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Research Article

Solar Tracker: Performance Analysis and Optimisation of Efficiency

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ABSTRACT

Solar energy is one of the richest source of renewable energy on Earth, thus its harnessing is very much necessary for the useful conversion of light energy into electric energy. Solar panels are developed in this direction. Many scientists have developed various methods to gather the solar irradiation in order to maximize the extraction of electric power from the Photovoltaic generators. However, the problem with the solar power is that it is directly dependent on light intensity. The main hindrance with solar panels is their low efficiency with huge investment. Studies show that a solar panel converts 20-40% of energy incident on it to electrical energy. The solution is to use a tracking system[1, 7] that maintains the panel's position orthogonal with the light source. There are many tracking systems designs available including passive and active systems with one or two axes of freedom.[8, 9] It has been found that the overall efficiency gain in single-axis solar tracker designed in[10] is 27% than that of fixed mechanism. We had optimised the tracker efficiency by performing the experiment with solar tracker for consecutive three days and thus results were analysed by using stat-ease software. Moreover, the testing showed that the power used by the tracking system was much less than that of power gained by tracking system. While working on the developed set-up, focus was given on the incremental efficiency of the solar power generation system. In the present work, further performance analysis is taken up with the help of various parameters viz. Specific Energy Production (SEP), Performance Ratio (PR), Ground Cover Ratio (GCR) and Surface Performance Ratio (SPR)[11] to further elaborate the efficiency enhancement in solar trackers as compared to fixed systems.

Keywords: Solar Tracking, SEP, PR, GCR, SPR, PV Panel, Optimization

Introduction

The sun's energy is considered as the leading source of fuel. Radiant sunshine and water are harnessed using various technologies which includes solar engineering, artificial photosynthesis, solar photovoltaic, solar energy and solar heating. It is estimated that at noon earth receives approximately 1000 Watts per square meter of area and therefore direct conversion from solar energy to electricity has already been made and solar power plants are now being set up on a large scale.

The success of solar energy systems depends upon the quality and amount of solar energy available at a specific location. However, the amount of electricity obtained is directly proportional to the intensity of sunlight falling on the photovoltaic panel. The efficiency of solar panel is limited due to some environmental conditions; thus, the efficiency of photovoltaic system needs to be enhanced which can generally be done by three methods. The first method is to maximize the power gain of solar cells. Second, enhance the efficiency of control algorithms. Third, opt for a tracking system for maximum possible effciency. Among all these three methods, the most feasible one is the solar tracking.[1,9]

A solar tracker is a mechanism configured in such a way that enables the movement of PV panel. This movement of the PV surface, aligns to the normal of the direction of solar irradiance with the aim of receiving the maximum sun light.[12-28] This tracking mechanism comprises of mechanical links, driving motors and the controllers.[10] The solar tracker starts following the sun rays from the morning, continue till evening and starts all over again.

The paper is organised as follows. Section 2 will discuss the design and experimental set-up for solar tracker with detailed description of its mechanical and electrical components.[10] In Section 3, performance parameters like SEP, PR, GCR, SPR etc. Were calculated to evaluate performance of solar tracker and compared it with fixed PV panel. In Section 4, discussion regarding optimisation of efficiency of solar tracker was done and finally Section 5, comprises of concluding remarks and future aspects of our work.

Design of Solar Tracker

Mechanical System

The complete structural design[10] of the solar tracker is shown in Figure 1. The total weight of solar tracking system is 1.5 kg with overall dimensions of 305 mm x 185 mm x 278 mm. The designed tracker is so compact that it can be placed on the roof as well as may be mounted on the wall. The main elements consist of a PV panel, stepper motor, electronic board and U-shaped aluminium structure. The design of the tracker enables the single-axis movement of the PV panel preferably East to West while in operation. The motor located on one side of the aluminium structure actuates the PV panel during tracking. The base of the aluminium structure is designed in such a way that all the electrical assemblies, as well as the battery, can be mounted on it thus making the structure more compact

Electrical System

The electrical part of the solar tracker includes main controller unit i.e. Arduino Mega 2560, lead-acid battery, resistors, real-time clock, sensors, etc. detailed in the Table 1.

