Solar Tracking by Vector Analysis for Controlling PV Panel Rotation

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Abstract

In this paper, the concept of deriving of the sun direction will be presented. The work has been done by utilizing vector analysis method. This paper shows that the sun direction from any location on earth can be derived at any time of day and any day of year. Conceptually, three Cartesian coordinate systems will be used for the analysis in this paper. First system is called universe coordinate system, in which the center of the sun is the origin. Secondly, earth coordinate system has N-S axis of the earth as the z-axis of the system. The third system is local coordinate system, in which the origin is at the where the PV panel is located. Hence, the sun direction will be referenced to the local coordinate system. After obtaining the sun direction, the PV panel angle control can be used to make the PV panel to be rotated to the sun direction. In this paper, the experimental results of sun directions are given in order to compare with those derived from using vector analysis method, in terms of rotation angles, accordingly.

Keywords: *Ecliptic, Latitude, Longitude, Greenwich Mean Time, Cross Product Vector, Dot Product Vector, Projection of Vector, Function arctan2, Sun tracking system.*

1. Introduction

One of the key factors for maximizing power from a PV panel is its aiming direction. If the aiming direction is directly to the sun, the energy will be harvested more than that not having direction directly to the sun. Therefore, a PV panel system without solar tracking may not be able to obtain the most energy from the sun light as it is supposed to be. There was a research study (Rizk & Chaiko, 2008) showing that the PV panel system with solar tracking could gain more energy up to 30% of that without solar tracking. From the previous studies, solar tracking, mainly, were done by using two approaches online tracking with utilizing light sensors (Rizk & Chaiko, 2008; Fathabadi, 2017; Lawles & Kärrfel, 2018) and offline tracking with using calculation (Sproul, 2007; Horvat & Wall, 2012). The work by (Sproul, 2007) used the concept that the earth is made to be stationary and the sun is assumed to move around the earth. On the other hand, the purpose of the work by (Horvat & Wall, 2012) was for shading projection in building design.

In this research work, the sun's direction tracking system was developed by using the vector analysis and is shown in this paper. This method is based on the basic principles of vector analysis, which is three dimensional coordinate system. Such basic principles are easy to use as compared to the other offline solar tracking systems. In addition, this offline method is easier to implement than that using light sensor for sun tracking, which requires complicated close-loop circuits. This can be used for controlling the rotations of PV panels in order to get maximum energy from the sun. The characteristic of the sun directions being looked from any point on earth different every day during a year. However, this characteristic of the sun directions a given day of year can be mathematically determined. Therefore, the vector analysis can be used for deriving the sun direction at a given time, on a given day of year and at any point on earth. Using the information obtained from the analysis, each PV panel can be rotated, accordingly, to be perpendicular to the sun direction at the given location for each given time. The sun tracking system proposed in this paper can be applied at every location on earth. In addition, this concept can be used for other applications, such as rotating satellite dish, building design to protect the heat from sun light and others etc.

2. Analysis of Sun direction

Earth orbit around the sun in a elliptical path and length of revolution around the sun is 365.25 days. The axis of earth (N-S) is inclined at 23.5° from the vertical line that perpendicular to the orbital plane. Earth rotate around its own N-S axis takes 24 hours for one round. Earth has an estimated diameter about 11,589 km and about 147-152 million km. from the sun.

In this paper, it will be assumed that the movement trajectory of the earth around the sun for one round is circular in 365.25 days; the N-S axis of the earth is always inclined by 23.5°; and the earth rotation around itself takes 24 hours in one round. Since the distance of the sun and the earth is much greater than the diameter of the earth, the direction of every particle of sun light going to the earth becomes parallel. The final assumption is that the shape of the earth is assume to be sphere.

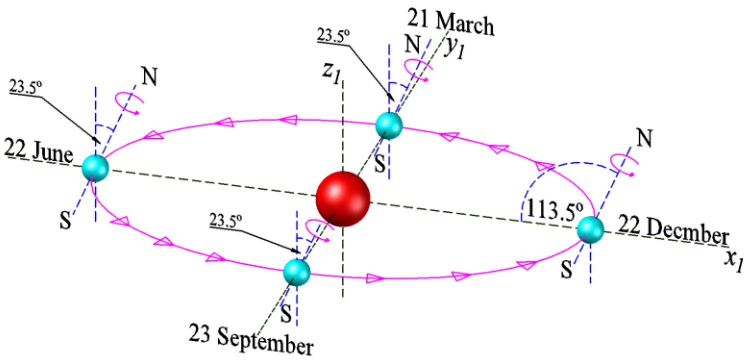


Figure 1 Earth's orbit around the sun

2.1 Concept

Vector is a quantity of magnitude and direction in coordinate of three dimension space. From Fig.2 $\mathbf{S} = \mathbf{S}_x + \mathbf{S}_y + \mathbf{S}_z$ or $\mathbf{S}_x$, $\mathbf{S}_y$, $\mathbf{S}_z$ are consisting of three components (vectors) in three direction *x*, *y*, and *z*. The same vector can also be written in another form, which is $\mathbf{S} = S_x\mathbf{u}_x + S_y\mathbf{u}_y + S_z\mathbf{u}_z$, where $\mathbf{u}_x$, $\mathbf{u}_y$ and $\mathbf{u}_z$ are unit vectors for *x*, *y*, and *z* axes, respectively. In this paper, the principle of vectors will be used to determine the direction of the sun. Three cartesian coordinate systems will be used. They are Universe, Earth and Local coordinate systems, which are briefly described below.

