Spacing Optimization Study of Single-axis Polar Mounted Solar-thermal Passive Tracker based Solar Photovoltaic Plant

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Received: 11.07.2016 Accepted:22.09.2016

Abstract- The deployment of Solar Photo Voltaic (SPV) systems is gaining more prominence in recent times when compared to other renewable energy technologies because of the attractive techno-economics, easy installation and maintenance. Non-motorized passive tracking SPV systems require less maintenance when compared to motorized systems and can boost the output of the SPV plants by about 25%. But, these systems need an efficient layout design of the solar field with minimized shadow effects. In the current paper, field optimization of single-axis polar mounted (SPM) solar-thermal passive tracker (SPT) for a 50 kWp SPV plant has been carried out using an in-house developed MATLAB based Graphical User Interface (GUI) tool. The optimization was carried out to arrive at a value of E-W spacing for the SPM SPT based SPV assemblies by keeping the N-S spacing constant, for installing a 50kWe plant at BHEL Corporate R&D, Hyderabad.

Keywords Solar Photovoltaic technology, Graphical User Interface, passive tracking system.

1. Introduction

Increasing energy demands and dwindling fossil fuel resources has led to the development and use of Renewable Energy Systems extensively for the last few years reducing the emissions. The Government of India is actively promoting solar energy to achieve ecologically sustainable growth while addressing India's energy security challenges. It will also constitute a major contribution by India to the global effort to meet the challenges of climate change.

Photovoltaic systems utilize the solar energy and produce electrical power. The PV Panels are normally installed on fixed tilt structures facing South in the northern hemisphere. Significant investments are made in R&D for increasing the conversion efficiencies of SPV cells and modules. The energy produced from these Solar PV systems can be further improved by 25 to 35 % when they track the Sun during the day. Different types of automatic and mechanical tracking systems have been developed and are in use for solar PV panels. The fully automatic tracking systems with motors, sensors and controls are costly and require maintenance. The semi-automatic and manual systems require daily human intervention, whereas the SPT system using the liquid balancing and tilting actuated with gravity force is simple, cost effective and maintenance free [1] (Fig. 1). BHEL has indigenously developed Solar Thermal Sun Trackers for Modular Capacity Solar Photovoltaic arrays.

Even though the use of tracking systems is advantageous, they need more land compared to fixed ones as they are mounted at much higher platforms and being tracked throughout the day. Large scale SPV power plants with passive tracking technology require about additional 20% land as they are mounted on elevated structures. This is because the tracking SPV modules cast shadow on their neighbours and to avoid this shadowing effect and to increase the non-shadow operation time. Many studies were conducted for studying the impact of the shadow cast on the SPV panel on its electrical output [1]. The shadow cast on SPV panels mounted on tracker structures is of two types (a) by structures surrounding the plant like control rooms, fencing, buildings around the plant area, trees, etc., (b) by the adjacent panel which depends on the spacing between two SPV structures. In case of the SPM SPT, the shadows cast by the objects are of significant importance. As shown in the Fig. 1, it works on the principle that both cylinders filled with refrigerant fixed along with shadow plates at the ends of the panel assemblies to receive same amount of solar radiation. Thus, if the sun changes its position, the differential heating causes the refrigerant to be transferred from the cylinder which receives more solar radiation to the cylinder which receives less radiation. The current paper tries to reduce the effect of shadow cast by adjacent modules by varying the spacing between the adjacent panels to determine the shadow free operation time of an SPV power plant of 50kWp capacity. The shadow plot techniques employed usually are based on the altitude and azimuth angles of the sun and the structures (which cast shadow on the SPV panels) [1]. These angles vary from place to place (based on latitude and longitude), from morning till evening (based on time of the day) and throughout the year (based on the day in a year). The MATLAB GUI tool used for the shadow plots uses transformation and projection matrices which utilizes latitude and longitude of a place, date and time for generating shadow plots for the SPV panels mounted on the structures. These matrices can be applied on the coordinates which create the objects of any geometry for obtaining its shadow behaviour patterns.