Table 1.Details of Electrical Components

S. No.	Item	Specifications	Function
1	Arduino	Arduino Mega 2560	Main Controller and Memory Storage Device
2	IC	LM317	Voltage Regulator for Solar Cell Output Control
3	IC	DS1307	Real-Time Clock Ic for Accurate Time and Date
4	Crystal	32.768 kHz	Crystal Oscillator for Clock Pulses to RTC
5	IC	L293D	Motor Driver IC for Amplifying Current and Voltage
6	IC Base	4 pins	Case to Place IC
7	IC Base	16 pins	Case to Place IC
8	Motor	DC 10 RPM	Angular Movements Are Controlled Using Motor
9	Resistor	10kΩ, 4.7kΩ, 220Ω, 680Ω	Resistors are used to Control the Flow of Current
10	Variable Resistor	10kΩ	Its Resistance can Varied by Moving its Mechanical Body
11	Battery	6V	Energy Storage
12	Diode	IN4007	Regulate the Current Flow Direction
13	Sensor	Current Sensor ACS712	Hall Effect Sensor

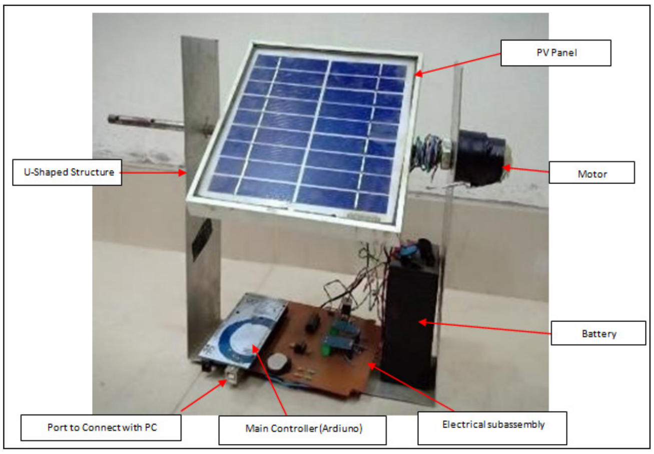

Figure1.Actual Set-up of Solar Tracker

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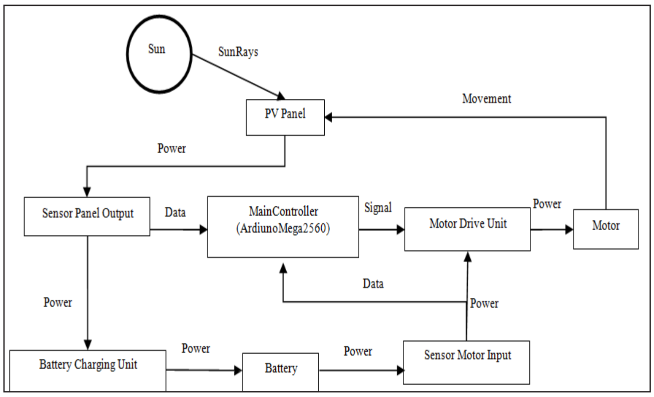

Figure 2.Block Diagram of Solar Tracker Working

Performance Analysis

Power versus Time

In order to validate the proposed solar tracker system in Figures 1 and 2, it was necessary to compare the results obtained experimentally of the solar tracking system with the PV system with fixed arrangement. In the plot Figure 3, tracking system generates relatively higher power (or more efficient) output as compared to the fixed solar panel. Here, the efficiency elaborated as the fraction of the variation between the sum of generated power by fixed panel and tracking system to the power generated by a fixed panel for the entire period of observation. The efficiency obtained by the experiment is about 27% higher than that of the fixed system, refer below Figure 3. During the complete day, the solar tracking system was inefficient in the noon period when the solar irradiance collected by both the fixed as well as with tracking system is almost the same. Therefore, the power generated by the fixed panel is quite comparable to that of generated by the solar tracking system and hence almost zero efficiencies were obtained for that period. This became the reason why the researchers are more inclined towards fixed panel especially for the locations where the maximum solar irradiance was received in the noon time only.