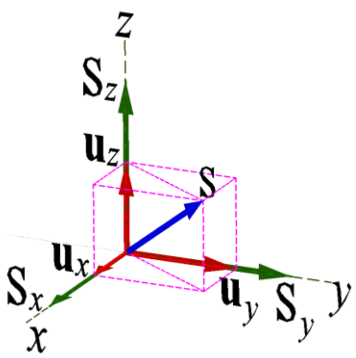


Figure 2 Vector quantity

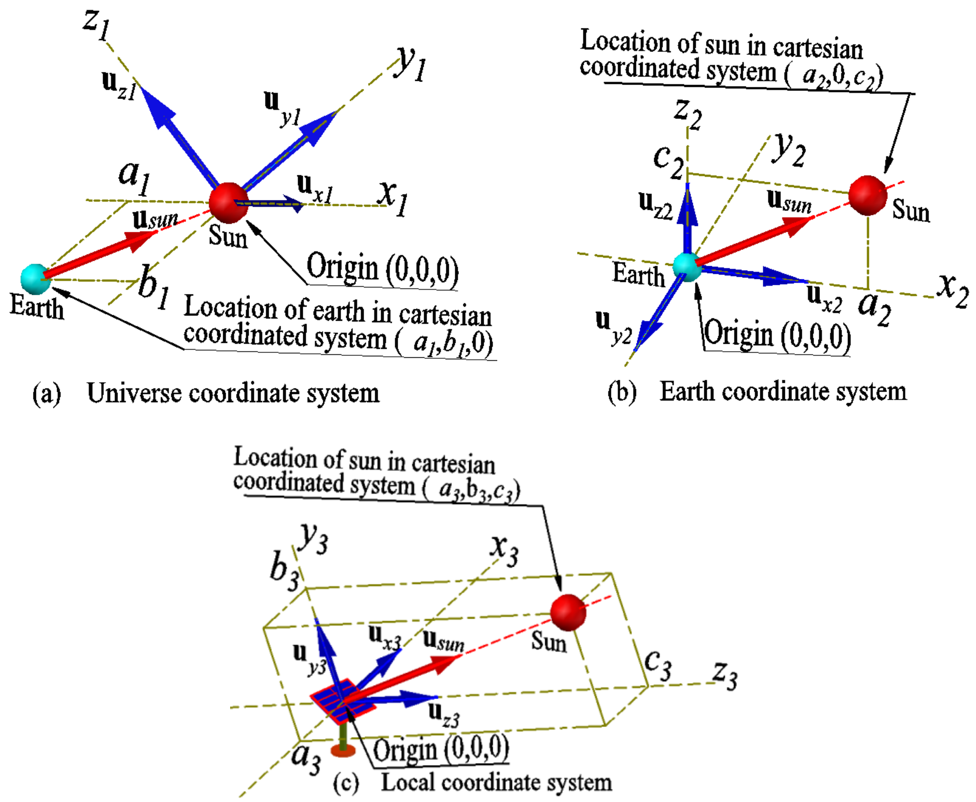


Figure 3 Three coordinate systems used for the analysis

Universe coordinate system: As shown in Fig. 3a, the origin point (0,0,0) of the system is at the center of the sun. The system consists of three axes, which are x_1, y_1 and z_1, accordingly. The center of the earth is at point (a_1,b_1, 0). $\mathbf{u}_{sun}$ is the unit vector of the direction from the center of the earth pointing to the sun, $\mathbf{u}_{x1}$, $\mathbf{u}_{y1}$ and $\mathbf{u}_{z1}$ are unit vectors of the directions of x_1, y_1, and z_1 axes, respectively. From Fig. 1, the direction of x_1 axis is from the center of the sun pointing to the earth at the location of 22 December. The direction of y_1 axis is from the center of the sun pointing to the earth at the location of 21 March, and is perpendicular to x_1 axis. Finally, z_1 axis is from the center of the sun pointing in the direction perpendicular to the earth orbital plane.

Earth coordinate system: As shown in Fig. 3b, the origin point (0,0,0) of the system is at the center of the earth. The system consists of three axes, which are x_2, y_2 and z_2. The center of the sun is at point (a_2,0, c_2). $\mathbf{u}_{x2}$, $\mathbf{u}_{y2}$ and $\mathbf{u}_{z2}$ are unit vectors of the directions of x_2, y_2, and z_2 axes, respectively. The direction of z_2 axis is from the center of the earth to North Pole. The direction of x_2 axis is from the center of the earth to the sun, but perpendicular to z_2 axis. Finally, y_2 axis is in the direction of cross product of $\mathbf{u}_{z2}$ and $\mathbf{u}_{x2}$ ($\mathbf{u}_{z2}\times\mathbf{u}_{x2}$).

Local coordinate system: As shown in Fig. 3c, the origin point (0,0,0) of the system is located at the location of PV panel. The system consists of three axes, x_3, y_3 and z_3. The center of the sun is at point (a_3,b_3, c_3). $\mathbf{u}_{x3}$, $\mathbf{u}_{y3}$ and $\mathbf{u}_{z3}$ are unit vectors of the directions of x_3, y_3, and z_3 axes, respectively. Since the system is originated on the earth surface, it is not that complicated to define the directions of the three axes. The directions of x_3 and y_3 are pointing to the east and the north, respectively, and the direction of z_3 axis is from the center of the earth to that location.

From Fig. 3, it can be seen that the unit vector $\mathbf{u}_{sun}$ can be observed in these three systems. However, $\mathbf{u}_{sun}$ observed in local coordinate system (x_3, y_3 and z_3) is the objective and required for this research work since the direction of sun light impacting PV Panel is needed. Therefore, the relations of any vector in these three system have to be derived. The conversion of a vector in one system to another may need to be done. The concept starts from finding the direction of $\mathbf{u}_{sun}$ at any given day of year in universe coordinate system referenced by x_1, y_1 and z_1. Then the direction of $\mathbf{u}_{sun}$ is to be converted to earth coordinate system referenced by x_2, y_2 and z_2 for any time of day. Then the direction of $\mathbf{u}_{sun}$ is to be converted to local coordinate system referenced by x_3, y_3 and z_3. The next step is to convert the direction of x_3, y_3 and z_3 axes into the environment of earth coordinate system for any point on the earth surface and any time of day. Once the directions of $\mathbf{u}_{sun}$ in universe coordinate system and the unit vectors of three axes in local coordinate system are converted to the same system, which is earth coordinate system, the unit vector $\mathbf{u}_{sun}$ can be disassembled to three components along the directions of x_3, y_3 and z_3 axes, accordingly. Finally, the direction of sun light at the given location and at any time can be derived from these three components of the unit vector $\mathbf{u}_{sun}$.

2.2 Universe Coordinate System

The trajectory of the earth movement around the sun can represent a plane. This plane will be the same plane that x_1 and y_1 axes in universe coordinate system represent. In Fig. 4, the directions of the three axes are given, accordingly. The objective for utilizing universe coordinate system is to find the angle between the earth axis (N-S axis) and the direction of the earth to the sun on any day of year. Below is the list of variables used for this system:

- $\mathbf{u}_{sun}$: The unit vector of the direction from the earth to the sun,
- $\mathbf{u}_{pole}$: The unit vector of the direction of the earth axis,
- θ_{sun}: The rotating angle of the earth around the sun referenced from the location of 22 June,
- θ_{incl}: The inclined angle of the earth axis, which is 23.5°,
- θ_{PS}: The angle between earth axis and the sun direction.

