Two-Axis Solar Tracker Analysis and Control for Maximum Power Generation

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Abstract

Many of the solar panels throughout the world are positioned with the fixed angles. To maximize the use of the solar panel we use a solar tracker which orients itself along the direction of the sunlight. The solar tracker positions the panel in a hemispheroidal rotation to track the movement of the sun and thus increase the total electricity generation. This paper focuses on the development of new approach to control the movement of the solar panel. The purpose of this paper is to simulate and implement the most suitable and efficient control algorithm on the dual-axis solar tracker which can rotate in azimuth and elevation direction. The simulation gives the tracker angles that position the solar panel along the sun’s rays such that maximum solar irradiation is absorbed by the panel.

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1. Introduction

A solar tracker is used to track the orientation of the sun. In case of two-axis trackers the panel is positioned to track the orientation of the maximum sunlight throughout the day by adjusting the tracker angles (both elevation and azimuth angles). A Photovoltaic (PV) device converts sunlight into electricity. Early works on solar tracking and positioning were presented by [1]. In this paper Pritchard details the design, development and evaluation of a microcomputer based solar tracking and control system (TACS) capable of maintaining the peak position of a PV array for maximum efficiency and changing the position of the array relative to the sun irradiance direction. In another paper presented by Kimiyoshi, Kohayashi [3], it details when a solar array is used as an input power source, the optimum point tracker is often employed to exploit more effectively the solar array as an electric power source and to obtain maximum electric power at all times even when the light intensity and environmental temperature of the solar array are varied. The paper presented by Weixiang Shen [4] has a different approach to determine the
mathematical model of the solar module. The mathematical model built based on the PV module temperature, radiation of the sun and the effect of the resistance in series. The data which is obtained under normal environmental conditions was used to find the parameters of the model. Then this data is used to simulate the energy yield of the PV module. The yielded results were then compared between the experimental method and conventional approach [2, 5, 8, 11].

The two-axis trackers ensure that the solar panel absorbs maximum sunlight to generate maximum electricity. This paper focuses on modeling a PV module composed of number of cells and also a modeling tracker angles. The modeling of the tracker angles generates the desired irradiation which is used by the PV model to generate power, current and voltage. The mathematical modeling may be used to study the different tracker angles and also the irradiation for each day of the year. The paper presents in details the equations that form two axis tracker angles, also the maximum power generation and method used to obtain the parameters for the equation. The paper provides reader necessary information to develop model and circuits used in simulation to generate the maximum power from a PV panel.

2. Modeling the PV Array

The difference between an ideal PV cell and practical PV devices are the presence of resistances (both series and parallel). Solar cell equivalent circuit [6], where \( I \) is the current through the circuit, \( V \) is the voltage in the circuit, \( R_s \) is the series resistance in the PV circuit, \( R_p \) is the parallel resistance in the PV circuit, \( I_p \) is the reverse saturation current of the diode. The Figure 1 shows an ideal solar PV cell equivalent circuit which mathematically describes the I-V characteristics of the PV circuit given by,

\[
I = I_{ph} - I_o \left[ \exp \left( \frac{qV}{akT} \right) - 1 \right]
\]

(1)

where \( I_{ph} \) - the current solar cell generates at optimum conditions.

The (1) does not represent the I-V characteristics of the PV cell array, as practical array consists many components and thus (1) requires additional parameters like the series resistance, represented as in (2) [6],

\[
I = I_{ph} - I_o \left[ \exp \left( \frac{V + R_s I}{V_a a} \right) - 1 \right] \frac{V + R_s I}{R_p}
\]

(2)

where \( R_s \) is the series resistance, \( R_p \) is the resistance in parallel of the solar cell array, ‘a’ is the diode ideality constant and \( V_o = \frac{N_{sep} kT}{q} \), where \( V_o \) is the thermal voltage of the solar cell array with \( N_{sep} \) connected in series.

Due to the affect of the temperature and linearity of the solar irradiation resulting in the generation of the current, is,

\[
I_{ph} = I_{ph,nom} + K_{cur} \Delta_T + \left( \frac{G}{G_{nom}} \right)
\]

(3)

where \( I_{ph,nom} \) - current generated in solar cell circuit at nominal conditions (when temperature is 25°C and irradiance of 1000 W/m²).

\( \Delta_T = T - T_{nom} \) T is actual temperature and \( T_{nom} \) is the nominal temperature,

\( G \) is the actual irradiation and \( G_{nom} \) is the nominal irradiation (usually 1000 W/m²).