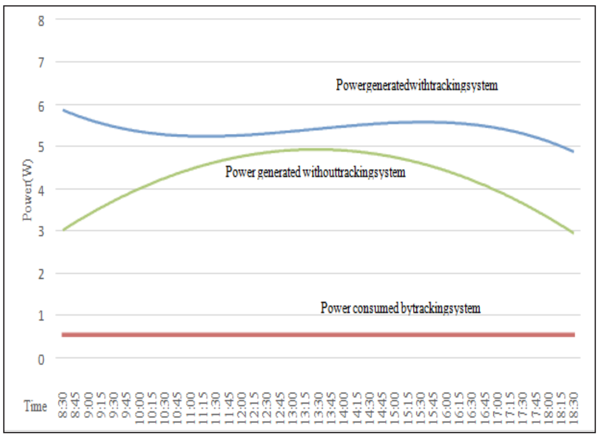

Figure 3.Plot Between Power and Time

Calculation of Performance Parameters

Four parameters had been calculated to evaluate the efficiency of the solar tracking system viz. Specific Energy Production (SEP), Performance Ratio (PR), Ground Cover Ratio (GCR) and Surface Performance Ratio (SPR). The readings were taken during the day for 10 hours from 08:30 am to 06:30 pm. Here are some specifications of the fixed solar panel and one with tracking system as in the below Table 2.

Table 2.Specifications of Fixed and Tracking System

Specification	Fixed System	System with One-axis Tracking
Longitude	31.32°	31.32°
Latitude	75.57°	75.57°
Peak Power, PP	12 W	12 W
Mounting	Fixed	One-axis
Modules, N	1	1
Module surface, Sm	342.25 cm^2	342.25 cm^2
PV Surface Proportion	85%	85%
Sensitive Area of PV Panel, S	255.75 cm^2	255.75 cm^2

Specific Energy Production (SEP)

SEP is the ratio of the measured energy production (**E***m*) to the peak power (**W**$_p$) installed in the system. The collected data was shown in the Table 3, and its analysis is shown in Figure 4.

The plot shows the difference in the specific energy production (ΔSEP) for fixed and tracking solar panel. From the plot, it is clear that ΔSEP is minimum during afternoon time and maximum during morning and evening time.

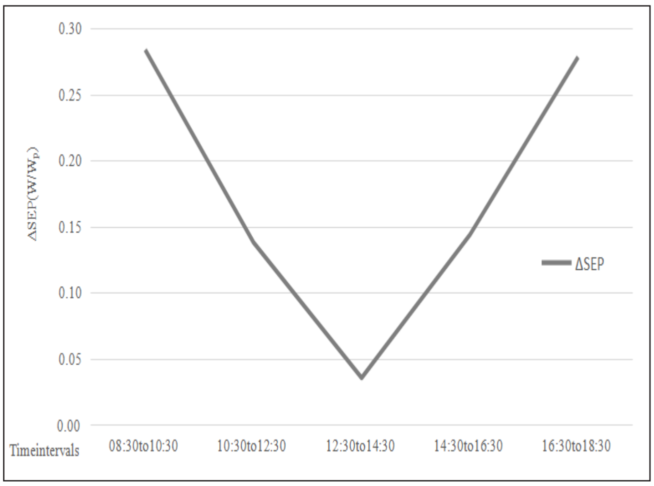

Figure 4.Plot Showing the Difference in SEP for Fixed and Tracking System

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Table 3.Sep Data for the Fixed and Tracking System at Regular Intervals of Time

Period	Em_{fi} (W)	Em_{tr} (W)	SEP_{fi} (W/W_p)	SEP_{tr} (W/W_p)	ΔSEP (W/W_p)
08:30 to 10:30	6.98	10.39	0.58	0.87	0.28
10:30 to 12:30	7.96	9.62	0.66	0.80	0.14
12:30 to 14:30	9.34	9.77	0.78	0.81	0.04
14:30 to 16:30	8.43	10.17	0.70	0.85	0.14
16:30 to 18:30	6.92	10.26	0.58	0.86	0.28

Performance Ratio (PR)

PR is the ratio of the energy production (E*m*), per unit photosensitive square meter (which is proportional to the peak power of the installed PV Panel) and the global irradiation on the flat / horizontal surface per unit m² (H*m*).

