DETERMINING THE ACCURACY OF SOLAR TRACKERS

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ABSTRACT

Are there studies that compare the performance of solar trackers according to their angular accuracies under different conditions? No articles determining the angular accuracy of non-algorithm based solar trackers by directly measuring the tracker angles were found. The economic value of solar trackers considering both the power production and angular accuracy has not been determined. This study aims to determine the economic value of solar trackers depending on their performance and angular accuracies. This thesis research is carried out at the Appalachian State University Solar Research Laboratory.

This thesis research is guided by one research question and four hypotheses. The question is “What is the accuracy of non-algorithm based one axis solar trackers and two axis solar trackers under varying Direct Beam Fraction (DBF), total irradiance, wind speed, wind direction, and time of the day?”. This research is an experiment to measure the elevation and azimuth angles of a non-algorithm based two axis active solar tracker and the azimuth angle of a non-algorithm based passive one axis solar tracker under real world conditions.

This paper explains and shows results of the experiment done on the Zomeworks UTR-020 passive azimuth tracker fixed at 45^o altitude angle.

1. INTRODUCTION

Interest in solar energy as a substantial energy resource has grown because it is our most abundant source of renewable energy. This contributes to mitigating greenhouse gases and therefore many policies have been undertaken worldwide to produce solar energy or reduce the production of greenhouse gases.

Photovoltaic (PV) technology has continued to develop in recent years. Technologies that track the sun to maximize power output of PV panels are just one area of improvement. Tracker manufacturers claim the increase in power produced from a PV panel mounted on a one axis solar tracker can be 30% higher than a fixed PV panel and 40% higher in the case of a mounted PV panel on a two axis solar tracker.

Irradiance is the primary factor that determines the power produced from a PV panel. Solar trackers adjust their orientation angles(s) (inclination and azimuth) angles in real time to track the movement of the sun through the sky. Determining the orientation angle(s) may be by an algorithm or by measurement, and achieving this angle may be accomplished actively or passively.

2. STATEMENT OF THE PROBLEM

Accuracy of non-algorithm based one axis and dual axis solar trackers is important to determining their performance because the accuracy, which is the degree to which the trackers point towards the sun, determines the amount of irradiance on the PV panel and the incident angle of the radiation. Understanding the accuracy of tracking systems is necessary to make critical decisions when choosing between the various tracking options available.

Direct Beam Fraction (DBF), or the fraction of irradiance that has not been scattered, is an important factor that determines PV power production. For the fixed PV panel, angle of inclination (called also the slope or tilt angle) and the angle of the surface on which it is mounted in relation to the south direction in the northern hemisphere of the earth (or the north in the southern hemisphere, or azimuth angle) are set at time of installation, and may be manually adjusted seasonally. For PV tracking technologies, the system's main generic components are the tracking device and the tracking algorithm, control system, positioning system, driving system, and sensing system (1). Algorithm-based trackers are typically used in commercial scale solar plants because of their high accuracy. However, residential scale solar trackers are not algorithm based for simplicity to the customer and for reduction in the cost. Hence it is very important to determine the accuracy of such residential trackers and identify the implications this accuracy will have on the power output of residential PV systems, so that the home owners and installers can make better decisions about what residential PV technology to install. No studies determining the tracking accuracy using empirical observations have been found.

3. SIGNIFICANCE OF THE STUDY

The lack of standards for describing the tracker performance makes it difficult to compare the performance of various solar trackers. "These challenges call for a method for accurately characterizing both absolute and relative tracking accuracy in the field, under a variety of weather conditions" (2). Stafford's research provides a generic, simple, and non-expensive set of feedback sensors for any solar tracking systems. It determines the accuracy of solar trackers. It studies both the irradiance and the tracking errors under varying conditions. It provides a development in the performance and the efficiency of the motion controller – driving system – positioning system interconnection in a typical solar tracking system as well. This is because it provides an instant visual readings and adjustments of tracking angles so that the surface of the PV panel becomes always normal to the solar beam radiation leading to the maximum power output per panel and the best possible efficiency of the PV system. The visual readings on the contrary of computational methods provide more understanding to the performance of solar trackers, inter-action between the operator person and the tracker, and the ability to report the tracker performance which provides instant troubleshooting avoiding any further probable inaccuracy, sudden maintenances, or performance defects resulting in preserving and increasing the life time of the trackers. This research sets up the second stage of a research chain to ultimately study the economic values of both an algorithm based and a non-algorithm based solar trackers in the industrial field so that the customer can be able to make critical decisions when choosing between solar trackers.

