systems on the current, voltage and power characteristics of a flat-plate photovoltaic system. The results showed that tracking systems comprising two axes, one vertical axis, one east-west axis and one north-south axis, and one north-south axis, increased the electrical output powers of the photovoltaic system by around 43.87%, 37.53%, 34.43% and 15.69%, respectively, compared to that obtained from a photovoltaic system with a fixed surface inclined at 32^o. Helwa [17], compared the stationary and tracking PV systems to assess the power consumption of tracking systems and the effect of tracking accuracy on the system output. The compared systems were: a fixed system tilted 40^o horizontally, one vertical axis tracker (using time, date and site parameters for control), a 6^o tilted axis parallel to the N–S direction (using time, date and site parameters for control) and two-axis azimuth/elevation tracker (controlled by microprocessor taking commands from a PC).Several revolution count sensor and limit switches were used. The comparison curves among different solar tracking systems showed that the increase in annual radiation gain from the two axis tracker, vertical axis tracker and tilt axis tracker over the fixed tilt system was 30%, 18% and 11%, respectively. The power consumption due to microprocessors, electric equipment, sensors, electrical switching and driving motors for tilted-axis tracker were50Wh/day and 22Wh/day when the tracking error were +/-0.56^{o}and +/-10$_o$, respectively . Chicco [18] experimentally assessed the production of the PV plants in the sun-tracking and fixed modes in three different sites. In the first site, 15 individual systems controlled by one coordinate tracking system were compared with a 0^o azimuth and 36^{o}elevation angles as fixed cases. In the second site, 90 individual systems with separate coordinate-controlled tracking were compared with 0^o azimuth and 30^o elevation fixed system. For the third site, the position of the sun-tracking system was being updated every 15 min and the fixed system maintained at a tilt angle of 30^o with 35^o elevation angle.

The results showed that the average improvement, using the sun-tracking system, was 32.9and 35.1% from the simulated values and 37.7 and 30.4% from the actual data for the first and second sites, respectively. For the third site, an annual improvement of 31.5% for the sun-tracking system was obtained. Nann evaluated the potentials for tracking systems relative to the cost and irradiance received from a fixed (40^{o}) system. It was mentioned although the fraction of direct normal irradiance on a surface normal to the sun was 54% greater than that of the fixed one, the surplus of irradiance received by one-axis tracking and two-axis tracking systems were 34% and 38%, respectively and at today's module costs, tracking the sun can improve the cost effectiveness of the PV plant by up to 20%. The comparison between three stationary, one-axis and two-axis tracking systems showed that irradiation received by one-axis tracker is nearly as the same as the two axis trackers; however its tracker cost is approximately half of that of the two-axis one [19].Gay, compared daily and annual energy-delivery performance for large-scale fixed-array and two-axis tracking photovoltaic generating systems and site sensitivities were also discussed. For the studied site, it was observed that a fixed-array system would use about 40% more modules than a two-axis tracking system, for equal annual energy collection [20].

Nafeh evaluated the optimum tilt of PV arrays by using maximum global insolation technique. Theoretically, he calculated the global insolation at solar noon, incident on an inclined PV array with a predefined tilt angle and simulated the case by MATLAB-SIMULINK to calculate the optimum tilt angle for every day, month or year. Comparison curves for daily adjusted tilt angle and insolation between proposed technique and the conventional technique were given. He concluded that if the tilt angle is daily or monthly adjusted to its optimal value, then the global insolation collected at solar noon using the proposed technique will be larger than that collected at solar noon using the conventional technique over all days of the year. It was found that to obtain maximum solar insolation, using both the latitude of the site and the sun declination is necessary to orient the PV arrays [21].Tomson [22] analyzed the performance of the two-positional control of single stand-alone flat plate concentrator. The collector was rotated around its single tilted axis twice per day with predefined deflections. The effect of different tilt angles, initial tilt angle, initial azimuth, and azimuth angle of the deflected plane were evaluated on the daily and seasonal gain. The comparison of simulation and experimental results indicated that using a simple tracking drive with low energy input for a brief daily movement, increased the seasonal energy yield by 10–20% comparing to that of a fixed south facing collector tilted at an optimal angle.

Kalogirou designed and constructed a one-axis sun-tracking system consisting of a control system with three light dependent resistor sensors and a DC motor. One sensor was responsible for direct beam detection; the second was cloud sensor and the third was daylight sensor. The control system consisted of relay, timer, many resistors and electronic parts. When any of the three sensors was shaded, the motor was switched on. The system tracked the sun in E–W direction and the final rotational speed of the collector was 0.011 rpm. Various tests of the solar collector showed that the tracking mechanism was very accurate. The accuracy for $100Wm^{-2}$ illumination was 0.2^{o} while for 600 m^{-2} illumination it was reduced to 0.05^{o} [23].Ai et al. proposed and compared the azimuth and hour angle three-step trackers. The day length on the south facing slope was divided into three equal parts in order to adjust the tilt angle. The sum of the direct radiation received in each time interval and the sky diffusion and ground reflection radiation during a day were considered to derive the mathematical formula for the three-step tracking system to estimate the daily radiation on planes. They concluded that for the whole year, the radiation on the slope with optimized tilt angle was 30.2% and that for the two-axis azimuth three-step tracking was 72% higher than that on the horizontal surface. No significant difference was found between one-axis azimuth three-step tracking and hour angle three-step tracking power [24].

Lorenzo et al. designed a single vertical axis (azimuth axis) PV tracker and evaluated backtracking features. Each of 400 trackers installed in Spain used a 0.25 hp standard AC motor. The tilt angle of the PV surfaces remained constant. They mentioned that the energy collected by an ideal azimuth tracker was about 40% higher than that corresponding to an optimally tilted static surface and 10% higher than that of horizontal axis tracking. They calculated the E–W and N–S shadowing between two adjacent trackers occurred in the morning or afternoon. They recommended that when shadowing occurs, it can be avoided by moving the surface's azimuth angle away from its ideal value, just enough to get the shadow borderline to pass through the corner of the adjacent surface (backtracking). Their comparison showed that the azimuth tracking land was 40% greater than static surface while the corresponding energy cost can be significantly reduced [25].Ibrahim constructed an electronically one-axis concentrating collector with an electric motor for forced circulation. The collector was hinged at two points for its tilt adjustment with a tightening screw to continuously track the sun from east to west through a range of 180^{o}.