The equation for calculating the PR is shown below:

$$PR=E_m/(H_m.n.S) \quad (1)$$

Where 'η' denotes the number of solar panels installed. Here, the value of η is 1 and 'S' denotes the surface area of Photos Sensitive region.

It is clear from the plot that PR value is higher than that of fixed panel during morning and evening times.

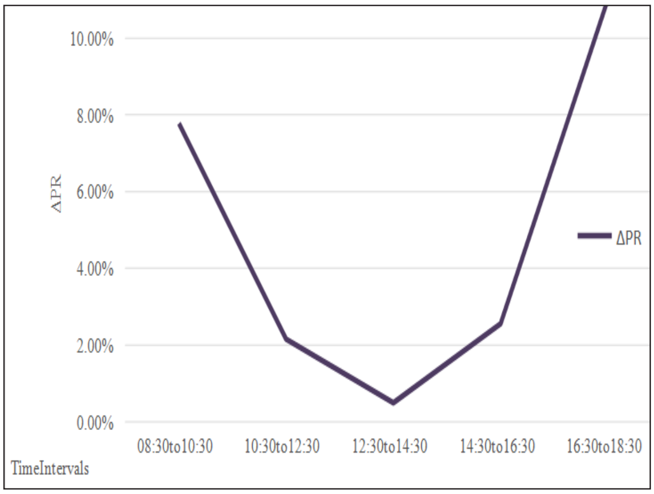

Figure 5.Plot Showing the Difference in PR for Fixed and Tracking System

Table 4.PR Data for the Fixed and Tracking System at Regular Intervals of Time

Period	Em_{fi} (W)	Em_{tr} (W)	Hm w/ m^2	PR_{fi} (%)	PR_{tr} (%)	ΔPR (%)
08:30 to 10:30	6.98	10.39	457.00	15.89	23.66	7.77
10:30 to 12:30	7.96	9.62	800.50	10.34	12.51	2.16
12:30 to 14:30	9.34	9.77	904.00	10.75	11.25	0.50
14:30 to 16:30	8.43	10.17	702.50	12.49	15.06	2.57
16:30 to 18:30	6.92	10.26	316.00	22.78	33.80	11.02

Ground Cover Ratio (GCR)

Ground Cover Ratio is defined as the ratio of the area occupied by the photo voltaic panel to that of the whole area occupied by complete tracking system. As the value of GCR getting higher, better is the utilization of the land area.

Table 5.Data of GCR

PV Panel Mounting	Area Covered by PV Panel	Ground Area Covered	GCR (in %)
Fixed	25575 mm²	34225 mm²	74.73
System with Tracker	25575 mm²	56435 mm²	45.32

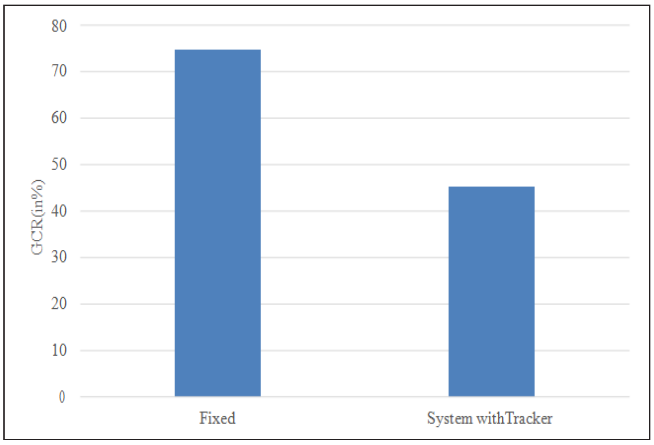

Figure 6.Plot Showing the GCR Values

Surface Performance Ratio (SPR)

SPR may be derived as the product of SEP and the Peak Power planted per unit of land in m². In equation form, SPR may be written as

$$SPR=SEP.P/S=E_m/P.P/S=E_m/S \quad (2)$$

The significance of SPR does not limit to the enhancement in the power generation, rather it also accounts for the areas required for the installation. It is necessary to highlight that value of SPR is independent to the size/ power of the panel installed.

