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Performance Comparison and Cost Analysis of Single Axis Tracking and Fixed Tilt PV Systems

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***Abstract*—Sun tracking systems are the most effective and efficient means of generating maximum photovoltaic (PV) power because the PV panel is continuously aligned to remain constantly normal to incident solar radiation throughout the day. Experimental studies were carried out using 37 Wp PV panels over a prolonged duration of one month (October, 2015) to evaluate the performance of a low cost tilted single axis tracker in comparison with a fixed tilted PV panel which is inclined at an angle equal to the latitude of Indore city (22º 43', North latitude), Madhya Pradesh , India. Performance of the proposed single axis tracker in comparison with a tilted fixed PV panel was observed to be quite encouraging with an average energy gain of 37% under sunny and clear sky conditions. However, performance of both the systems deteriorated with decrease in duration of direct solar irradiance during cloudy and heavily overcast conditions. Cost analysis of the systems show that payback period of the tracking system is well within acceptable limits and that a tilted single axis sun tracking system is economically viable and can be used with advantage.**

***Index Terms*— Single axis sun tracking system, PV panel, Energy gain, Performance comparison, Cost analysis, Payback period.**

I. INTRODUCTION

RENEWABLE energy sources do not cause environmental degradation but provide the most sought after clean and green energy that can protect and safeguard the environment. Among all the renewable energy sources solar PV power generating systems are becoming exceedingly popular, will continue to do so due to the steep reduction in installation cost, and increased cell efficiencies [1]. The annual average growth rate of solar PV operating capacity in the world was the highest at 55% during 2008 through 2013 followed by wind power at 21%. India receives an annual average Global Horizontal Irradiance (GHI) of about 5kWh/m^2/day. With nearly 58% of the geographical land area having the potential for solar energy production, this gets translated into a solar potential of nearly 9 million GWh per day [2]. Thus, solar PV proves to be the most logical alternative to overcome the impending energy crisis.

Experimental analysis was carried out for a prolonged duration of one month to validate the performance of the proposed PV power generating system. Three types of weather conditions prevailed during this test period of October, 2016. Ten intermittent days during the test period were quite sunny and clear sky with good values of Direct Normal Irradiance (DNI), 17 intermittent days were sunny and cloudy conditions with normal values of DNI and 4 days were cloudy and heavily overcast conditions with poor values of DNI. Performance of the tilted single axis sun tracking PV system was compared with that of a fixed tilt PV

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system considering all the three weather conditions.

Tilt angles of both the fixed and tracked systems was identical with a south facing downward tilt of 23° N, which is equal to the latitude of Indore city (Madhya Pradesh, India). Identical poly crystalline PV panels with a power rating of 37 kWp were used in the experiment to compare the performance of the tilted single axis tracker with a fixed tilt PV system. All electrical parameters were measured using calibrated digital measuring instruments with their inaccuracies taken into consideration. It was observed that the performance of the single axis tracking system was exemplary during sunny and clear sky conditions with a very good value of average energy gain in the range of 37%. The average energy gain over a period of 17 days was in the range of 30% for sunny and cloudy conditions. However, energy gain of the single axis tracking system was miserably poor at 1.01% during cloudy and heavily overcast conditions.

Cost analysis of the fixed and tracking systems was carried out to estimate the payback period of the tracking system and its economic viability. It is observed from the cost analysis that the difference in cost of the tracking system is quite nominal and the payback period is in the range of about 20 months. From the performance test and cost analysis, it is observed that the tilted single axis sun tracking system is able to provide encouraging values of energy gains with a reasonable cost increase and payback period.

II. NEED FOR SUN TRACKING

In order to ensure maximum power output from PV cells, the sunlight's angle of incidence needs to be constantly normal to the solar panel throughout the day. This is achieved by constantly aligning the PV panels in accordance with the sun's daytime movement. This optimal positioning of solar panels to obtain maximum power output can be achieved using Automatic Sun Tracking Systems [3].