The collector efficiency was measured for different values of mass flow rates. It was concluded that the collector efficiency increases (reaching the maximum value of 62%) as the mass flow rate increases [26].Brunatte et al. investigated a two-stage concentrator with one axis tracking system around a polar N–S axis. The half rim angle of the first concentrating stage was chosen to be equal to the sun's maximum declination of 23.5^{o}. They tested the system for various conditions and theoretically calculated the concentration factor for E–W and N–S tracking. They concluded that thermodynamically, concentration factor increases by a factor of three. For the first prototype, concentration optical efficiency of 77.5% was measured at normal incidence [27]. Clifford et al. presented a novel passive solar tracker modelled with computer. They mentioned that although the expanding metals generated deflections were small, the corresponding forces were large. Their passive solar tracker design incorporates two bimetallic strips made of aluminium and steel, positioned on a wooden frame, symmetrically on either side of a central horizontal axis. The bimetallic strips are shaded so that the strip further from the sun absorbs solar radiation while the other strip remains shaded in a similar fashion to the design illustrated in Fig.4.1 [28].

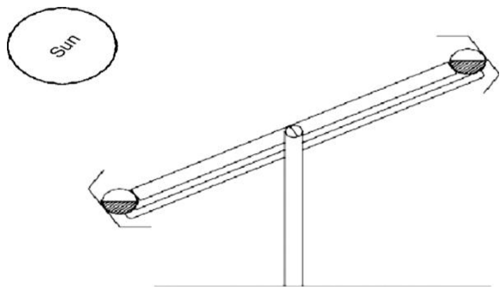

Fig.4.1 A passive solar tracker using two identical cylindrical tubes filled with a fluid under partial pressure [28]

To prevent oscillation or too sluggish respond, a damping system is linked to the sun tracker. They compared the computer model and experimental results of deflections of the bimetallic strip due to the effects of thermal radiation (in mm) and time taken for the solar tracker to reorient from W–E (in s). The computer model and experimental data showed results very similar to each other. The designed solar tracker had the potential to increase solar panel efficiency by up to 23%. Finally, they recommended night return mechanism, manually tilted axis and dual axis system for future development. Al-Mohamad designed a single-axis sun-tracking system based on a programmable logic controlling (PLC) unit to investigate the improvement in the daily output power of a photo-voltaic module. Two photo-resistive sensors were separated by a barrier to provide shadow for one of them. As solar radiation intensity increases the resistivity of the sensor decreases. Two output signals of the unit are connected directly to the analogue inputs of the PLC and compared in order to produce a proper output signal to activate an electromechanical sun-tracking system. The tracker scans through an angle of about 120^{o} E–W. For PLC, a proper program to control, monitor and to collect data was developed using special software. A special computer program for automatic detection and PC communication with RS232 was developed using Visual Basic 5. The performance of the sun-tracker was evaluated and monitored. The output power showed a considerable increase during the early and late hours of the day. In fact, the overall improvement, in the tracking mode, exceeded 40% for the period from 6:00 to 10:00 a.m. and for the period from 15:00 to 17:00 p.m. However, the improvement was about 2–4% during mid-day. The average overall improvement during the whole day was better than 20% in comparison with that of a fixed module [29].

Abu-Khader et al. designed and constructed a PLC-controlled solar tracker system. The electromechanical system consisted of two drivers: the first for the joint rotating about the vertical axis and the second for the N–S or E–W tracking. Two bridges rectified a 220 VAC of supply network into 24 VDC to power the PLCI and into 24 VAC to supply the power for one of the electrical motors. The voltage of the second motor was 36 VDC with a worm gear while for the other motor a spur gear was used. The estimated consumed power by the electrical motor and control system was less than 3% of the collected energy by the tracking system. The PLC programming was based on the solar angles analysis divided into four intervals with corresponding motor speeds. Measurements on the PV system with and without sun-tracking showed that there was an overall increase of about 30–45% in the output power for the N–S tracking system compared to that of the fixed PV system. The optimum PV-tracking axis was the N–S that corresponded to the maximum possible power [30].

Girasolar company designed and constructed a programmable sun-tracker that can track the sun in two axes: azimuthal and zenithal. Its surface area was 58 m^2 with 2100 kg weight capable of turning with azimuthal speed of 0.5 rpm and azimuthal movement (pitch) speed of 0.06 rpm. Maximum angle of deviation was 2^o from sun position. Its structure was designed to withstand wind velocity up to 105 km/h. It has been reported that its production growth is of up to 35% over fixed installations [31].Contreras et al. in Texas University constructed a portable solar tracker using three linked robotic arm controlled microcontrollers. Its major components were PIC microcontroller, H-bridges, DC motors, PVC custom parts, IR sensor, photo-resistor and DC outlets. The first DC motor was a 10 A, 12 V, with 500:1 gear ratio, the second motor was 75 mA, 24 V, with 3000:1 gear ratio and the third motor with 220 mA (under load), 12 V and 1000:1 gear ratio. They programmed three microcontrollers using programming language PIC Basic PRO. It was concluded that the efficiency was increased by 30% [32].