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Table 6.Data for PR

PV Panel Mounting	Sensitive Area PV Panel (mm^2)	$\sum Em$(w)	SPR (kWh/m^2)
Fixed	25575.00	39.63	1.55
System with Tracker	25575.00	50.21	1.96

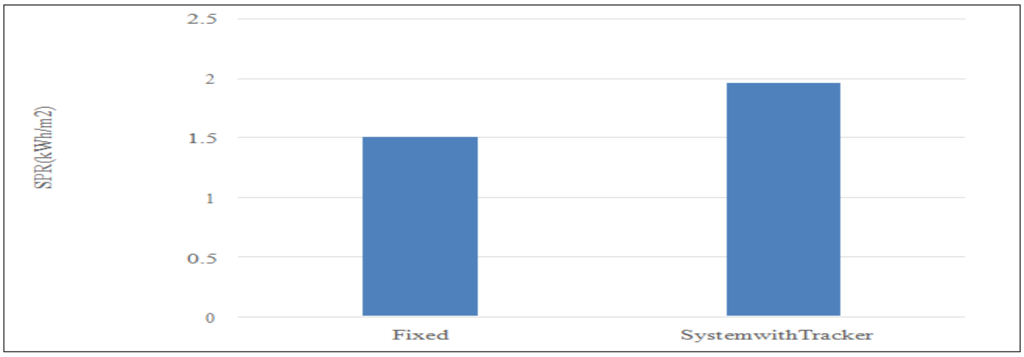

Figure 7.Plot Showing the SRP Values

Optimisation (Maximisation) of Tracker Efficiency

In order to maximise the efficiency of solar tracker, an experiment was conducted for three days and readings were noted. Each day, different time gap (of tracking) had been set in the system and accordingly data was captured. A software named stat-ease/ Design-expert (version 12) software had been used for this purpose. Design-Expert provides amazing tools to spread out a perfect investigation on the procedure, blend or mix of variables and segments. This software tool performs the calculation/analysis in the three steps viz. designing of experiment, analysing of data and finally the visualisation of results.

Design of Experiment

Following parameters had been considered for the optimisation study:

1. Input parameters: Angle traversed by tracker (Degrees) and Time Gap in tracker movement (Minutes). Angle traversed by trackers corresponds to the Azimuth angle traversed by the Sun.
2. Output parameters: Power consumed by the system (Watts) and Power Generated with tracking system (Watts).

Table 7.Input Variables/ Factors

Fator	Name	Units	Minmum	Maxmum	Coded Low	Coded High	Mean	Std. Dev.
A	Angle	Deg	38.00	171.00	-1 ↔ 38.00	+1 ↔ 171.00	100.34	48.37
B	Gaps in Tracking Steps	Min	5.00	15.00	-1 ↔ 5.00	+1 ↔ 15.00	10.00	3.65

Table 8.Output Variable/ Response

Response	Name	Units	Observations	Minimum	Maximum	Mean	Std. Dev.	Ratio	Model
R1	Power Consumed	W	16	0.44	0.68	0.52	0.06	1.55	2FI
R2	Power Generation	W	16	2.56	5.67	4.21	1.05	2.21	2FI

Table 9.Variables Matrix Defined by the Software

Name	Units	Type	Std. Dev.	Low	High
Angle	deg	Factor	0	38	171
Gaps in tracking steps	min	Factor	0	5	15
Power Consumed	W	Response	0.052	0.44	0.68
Power Generation	W	Response	1.144	2.56	5.67

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After giving the input to the system by defining all the relevant data of the input and output parameters (Table 7 to 9), the software had generated the below Table 10, with first three columns filled. In the remaining two columns of output parameter, obtained experimental data was filled.

Table 10.Data Of Input and Output Variables

Run	Angle (^{0})	Gap (min)	Power Con (W)	Power Gen (W)
1	38	10	0.46	3.37
2	104.5	10	0.52	5.52
3	104.5	5	0.68	5.63
4	71.25	15	0.51	4.08
5	171	10	0.48	3.17
6	71.25	5	0.61	4.12
7	171	15	0.44	3.37
8	104.5	10	0.52	5.52
9	171	5	0.57	2.56
10	38	5	0.51	3.74
11	171	10	0.48	3.17
12	71.25	15	0.51	4.08
13	71.25	10	0.58	4.55
14	104.5	15	0.49	5.67
15	104.5	10	0.52	5.52
16	38	10	0.46	3.37

Analysis of Data

The data were analysed by the Stat-Ease Software and various graphs/ values/ concepts showing the impact of both the input parameters to the output parameters respectively. Thereafter the data had been analysed and the iterations had been calculated which is providing the maximum output of the solar tracker.

