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Review Article

Solar Tracking Techniques and Implementation in Photovoltaic Power Plants: a Review

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Abstract: Electricity is one of the basic needs of life. Emission of harmful gases during the process of electricity generation leads to greenhouse affects. However, by employing photovoltaic (PV) panels, electricity can be generated without creating air, noise and water pollution caused by the emission of harmful gases. Geographically, Pakistan is located in a region of the world where solar irradiance is approximately 2000 KWh/m^2. In recent decades, grid-connected PV power plants have been implemented worldwide to fulfill the power requirements. Usually, these power plants are mounted fixed. However, with advancement in technology solar trackers have increased the yield. In this study, after reviewing and analyzing various PV tracking techniques, an open-loop single axis technique is suggested for use in the huge PV power plants.

Keywords: Renewable energy, PV system, single axis-tracking, dual-axis tracking

1. INTRODUCTION

Solar energy is an everlasting resource [1] for tomorrow because it is free, practically inexhaustible, and involves no polluting residues or greenhouse gases emission [2]. Photovoltaic (PV) solar cell directly converts sunlight to electricity. A solar system with 10% efficiency covering 0.16% of earth would provide 20TW (Terawatt) energy, about twice the world consumption rate of fossils energy [3, 4].

Recently, all over the world the energy demand has greatly increases. Meanwhile the resources of fossil fuels are depleting with the passage of time. The world's demand for energy will be almost triple in the forthcoming three decades [5]. This situation appeals the research community to pay attention toward renewable energy system. To find sufficient pollution free energy resources for future is one of the great challenges for society. Research in the field of renewable energy can solve this problem. Energy generated from natural renewable resources such as wind, waves, tides, solar radiation etc. are termed as renewable energy.

In South Asia, especially Pakistan is facing an acute shortage of electricity since 2000. In 2014, the short fall reaches 4500-5500 MW [6]. To meet Pakistan's soaring demand in energy, there is a need to devise efficient energy system which is capable to fulfill energy needs at present and is sufficient in future too. The world's scientific advanced countries are using renewable energy systems to meet their needs [7]. These energy resources are environmental friendly and everlasting.

Many regions in Pakistan receive solar energy abundantly and sun light is present almost throughout the year. The yearly sum of global irradiance is approximately 2000 KWh/m^2 as shown in Fig. 1. Moreover, in most cities in Pakistan sun rise hours range 2200 – 2500 per year [5].

Photovoltaic energy is one of the mature technologies amongst all renewable sources. To

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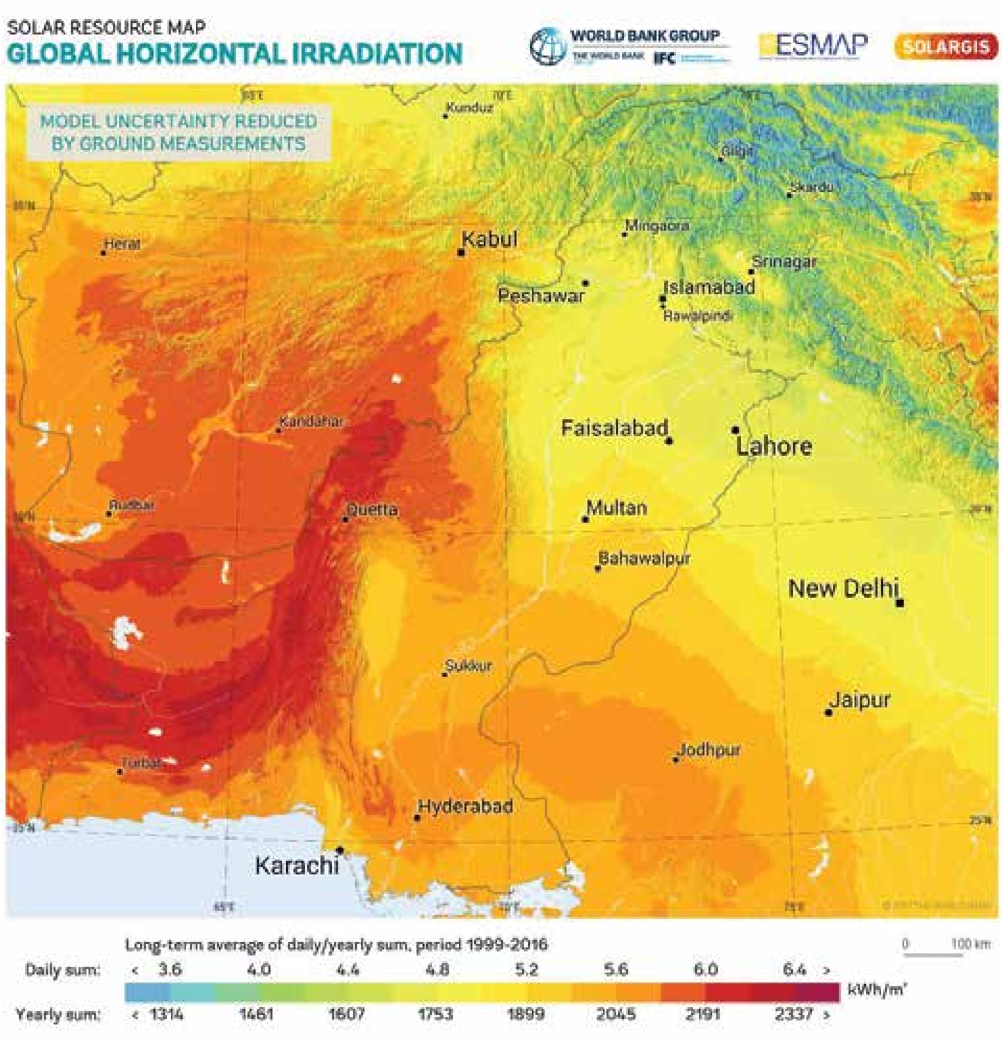