A PV panel converts light energy into electrical energy; the amount of electrical energy generated is dependent on the intensity and angle of incidence of the incident direct solar radiation. The power generated by a fixed tilt PV panel reduces as the cosine of the incident angle. This direct loss of power due to the angular incidence of solar radiation is given by the cosine of the angle between the PV panel and solar radiation (ϴ).

$$\text{ie. Direct power lost} = (1 - \cos \Theta)$$

As the incident solar radiation makes an angle of incidence of 80 to 85° there will be a loss of around 85% energy during the morning and evening times. This loss can be made good by rotating the PV panel in the east-west direction (azimuth) to follow the position of the sun continuously throughout the day using a single axis sun tracking system.

The sun also moves through an angle of 46° from north to south over a period of one year. A PV panel positioned at midpoint between the north-south extremes will see the sun move by 23° on either side causing an energy loss of nearly 8.3%. This loss can be made up by using a dual axes sun tracker that continuously tracks the sun both in east-west and north-south directions. Thus, the automatic sun tracking systems help in reducing power losses that occur during the morning and evening times when values of ϴ are quite large [4].

III. LITERATURE REVIEW

The choice to opt for either a single axis or dual axis tracking system is mainly dependent on the amount of cumulative energy generated by the systems. Dual axis tracking systems generate maximum power but are complicated and costly. Single axis tracking systems generate relatively lesser power but are simple and cheap. The choice between the two types of trackers is therefore a compromise between the amount of power generation and cost.

Literature survey shows that researchers all around the globe have obtained encouraging values of energy gains using single axis sun tracking systems as shown in Table I. Based on the literature survey, it is observed that single axis tracking systems are able to provide encouraging values of average energy gains ranging from 11 to 45% during all seasons. It was therefore decided to use a tilted single axis tracking system for obtaining fairly good values of energy gain with nominal investment.

IV. THE PROPOSED SYSTEM

This paper presents a simple, reliable, cost effective and efficient method of low power PV generation using a single axis automatic sun tracking system. The proposed low power sun tracker is a closed loop system with simple electronic circuitry in which the intensity of solar radiation incident on the light sensors is sensed, processed and then fed to a control circuit. The motor control circuit then drives a DC motor which ensures that the PV panel is aligned to remain normal to solar radiation at all times of the day from sunrise to sun set. The light sensing devices are Light Dependent Resistors (LDRs), which effectively respond to the entire spectrum of visible light. The LDR outputs are fed to a dual comparator in which one of the inputs will be a fixed reference voltage and the other input will be voltage drop across the LDRs. Depending on the difference of the two inputs,

TABLE I. SUMMARY OF ENERGY GAINS OBTAINED FROM LITERATURE REVIEW

Sl. No.	Researchers / Publication year	Percentage energy gain			Sunshine hours
		Minimum	Maximum	Average	
1	Cemil Sungur (2007) [5]	--	--	32.5	13
2	Abdallah and Badran (2008) [6]	22	40	--	11
3	Colak and Demirtas (2009) [7]	--	--	45	13
4	Kansal and Singh (2009) [8]	11.76	35.5	--	10
5	Milea (2010) [9]	11	25.34	--	--
6	Huang, Ding and Huang (2011) [10]	--	35.6	23.6	--
7	Ponniran, Hashim and Munir (2011) [11]	--	--	31.9	--
8	Dakkak and Babelli (2012) [12]	--	--	31	7
9	Hamed and Md. El-Moghany (2012) [13]	--	--	24	12
10	Zubair, Suleiman, Abdulazzez and Salihu (2012) [14]	10	45	--	--

the comparators will generate outputs that are fed to a motor driver circuit that drives a DC motor and rotates the PV panel. The geared motor drive mechanism has an advantage that it can drive the PV panel using a low power, high torque motor, thus making the drive system quite energy efficient with its energy consumption being less than 1.5% of the energy generated in a day. Accuracy of the control circuit ensures that the PV panel tracks the sun precisely, thereby providing appreciable energy gain for the PV power generating system. Details related to the fixed and tracked system are appended below.

A. PV Panel

A 36 cell polycrystalline solar PV module (Eldora 40P - Vikram solar make) with a maximum power rating of 37 W_p was used during the field test. The PV panel's physical dimensions are (666 mm × 464 mm × 34 mm) and its weight is 3.8 kg. The PV panels shown in Fig. 1 and Fig. 2 have a V_{OC} = 22 V and I_{SC} = 2.7 A and efficiency of 14% [15].