Rosell et al. designed and built a PV/thermal low concentrating system and validated the developed analytical model. A two-axis sun-tracking system with two DC linear actuator and reed sensors was constructed to maximize the energy collection. In their system, mirrors reflect light onto the focal band and the solar cells are illuminated with approximately 11.1 times the solar irradiance incident beam. To obtain greater accuracy and to compute the sun position, a PLC system was designed and constructed. They quoted a 50% energy increase in comparison to that of an optimally tilted static surface [33]. Hamilton, in his thesis designed and constructed a microcontroller based sun-tracking device that used two motors to tilt the array in two planes of movement. The algorithm was designed to read and amplify sensor values and then to compare the data digitally to determine the exact position of the sun to activate the positioning uni-polar stepper motors. The sensor was a four sided pyramid in structure with solar cells mounted on each side. The microcontroller was programmed in C language. The device was tested both in the field and in the laboratory using a portable light source that was set up at 16 positions inside of a spherical area. The results showed that the sun-tracking system collected maximum energy throughout the day while stationary system collected maximum energy just when the sun was positioned overhead [34].

Huang et al. designed and evaluated a one-axis tracking mechanism for adjusting the PV position only at three fixed angles (three position tracking): morning, noon and afternoon. The mechanism includes a single pole support, a tilt adjustable platform, a PV frame driven by a motor and a solar position sensor. The sun position sensor consists of two photo-sensing elements divided by a vertical shading plate. Three touch switches were mounted on the transmission gear of the frame to signal the control circuit. The PV frame stops at the touch of the next switch once it is triggered. The designated location of the switch, thus, determines the stopping angle. Many analytical studies show that the maximum solar incident radiation can be obtained if the tilted surface angle approximately equals the latitude. For each stopping angle, they calculated the yearly total energy at various switching angles of the sensor and found the maximum yearly total energy. The results showed that the optimal stopping angle was 50^o, and the optimal switching angle was 25^o, which was half of the stopping angle. By repeating the calculation for different solar noon tilt angles at different latitudes, it was concluded that the optimal stopping angle was about 508 regardless of the latitude, and the optimal switching angle was half of the stopping angle. It can be shown from the results of the calculated yearly total energy that the PV power generation will increase by 24.5% as compared to that of a fixed PV module [35].Kalogirou designed and constructed a one-axis sun-tracking system consisting of a control system with three light dependent resistor sensors and a DC motor. One sensor was responsible for direct beam detection; the second was cloud sensor and the third was daylight sensor. The control system consisted of relay, timer, many resistors and electronic parts. When any of the three sensors was shaded, the motor was switched on. The system tracked the sun in E–W direction and the final rotational speed of the collector was 0.011 rpm. Various tests of the solar collector showed that the tracking mechanism was very accurate. The accuracy for $100Wm^{-2}$ illumination was 0.2^o while for $600Wm^{-2}$ illumination it was reduced to 0.05^o [36].

Khalifa et al. investigated the performance improvement of a two-axis sun-tracking compound parabolic concentrator. The system consisted of photo-transistors separated by a partition from one another. When two sensors are unequal, the voltage difference amplifier activates a DC motor. The system tracks the sun every three to four minuets in horizontal plane and every four to five minuets in the vertical plane (depending on the height of partition). The tracking system power consumption was 0.5 Wh. To investigate the effect of two-axis tracking on the collector performance a number of tests were carried out. During these tests, the fixed collector was oriented due south at a tilt angle of 33^o. It was concluded that a two-axis tracking system may increase the energy gain of a compound parabolic concentrator collector by up to 75% [37].

Canada et al. designed and constructed a sun-tracker with a maximum positional error of 28, for the measurement of global and direct spectral solar irradiance in the 330–1100 nm range. They designed a sun-tracker according to their specific needs and for a relatively low cost allowing up to 1 week work without the need for any operator supervision and returning each night to a rest position avoiding turning back over itself. The movement of the whole system is commanded by a step motor and gear speed reducer to adjust the step required. The system had 2^{o} of freedom, one rotation in the azimuth plane over a fixed base, and the other rotation in the principal solar plane. The pass motor control is carried out by a control board that was specially designed for this type of motor, including a compatible interface that is connected to the parallel port of the PC through optical couplers. This configuration was to give the system a reference point from which to correctly position itself. Two on/off sensors indicating the initial position for each of the degrees of freedom were used. These are optical pass detectors made of an LED and a photo-detector working in the infrared zone. To cut out the sensors at the desired position, fixed aluminium reference points are used to identify the geographic north and the zero solar elevation. All codes were written in C++ Builder under Windows environment to: (a) provide movement relative to the sun, (b) control motor, (c) adjust and return to the rest position, and (d) alarm and activate/deactivate sensors. From these data, by using a subtractive method, the diffuse irradiance on a horizontal plane is calculated. Finally, using the Bouguer–Lambert–Beer law, the algorithm calculates total atmospheric thickness and aerosol optical depth in the 330–1100 nm range [38].

Gagliano et al. designed and simulated a two-axis sun-tracking system based on a photo-resistor sensor and investigated the effects of energy gain between a fixed PV panel and a tracked one. The sensing device consisted of a nine light-dependent resistor (LDRs) for rotation, and three aligned LDRs for inclination, positioned into suitable plastic supports. It was concluded that the main advantage of the proposed tracking system was the low cost of the sensing apparatus, gained from a real time elaboration procedure on sensors data [39].Auxiliary solar cells (panels) connected directly to a permanent magnet DC motor are fixed to a rotary axle of the tracker and can both sense and provide energy for tracking. Poulek et al. described a very simple, reliable solar tracker for space and terrestrial applications. Unreliable and expensive components like batteries and driving electronics were completely eliminated (Fig. 4.2).

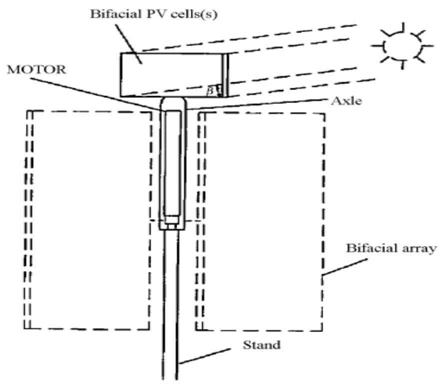

Fig. 4.2.Scheme of the terrestrial tracker [40].