Fig. 1. Annual mean of global horizontal irradiance in kWh/m^2/day [27].

harvest solar energy, solar tracker is used which keeps panel normal to the sun radiations in sunrise hours therefore, more energy could be collected.

One of the main objectives of this study is the investigation of solar tracking system and its various types, i.e., single and dual axis and their techniques along with open and closed loop system used in solar trackers. This study also discusses the implementation of tracking system in PV power plants and its effectiveness on the yield gain.

The reminder of this paper is organized as following: Solar tracker and its types are discussed in section II while Section III comprises of critical analysis of different techniques adapted by researchers to upgrade the efficiency of PV panels. To know the effective tracking method for PV power plant, conclusion is drawn in section IV.

2. SOLAR TRACKER

An automated system (in which solar panels are mounted), tracks sun's position accurately in order to maximize the power yield. Everyday sun rises in the east and move across the horizon toward west (solar azimuth angle) as illustrated in Fig. 2. A field of sunflowers rotate according to the sun motion (east to west) throughout a sunny day such that each leaf seek maximum light heliotropism, a clever bit of natural engineering [1, 2].

Sun changes its position throughout the days, years and seasons. To increase the energy production from PV panels, it is necessary to rotate the PV panels accordingly. It can be realized that more power will be generated it PV panel is exposed (for more time) towards the sun, so they can harness more sunlight. This idea describes solar tracking

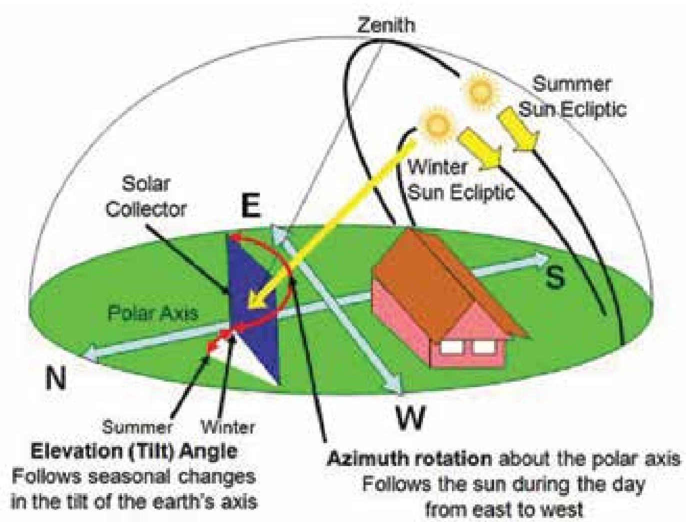

Fig. 2. Daily and seasonal movement of sun [9].