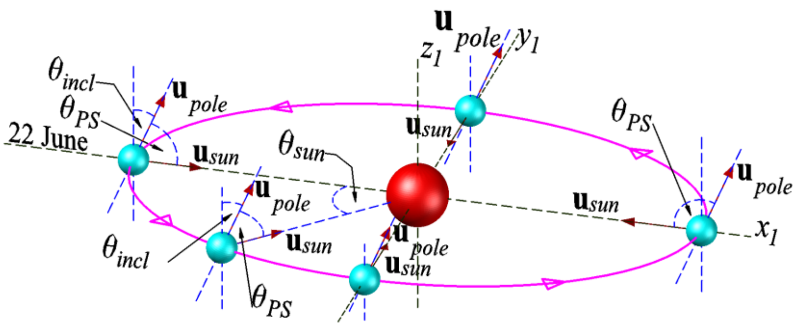


Figure 4 Universe coordinate system

Using graphical explanation from Fig. 4, the following relations can be obtained,

$$\mathbf{u}_{pole} = \sin\theta_{incl}\,\mathbf{u}_{x1} + \cos\theta_{incl}\,\mathbf{u}_{z1}, \tag{1}$$

$$\mathbf{u}_{sun} = \cos\theta_{sun}\,\mathbf{u}_{x1} + \sin\theta_{sun}\,\mathbf{u}_{y1}, \tag{2}$$

where

$$\theta_{sun} = \left[\frac{Number\ of\ days\ away\ from\ 21\ June}{365}\right] \times 360°, \tag{3}$$

$$\theta_{incl} = 23.5°.$$

Applying dot product to the vectors in equations (1) and (2), accordingly, the angle between the sun direction and the earth axis can be derived as

$$\theta_{PS} = \cos^{-1}(\sin\theta_{incl}\cos\theta_{sun}). \tag{4}$$

2.3 Earth Coordinate System

As mentioned earlier, earth coordinate system has the origin at the center of the earth. The directions of its three axes are shown in Fig. 5, accordingly. It can be seen from this figure that x_2 and z_2 axes, and the unit vector $\mathbf{u}_{sun}$ are in the same plane. This figure also shows that the last axis, which is y_2, is perpendicular to this plane.

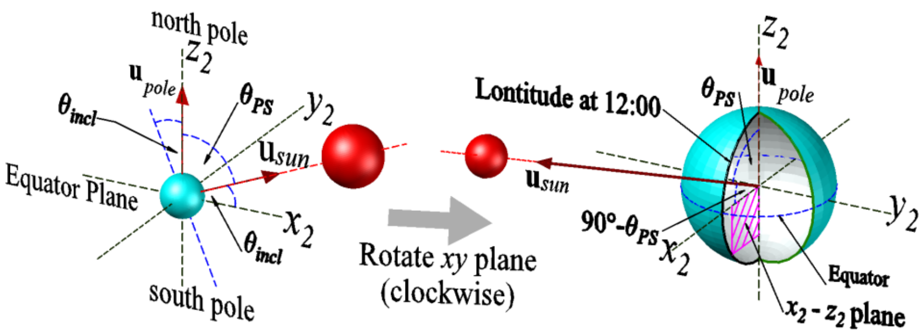


Figure 5 Earth coordinate system

Since the angle $\boldsymbol{\theta_{PS}}$ is the angle between $\boldsymbol{z_2}$ axis and $\mathbf{u}_{sun}$ and is obtained from equation (4), the unit vector $\mathbf{u}_{sun}$ can be easily derived in the environment of earth coordinate system by the following equation,

$$\mathbf{u}_{sun} = \sin\theta_{PS}\mathbf{u}_{x2} + \cos\theta_{PS}\,\mathbf{u}_{z2} \tag{5}$$

It can be noticed that the direction of z_2 axis is always from the center of the earth to North Pole, while those of the other two axes depend on time of day as related to the location on the earth.

2.4 Local Coordinate System

The origin, point (0,0,0) of this system is located at the location of the PV panel. The directions of the three axes, x_3, y_3 and z_3 depends on latitude/longitude position of the location. Fig. 6 shows the directions of the three axes, accordingly, of local coordinate system at anywhere on the earth.

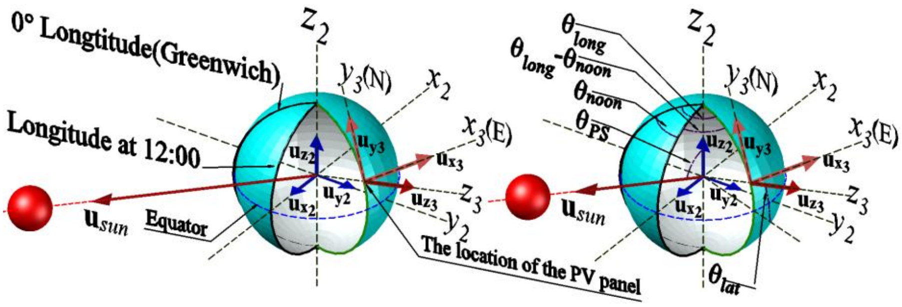


Figure 6 Local coordinate system: x_3, y_3 and z_3

According to the definition of the directions of x_3, y_3 and z_3 given earlier, the unit vectors $\mathbf{u}_{x3}$, $\mathbf{u}_{y3}$ and $\mathbf{u}_{z3}$ representing these directions, respectively, can be derived in the environment of global coordinate system as

$$\mathbf{u}_{x3} = -\sin(\theta_{long} - \theta_{noon})\mathbf{u}_{x2} + \cos(\theta_{long} - \theta_{noon})\mathbf{u}_{y2}, \tag{6}$$

$$\mathbf{u}_{y3} = -[\sin\theta_{lat}\cos(\theta_{long} - \theta_{noon})]\mathbf{u}_{x2} - [\sin\theta_{lat}\sin(\theta_{long} - \theta_{noon})]\mathbf{u}_{y2} + \cos\theta_{lat}\mathbf{u}_{z2}, \tag{7}$$

$$\mathbf{u}_{z3} = [\cos\theta_{lat}\cos(\theta_{long} - \theta_{noon})]\mathbf{u}_{x2} + [\cos\theta_{lat}\sin(\theta_{long} - \theta_{noon})]\mathbf{u}_{y2} + [\sin\theta_{lat}]\mathbf{u}_{z2}, \tag{8}$$

Where θ_{long} and θ_{lat} are longitude and latitude of the given location, respectively, and θ_{noon} is the longitude of the location facing the sun and can be found as.

$$\theta_{noon} = \left[\frac{12:00AM - (Time\ at\ Greenich)}{12}\right] \times 180° \tag{9}$$

It can be noticed that the directions referenced in earth coordinate system of the unit vectors $\mathbf{u}_{x3}$, $\mathbf{u}_{y3}$ and $\mathbf{u}_{z3}$ given in equations (6), (7) and (8), respectively, depend on time of day and the location on the earth.