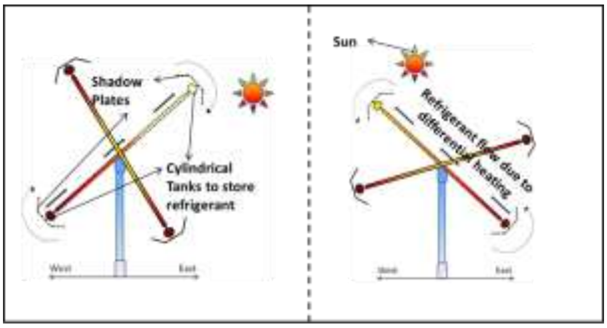

Fig. 1 Schematic of the Passive SPV tracking system

2. GUI Development

For GUI development, a demo SPV plant of 50 kWp is considered. The GUI takes below mentioned input parameters

a) Latitude, longitude and standard longitude of a place

b) Date and Time of the simulation event

c) Width, length and height of the panel assembly of an individual module

d) Number of modules in a single row

e) X and Y coordinates of the modules

f) E-W Spacing between two adjacent modules

g) N-S Spacing between two adjacent rows

In this study, factors b, d, e and f were varied for most of the time, keeping the latitude and longitude fixed for Hyderabad, dimensions of the panel assembly and tilt keeping constant. The GUI was developed using three algorithms as described below.

2.1. Sun Position/Angle and Tracking Algorithm

It first calculates sun's position (Fig. 2) in terms of latitude (Φ) and hour angle (ω) for the nth day of a year using Eq.(1), Eq.(2), Eq.(3) and Eq.(4) [4] based on longitude of the place, date and time

$$\omega = (\text{LAP} - 12) \times 150 \tag{1}$$

where LAP is local apparent time is calculated as below

$$\text{LAP} = \text{Standard time} \pm 4 \times (\text{Standard time longitude} - \text{longitude of location}) + E \tag{2}$$

Here E is equation of time correction is defined as

$$E = 229.18 \times (0.000075 + 0.001868 \times \cos B - 0.032077 \times \sin B - 0.01415 \times \cos 2B - 0.04089 \times \sin 2B) \tag{3}$$

$$\text{where } B = (n - 1) \times (360/365) \tag{4}$$

Then based on the dimensions of tracker assembly (i.e. size of structure which accommodates the SPV panels as an array along with liquid balancing tracking mechanism), a surface which represents the total size of SPV assembly is plotted X-Y plane. This surface is positioned at latitude angle (lat) of 17.4^0 (latitude of Hyderabad) along X-axis (local N-S direction) and then rotated along this inclined Y-axis (E-W tracking) by a track angle (tag) using transformation matrix T calculated using Eq. (5) in 3D space, P_1 , P_2 and P_3 being the X, Y and Z coordinates of the tracker assembly.

$$T = \begin{bmatrix} 1 & 0 & 0 & P1 \\ 0 & 1 & 0 & P2 \\ 0 & 0 & 1 & P3 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\Phi) & -\sin(\Phi) & 0 \\ 0 & \sin(\Phi) & \cos(\Phi) & 0 \end{bmatrix} \begin{bmatrix} \cos(\beta) & \sin(\beta) & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\beta) & \cos(\beta) & 1 & 0 \end{bmatrix} \tag{5}$$

This track angle (β) is the minimal angle between the normal to the tracking surface and the incident sun rays (since, it is single axis tracking minimal angle is considered when compared to double axis tracking where the angle between the normal and incident sun ray is zero) using following equations 6 and 7[4]:

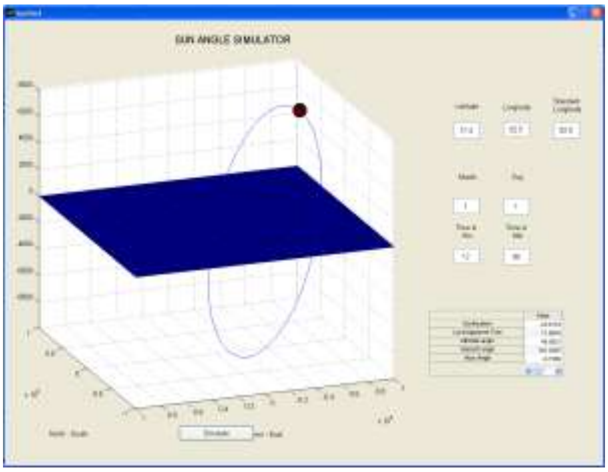

Fig. 2 GUI simulating sun's position

$$\beta = \tan^{-1}\left(\frac{\cos\delta \times \sin\omega}{(\sin\Phi \times \sin\delta + \cos\Phi \times \cos\delta \times \cos\omega)}\right) \quad (6)$$

where δ is Sun's declination calculated as follows

$$\delta = 23.45 \times \sin\left(\frac{360\times(284+\mathrm{n})}{365}\right) \quad (7)$$

2.2 Shadow plot algorithm

It was developed to calculate the time when the adjacent tracker assemblies (each consisting of 10 panels mounted on two pole support structure) don't cast any shadow on each other both in the mornings and evenings. For illustration consider figure 3; the shadow plots were generated using projection matrices on to the X-Y plane in MATLAB (as shown in Fig. 4). Now, consider the tracker assembly P_1 as shown in the Fig. 3, which casts a shadow $S_1S_2S_3D_2$ on tracker assembly P_2. For the P_1 which casts shadow on P_2, an algorithm was developed which plots the dot product value of vectors $\overline{D_2S_2}$ and $\overline{D_2C_2}$. Now the time at which this plot cuts the time axis (i.e., when dot product of $\overline{D_2S_2}$ and $\overline{D_2C_2}$ is zero), is the time at which P_1 doesn't cast any shadow on P_2. The reason for considering this condition is that when two panel assemblies are facing the sun and not casting any shadow on each other, the vectors $\overline{D_2S_2}$ and $\overline{D_2C_2}$ become perpendicular to each other. This is because as the shadow size reduces the edge of the shadow S_2S_3 moves towards S_1D_2 till the time S_3 merges with D_2. Thus, by determining the point S_2 using transformation matrices the area not available for direct sun radiation called Shadow loss (S_{loss}) is determined using Eq. 8.

$$S_{loss} = 2 \times (\overline{S_3D_2} \cdot \overline{S_3S_2}) \quad (8)$$

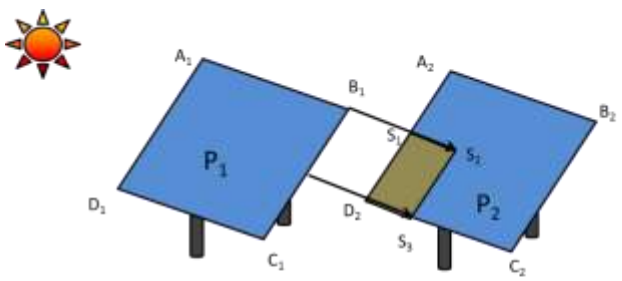

Fig. 3 Schematic showing the shadow cast by P1 panel assembly on the P2 panel assembly

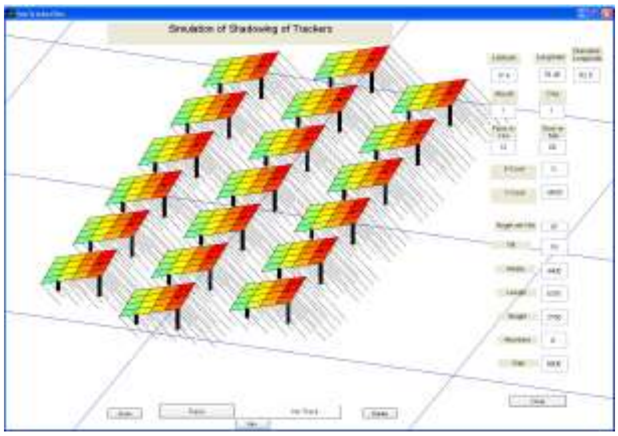

Fig. 4 GUI simulating the shadow pattern for 50kWp plant

This S_{loss} is the area that will generate very less power after shadow free operation time as it receives only diffused radiation. Using this principle, the total power generated by such tracking SPV plant is determined to estimate the impact of the shadow free operation time which is in turn depends on the E-W spacing between the panel assemblies by incorporating the shadow loss as calculated above.