4. REVIEW OF LITERATURE

4.1 Solar Irradiation and Meteorological Conditions

"As radiation passes through the atmosphere, the incidence angle changes, making it diffuse rather than direct" (3). The irradiance of the solar energy doesn't reach completely to the surface of a PV panel. It is scattered due to collision with air molecules only in clear weather. If the weather is windy, cloudy, rainy, or snowy, there will be more scattering, reflections, and inter-reflections of solar rays that are incident on the PV panels. And hence, the concepts of the terms Direct (called also Normal or Beam) Radiation, Diffuse Radiation, Albedo, and Direct Beam Fraction (DBF) came into focus of scientists and researchers interested in the solar energy discipline. The direct radiation which is sometimes called Direct Normal Irradiation (DNI) as well is "The radiation that is not reflected or scattered and reaches the surface directly" (4). The diffuse radiation is "The scattered radiation reaching the ground" (4). The diffuse radiation is defined more precisely as the "radiation that has been scattered either by clouds, rain, or any other potential hazard" (2). The albedo is defined as "the fraction of radiation reaching the ground that is reflected back to the atmosphere from which a part is absorbed by the receiver" (4). The DBF is a term that "describes the ratio of direct beam to total radiation" (2).

4.2 Solar Tracking Geometry

Solar radiation measurements usually provide data referring to the amount of sunlight hitting horizontal surfaces. For a tilted surface, the incident radiation is a ratio of that incident on a horizontal surface. The irradiance is the total of the direct radiation, diffuse radiation, and ground reflected radiation. The direct radiation depends on the position of the sun and the position of the surface. The diffuse radiation depends on the view factor between the surface and the sky. The ground reflected radiation depends on the view factor between the surface and the ground. The necessary geometry is described by the inclination angle β, the incidence angle θ, and the zenith angle θz, as shown in Figure 1.

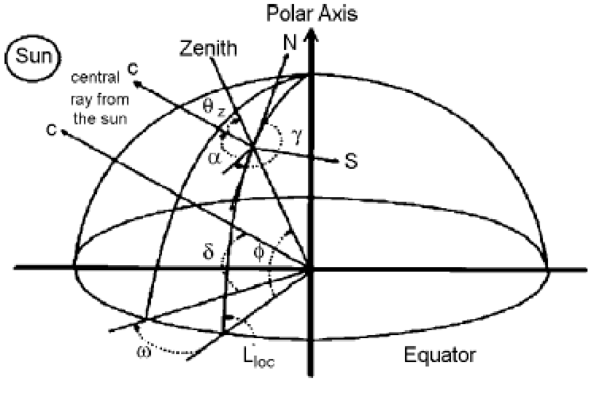

Fig. 1: Schematic representation of the solar angles.

By using spherical triangles trigonometric relations of spherical triangles nvs and NPQ shown in Figures 2 and 3 respectively, equations calculating β, θ, and θz can be derived (5).

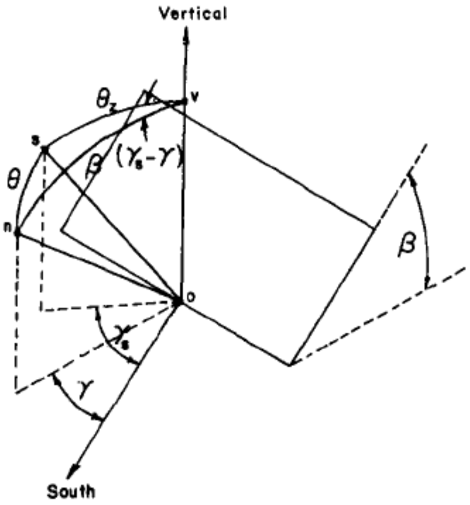

Fig. 2: Surface-Sun geometry.