3. Approaches for PV Panel Rotation Control

Once $\mathbf{u}_{sun}$, $\mathbf{u}_{x3}$, $\mathbf{u}_{y3}$ and $\mathbf{u}_{z3}$ are given in the same coordinate system as seen in equations (5), (6), (7) and (8), respectively, the components of $\mathbf{u}_{sun}$ in x_3, y_3 and z_3 axes denoted by $v_{sun,x3}$, $v_{sun,y3}$ and $v_{sun,z3}$, respectively, can be derived using dot product and given by the following equations,

$$v_{sun,x3} = \mathbf{u}_{sun} \cdot \mathbf{u}_{x3}, \tag{10}$$

$$v_{sun,y3} = \mathbf{u}_{sun} \cdot \mathbf{u}_{y3}, \tag{11}$$

$$v_{sun,z3} = \mathbf{u}_{sun} \cdot \mathbf{u}_{z3}. \tag{12}$$

The results of equations (10), (11) and (12) are scalar. It can be noticed that each result of these equations will come out positively when having the same direction with the axis and come out negatively when having the opposite direction.

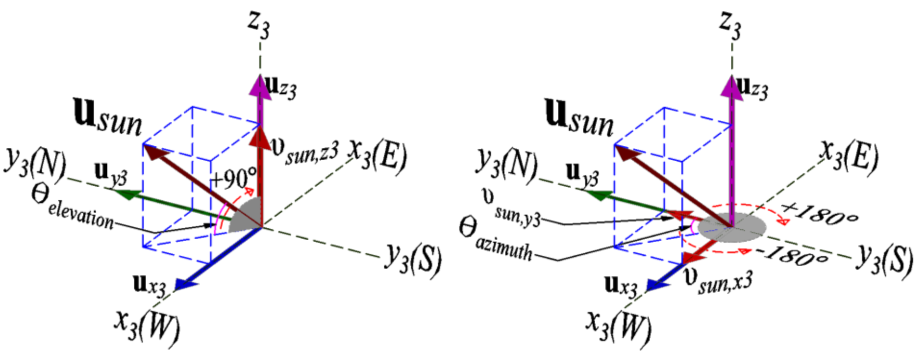
This paper will give two approaches for presenting the sun direction from the PV panel location at any time of day and on any day of year. The first approach is to provide elevation and azimuth angles. The elevation angle is the angle measured from the ground plane of the location having range from 0° to 90°. The azimuth angle is the angle measured from the rotation away the north direction having range from

-180° to 180°, where rotating to the east becoming positive angle and negative value representing rotating to the west. Since the directions of x_3, y_3 and z_3 axes are to the east, to the north and perpendicular to the ground, respectively, these two angles denoted by $\theta_{elevation}$ and $\theta_{azimuth}$ can be derived, respectively from the following equations,

$$\theta_{elevation} = \sin^{-1} v_{sun,z3}, \tag{13}$$

$$\theta_{azimuth} = \text{arctan2}\left(v_{sun,x3}, v_{sun,y3}\right), \tag{14}$$

where arctan2 function turns out the angle with range from -180° to 180° by giving components of $\mathbf{u}_{sun}$ on x_3 and y_3 axes, respectively, as inputs. The graphical explanation of these two angles is given in Fig. 7. It can be noticed that the elevation angle greater than 90° implies that the time used is either before sun rise or after sun set at the given location on the given day of year.



(a) $\theta_{elevation}$ (b) $\theta_{azimuth}$

Figure 7 Sun direction by elevation and azimuth angles

The second approach is to provide north-south and east-west angles. There are two axles that the PV panel will be rotating around, namely east-west axle providing north-south rotation and north-south axle providing east-west rotation. For this approach, the base of PV panel structure will rotate in north-south orientation. Zero degree angle means the direction is perpendicular to the ground. Positive or negative angle means rotating to the north or the south, respectively. Using the components of $\mathbf{u}_{sun}$ given by equations (10), (11) and (12), north-south angle can be derived as

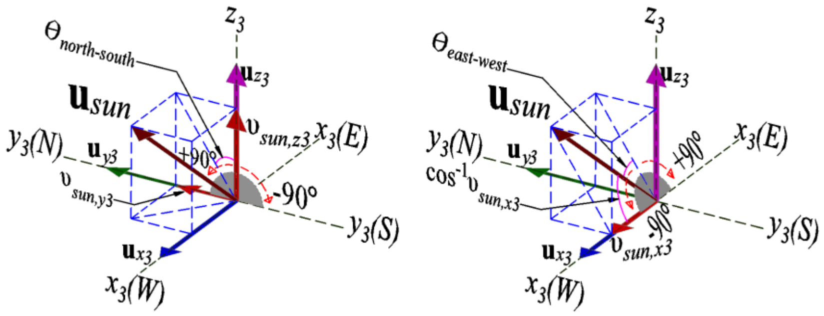
$$\theta_{N-S} = \text{arctan2}\left(v_{sun,y3}, v_{sun,z3}\right). \tag{15}$$

North-south axle used for east-west rotation will be hosted on the base. Besides rotating east-west around this axle, the axle itself will also rotate north-south around east-west axle. With this concept, east-west angle can be derived by the following equation,

$$\theta_{E-W} = 90° - \cos^{-1} v_{sun,x3}. \tag{16}$$

If east-west angle is zero, the direction will be perpendicular to the base. If this angle is positive or negative, the rotation will be to the east or to the west, respectively. The graphical explanation is given in Fig. 8.

From the above mentioned, the Cartesian coordinate system used in the analysis is local coordinate system. The direction of the unit vector $\mathbf{u}_{sun}$ is the direction of the sun at the selected location. The angles for both approaches can be derived from components of the unit vector $\mathbf{u}_{sun}$ in x_3, y_3 and z_3, which belong to local coordinate system. These three components can be derived from equations (10), (11) and (12), accordingly.



(a) θ_{E-W} (b) θ_{E-W}

Figure 8 Sun direction by north-south and east-west angles

In order to initially confirm results from the analytical work, two locations were used at two different times of a year, accordingly, for the calculation. The first location is an area in Bangkok, Thailand on the 4th of July 2018. The information of latitude and longitude of Bangkok together with several times on the given date were used. Supplying all parameter for each time to equations (1) to (12), the component on each axis of the sun direction can be obtained. Using equations (13) to (16), elevation, azimuth, north-south and east-west angles for each time could be derived and are shown in Table 1. It can be noticed that the selected date is in summer and the North Pole is tilted to the sun, so the sun should be located to the north direction for all day. The analytical results can be confirmed with north-south angles, which are in the range of 0° to 90° for all time during that day.

Similarly, an area in Sapporo, Japan is used on the 29th of January 2018, which is in winter. The analytical results at several times on the given day are shown in Table 2. It can be noticed from Table 2 that the elevation angles are negative at the time before 06:30 and after 16:30. These two conditions imply that the time before 06:30 is not yet sunrise and the time after 16:30 is already sunset.