The diode saturation current \( I_o \) and its dependence on temperature can be given by,

\[
I_o = I_{o,nom} + \exp \left( \frac{T_{nom}}{T} \right)^3 \exp \left[ \frac{qE_g}{ak} \left( \frac{1}{T} - \frac{1}{T_{nom}} \right) \right]
\]

(4)

Here \( I_{o,nom} \) is the diode saturation current at nominal conditions and \( E_g \) is the bandgap energy of the semiconductor which is usually taken as 1.12eV [7]. The value of the \( I_{o,nom} \) can be found out from,
The value of the diode ideality constant can be randomly selected within the range of $0 \leq n \leq 1.75$. But for the calculation in this research work the value of ‘a’ is taken as 1.5 [6]. For modeling purposes, we use the module KC200GT manufactured by Kyocera. The PV module is made up of multi-crystalline silicon having 54 solar cells in series connection. The PV module provides a maximum power of 200 watts. Table 1 shows the Electrical specifications of the PV module [9, 15]

Table 1. The PV array electrical characteristics

<table>
<thead>
<tr>
<th>Electrical Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power ($P_{Max}$)</td>
<td>200W</td>
</tr>
<tr>
<td>Voltage at $P_{Max}$ ($V_{Max}$)</td>
<td>26.3 Volts</td>
</tr>
<tr>
<td>Current at $P_{Max}$ ($I_{Max}$)</td>
<td>7.61 Amps</td>
</tr>
<tr>
<td>Open-circuit voltage ($V_{oc}$)</td>
<td>32.9 Volts</td>
</tr>
<tr>
<td>Short-circuit current ($I_{sc}$)</td>
<td>8.21 Amps</td>
</tr>
<tr>
<td>Temperature coefficient of $I_{sc}$, $K_{cur}$</td>
<td>$3.18 \times 10^3$ A/°C</td>
</tr>
<tr>
<td>Temperature coefficient of $V_{oc}$, $K_{volt}$</td>
<td>$-1.23 \times 10^{-1}$ A/°C</td>
</tr>
<tr>
<td>NOCT</td>
<td>47°</td>
</tr>
</tbody>
</table>

3. Derivation of the Tracker Angles

Due to sun’s movement, its position varies both in day and with the seasons. The solar energy intercepted by the fixed position solar panels during the course of the day is not sufficient due to its position always being static; this decreases the coverage of the panel towards the sun. The position of the sun changes throughout the day as well as seasons. Depending upon cost, character and performance there are many varieties of solar trackers. The usage of the solar tracker decides the position of the panel [7, 10].

3.1. Variations in the Altitude of the Sun at Solar Noon Seasonally

The solar declination angle varies between $+23.50$ and $-23.50$ throughout the year as the earth revolves around the sun. The earth’s elliptical path covers four different equinoxes and solstices, respectively. The characterization of declination angle is $23.50$ during the summer in northern hemisphere and $-23.50$ during the winter. During the spring and the autumn seasons the declination angle is usually zero [14]. The declination angle can be given by a simple sinusoidal,

$$\delta = 23.45 \sin(0.9863(284+n))$$

where $n$ is the number of the day for which the declination angle is calculated. By knowing declination angle one can easily find the altitude angle ($\alpha$) which can be found out by $\alpha = 90° - \delta$

3.2. Hour Angle ($\xi$)

For the calculation of the hour angle, the true local time, longitudinal correction, and small deviation known as equation of time, $E_{time}$ should be taken into consideration which is given by [14]

$$E_{time} = 228[0.000075 + 0.002068 + \cos B - 0.022077 + \sin B - 0.015615 \cos 2B - 0.039849 \sin 2B]$$

where, $B$ $\left[360 \times \frac{n-1}{365}\right]$ n= number of days.

Furthermore, an extra local time correction is required as areas lying in the $15^0$ longitude will be having their own standard time but for other regions a longitudinal correction needs to be applied; the longitude correction $L_{correct}$ can be given by,

$$L_{correct} = 4(L_x - L_{loc})[\text{min}]$$

where, $L_x$ - Standard Time Meridian, $L_{loc}$ - Degree of deviation.

The solar time or the true local time is the result of the standard time corrected by the longitudinal correction and the equation of the time. The true local time $T_{LT}$ is given by,

$$T_{LT} = \text{Standard Time} + L_{correct} + E_{time}$$

Finally, knowing the total local time or the solar time we can find out the hour angle $\xi$ which is given by,
where, hr - standard time of the day.

### 3.3. Periodical Variations of Sun’s Position

The position of the sun during any time of day is calculated by knowing the azimuth and the elevation angles. Figure 2 shows both the azimuth angle φ and elevation angle \( \varepsilon \) measured from any point on the earth’s surface.

![Figure 2. Altitude Angle and Azimuth Angle of Sun from the Observer O](image)

For the horizontal coordinates, the azimuth angle \( \phi \), is given as 0° in north direction, east +90°, west 270° and the south 180°. The azimuth angle is given by,

For Total local time >12.00 hr, \( \phi = 180^0 + \cos \left( \frac{\sin \beta \sin L \sin \delta}{\cos \beta \cos L} \right) \) (11)

And for total local time < 12.00hr, \( \phi = 180^0 \cos \left( \frac{\sin \beta \sin L \sin \delta}{\cos \beta \cos L} \right) \) (12)

Where L - latitude of the location, \( \beta \) is the elevation angle and \( \delta \) is the declination angle.