Power Consumed

The final equation obtained from software in terms of actual factors

Power consumed = 0.540103 + 0.000862 * Angle – 0.001046 * Gaps in tracking steps – 0.000094 * Angle * Gaps in tracking steps

The significance of the above equation is that it shows the various interlinkage of the factors/input parameters, which further helps is making the predictions of the response/ output parameters. On its contrary, this equation must not use for predicting the output pertaining to the relative change in the individual factor.

Figure 8, displays the plot of actual values of response versus the predicted values of response 1 (Power Consumption). It also helps in segregating the observations that are not predicted exactly by the model. The coloured points showed the actual values of obtained through experiment. Actual values range from 0.44 W to 0.68 W. Here, the straight line with the slope of 45^0 is the predicted value and the square coloured dots are the actual ones. The majority of actual values are scattered near to centreline except one with value of 0.68 W.

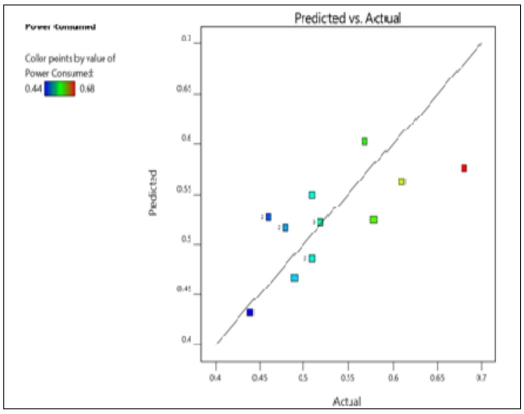

Figure 8: Power Consumed: Predicted vs Actual

Figure 9, corresponds to the Perturbation Graphs for response 1 named Power Consumed: The perturbation graph indicates the comparison of impact by input variables laid at specific location lying within the boundaries of design space. The value of output variable derived out by varying the value of one input variable throughout its complete range is plotted, keeping all other conditions in the design space as constant. The steepness in this plot pertaining to that input factor shows the sensitivity of the output variable in relation to the respective input factor. On the other hand, the flatness in the curve pointing towards Insensitivity or resistance to change in reference to that factor. As observed in this Figure, the change in the value of input factor 1 i.e. angle had made less impact on the Power Consumption but on the contrary, gaps in tracking steps have the significant impact on the same.

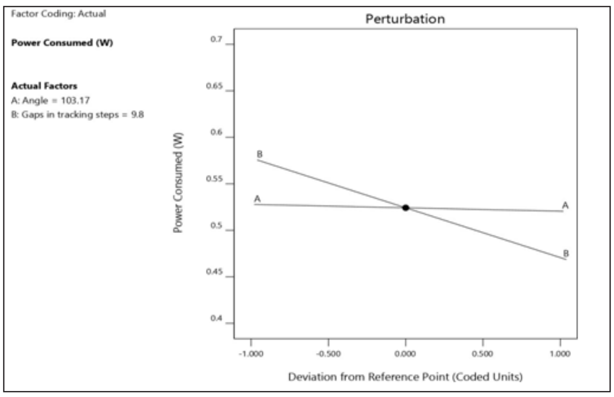

Figure 9.Perturbation Graph of Response1 (Power Consumed)

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Power Generated

The final equation obtained from software in terms of actual factors

Power Generation = 4.58108 – 0.006920 * Angle + 0.009517 * Gaps in tracking steps – 0.000230 * Angle * Gaps in tracking steps

Figure 10 plot of actual values of response versus the predicted values of response 2 (Power Generation). It also helps in segregating the observations that are not predicted exactly by the model. The coloured points showed the actual values of obtained through experiment. The cluster of actual values ranges between 2.56 W to 5.67 W. Majority of the values are in the close vicinity of predicted values but for the few (near to 5.67 W - shown in red colour) values the difference between the predicted and actual value has gone wider.