3. Simulation Results and Discussions

3.1 Determining shadow free operation time

The above mentioned GUI was run for a typical year (365 days) to determine the start and end times of the shadow-free operation for E-W spacing values of 5m, 6m, 7m, 9m and 10m and plotted as Fig. 5 and Fig. 6 by keeping the N-S spacing constant at 8m. Then, by using hourly solar radiation data for Hyderabad location (obtained from Ramaswamy, etal., database)[2][4], the GUI calculates the total power that can be produced by the 50kWp power plant using the shadow free times after incorporating the shadow losses.

The start and end times of shadow free operation were plotted as Fig. 4 and Fig. 5 and it can be observed that as the E-W spacing values increases the start time of the shadow free operation decreases and end time increases. Thus, as the spacing increased the total non-shadow operation time increases as shown in Fig. 7.

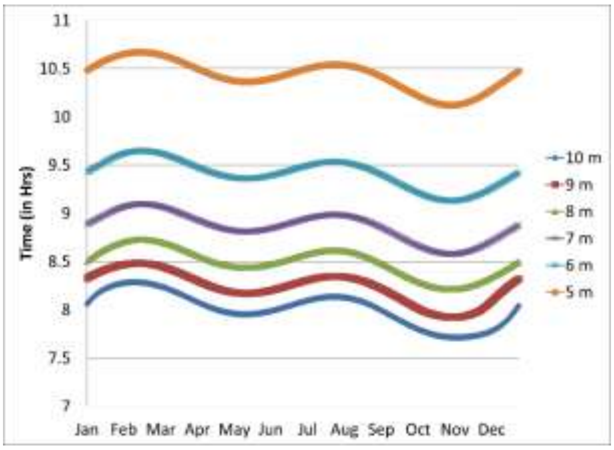

Fig. 5 Graph showing the start time of shadow-free operation of passive tracker

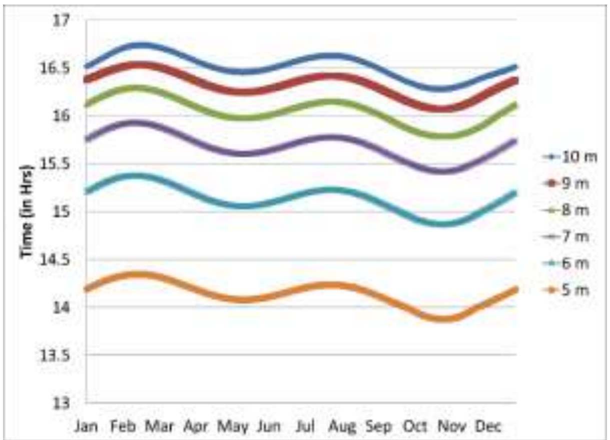

Fig. 6 Graph showing the end time of shadow-free operation of passive tracker

3.2 Impact of E-W spacing on the Total Energy Output

The Fig. 6 shows, how the total hours of shadow free operation of tracker varies monthly for specified spacing values. The variation in the values throughout the year is very less for Hyderabad as it is located at latitude of 17.4^0 N. But, it can be observed that the distance between the adjoining curves decreases as the E-W spacing between the modules increases from 5m to 10m.