principle [8]. It increases the system's efficiency while reduces its size and overall cost. For solar trackers, it is challenging to always align the panel with sun. In crystalline or thin film PV power plants it is observed that if the tracker missed the target (sun) by few (up to 10) degree the yield still remain 98.5% of the full-tracking maximum, due to diffuse light [2, 9]. However, the concentrated solar power (CSP) system must be normal to solar radiations all the time. Tracker keeps the array of solar panels in focus with the sun for whole day, year and season – maximize the power yield [9]. In 1962, Finster [10] introduced first ever tracker which was completely mechanical, in the following year, Saavedra [11] presented a tracker with an automatic electronic control mechanism, which was used to operate pyrheliometer. Mousazadeh et al. [3] further explore this idea in 2009 via examining their basic principles and subsequently analyzed various tracking techniques.

In light of the above discussion it is obvious that solar tracker is necessary for PV operation however avoiding tracking would affect performance [1]. The use of solar tracker not only increases energy harvesting but, also affects its cost, reliability, maintenance, performance and energy consumption [1, 12]. The energy gain from different tracking

Table 1. PV system gain tracking efficiency: a comparison.

Reference No.	Control unite	Drive method	Control mechanism	Orientation	% Gain
5	Microcontroller	Active	Close loop	Dual axis	40.0%
8	Microcontroller	Active	Open loop	--	26.0%
8	Microcontroller	Active	Close loop	--	33.0%
18	Microcontroller	Active	Open loop	Single axis	18-64%
20	Microcontroller	Active	Close loop	Single axis	20.0%
21	Microcontroller	Active	Open loop	Dual axis	64.0%
22	PLC	Active	Open loop	Dual axis	38.0%
23	Microcontroller	Active	Close loop	Dual axis	50-60%
24	Microcontroller	Active	Close loop	Dual axis	57.0%
25	Microcontroller	Active	Close loop	Dual axis	28.9%
12	Hybrid	Active	Close loop	Dual axis	25.0%
26	Volatile liquids	Passive	Open loop	--	23.0%
29	Volatile liquids	Passive	Open loop	Single axis	23.0%

Fig. 3. Zomework UTRF-168-2 passive solar tracking model [28].

techniques (reviewed in this paper) are categorized in Table 1. An ideal tracker keeps the PV module accurately towards the sun, compensates for both changes in elevation sun angle to track the sun throughout the day.

Solar trackers are categorized as active and passive on the bases of drive methods and discussed in the following sections.

2.1. Methods of Drive

2.1.1. Passive Trackers

In these trackers, a volatile fluid is compressed in containers, which is attached to both end of rack, and is shown in the Fig. 3. The solar radiation creates pressure inside the container which make the system imbalance–tends the system to move accordingly. This non-precise orientation makes it unsuitable for concentrating PV collector or tower solar concentrating system, however works better in mono or poly crystalline PV panel system [2]. The system does not use any gear and motor for rotation hence, power is not required. Zomework Corporation [2] a leader in passive solar energy products since 1969, while from 1980, more than 19,000 tracking system have been installed in different climates on nearly every continent on earth [2, 13]. Fig. 3 illustrates Zomework UTRF-168-2 passive solar tracking model mounted on top of the pole.

2.1.2. Active Trackers

In these tracker gears and motor are used to drive the panel rack. The control circuit (microcontroller, Programmable Logic Controller (PLC), Personal Computer (PC), etc.) sends a command the motor to rotate – in order to track the sun. Since the motors consume energy so, they could be used only once required [2, 9].

2.1.3. Chronological Trackers

These tracker moves with the apparent speed of the earth but in opposite direction, i.e., 15^{o}/h or one revolution per day, thus keep themselves align with sun. The speed of sun varies with season so, equation of time is used for high tracking accuracy – sundial time [2].

To provide feedback signal to the controlling circuit, solar trackers are classified into two categories i.e. open and closed loop trackers. Open loop trackers are simpler however, have low efficiency while closed loop trackers are more efficient with complexity. The complexity and efficiency have a tradeoff consideration. Close loop tracker's control mechanism is either based on