It works also at low temperatures down to -40^{o}C. The area of the auxiliary solar panel of the tracker is about 1% of the total area of moved solar arrays. Their auxiliary bifacial solar cell together with bifacial solar arrays enables backtracking from any position (360^{o} tracking angle) while trackers based on similar technology with standard mono-facial solar cells have a tracking/backtracking angle of 120^{o}. They concluded that the tracker follows the sun with deviation of +/-5^{o} without any reduction in the collected energy. The system collected more than 95% of the energy of an ideal tracker [40].In another work they designed and constructed a solar tracking system based on an auxiliary bifacial solar cell capable of backtracking within 5 min and average tracking accuracy of +/-5^{o} to be installed above a V-trough concentrator with bifacial solar panel. Two anti-parallel arrangements of solar cells with 1% of the area of the moved solar collectors were connected directly to a reversible DC motor with a self-locking transmission. In a cloudy condition, once the sun starts shining, collectors will start moving. Their experimental result shows that the bifacial PV modules with reduced temperature sensitivity can boost energy gain by 15–25% in comparison with the same tracker/concentrator with mono-facial modules.

The polar axis solar tracker with C–Si bifacial PV modules will therefore deliver about 50% more energy than that of a fixed C–Si mono-facial PV array with the same rated output power. The tracking bifacial soft concentrators even double the energy gain against a fixed mono-facial PV array [41].In the Alata et al. work, the formulation of equations that describe the sun motion in the sky and the design of three types of multi-purpose sun-tracking systems are introduced. The formulation is a replacement of the mathematical equations of altitude, azimuth, declination and hour angles by fuzzy IF–THEN rules using subtractive clustering along with ANFIS as a rule extraction method. Then, a 3D simulation of various sun-tracker types, driven by a DC motor for each axis of tracking, is demonstrated throughout a virtual reality (VR) mode. Each output of the fuzzy inference system is related directly to two inputs: the day number during the year and the time of the day in hours. The results are shown using simulation and in VR mode [42].Rubio et al. discussed the design and implementation of a two axis PV sun-tracker using a combination of an open loop tracking strategy with a microprocessor in which the controller is based on a solar movement model, and a closed loop strategy which corresponds to the electro-optical controller. The instantaneous power generated by the arrays is measured by a sensor that emits a signal proportional to this power. Finally, they implemented a proportional and integral (PI) control strategy for each coordinate, independently. Their tracking strategy produced a close approximation of the evolution of the sun's elevation and azimuth even if the solar equations yield quite large errors. Fig. 4.3 shows a simulated example of the evolution of the three variables the sun's real movement (SMv), the progression of the values yielded by the solar equations (SEq) and the evolution obtained after the corrections (CEq).

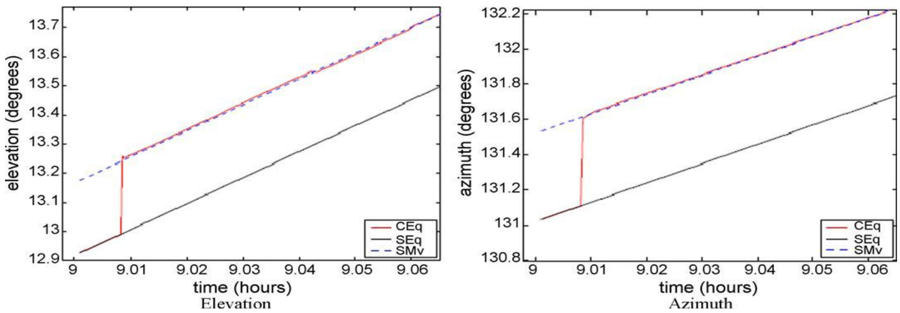

Fig. 4.3.Evaluation of the coordinates [43].

They concluded that the electric power generated using the hybrid strategy is, in mean values, 55% higher than that of the open loop one [43]. Bakos designed and constructed a two-axis sun-tracking system which is based on the combination of the conventional photo-resistors and the programming method of control. The electromechanical device consists of four relays, two electronic circuits, two photo-resistors connected in series and two AC motors. For manual operation, drawing a graphical representation and defining sunrise and sunset times, for the system connected to a computer a code is written in Visual C++ programming language. The system can track the sun in E–W and N–S direction. It was concluded that the two-axis tracking system is up to 46.46% more efficient in comparison to that of the fixed surface tilted 40^{o} from the south [44]. Durisch et al. developed and tested a single cells and modules with sun tracker PC-based, in order to provide outdoor data under real operation conditions for optimum utilization of PV power. In their design, daily sun's declination was taken into account by a specially developed crank mechanism. A simple open-loop control provided precise tracking for both polar and declination axes, via step motors and worm gears. To measure insolation incident on the cells and modules, six pyranometers were connected in series and a reference cell was mounted on the tracker. Several measurements such as ambient and module surface temperature, direct normal irradiance, wind speed, voltage and current sensors were taken into account.

The collected data were sent to a PC and the voltage-current and power–voltage curves were drawn. Their tests revealed that the difference in the highest power obtained via two methods: one from searching highest power during voltage-current scans and second found by mathematical methods, was less than 0.02% [45].Sangani et al. fabricated and tested a V-trough (2-sun) concentrator using different sun trackers to reduce generated electric cost with PV. Their tracking modes were seasonal tracking (A), one-axis N–S tracking (B) and diurnal tracking (C). Experimental results for I–V characteristic curves and output power from the PV module at an insolation level of 900 W/m2 assembled at different tracking modes are shown in Fig. 4.4 [46].