B. Mild Steel (MS) Supporting Frame

The PV panel is supported on axial shafts mounted on sealed ball bearings. The sealed bearings are fixed on both the vertical arms of a mild steel rectangular tube frame as shown in Fig.1, to allow smooth frictionless rotation of the PV panel. The worm gear assembly along with the DC motor is mounted on one side of the rectangular frame as shown. The entire MS structure is mounted on a base supporting structure to provide the required tilt of 23° N and mechanical stability to the tracker. The fixed PV panel is also mounted on a pedestal as shown in Fig. 1.

C. Drive System Motor

A simple but effective closed loop motor control circuit was designed using a light sensing circuit along with a dual comparator based discrete component electronic circuit. The electronic control circuit controls the DC motor that rotates the PV panel. A 3.5 rpm, 12 V DC, side shaft, geared motor was used in the proposed system. The DC motor was drawing a rated current of 60 to 65 mA with a rated voltage of 12 V; hence, power consumption of the motor was about 750 mW (0.75 W). It is comparatively easier to design a DC motor drive circuit, hence it was economically and technically advantageous to use a DC geared motor for bidirectional rotation of the PV panel.

D. Light Sensor and Motor Control Circuit

Two LDRs are fixed on an insulating sheet on either sides of an opaque separator sheet. The opaque separator sheet does not cast a shadow on the LDRs when the solar radiation is normal to the PV panel and both LDRs are exposed to the sun. As the sun apparently starts moving towards the west, the separator sheet casts a shadow only on the east LDR. This will cause an increase in resistance of the LDR under shadow while resistance of the LDR, which is under direct sunlight, remains unchanged. This change in resistance is detected by the comparator circuit which then causes rotation of the PV panel until both LDRs again come under direct solar radiation i.e. until the PV panel is normal to solar radiation to generate maximum power. The DC motor is used to rotate the PV panel to track the sun as it moves from east to west.

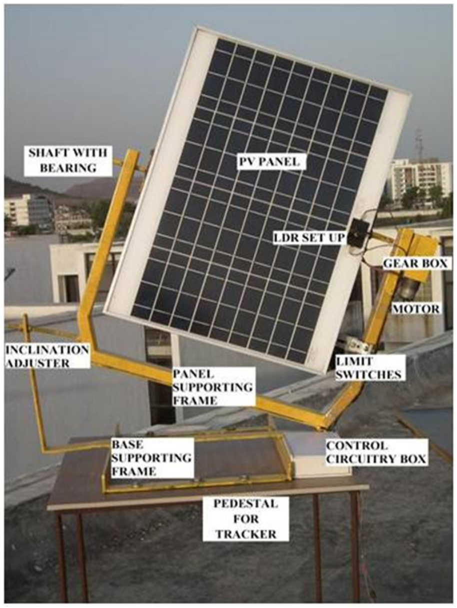

Figure 1. Tilted single axis sun tracker

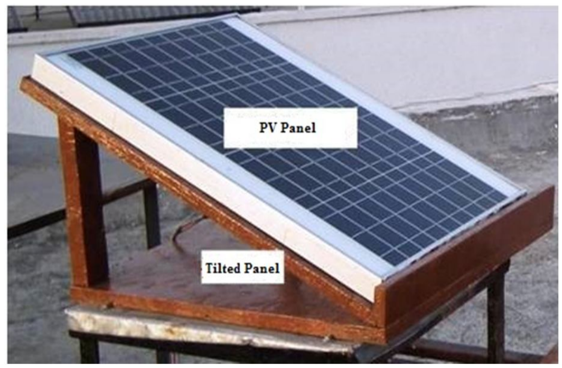

Figure 2. Tilted fixed PV panel

A LM 358 dual comparator based motor control circuit that feeds input signals to a motor driver L293D controls this motor rotation. Fig. 3 shows the block diagram of the motor control circuit. When the comparator outputs are unequal, due to unequal light intensity on the LDRs, the motor driver causes motor rotation and makes the PV panel normal to incident radiation. Again due to sun movement, light incident on the LDRs becomes unequal and results in unequal comparator outputs and again causes rotation of the PV panel until it is aligned to be normal to the incident solar radiation. This process continues and thereby the PV panel is maintained normal to incident solar radiation throughout the day. Fig. 4 shows the experimental set up involving all the digital measuring instruments used in the experimental test procedure.