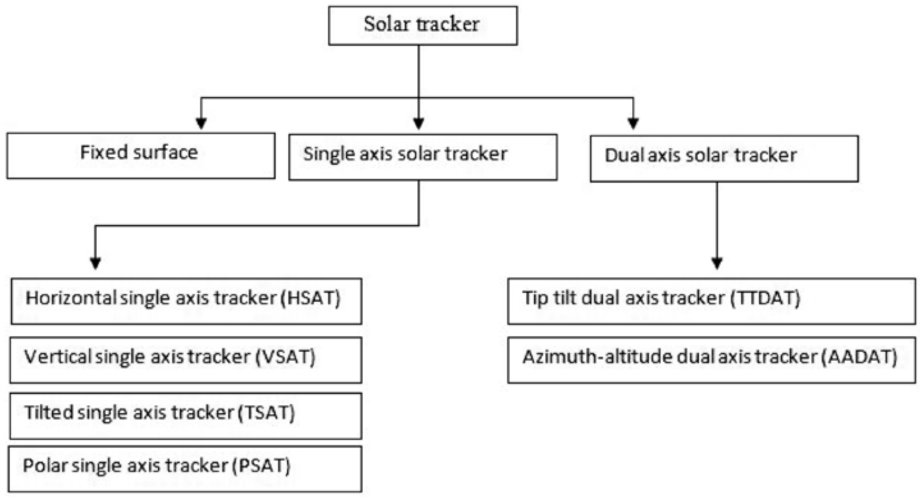

Fig. 4. Some common types of solar tracker; based on orientation capabilities.

microcontroller and optical sensor (Light dependent (LDR), Photodiode, etc.) or PC controlled based, auxiliary bifacial solar cell or a combination of both. Closed loop tracker is relatively complex however provides high accuracy [8].

Solar trackers are further classified into three categories by orientation capabilities: (i) the fixed mount; (ii) single axis; and (iii) dual axis trackers ;as illustrated in Fig. 4.

2.2. Types of Solar Tracker based on Orientation Capabilities

2.2.1. Fixed Mount Solar System

PV panels are mounted at fixed tilt angle (local latitude) facing south. Domestic, small scale commercial PV systems and solar geyser usually use fixed surface solar system. The 100 MW Quaid-i-Azam Solar Park (QASP), Bahawalpur, (the first ever PV power plant) in Pakistan use fixed surface technique [14]. Fig. 5 exhibits a view of the Quaid-i-Azam Solar Park, Bahawalpur.

2.2.2. Single Axis Tracking System

This system traces the sun in single direction. Single axis tracking system offers one degree of freedom, which acts as an axis of rotation that is typically aligned along true north meridian. It is possible to align single axis tracker in any cardinal direction with advance algorithms [15, 19]. Such a system can be implemented in various configurations, such as horizontal single axis tracker (HSAT), vertical single axis tracker (VSAT), tilted single axis

Fig. 5. The 100 MW Quaid-e-Azam Solar Park, Bahawalpur, Pakistan [14].

tracker (TSAT) and polar aligned single axis tracker (PSAT) and is most effective at equatorial latitudes [1, 3]. As this system move in uni-direction; hence less operation is required and as a result less energy is consumed. Moreover, the simple nature makes it robust, thus less maintenance is need. On other hand, due to no proper alignment with sun rays, it harvest less energy hence its efficiency is low. The robust nature makes it suitable for PV power plant. In Greece [16], 8 MW PV power plant was installed using horizontal single axis tracker as shown in Fig. 6.

2.2.3. Dual Axis Solar Tracking System

Dual axis tracker tracks the sun in two directions; it has two degree of freedom that acts as axis of rotation. These axes are perpendicular to each other. Such a system incorporates the daily and seasonal changes which occurs in sun's path – exposes the PV panels to the solar radiations to harvest optimum energy. This system can be implemented in two ways: (i) tip-tilt dual axis trackers (TTDAT); and (ii) azimuth-altitude dual axis trackers (AADAT) [1]. The above mentioned two types are the most popular of dual axis solar trackers and are used in various applications as illustrated in Fig. 7a and Fig. 7b.

3. TECHNIQUES USED TO ENHANCE EFFICIENCY OF PV PANEL

Single and dual axis tracking techniques were widely used throughout the world in PV power plants to maximize energy harvesting. These both techniques have some pros and cons. Dual axis tracking system offers high cost and high accuracy however low reliability (more down time more wear and tear). On contrary, single axis tracking system offers with low cost and less accuracy but high reliability (contains fewer things that can

Fig. 6. The 8 MW PV plant using horizontal single axis solar tracker in Greece [16].

Fig. 7(a). The TTDAT PV power plant [16].