Table 1 Calculation results at 4th July 2018 in Bangkok, Thailand.

Date/Month/Year	Time	$\theta_{elavation}$	$\theta_{azimuth}$	$\theta_{N\text{-}S}$	$\theta_{E\text{-}W}$
04/July/2018	06:30	8.048	68.308	69.088	66.938
04/July/2018	07:30	21.698	70.538	39.978	61.178
04/July/2018	08:30	35.488	71.528	23.988	50.578
04/July/2018	09:30	49.288	70.798	15.828	38.038
04/July/2018	10:30	62.888	66.428	11.588	24.698
04/July/2018	11:30	75.458	49.488	9.578	11.018
04/July/2018	12:30	80.448	-17.108	9.158	-2.808
04/July/2018	13:30	70.638	-59.308	10.178	-16.578
04/July/2018	14:30	57.428	-68.908	12.968	-30.158
04/July/2018	15:30	43.708	-71.408	18.508	-43.248
04/July/2018	16:30	29.888	-71.308	29.188	-55.208
04/July/2018	17:30	16.148	-69.808	50.088	-64.338

Table 2 Calculation results at 29th January 2018 in Sapporo, Japan.

Date/Month/Year	Time	$\theta_{elavation}$	$\theta_{azimuth}$	$\theta_{N\text{-}S}$	$\theta_{E\text{-}W}$
29/January/2018	06:30	-2.618	112.488	-96.798	67.388
29/January/2018	07:30	7.098	122.958	-77.128	56.388
29/January/2018	08:30	15.638	134.608	-68.288	43.298
29/January/2018	09:30	22.508	147.848	-63.938	29.468
29/January/2018	10:30	27.098	162.728	-61.828	15.348
29/January/2018	11:30	28.868	178.758	-61.138	1.108
29/January/2018	12:30	27.568	-165.138	-61.638	-13.158
29/January/2018	13:30	23.378	-150.028	-63.498	-27.308
29/January/2018	14:30	16.818	-136.538	-67.408	-41.198
29/January/2018	15:30	8.498	-124.658	-75.298	-54.458
29/January/2018	16:30	-1.068	-114.038	-92.608	-65.958
29/January/2018	17:30	-11.408	-104.158	-129.538	-71.908

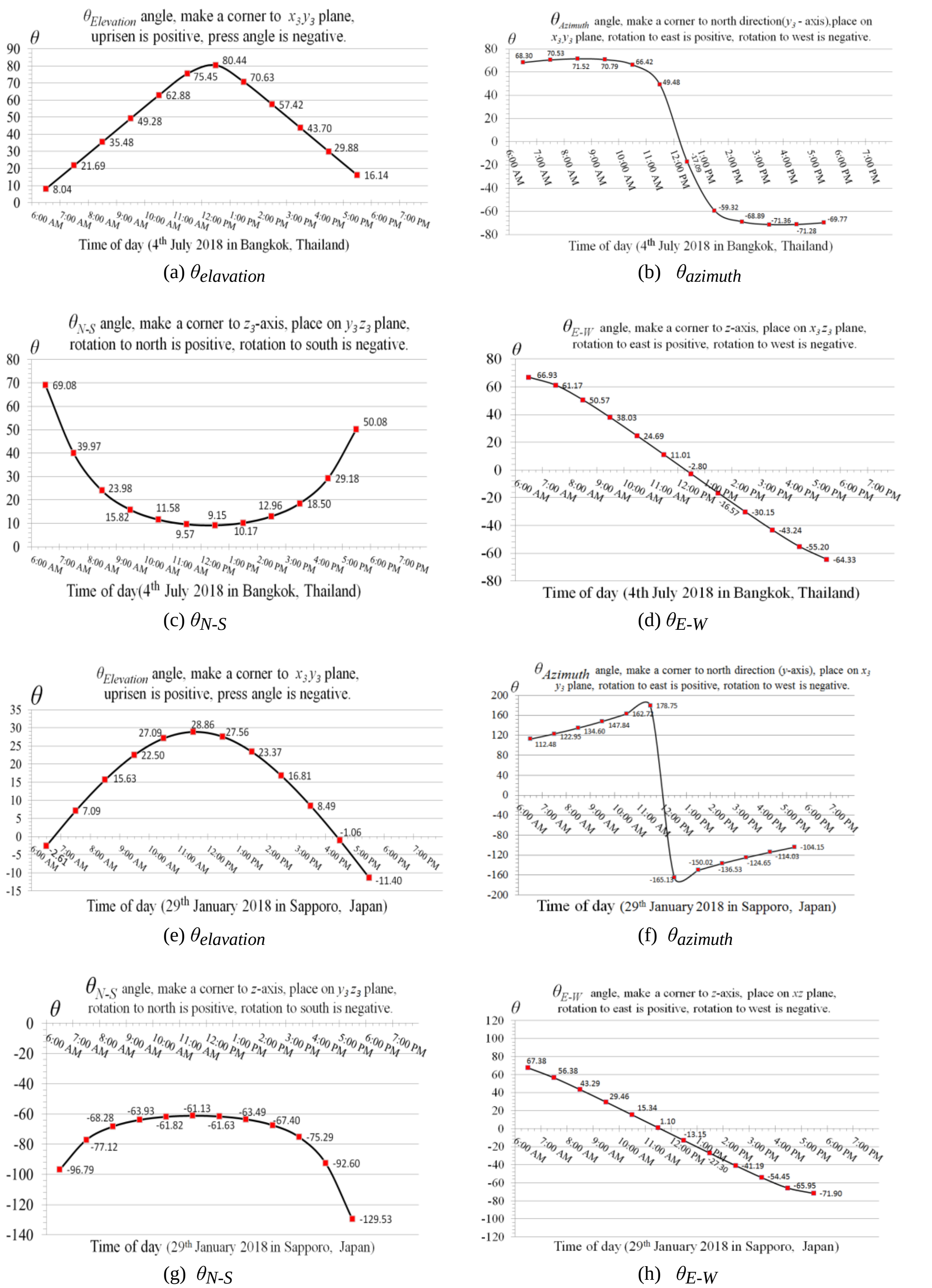


Figure 9 Graphs of angles from calculation results: (a), (b), (c), (d) for Bangkok, Thailand and (e), (f), (g), (h) for Sapporo, Japan

Tables 1 and 2 are the results from the analysis using vector analysis for areas in Bangkok and Sapporo, respectively. They can be examples being used for controlling rotation angles of PV panels. Fig. 9 shows how each angle changes during the day. For the case of Bangkok, which is Table 1, the movement of elevation and azimuth angles during the selected day are shown in Fig. 9a and 9b, respectively. Similarly, the graphs of north-south and east-west angles for Bangkok during the same day are displayed in Fig. 9c and 9d, respectively. By doing the same for the case of Sapporo, which is in Table 2, the graphs for elevation, azimuth, north-south and east-west angles during the given day are displayed in Fig. 9e, 9f, 9g and 9h, respectively.