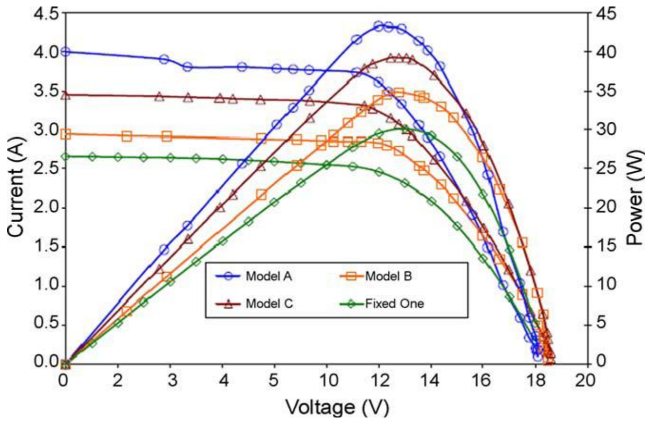

Fig. 4.4 I–V curves and power output for different V-troughs concentrator PV systems assembled according to model-A, model-B and model-C [46].

Pavel et al. analyzed experimentally and theoretically the collected energy in original tracking and non-tracking bifacial and non-bifacial PV solar systems. The calculated and measured tracking effect showed an increase of 30–40% in collected energy while for tracking case with bifacial panels and reflector collecting solar radiation for the rear face gave an increase in collected energy of 50–60% for the same panel [47]. Felske evaluated the variation of azimuth and tilt angle on effectiveness of flat plate solar collectors. It was concluded that for a given tilt angle, the yearly energy collection is almost insensitive to azimuth angle until the vertical orientation is approached at which the collected energy actually increases with increasing the azimuth angle. In this case, the optimum tilt angle is quite insensitive to azimuth angle. For a given azimuth angle, an optimum collector tilt angle is between 38 and 108 less than the latitude. Finally, it was mentioned that even for locations having symmetric irradiation about solar noon it is desirable to orient the collector west of south, since afternoon temperatures are usually higher than morning temperatures [48].Stern et al. designed, fabricated, tested and demonstrated a modular and fully integrated 15-kW-AC, one-axis solar tracking PV power. The tracker used potentiometer and integral pendulum to provide a positive feedback signal to the tracker motor and actuator. It was concluded that single-axis solar tracking provides 20% more energy in a typical year than that of a fixed-axis PV system. Also, the net reduction in the total cost of single-axis solar tracking grid connected PV power system was found to be 23.3% [49].

Naidoo et al. developed three algorithms for parabolic trough solar collector tracking. In the first method, they used discrete number of pulses to position the trough. The rotary encoder used in this project to provide feedback on the absolute angular position of the trough had 0.144^{o} per pulse. In the second, method the trough is positioned in the N–S axis in order to track the sun in the E–W direction. In order to position the sun, a mathematical algorithm in a PLC programmed software was used along with longitude and latitude based on the geographical location of the trough. In the third system, a fuzzy logic controller based on an intelligent control algorithm was used. Fluid temperature, wind speed and trough position were inputs where trapezoidal form and drive speed were outputs. The relation between inputs and outputs was defined with IF–THEN rule. No report was provided for any comparison or efficiency evaluation [50]. Stolfi et al. designed and constructed a working prototype two axis solar tracking and concentrating apparatus for a heliostat array. To actuate the necessary motion of the apparatus, two step motors were used. To provide a horizontal motion, the unit moves on a turntable controlled by a pair of worm gears. The reflective panel tilts up and down using a simple spring-driven hinge. In this system, a master unit is used to position the slaves. This is accomplished by both monitoring the output of the PV array and using an automatically generated database of previous known good slave positions with corresponding reflected lights, solar position, and/or time of day values. The tests showed that the tracking increases the power output by increasing the output current. These tests also showed that the reflectors created uniform, concentrated light areas suitable for focusing onto the PV cells [51].

Mwithiga et al. designed and constructed a dryer with limited sun-tracking capability that operated manually. The dryer consisted of a gauge 20 mild steel flat absorber plate formed into a topless box. The drying unit was bolted onto a shaft which in turn was mounted on to a stand so as to face E–W direction. A selector disc on the stand allowed the tilt angle that the drying unit made with the horizontal, to be easily adjusted in increments of at least 15^{o}. This way, the collector plate could be intermittently adjusted in order to track the sun during the day. Four dryer settings for tracking the sun were created. The dryer was set at an angle of 60^{o} to the horizontal facing east at 8.00 a.m. They adjusted the angle of the dryer made with the horizontal either one, three, five or nine times a day when either loaded with coffee beans or under no load conditions. The results showed that the solar dryer can be used to successfully dry grains. Drying of coffee beans could be reduced to 2–3 days as opposed to sun drying without tracking system, which takes 5–7 days and the temperature inside the chamber could reach a maximum of 70.4^{o}C [52] Rumyantsev et al. designed and constructed a close-loop sun-tracking system for 1 kWp solar installations. Their design of the sun-tracker was based on constructing the cheapest structural materials, such as roll-formed perforated channels and bendings, made of zinc-protected steel. Tracking mechanism was fully automatic managed by an analogue sun sensor. Tracker consisted of two main moving parts: a base platform moving around vertical axis and a suspended platform with PV modules moving around horizontal axis. The base platform was equipped with three wheels one of which was connected to an azimuth drive. The suspended platform was a frame where concentrator modules were installed as three steps of a stair. Position of the suspended frame can vary in the range of +/- 45^{o} symmetrically about a horizontal plane ensuring alignment of the modules in elevation. The base platform was driven by one of the wheels moving along a circle of a large radius. If motors (DC 12 V) were switched in use continuously, rotation velocity of the platforms was near to 1 rotation per hour, i.e. much faster, than it was necessary for a normal tracking. Continuous rotation of the motors was carried out for returning the trackers from “sunset” to “sunrise” position and for fast “searching” the sun, after cloudy periods. At normal tracking, the motors were switched on periodically, after each 8–10 s [53].