Fig. 7(b). AADAT based PV plant in Toledo, Spain [16].

go wrong over the life time), hence requires less maintenance. In 1986, Akhmedyarov et al. [17] proposed an automatic sun tracking system in solar photoelectric station in Kazakhstan to increase the output power from 357 W to 500 W [15].

3.1 Single-axis Tracking Mechanism

Moniruzzaman et al. [18] performed a detail analysis of three level solar panel tracking system. The proposed system was compared with fixed PV system of the same number of panels. Three panels were mounted one above another with the height of half panel's width. The control circuit was microcontroller based open loop with fixed tilt angle equal to latitude along north – south. Unlike continuous rotation the proposed system was operated step-wise to reduce self-energy consumption. Gain in yield of 18-64% was recorded and compared to static PV system; however, occupied 33% less space. Therefore, the system is suitable for use in urban areas where less free room is available.

Anuraj et al. [20] have designed a solar tracker prototype with single degree of freedom; tracking the sun using Light Dependent Resistors (LDR). Their proposed system was microcontroller (ATMEGA 16) based automatic solar tracker. LDR detects sun light, which activate stepper motor to position PV panel, such that it receives maximum irradiance. The proposed tracker provides three mode of operation.

3.1.1 Normal Day Light Conditions

In daily sun's east-west motion, LDR1 needs to provide higher voltage then LDR2 to sense the rotation of sun. The tracker rotates 3.75^{o} after every 15 minute.

3.1.2 Extreme Weather Conditions

In cloudy weather, a part of sunlight strikes both LDRs, as a result not enough voltage drops is measured across each LDR to judge the position of sun. To overcome this, a short delay of 1.5 minute is provided which checks the voltage of both LDRs. If voltage remains less than the defined threshold voltage, microcontroller check consecutively 10 times to make a wait state equal to 15 minutes to get one-step, i.e., 3.75^{o}.

3.1.3 Bi-directional Rotation

The tracker rotates from east to west throughout the day to follow the sun. At dusk the tracker faces west. Tracker is required to come back to initial position for next day. A variable *I* counts tracker steps it takes throughout the whole day; approximately 40, equals to 150^{o} rotation. Once the variable *I* counts greater than 40 steps, tracker moves back to its initial position for the next day and power supply turned off until LDRs receive sunlight at Dawn. A brush along roller was added to clean the dust accumulated on the surface of panel, twice a day. Analysis and calculation shows that the proposed system can harvest 20% more energy, compared to fixed mount system. Huynh et al. [8] compared and analyzed open and closed loop trackers theoretically and experimentally. Data comprises of current and voltage output of each tracker was recorded on May 15th, 2013 from 7:00 am to 5:00 pm. Mathematical calculation in [8] shows that power gain for open and closed loop trackers were 25.96% and 33.00% compared to static panel of same size.

3.2 Dual-axis Tracking Mechanism

Furkan et al. [21] designed and analyzed an open loop, dual axis solar tracker. The performance of fixed tilted (37^{o}) and dual axis movable solar tracker was analyzed theoretically and experimentally for climatic condition of Denizli, Turkey. DC motors were used to control the movement of solar tracker. Microcontroller along with external real time clock (RTC), two position sensors (potentiometers) and motor driver circuit were used to calculate the position of sun. In addition to experimental data, visual C#2005 computer programming was used for equations of solar radiations values of fixed and moving PV systems. The performance of two-axis tracker over fixed one was compared for the month of May and June, and was found the energy increase up-to 64% for tracking system.

Mahmood et al. [22] designed and implemented an open loop dual axis solar tracker using programmable logic controller (PLC). For PV panel rotations, direct current (DC) motors were used. The built-in yearly, weekly and hourly timers of PLC were used to accurately track the sun throughout the year. The angles that were used in tracking have been calculated during rise hours of the day, for all days of years. MATLAB was used for computation and plotting. The equations of zenith angle and sun rise hours were converted to executable *m.file*. The programming performs calculation on the basis of these equations in [22] and extracts angles for vertical and horizontal angles for each and every day of the years. A simple solar positioning algorithm was presented in their study. Power outputs of the proposed system and fixed one were compared. A power gain of 38% was obtained with their proposed system.