It can be noticed that sunrise and sunset times can be estimated from elevation angle. It can be assumed that the sun starts shining at zero degree of elevation angle and sets at zero degree of elevation angle again. Since both cities are located above the equator, the day time is longer than 12 hours for the case of Bangkok and the day time is less than 12 hours for the case of Sapporo as estimated by using Fig. 9a and 9e, respectively.

4. Comparison between Analysis and Experimental Results

In order to confirm the analytical work, the experiment was done and the angles were measured several times during a day. The two approaches (elevation and azimuth angles, and north-south and east-west angles) are derived from the same analysis by using equations (1) to (12). Both approaches use results from equations (10), (11) and (12) to calculate the desired angles. Therefore, using either one of these approaches would be sufficient for confirming the results from the analysis. Since the elevation-azimuth approach is easier to measure angles than the other approach during the experiment, the elevation-azimuth approach was selected for the experiment. The experiment was set up on 14th January 2019 in Bangkok area.. Several times during the day were selected for the measurement. The experiment was started with using a compass to find north direction and then N-S and E-W lines were drawn on flat surface with open sky. A pole was put vertically at the cross section of N-S and E-W lines.

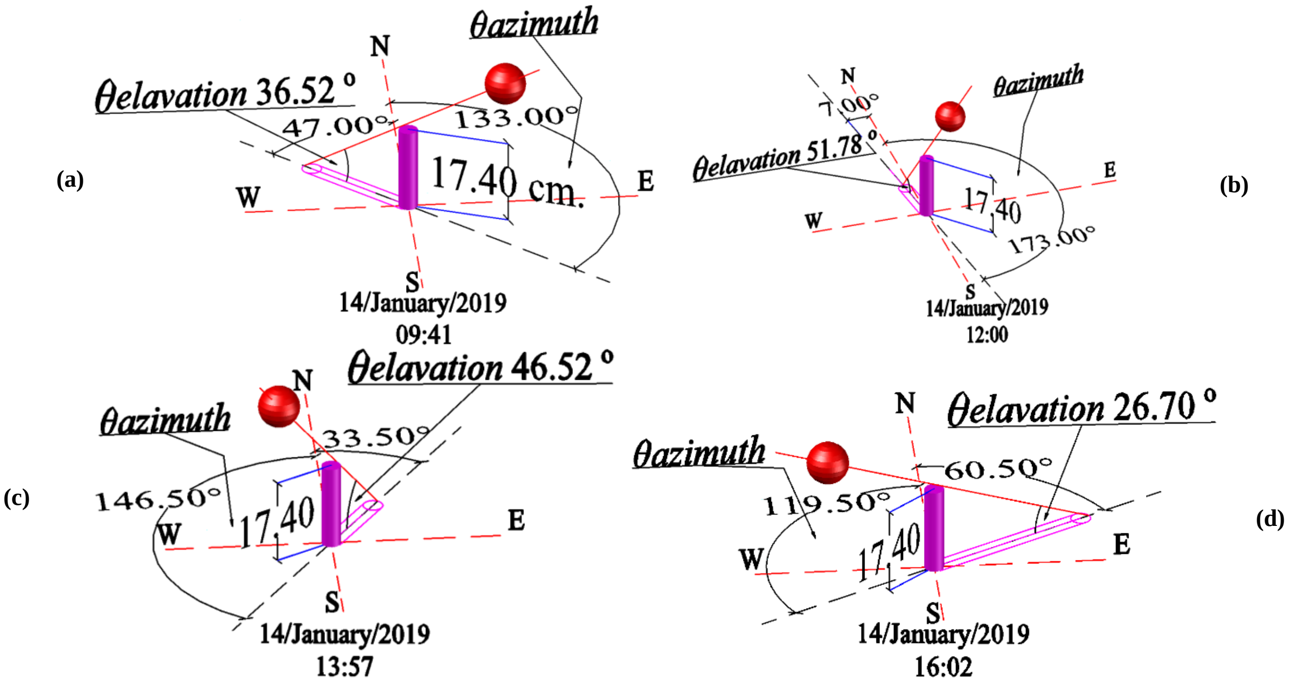


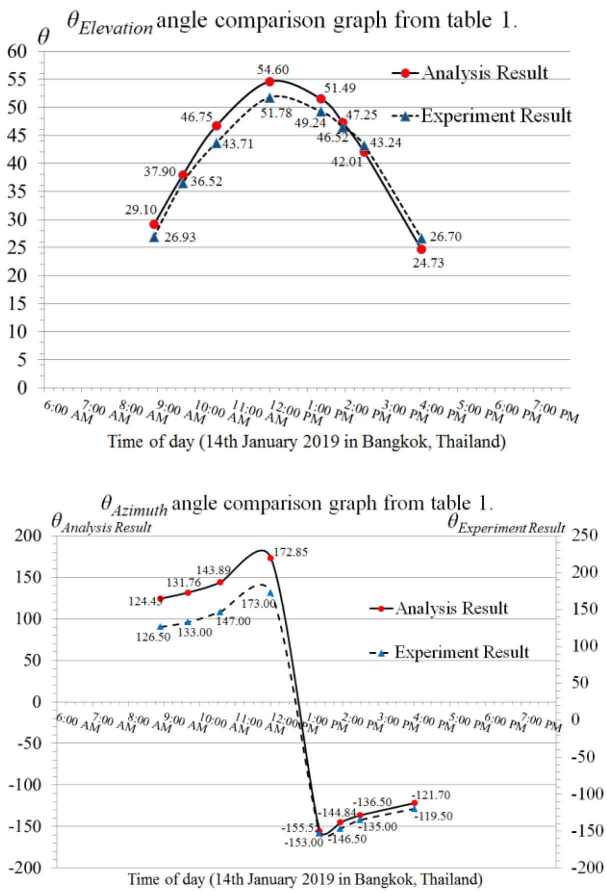
Figure 10 Measurement in the experiment at different times: (a) 09:41, (b) 12:00, (c) 13:57 and (d) 16:02

At each measurement, the lengths of the pole and its shadow were used for calculating the elevation angle. The angle between the pole's shadow and the north direction will lead to the azimuth angle.The measurement in the experiment was shown graphically in Fig. 10.

The results of the experiment were recorded and compared with the analytical results with the same times of day, accordingly, same day of week and same location. The numerical results are shown in Table 3. Fig. 11 shows result comparison for elevation and azimuth angle, graphically.