V. Details Of Experimental Setup

Performance test of the proposed single axis tracking system was carried out during the month of October, 2015 on the 3rd floor roof top of our college building. Field test was conducted soon after the monsoon season during the entire month of October, 2015. Performance of the single axis tracker was compared with the tilted fixed PV panel. The fixed panel was placed making an inclination of 23° N (latitude of Indore) with the downward slope towards south. A magnetic compass was used to locate the geographical N-S and E-W directions to align both the panels appropriately. The PV power generating systems were placed on 3 feet high pedestals to avoid any shadows being cast on them. Readings were recorded manually using calibrated digital meters as shown in Fig. 4 at regular half hourly intervals, between 6.30 AM to 6.00 PM (Total duration of 11 hours 30 minutes).

VI. Results And Discussions

The performance of PV systems is strongly dependent on certain basic parameters - month of the year, day length, solar radiation, temperature and to some extent on relative humidity and wind velocity. Performance comparison of the proposed single axis tracking system in terms of its average daily output energy and energy gain has been carried out based on the three weather conditions viz. (a) Sunny and clear sky conditions (b) Sunny and cloudy conditions (c) Cloudy and heavily overcast conditions [16].

A. Sunny and Clear Sky Conditions

Ten days during the month of October, 2015, the sky was clear and sunny with good values of DNI. The average per day energy generated by the tracking system was 226.02 Wh while that for the fixed panel was 164.94 Wh as seen from Table II.

Energy gain of tracking system is calculated using the formula: $[(E_T – E_F) / (E_F)]$

Where E_T is energy generated by tracked system and E_F is energy generated by fixed system.

Energy Gain = [(226.02 – 164.94)] / (164.94) = 0.3704 = 37.04%

It is thus observed that energy gain of the single axis tracking system is quite encouraging during sunny and clear sky conditions.

B. Sunny and Cloudy Conditions

For 17 days during the test period, weather conditions were such that there would be intermittent sunny and cloudy conditions with the average value of DNI being less than during sunny and clear sky conditions. Hence, the average per day energy generated by both the systems turn out to be less than the sunny and clear sky conditions. From Table II it is observed that the average per day energy output of the tracking system is 190.74 Wh, while that of the fixed panel is 147.01 Wh. Thus, energy gain of the single axis tracking system turns out to be 29.75%.

C. Cloudy and Heavily Overcast Conditions

The weather was cloudy and heavily overcast for four days during the month of October, 2015. On such days, the DNI values were too small resulting in very low values of output energy. It is observed from Table II that the average per day energy output of the tracking system was 50.40 Wh, which is quite close to that of the fixed panel of 49.86 Wh.

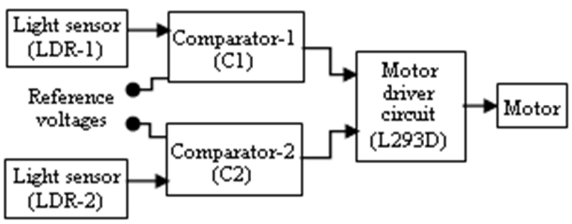

Figure 3. Block diagram of closed loop motor control circuit

Figure 4. Experimental set up

Thus, the energy gain turns out to be 1.01%, which is almost equal to 1. This means that the tracking system is not able to provide energy gain during cloudy and heavily overcast conditions.

Single axis sun tracking systems provide very high values of energy gains both in the early morning and in late afternoons as seen in Fig. 5. The energy gain value on sunny and clear sky days is seen to be quite high until 10.00 AM, and then remains low in the forenoon and mid noon. The gain then starts increasing from 3.00 PM to 5.30 PM. This results in an overall high-energy gain for the tracking system.