Bingol et al. proposed, implemented and tested a microcontroller based two-axis solar tracking system. They used light dependent resistors as sensors, stepper motors as actuators and a microcontroller. In addition, the system was connected to a PC via RS232 for sun position monitoring. A crystal with a frequency of 4 MHz was used as a clock signal generator for the microcontroller. The panel degree from vertical axis was fixed at 50^{o}. The experimental study for two solar collector panels, one stationary and the other rotary were employed in the test. Temperature of the panels versus time was measured with a minute interval and 50 data were captured. The angle of intervals was almost 5.2^{o}. A distinction of 9 8C between rotary and stationary panel was observed. This result verified that the rotary panel containing solar tracking system took more light density than the stationary panel [54]. Lakeou et al. designed and constructed a two-axis sun-tracking system to follow the sun in azimuth and solar direction based on a programmable logic device (an 84-pin, Xilinx XC95108). Through an H-bridge structure, a controller is connected to DC motors. Initially, once the location is selected, the azimuth elevation range is determined and the angular steps are calculated. The total number of tilt steps was 12. For monitoring the power generation, they also connected this tracking device to a PC by a code written in Assembly or C++ languages. They concluded that the proposed sun-tracker was cost effective and flexible [55].

An MPPT system consists of two basic components: a switch-mode converter and a control/tracking section. The switch mode converter is the core of the entire system and allows energy at one potential to be drawn, stored as magnetic energy in an inductor, and then released at a different potential. By setting up the switch mode section in various different topologies, either high-to-low or low-to-high voltage converters can be constructed. The goal of an MPPT system is to provide a fixed input voltage and/or current, such that the solar panel is held at the maximum power point, while allowing the output to match the battery voltage. In [56], the converter was controlled to track the maximum power point of the input source under varying input and output parameters and was shown to provide a minimum input source saving of 15% for 3-5 kWh/day systems. Brown and Stone [57] developed a tracking system for solar concentrators in which a neural network was applied to an error model in order to compensate for tracking errors. The test data showed that the resulting system was capable of reducing the tracking error to a value of less than 0.01^{o} (0.2 mrad).

In 1997, Stone and Sutherland [58] presented a multiple tracking measurement system comprising more than 100 heliostats for tracking the sun’s position on an hourly basis from early morning to late evening. Hua and Shen [59] compared the solar tracking efficiencies of various MPPT algorithms and implemented a simple control method which combined a discrete time control scheme and a proportional-integral (PI) controller to track the maximum power points (MPPs) of a solar array. Kalogirou [60] presented a one-axis sun-tracking system utilizing three light-dependent resistors (LDRs). The first LDR detected the focus state of the collector, while the second and third LDRs were designed to establish the presence (or absence)of cloud cover and to discriminate between day and night, respectively. The output signals from the three LDRs were fed to an electronic control system which actuated a low-speed 12 - V DC motor in such a way as to rotate the collector such that it remained pointed toward the sun (Fig 4.5)

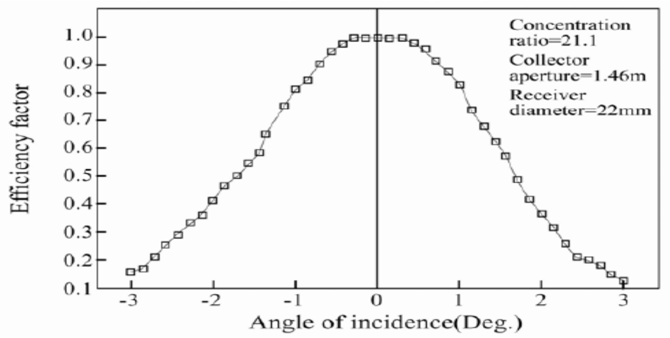

Fig 4.5 Collector acceptance angle [60].

Khalifa and Al-Mutawalli [61] developed a two-axis sun tracking system to enhance the thermal performance of a compound parabolic concentrator. The system was designed to track the sun's position every three to four minutes in the horizontal plane and every four to five minutes in the vertical plane. As shown in Fig 4.6.

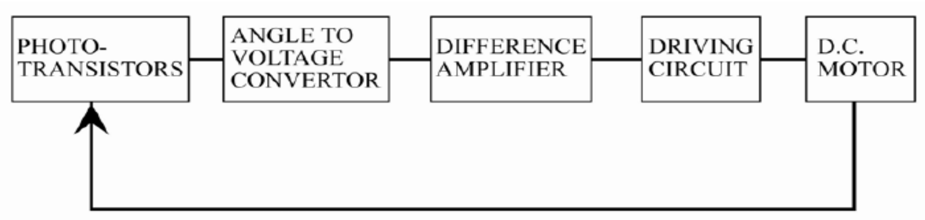

Fig 4.6 Block diagram of sun-tracking system [61]

The tracking system was comprised of two identical sub-systems, one for each axis, with each sub-system consisting of two adjacent photo-transistors separated by a partition of a certain height. In the tracking operation, the difference in the voltage signals of the two photo-transistors was amplified and used as a command signal to drive the collector around the corresponding axis until the voltage difference reduced to zero, indicating that the sun's rays were once again normal to the collector surface. It was shown that the tracking system had a power consumption of just 0.5 Whr and yielded an improvement of around 75% in the collected solar energy, compared to a fixed collector of equivalent dimensions.

Aiuchi*et al.* [62] presented a simple sun tracking photo-sensor designed to ensure a constant direction of the reflected solar radiation. In the proposed device, two photo-cells were placed side by side at the bottom of a box with an aperture. When the reflected solar radiation passed through the aperture, the photo-cells were fractionally illuminated and produced an electric current proportional to the size of the illuminated area. A constant direction of the reflected solar radiation was maintained simply by monitoring the output signals of the two photo-cells and adjusting the angle of the reflection mirror as required to ensure that the two signals remained equal at all times. It was shown that the resulting system achieved a tracking error of less than 0.6 mrad on a sunny day.