Table 3 Comparison between Analytical and Experimental Results

Date/Month/Year	Time	Analytical		Experimental	
		$\theta_{elavation}$	$\theta_{azimuth}$	$\theta_{elavation}$	$\theta_{azimuth}$
14/January/2019	08:55	29.108	124.438	26.938	126.5
14/January/2019	09:41	37.908	131.768	36.528	133.0
14/January/2019	10:35	46.758	143.898	43.718	147.0
14/January/2019	12:00	54.608	172.858	51.788	173.0
14/January/2019	13:22	51.498	-155.558	49.248	-153.0
14/January/2019	13:57	47.258	-144.848	46.528	-146.5
14/January/2019	14:31	42.018	-136.508	43.248	-135.0
14/January/2019	16:02	24.738	-121.708	26.708	-119.5



(a) $\theta_{elevation}$

(b) $\theta_{azimuth}$

Figure 11 Result comparison graphs, (a) elevation angle and (b) azimuth angle

From the result comparison in both Table 3 and Fig. 11, it can be seen that each result from the experiment is very much close to that from the analysis. There is a little error that might have been caused by measurement reading and the north direction guided by the compass. Besides error from the measurement, the error may come from the assumptions made for the analysis.

5. Applying Concept for Solar Farm

This section will describe how to apply the proposed concept to the solar farm industry. Using this concept, light sensor is not required for track the sun. North-south and east-west rotation approach is more suitable for the application since one set of motor can be used for driving multiple of PV panels in the same row. The values of north-south and east-west angles can be calculated in a computer at each time of day, day of year and at the site location. This information is sent to the farm every certain of time in order to adjust the direction of PV panels. Every 15 minutes would be quite sufficient to obtain maximum energy from the sun since the sun does not move that much within 15 minutes. The processing facility can be done by have the computer system at the site or using a web service that provides angle information from a cloud system.

5.1 On-site Computer System

Electronic control system is design to give an accurate control signal to the mechanical system in order to get maximum power generation from the solar farm PV. The mechanism of the system is shown in Fig. 12. The solar farm PV panels are controlled by using main controller. The main controller mainly consists of a computer system. The computer system will do the calculation for north-south and east-west angles from a set input information that consists of time of day, day of year, site location (longitude and latitude) and time zone (GMT). The set of angle information is sent to north-south and east-west controllers, accordingly. North-south controller will control the motor that drives the base of PV panels in north-south rotation. At the same time, east-west controller will control the motor hosted on the base that drives the set of PV panels in east-west rotation.

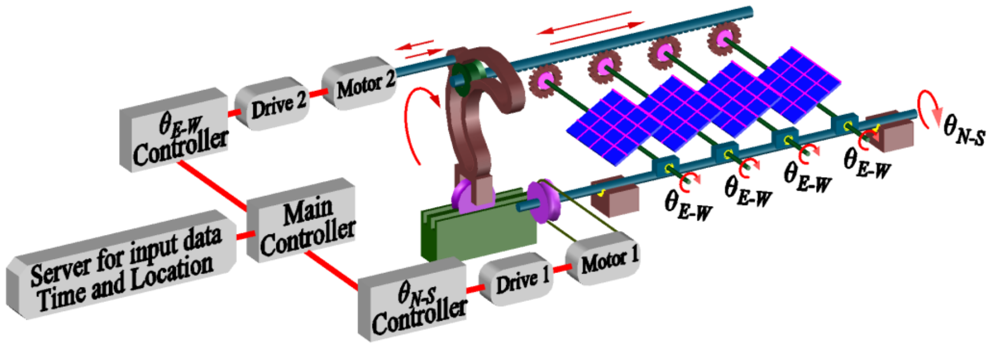


Figure 12 Applying concept for solar farm with on-site computer system

5.2 Cloud Service System

The facility for motor drive controller still have to be present at the site for using this system. The concept for using cloud service system is to have the computer system for processing installed in a cloud. This cloud system can be used as a web service that provided the information of sun direction for each day to any solar farm with subscription via Internet. The mechanism of the system is shown in Fig. 13.

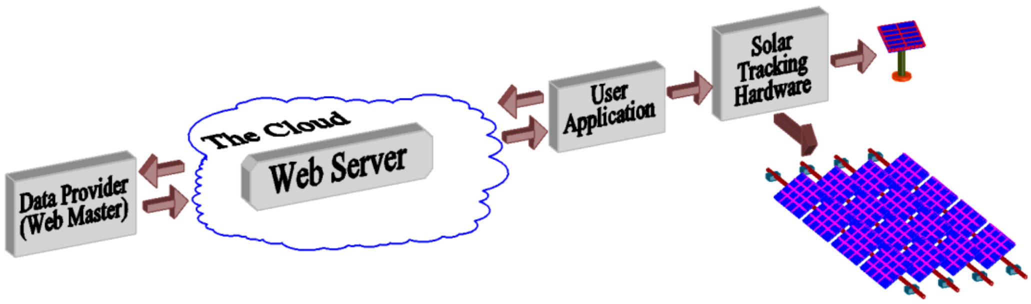
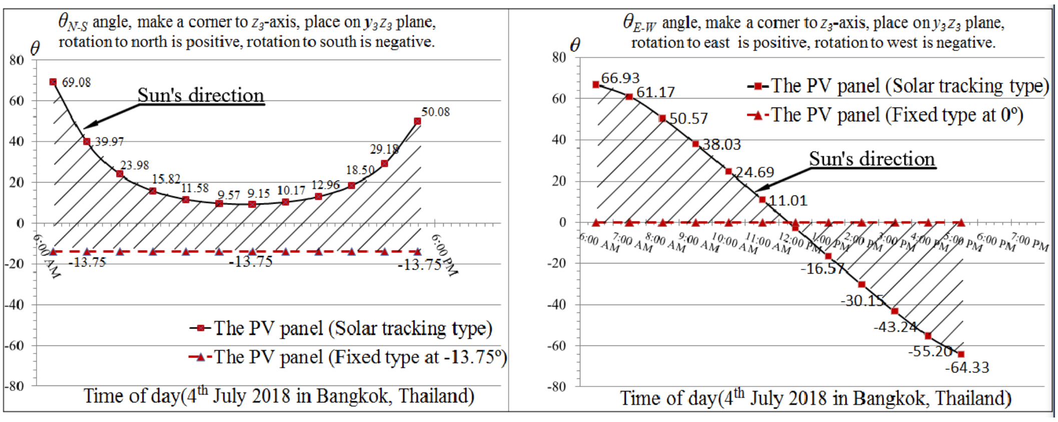


Figure 13 Applying concept for Sun direction via web service

6. Conclusion and Future Work

An experiment was done in order to confirm the analytical results obtained from the analysis. From the result comparison in both Table 3 and Fig. 11, it can be seen that each result from the experiment is very much close to that from the analysis. There is a little error that might have been caused by measurement reading and the north direction guided by the compass. Besides error from the measurement, the error may come from the assumptions made for the analysis, for example the world being assumed to be a sphere, the trajectory of the earth around the sun being assumed to be circle, and the period of the earth moving around the sub being assumed to be 360 days etc. However, the analytical results would be good enough to control the rotations of PV panels in order to gain more energy from the sun light as compared with that from non-rotated PV panels.