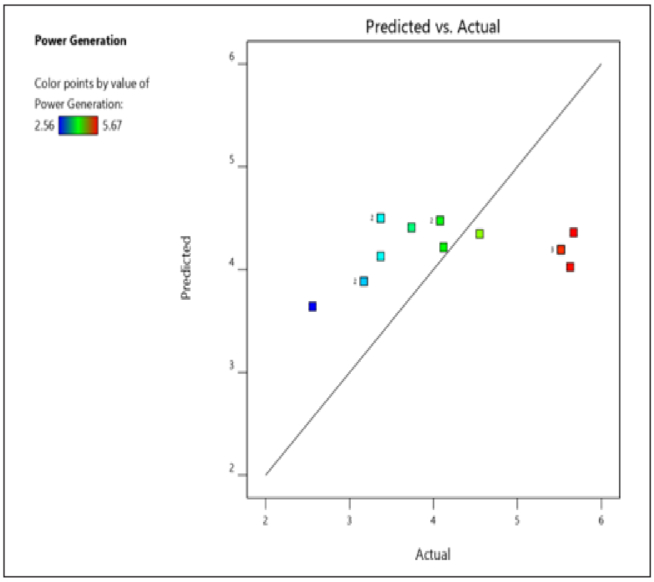

Figure 10: Power Generation : Predicted vs Actual

Figure 11, corresponds to the Perturbation Graphs for response 2 named Power Generation: The perturbation graph indicates the comparison of impact by input variables laid at specific location lying within the boundaries of design space. The value of output variable derived out by varying the value of one input variable throughout its complete range is plotted, keeping all other conditions in the design space as constant. The steepness in this plot pertaining to that input factor shows the sensitivity of the output variable in relation to the respective input factor. On the other hand, the flatness in the curve pointing towards insensitivity or resistance to change in reference to that factor. As per this graph, both the input parameters shown the slight impact on the value of this output variable. Increment in the Gaps in tracking steps has made the positive impact whereas increment in the angle shown the negative impact on the value of output parameter viz. power generation.

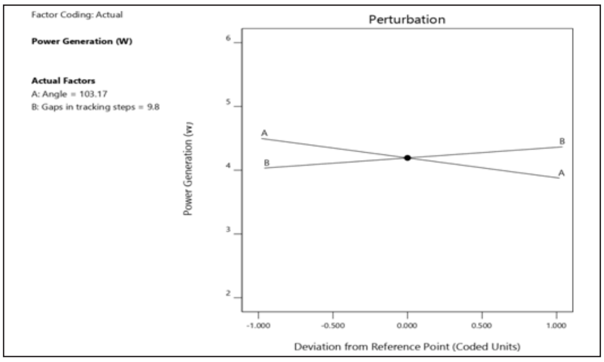

Figure 11: Perturbation Graph of Response 2 (Power Generation)

Visualisation of Results

Trend of Responses w.r.t. factors in reference of the desirability is shown in Figure 12. The optimization model configured through stat-ease software, derive the combinations of the level of factors which simultaneously fulfilling the criteria defined for responses and factors. Desirability is an objective function with the value ranging from zero to 1. This optimization done numerically locates the point that maximizes the value of desirability function. The goals are combined into an overall desirability function. The derived value is totally reliant on the lower and upper limits of the set-in relation to the actual optimum. The aim of maximization / optimization is to find maximized value of the desirability function, not to get to a desirability value of 1.0. Optimization aims to locate the good set of conditions through which the required goals can be achieved.