Farhana et al. [23] discussed the structure and application of azimuth-altitude dual axis solar tracker. Mathematically, in [23] it was proved that solar energy increases 50-60% when dual axis solar tracker was used. The controlling circuit consists of microcontroller (PIC 18F452), two stepper motors (one for azimuth angle and the other one for latitude), six LDRs (three for azimuth tracking and the remaining three for elevation tracking). Energy output of fixed PV system and dual axis solar tracker was calculated which is 7.6KWh/m^2/day and 12 KWh/m^2/day respectively. It was shown that dual axis solar tracker maximize the energy output twice. Daily electricity expenditure was calculated for an ideal house of four family members i.e. 15.58KWh/day and the proposed solar tracker generates 12 KWh/day. From the national grid about 3.58 KWh/day energy was required.

Titirsha et al. [24] performed valuable advancement in dual axis tracking system. Mirrors were used on both sides of PV panels; to re-capture the reflected light from PV panel. The more photon strikes on PV panel the greater energy will be produced. Mathematical calculations in [24] were carried out and energy production for all day was calculated. It was realized that using the proposed system an increase of 57% would be achieved in output energy.

Bajpai et al. [25] designed automatic, two-axis solar tracker. The control circuit consists of microcontroller (ATMEGA 32L). Three LDRs (for sensing sunlight) mounted on rectangular plate at 120^o separation to each other at top in center of PV module and two DC motors. Their experimentation consists of Wheatstone bridge circuit mechanism. Code Vision AVR (software) was employed to generate the code for microcontroller and PROTEUS (software) was employed for logic simulation. In experimental studies 37W PV panel was used for static as well as for tracking system. Comparative performance analysis was carried out for static (37^o *tilt* angle) and for proposed two axis tracking system. The data was recorded on hourly basis from 6AM to 5PM. The ambient temperature at the time of experiment was 27^o C. The performance of both systems was comparatively analyzed for the following parameters:

a) Solar irradiation received on collector.
b) Maximum hourly electrical power (P_{max}) and efficiency gain (η gain).
c) Short circuit current (I_{sc}) and Open circuit voltage (V_{oc}).
d) Fill Factor (FF).

The irradiation gain for proposed tracking system was insignificant from 11 AM to 1 PM due to small azimuth angle. For the rest of sunshine hours the gain was significant due to non-alignment of sun rays with plane perpendicular to fixed PV module. Maximum irradiation gain of 22.19 W/m^2 was recorded at 8 AM while minimum gain of 2.33 W/m^2 has been recorded at 1 PM (output degrades with high ambient temperature).

The electrical output for both systems along with gain in yield was recorded hourly and compared. Furthermore, due to low cell temperature, high power gain was recorded at morning and evening session. Each degree rise in ambient temperature decrease the output by 0.5% of crystalline silicon solar cell. The maximum (efficiency gain) η_{gain} of 59.6% and 76.96% at 7 AM and 4 PM, respectively, had been recorded. While the minimum η_{gain} of 1.02% and 0.04% at 11 AM and 12 PM respectively was recorded because of high temperature.

Hourly variation of V_{oc} (open circuit voltage) and I_{sc} (short circuit current) was recorded. Comparison shows that from 11 AM to 1 PM, V_{oc} obtained with their proposed tracking system remain the same however, I_{sc} remains higher for tracking system compared to fixed system. V_{oc} also depends upon insolation (amount of solar energy per square centimeter per minute) received so at evening and morning V_{oc} was minimum with static system due to less solar radiation.

Fill-Factor (FF) was correlated with series and shunt resistances. From 6 AM to 3 PM the solar cell temperature was high for tracking system; increases series while decrease the shunt resistance – cause losses. Fill Factor was low for the proposed system indicates its effectiveness at low temperature.

The average η_{gain} and max power obtained by this proposed dual axis solar tracker was 28.87% and 5.0423 W/hr, respectively, compared to the static PV system.

Pakistan receives abundant sunlight almost though out the year. Waleed et al. [5] discussed the geographical location of Pakistan. In Pakistan annual irradiance is approximately 2200-2500 hours per year. They designed closed loop, dual axis solar tracker which follows the sun. The control circuit consist of microcontroller (PIC 16877), LDR GM9516 and two stepper motors of rating 6 V & 0.6 A. Four LDRs were used for sun tracking, each pair for horizontal and vertical. On four sides of PV panel LDR was mounted. The light intensity on each LDR should be the same. On horizontal plane if left LDR receive less light than right LDR, the controller will move the PV panel in such direction that the both LDRs receives same light intensity. The same procedure was applies for vertical movement. Monocrystalline PV panel of 16x16 dimensions was used for experiment. The data was recorded on hourly basis from 8:00 AM to 6:00 PM. First, *V-I* parameters were recorded for fixed, single axis and dual axis trackers and subsequently power output for each system was calculated. Power output for all the three systems were compared, it was observed that using dual axis solar tracker one can achieve power gain up-to 40% compared to static PV system.