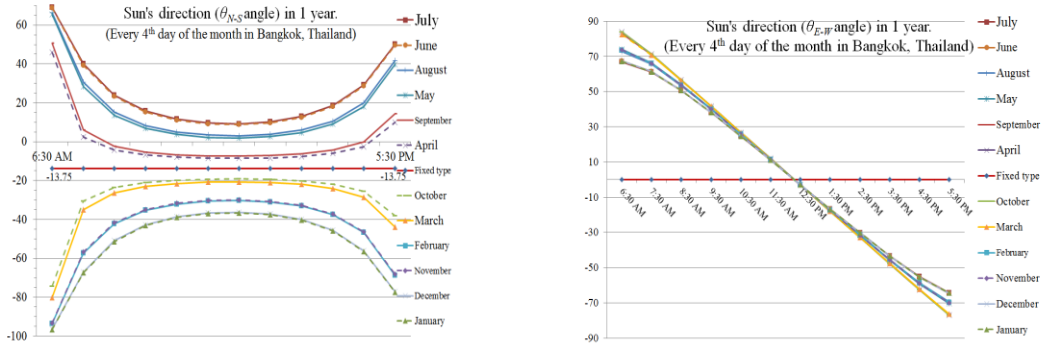
Deriving for the sun direction by utilizing vector analysis method is given in this paper. This concept can be used to control PV panel in order to get a perpendicular to sun light at any time. It may not be precisely perpendicular to sun light because parameters entered into the system may not be exactly right. This may be due the assumptions made for the analysis, such as the circular rotation of the earth around the sun and 365 days per one rotation cycle etc. As seen from the experimental results, the analytical results should be considered to be sufficiently good enough for the real practice. Rotating the PV panel according to the calculated information can gain a lot more energy than that from the PV without sun tracking. From Fig. 9 (c) showing θ_{N-S} and Fig. 9 (d) showing θ_{E-W}, it can be seen that these two angles have been changed a lot during the day. If the tracking system is not utilized, each PV panel cannot retrieve maximum energy from sun light.



(a) θ_{N-S} (b) θ_{E-W}

Figure 14 Comparison between the PV panel with solar tracking and without solar tracking (4th July 2018)

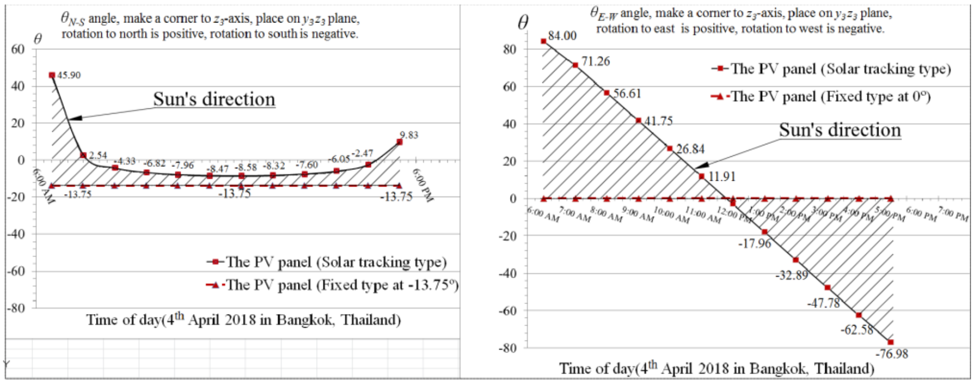
From Fig. 14, the area under the graph (shaded area) may need to be eliminated by adjusting the PV panel to angles along the direction of the sun. It can be concluded that the size of shaded area will be directly proportional to the energy gained by using sun tracking. Autocad 2015 can be used for calculating the shaded areas in both θ_{N-S} and θ_{E-W} graphs. After calculation, the shaded areas in θ_{E-W} and θ_{N-S} graphs are 100 and 95 units, respectively. (Rizk & Chaiko, 2008) showed that the PV panel system with single axis (θ_{E-W}) solar tracking can gain more energy up to 30% of that without solar tracking. Hence, it can estimated that the PV panel system with single rotation (θ_{E-W} only) of solar tracking can gain more energy up to 28.5% of that without solar tracking. Hence, the PV panel system with two rotations (θ_{E-W}, and θ_{N-S}) of solar tracking can gain more energy much more than 30% of that without solar tracking.



(a) θ_{N-S} (b) θ_{E-W}

Figure 15 Sun's direction in 1 year (Calculation every 4th day of the month in Bangkok, Thailand)

From Fig. 15 (b), it can be seen that the direction of the sun every day of the year is almost no different each day. Therefore, the energy obtained from the system with single rotation (θ_{E-W}) of solar tracking will be stable around 30% as shown by Rizk and Chaiko (2008). From Fig.15 (a) it can be seen that the direction of the sun every day of the year in the north-south direction will change every month which is caused by the orbit of the earth around the sun. Therefore, the extra energy gained from the system with north-south rotation (θ_{N-S}) of solar tracking will vary each month. The months with the most energy gain are January and July, while April and October would be the least. From the above mentioned that the PV panel system with single rotation (θ_{N-S}) of solar tracking can gain more energy up to around 28.5% of that without solar tracking in 4th July as seen in Fig. 14 (a).



(a) $\theta_{N\text{-}S}$ (b) $\theta_{E\text{-}W}$

Figure 16 Comparison between the PV panel with solar tracking and without solar tracking (4th April 2018)

For the case of 4th April shown in Fig. 16, the PV panel system with single rotation of (θ_{N-S}) of solar tracking can gain more energy up to about 8% of that without solar tracking. Hence, the PV panel system with dual axis (θ_{E-W}, and θ_{N-S}) solar tracking can gain more energy up to approximately 38% of that without solar tracking.

The next step of the work is to develop an application for calculating the angles of the sun direction for any time of day and any day of year. In this paper, Microsoft Excel 2010 was used for the calculation. If the program is in a form of computer application, selecting time and location will be more automated. The motor drivers for PV panel rotation may have to be designed. In addition, the interface between the application and the motor driver will also have to be investigated.

7. References

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