The elevation angle \( \varepsilon \) is calculated with respect to the horizontal plane and can be described as the angle between the sun rays and the horizontal surface. The elevation angle is said to be complimentary to the zenith angle \( \theta_{zen} \). The zenith angle is nothing but the angle between the sun’s rays and the imaginary line drawn vertically perpendicular to the horizontal surface of the observer [13, 14]. The elevation angle is given by,

\[
\sin \beta \sin \delta \sin L + \cos \delta \cos L \cos \theta_{zen} = \xi
\]

The solar panel is positioned using the elevation and azimuth angles of the sun, thus the solar panel will receive sun rays in perpendicular direction resulting in maximum efficiency.

### 3.4. Components of the Terrestrial Radiation

The global irradiance or the horizontal irradiance can be represented by,

\[
G_g = G_B + G_d
\]

When calculating the horizontal irradiance, the elevation angle \( \beta \) has to be considered as it is a function of the collector’s tilt angle.

\[
G_g = 2.609 + 182.609 \sin \beta \left[ \frac{W}{m^2} \right]
\]

The diffuse radiation can be calculated by,
Finally, the direct irradiance can be calculated by

\[ G_d = G_g \times 0.165 \text{ for } G_{th} \geq 0.8 \]  

(vis. 16)

For the horizontal global radiation to beam on the inclined surface, the conversion involves separation of direct radiation and diffuse radiation. In case of direct irradiance, the intensity depends on the incident angle \( \theta_{inc} \). The total irradiance reflected by the ground is assumed to be isotropically divided and the model starts from the diffuse irradiance in the sky, which results in little visible proportions of the arising surface inclinations. The sum of ground reflection proportional to reflection coefficient, isotropic diffuse irradiance and direct irradiance gives the total irradiance on any inclined surface \( G_{tot} \). The total irradiance can be given by,

\[ G_{tot} = \frac{G_g}{\cos \theta_z} \cos \theta + G_d F_{surf \_sy} + G_g F_{surf \_grnd} \rho \]  

(vis. 18)

Where \( \rho \)-coefficient of reflection

\( F_{surf \_sy} \text{ And } F_{surf \_grnd} \) are the form factors amid the receptor surface and the sky or ground. The total irradiation on any horizontal surface which can be represented by,

\[ G_{tot} = \frac{G_g}{\cos \theta_z} \cos \theta + G_d \frac{1 + \cos \theta_{inc}}{2} + G_g \frac{1}{2} \cos \theta_{inc} \rho \]  

(vis. 19)

### 4. Results

Two identical 12 Volts DC motor were selected for the solar platform. Each motor provides the torque to move the panel in both azimuth and elevation directions. At the maximum efficiency conditions the motor provides an output of 123 Watts.

The open loop transfer function for the solar platform system is given as

\[ G(s) = \frac{k_{mot}/l_{arm}}{s^3 + \left[ \frac{r_{arm} + l_{arm}}{l_{arm} l_b} \right] s^2 + \left[ \frac{r_{arm} + k_b \cdot k_{mot}}{l_{arm} l_b} \right] s + \frac{k_r \cdot r_{arm}}{l_{arm} l_b}} \]  

(vis. 20)

\[ G(s) = \frac{15 \times 10^8}{s^3 + s^2 \times 1607 + s + 10852 + 10848} \]  

(vis. 21)

The PV array circuit was simulated for a time period of 12 hours i.e. 43200 seconds. Figure 3 shows relation between Elevation, Azimuth, and Zenith angles.

The actual irradiation data is used for simulation which generates power as one of the output along with current and voltage. The power output when compared to the specifications of the solar panel show that the simulation model is able to achieve the maximum power of 200 watts at solar noon when the irradiation reaches maximum.

When the PID controller is applied to the solar tracker platform we see the results being plotted in the below Figure 4 and Figure 5, the response from the system (actual elevation and azimuth angles) with the PID controller have similar response to that of desired azimuth and elevation angles.

Thus the system achieves 90% efficiency. The response from the system before and after using the controller totally depends on the dynamics of the solar platform.
As the solar tracker follows the sun’s path, the results obtained for the irradiation data of the simulink model are plotted. The tracker follows the sun’s path such that intensity of the light on the solar panel is close to the irradiation generated during the day. When the desired irradiation is compared with actual irradiation from the simulation results (Figure 6), we see that actual one closely follows the desired irradiation.

References
8. Akihiro Oi, Design and Simulation of Photovoltaic Water Pumping System, 2005