Ferdaus et al. [12] performed designing, implementation and testing of a hybrid dual axis solar tracking system. The tracker operates on two motors to rotate the solar panel. One for east-west motion whiles the other for north-south motion. The proposed system was operated and tested in three modes, i.e., static, continuous and hybrid. It was realized that the hybrid mode harvest 25.62% more energy than static mode while 4.2% less than continuous mode but further comparison of results showed that the hybrid movement consume 44.44% less energy compared to continuous mode.

3.3 Passive Tracking Mechanism

Narendrasinh et al. [2] designed open loop single axis passive solar tracking system works on Zomework principles. High volatile liquid filled in two metal (stainless) canisters with high pressure, fixed on both sides of the rack. Both canisters were connected to each other by a metal pipe. The complete system mounted on a fixed pole, that PV panels could easily be rotated. Aluminum plates were fixed on both cylinders in such orientation that outer half portion was shaded. The model start the day, facing west but when sun raises in the east, the radiations strikes the west side of cylinder filled with volatile liquid of low boiling point. The liquid gets heat in narrow tubes and moves toward east which cause the imbalance, rotates the tracker eastward. In their experimentation, aluminum plates were used to control the heating process of cylinder. If one cylinder exposes more to sun radiations than other, its vapor pressure increases and enforces the liquid to move toward the cooler side. This imbalance rotates the rack until the cylinders are equally shaded. The tracker completes its daily cycle facing westward and sleeps in this position throughout the night until the sun rises in the next morning. The performance of this tracker was test using three different liquids having following properties mentioned in Table 2.

The power output was calculated for both static mounted PV modules and the desired tracker PV modules. Using the desired tracker an increase of 23.33% in power output was recorded. Further, a solar system of 12-modules with the desired tracker delivers the same power as 15-modules mounted on static rack. Hence, time of three modules was saved.

Clifford et al. [26] designed a novel passive solar tracker that have low cost and is suitable for operation in equatorial regions. The tracker works on passive mechanism; high pressure and low boiling liquid was filled in the cylinders attached

Table 2. Liquid's properties test.

S. No	Properties	Volatile liquids		
		Thinner	Methanol	Acetone
1	Chemical formulae	CH_2Cl_2	CH_3OH	$(CH_3)_2OH$
2	Boiling point (°C)	4.00	64.6	56.2
3	Vapor pressure (mm Hg)	300.0	96.0	181.7
4	Density (g cm^{-3})	1.325	0.271	0.784
5	Molar weight (g mol^{-1})	84.94	32.04	58.1
6	Specific gravity (at 25°C)	1.315	0.791	0.788

on two sides oppositely. The striking beam of sun rays produced imbalance of pressure, which moves the tracker. Computer modeling were performed which predicts an increase in efficiency up to 23% compared to static PV panels.

It is obvious from the above discussion that tracking system has good impact on the efficiency of the PV system. Furthermore, the literature review suggest that tracker is favorable in large power system however, not suitable for small scale power system because extra power is needed for its operation as well as technical persons are also need to ensure proper maintenance on time.

3. CONCLUSIONS

Solar tracker is employed to harvest maximum energy from the solar system. In tracking, it is essential to align the panels normal to solar irradiance. In this study, various developed tracking techniques were reviewed and analyzed. Obviously, the open loop trackers are simpler, less expensive to maintain compared with closed loop trackers and are reliable. The open loop trackers have no feedback mechanism; therefore, often their efficiency is lower than the closed loop trackers. The closed loop trackers can perform more efficiently by introducing the feedback phenomenon to track sun irradiance. Alternatively, closed loop trackers are expensive and complex to manage, compared to open loop trackers. Concentrated PV panels (multi junction solar cell) and concentrated solar power (tower solar system) need high accuracy while flat solar panels yield about 98%, if the target (sun) is off by 10 degrees. It was further observed that single axis tracker system might be one of the best options for operating flat panel solar power plants; however, for concentrated solar power plants dual axis tracking system would produce an enhance amount of power.

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