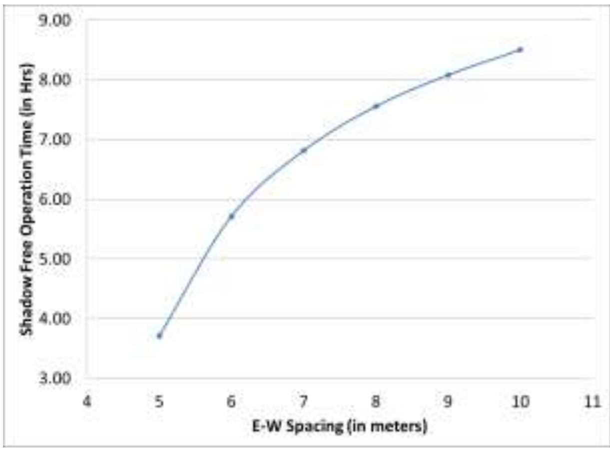

Fig. 7 Graph showing the average shadow free operation time varying with E-W spacing

The average shadow free operation time for a year is plotted for different E-W spacing values in Fig. 7. It can be observed that as spacing increases the average shadow free operation time also increases. In order to determine the relationship between the energy produced and land area requirement, an analysis was carried out using shadow plot algorithm. As the spacing increases the land requirement for the power plant also increases. Hence, the additional power produced per unit increase in land area requirement due to the increased spacing also known as Annual Increase of Energy Output per acre (AIEO) is plotted in Fig. 8, for change in spacing values from 5m to 6m, 6m to 7m, 7m to 8m, 8m to 9m and 9m to 10m.

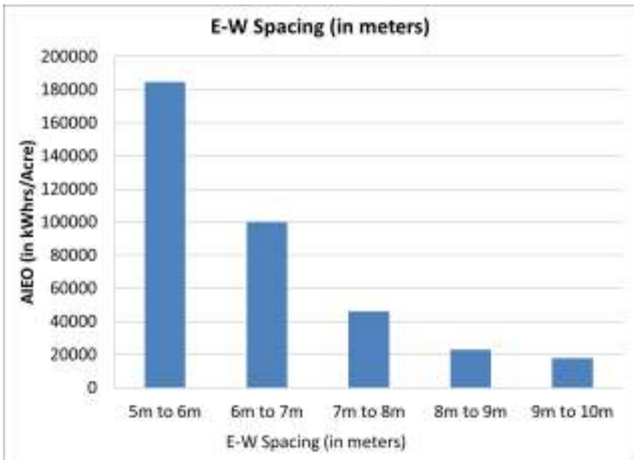

Fig. 8 Graph showing Annual Energy Increase per Acre for increase in E-W spacing from 5m to 6m, 6m to 7m, 7m to 8m, 8m to 9m, 9m to 10m.

4. Conclusions

The estimated AIEO is maximum for when the spacing is changed from 5m to 7m and this value decreases as the spacing is increased from 7m to 10m. But, the increase of spacing from 8m to 9m and further from 9m to 10m doesn't give much value as the AIEO value falls below 25% of the previous value. Thus, it can concluded that the optimum spacing for in E-W direction for the 50kWe SPV power plant based on SPM SPT technology is 8m. However, if the cost of the land is not an important factor, then other spacing options i.e., 9m and 10m can be considered.

5. References:

[1] Ramesh Pawar Mamidi, Solar Thermal Sun Tracker, Patent Application Publication, India, Application No. :818/KOL/2010, Journal No. - 37/2014 Publication Date : 12/09/2014

[2] Ramaswamy M A, Rao Badri S, Thirumali N C, Suresh N S ,Centre for study of science ,technology and Policy, Annual report,84-95, March 2013

[3] Sean Ong, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath, Land-Use Requirements for Solar Power Plants in the United States, Technical Report, NREL/TP-6A20-56290, pp.10-13,2013

[4] S P Sukhatme, J K Nayak, Solar Energy, Principles of Thermal Collection and Storage, Third Edition, pp.79-88, 207-209, 2013

[5] Ajit P. Tyagi, Director General of Meteorology, Editor-in-Chief, India Meteorologıcal Department Solar Radıant Energy over India