VII. Cost Analysis

The advantage of any system can be validated only if the system works out to be technically viable and economically feasible. It has been experimentally proved that the tilted single axis tracking system has reasonably good values of energy gains both during sunny and clear sky conditions and during slight cloudy conditions.

The tilted single axis tracking system and the tilted fixed PV panel were fabricated with locally available materials, components and accessories in the college workshop. The breakup of fabrication cost of the single axis tracking system and the tilted fixed PV panel is appended below.

a. Cost of fabricating mechanical structure of the tracker - INR. 900.00 ($29.65)
b. Cost of electrical and electronic components for motor control system- INR. 800.00 ($ 11.86)
c. Cost of PV panel- INR. 2000.00 ($29.65)
d. Total cost of only tracking system - INR. 1700.00 ($ 25.2)
e. Cost of fabricating tilted fixed PV panel - INR. 400.00 ($5.93)

f. Difference in cost between tracking and fixed systems - INR. 1300.00 ($19.27)

g. Percentage increase in cost of the tracking system - 30.76%

Considering a power tariff of INR 9.00, the payback period will be about 20 months. Thus, the excess amount of money spent on the tracking system can be recovered back in 20 months and thereafter the benefit of harvesting excess energy is available free of cost. Thus, the proposed system is technically viable and economically feasible.

TABLE II AVERAGE PER DAY ENERGY GENERATED BY FIXED PANEL AND SINGLE AXIS TRACKER

Sl. No.	Weather conditions	Average per day energy generated (Wh)		Percentage Energy Gain
		Fixed Panel	Single Axis Tracker	
1	Sunny and clear sky	164.94	226.02	37.04
2	Sunny and cloudy	147.01	190.74	29.75
3	Cloudy and heavily overcast	50.40	49.86	1.01

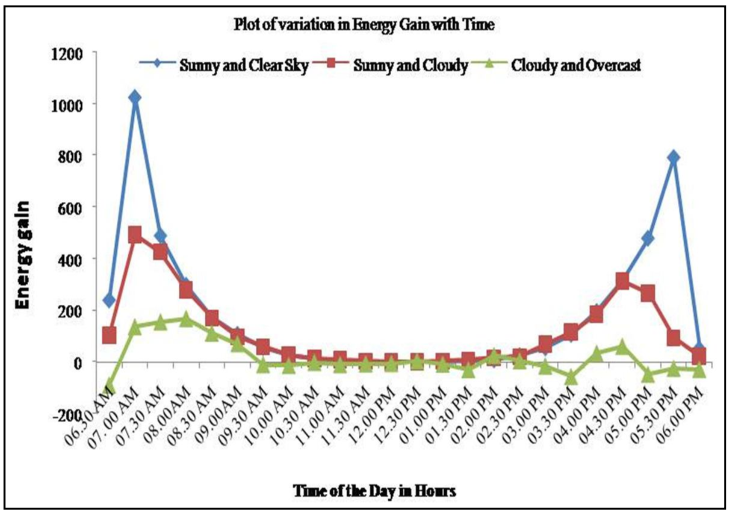

Figure 5. Graph of variation in Energy Gain with Time

VIII. CONCLUSION

After experimentally verifying the operation of the proposed single axis tracking system and carrying out the cost analysis, we have arrived at the following conclusions:

1. The tilted single axis tracking system provides exemplary values of energy gains in the range of 37% when compared to a tilted fixed PV panel during sunny and clear sky conditions.
2. With intermittent sunny and cloudy conditions, energy gain obtained is still quite good and is in the range of 30%.
3. Very high values of energy gains are obtained in the morning and late afternoons on all days, thereby resulting in overall high values of average energy gain for the tracking system in comparison with fixed system.
4. Cost analyses of the PV power generating systems indicate that the tracking system has a reasonably good payback period of 20 months with a feed in tariff of INR. 9.00
5. The proposed tilted single axis tracking system is therefore technically feasible and economically viable as a power-generating source without causing any environmental pollution and degradation.
6. The proposed tracking system is cost effective and efficient and can therefore be up scaled with advantage to be used in high power generating systems.
7. The system can produce much higher energy gains during the summer season when the solar irradiation is high and duration of daylight hours is more than in the month of October.

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