In 1983, Al-Naima and Yaghobian [63] developed a solar tracking system featuring a two-axis equatorial mount and a microprocessor, in which the tracking operation was performed on the basis of the astronomical coordinates of the sun. The experimental results demonstrated that the proposed system yielded a significantly better tracking performance than that obtained by a conventional sensor controlled system. Several years later, Lorenz [64] proposed a set of design guidelines for a window glazing which rejected solar radiation during the summer, but accepted it during the winter. The design featured a purely passive control algorithm based on seasonal changes in the incident angle of the solar rays.

Jinayim et al. designed a highly efficient low power consumption tracking solar cells of a white LED-based lighting system. Their evaluated one-axis tracker used a stepping motor commanded by a PIC microcontroller. A photo-resistor was put in a dark box with small hole on the top. With maximum illumination detection it worked by the PIC command. If no sun light is detected by the photo resistor, the zero state actuates the system until the real state is detected.

The sun energy curves and fixed and tracking panel energy curves were drawn and it was concluded that although the tracking mode was 100% efficient, the actual charge current was somewhat lower, as some power was lost due to the solar cell temperature. Finally, they recommended not using tracking system for small solar panels because of high energy losses in the stepping motor [65]. Hatfield designed, constructed and tested a microcontroller based two-axis sun-tracking device. Movement of the PV module was achieved with a 12 V linear actuator where its full course was 20 cm. A potentiometer with a voltage range of 0–5 V was used for angle measurement for a full revolution (360^o) of the pot. Control of the tracker was via the light sensor and a micro controller. A DC relay was used to disconnect the load from the solar module during the open circuit voltage read by the A/D converter on the micro controller. The final results showed an efficiency increase of 27% when compared to that of a fixed panel [66].

Aiuchi et al. developed a closed loop photo-sensor controlled heliostat using an equatorial mount. Also, two sensors were used a fixed one with 32^o inclination to the south. The required position was calculated in advance and was programmed into PLC. The PLC controls the actuator to adjust the panel to maintain position perpendicular to the sun. They claimed that consumed power by the control system was less than 2% of the collected energy by the tracking system. After drawing several voltage-current and power generation characteristic curves for different sun trackers, they concluded that there were increases up to 43.87, 37.53, 34.43 and 15.69% of electrical power gain, respectively for the two-axis, E–W, vertical and N–S tracking, as compared to that of the fixed one [67]. Zeroual et al. designed and constructed a closed loop sun tracking microprocessor with electro-optical sensors to control a water heating solar system. Many parameters such as wind velocity, pressure and ambient temperature were also controlled. The long period tests in variable conditions, confirmed the accuracy of the system [68].

Ioffe Institute PV Lab., designed a 1 kW closed loop tracker in which the turn angle can vary in the range of +/-70^o about horizontal and vertical planes. Continuous rotation of motors, turn the structure from sunrise to sunset. At normal operation, motors are switched on automatically every 5–8 s. Two multi-junction III–V cells are used as the light sensitive elements in the side walls and back walls of a special element namely main sensor and additional sensor. Photocurrent from these cells goes to a transistor and a relay to activate motor in the desired direction [69]. Gagliano et al. designed and simulated a two-axis sun-tracking system based on a photo-resistor sensor and investigated the effects of energy gain between a fixed PV panel and a tracked one. The sensing device consisted of a nine light-dependent resistor (LDRs) for rotation, and three aligned LDRs for inclination, positioned into suitable plastic supports. It was concluded that the main advantage of the proposed tracking system was the low cost of the sensing apparatus, gained from a real time elaboration procedure on sensors data [70].

Zogbi et al. designed and constructed a low cost two-axis (elevation and azimuthally) sun-tracking system by classical electronic units. Four electro-optical sensors were placed in each quadrant formed by two rectangular planes intersecting each other in a line. The tracking control unit consists of an amplifier and other electronic parts to compare the received signals from each pair of sensors and to command two motors for device rotation. The system had an east return-and-stand by circuit to system stand at night and return eastward in the following morning. If the output from one of the sensors becomes greater than the threshold, the corresponding motor is activated by an amplifier until the error signals reduce to be less than the threshold. The corresponding time duration was 15 s. It was concluded that the constructed prototype operates successfully under variable light intensity [71]. Rumala designed and constructed a closed loop automatic sun-tracking system based on the shadow method. Photo-resistive sensors were placed on a platform under a pair of back to back mounted semi-cylinder in an E–W and N–S facing. The rigid platform had two ball jointed track arms for elevation and lateral tracking that were actuated by cam driven motors. A signal conditioning circuit of a pre-amplifier along with a low pass filter feed an amplifier to move the servomotor and to correct the differential in detected solar irradiation. The shade remains in the sunset position until the auto start up of the morning of the following day [72]. Urbano et al. assessed 5-W-peak PV module for tracking solar oven concentrator system with 2.6 kW/sub-th/capacity with 200 kg weight. The tracking system was driven by means of two 36 W, 12 V DC motors to follow the sun independently in altitude and azimuth directions. The electronic circuit commands DC motor to rotate as a function of the optical sensors for altitude and azimuth positions [73]. Karimov et al. constructed a one-axis PV tracker system with four solar modules installed on a rotor; its other axis was manually adjustable in order to fix the inclination angle of modules at 23^o, 34^o and 45^o. Solar modules were divided into two pairs and the angle between the modules of a pair was 170^o. Main modules was used both for the sensing and energy conversion purposes.