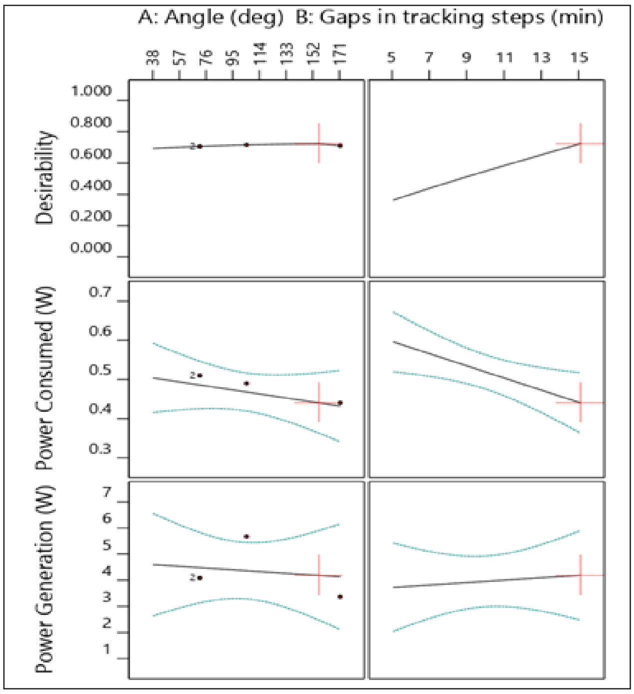

Figure 12.Trend of Responses W.R.T. Factors in Reference of the Desirability

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Maximised Result: In Figure 13, at an angle of 155^0 and with a gap of 15 min tracker speed, the power consumed by the system is 0.44 W and power generated by the system at the corresponding entry is 4.18 W. Net power generation is the difference between 4.18W and 0.44 W, which is 3.74 W, which is maximum.

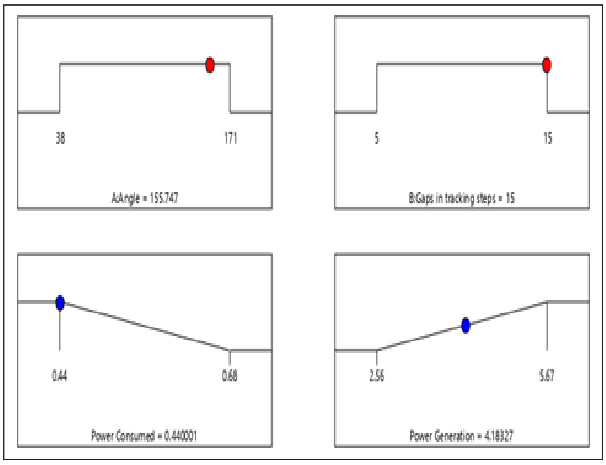

Figure 13.Plot Showing the Optimised Value of Both the Output Parameters

Conclusion and Future Direction

After obtaining the values of all the parameters for both the models, the following points can be concluded:

- SEP is higher in the afternoon especially in the period of 12:30 pm to 02:30 pm for both the systems. Moreover, the difference in SEP indicates that solar tracking becomes more effective in the morning and evening timings rather than the period of the afternoon
- Value of PR is always greater in the solar tracking system in comparison to that of fixed PV system. Further it was observed that throughout the day, PR value of tracking is greater than that of fixed system. In the evening and morning periods, PR value of the tracking system exceeds than the fixed system by 11.02% maximum
- Analysing the land requirements through the SPR and GCR parameter, it was observed that the fixed system is better utilizing the land in reference to the tracking system

Further more, optimisation (maximisation) of the input parameters was performed, which is having the maximum impact on the performance parameters of the tracking system viz. Power Consumed and Power Generated from PV panel with tracking system installed. Input parameters are the Angle Traversed by tracker (degrees) and Time Gap in tracker movement (minutes). At an angle of 155^0 and with a gap of 15 minutes tracker speed, the power consumed by the system is 0.44 W and power generated by the system is 4.18 W. Net power generation is the difference between 4.18 W and 0.44 W, which is 3.74 W, which is the maximum output obtained through the day.

For future research, the system with the same concept can be developed for dual axis solar tracking, by feeding the data of the sun's movement throughout the year while programming. Correspondingly, the optimisation for the panel movement including both the angles viz azimuth and elevation angle can be performed. Solar tracker is a set of mechanical and electrical components that tilts the Photovoltaic panel according to the movement of the sun; where the moving components come into existence, their regular maintenance, calibration, repair or replacement of shattered parts needs extra care. This becomes the major hindrance to ensure the long life of the tracking system in reference to the life of the photovoltaic panel. Therefore, in order to increase the life of the tracking system, future work can be done by developing new links and mechanisms so that net power generated by the solar tracker can be maximized in comparison to fixed system.

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