The modules were connected to bridge circuit very similar to the Wheatstone bridge. If the output voltage from modules is not equal, the voltage applied to the DC motor is not zero and as a result, the motor starts turning. Their research shows for tracking system, unlike the fixed modules, the voltage output in the evening and morning are not very different and the tracking mode collects 30% more energy [74]. Aliman et al. developed a new sun-tracker to gain high concentration solar energy. Their system consists of a master mirror surrounded by several slave mirrors. The master mirror reflects sun beams to a stationary target. Sun image in this target acts as a reference for all slave mirrors. The sun-tracker had two tracking axes perpendicular to each other. One is the rotational axis pointing toward the target; the other is the elevation axis parallel to the reflector. As the sun moves through the sky from the morning to solar noon, the mirror plane will rotate starting from horizontal and turning to vertical. The angular movement about this rotation axis is denoted as ρ. They derived a formula based on time and date for ρ to represent an elevation/rotation tracking mode which was proved to be successful [75]. Saxena et al. designed and fabricated a two-axis microprocessor based controller for sun-tracking that follows the sun in azimuth and altitude directions by two step motors. The system acts in both closed-loop and open-loop modes. Their system consisted of data acquisition and storage facility, battery control facility, system monitoring, RAM, converter card, microprocessor card, and sensor card for wind, cloud, altitude reverse, altitude forward, azimuth reverse, azimuth forward detection. In the closed-loop mode, the tracker starts at about 5 a.m. and moves under CLOUD mode till the sun is out. In the evening, further forward motion stops. The tracker is brought back to HOME position in the night. The data for the PV parameters and meteorological parameters are acquired every 10 min [76].

Nuwayhid et al. presented a simple exercise in designing, building and testing a PC connected two-axis solar tracker concentrator. They predicted the solar position by using solar altitude and the solar azimuth angles which in turn vary in sinusoidal form and both functions of time. Each axis was connected to a DC motor and each motor had a relay to count certain number per revolution. The angle-per-counts relation was determined from experimental data. When the speed of the hour angle motor is reducedto0.23 rpm, an installed gear box increases the speed to 23 rpm. The motors and their position sensors were connected to a PC. The PC computes solar time and solar angle at a given site. The system uses a temperature sensor and also nine LDR sensors in a tube to define sun image. It was concluded that tracking increases the working fluid's temperature in the range of 200–600^{o} C in comparison to that of un-tracking that operates in the range of 80–200^{o} C. But simple design and low cost of the un-tracking systems are attractive options to be overlooked easily [77]. Al-Jumaily et al. studied the performance of a flat linear Fresnel lens concentrating solar radiation on two absorbers connected in series. It was manufactured in such a way to track the sun in two dimensions (the altitude and azimuth angles). More than 200 tests were carried out to evaluate the thermal and optical efficiencies versus hour angle and fluid inlet and outlet temperatures. They found that due to use of two dimensional sun-trackers that keep the incident flux always perpendicular to the collector, the optical efficiency maintained constant thorough the day (about 64%) [78].

Koyuncu et al. evaluated a microprocessor based sun-tracking system to control the movement of a solar panel. To limit panel movement, the maximum positions at east and west were limited using two limit switches. The status of the limit switches is read by the microprocessor. They concluded that using tracking device to keep panels perpendicular to solar direction maximizes the thermal energy obtained from the solar panels [79]. Shaltout et al. designed and constructed a V-trough concentrator on a PV full tracking system. The system gave relatively high gain in the amorphous Si solar cell's power which was about 40% more than that without a concentrator. Their graphical comparison between concentrated horizontal and tracking radiation showed an increase in gain of about 23% for the latter one [80]. Baltas et al. evaluated the power output for fixed, step tracking and continuous tracking systems in several locations. They used direct radiation, total radiation on horizontal surface and dry bulb temperature data for computer simulation. They stated that Freon driven trackers are good for a flat plate array unlike for concentrating PV systems, due to their independence of good tracking accuracy. By comparing the energy output from various tracking systems for a typical year, they concluded that the two step tracking arrays (E–W direction varying twice per day, south facing tilt varying monthly) provides about 95% of the energy obtained from continuous tracking arrays. Also, the continuous tracking mode provided 33, 25.5 and 22.5% more energy in different locations over fixed arrays, respectively. Continuous tracking increased the energy production 29.2 and 33% over south facing fixed arrays, respectively, for reflection non-accounting and reflection accounting systems [81]. Abdallah [82], designed and constructed a two-axes, open loop, PLC controlled sun-tracking system. Two tracking motors, one for the joint rotating about the horizontal N–S axis and the other for the joint rotating about the vertical axis were used. The daylight divided into four intervals and during each of them the solar and motors speed was defined and programmed into PLC. He predicted that the power consumption to drive motors and control systems hardly exceeds 3% of power saved by the tracking system. Fig. 4.7 shows energy comparison between the tracker and the fixed surface inclined at 32^o. He concluded that the use of two-axes tracking surfaces results in an increase in total daily collection of about 41.34% as compared to that of a fixed one.

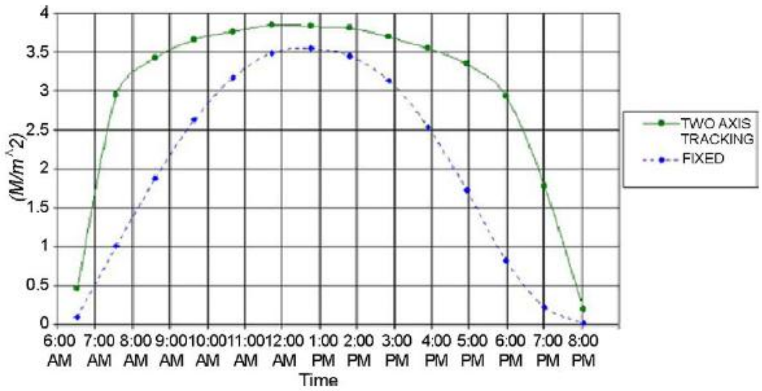

Fig.4.7. Energy comparison between tracking and fixed solar system [82]

4.1 Conclusion

Advances in the improvement of sun tracking systems have enabled the development of many solar thermal and photovoltaic systems for a diverse variety of applications in recent years. Compared to their traditional fixed-position counterparts, solar systems which track the changes in the sun's trajectory over the course of the day collect a far greater amount of solar energy, and therefore generate a significantly higher output power. This paper has presented a review of sun tracking systems developed over the past years. Overall, the results presented in this review confirm the applicability of sun tracking system for a diverse range of high performance solar-based applications.

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