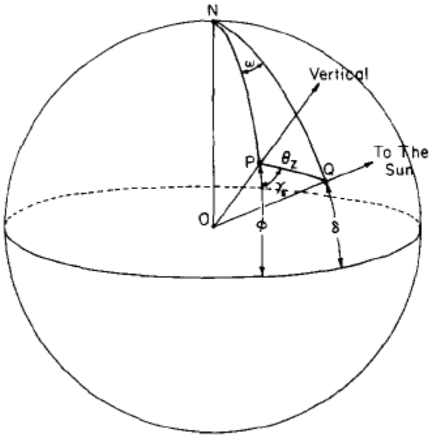

Fig. 3: Earth-Sun geometry.

4.3 Components of the Solar Tracking System

The main components of the solar tracking system are the tracking device, the tracking algorithm, the control unit, the positioning system, the driving mechanism, and the sensing devices. The algorithm calculates the angles that are used to determine the position of solar tracker. There are two types of algorithms which are astronomical algorithms and real-time light intensity algorithms. The astronomical algorithm is a purely mathematical algorithm based on astronomical references. The real-time light intensity algorithm is an algorithm that utilizes real-time light intensity readings. The control unit executes the tracking algorithm and manages the positioning system and the driving mechanism so that the tracking device is directed towards the direction calculated. The positioning system is the system that moves the tracking device to face the sun at the calculated angles. The positioning system can be electrical or hydraulic. The driving mechanism is the mechanism that is directly responsible for moving the tracking device to the position determined by the positioning system. The sensing devices are group of sensors and measurements that measure the ambient conditions, the light intensity in case of real-time light intensity algorithms, and the tilt angle of the tracker (by means of an inclinometer or a combination of limit switches and motor encoder counts) (1).

4.4 Solar Tracking Technologies

“The presence of a solar tracker is not essential for the operation of a solar panel, but without it, performance is reduced” (4). Solar tracking technologies are usually classified into passive (mechanical) and active (electrical) devices. They can be classified into one axis solar trackers and dual axis solar trackers as shown in Figure 4 as well.

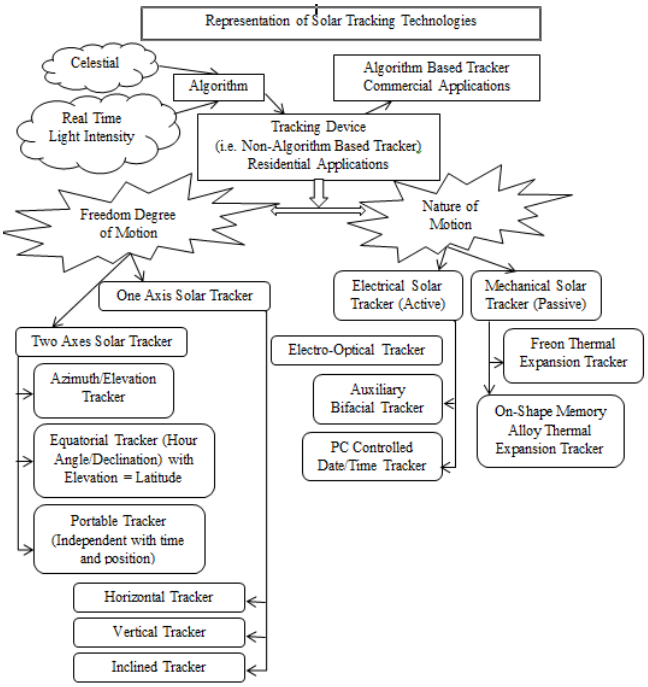

Fig. 4: Representation of Solar Tracking Technologies.

Passive solar trackers are trackers of a thermal expansion rotating motion. Passive solar trackers contain two identical cylindrical tubes filled with a pressurized fluid (usually Freon or on-shape memory alloys). The two cylindrical tubes are actuators working in opposite directions to each other. These two actuators are balanced by equal, in opposite directions, amounts of illumination of the pressurized fluid. The pressurized fluid thermally expands when it is subjected to the sun causing differential illumination leading to unbalanced forces that orient the tracker towards a certain direction till equilibrium restores and so the actuators are balanced.

Active trackers are trackers of a motorized motion. “Major active trackers can be categorized as microprocessor and electro-optical sensor based, PC controlled data and time based, auxiliary bifacial solar cell based, and a combination of these three systems” (4). Electro-optical sensor based active tracker contains at the least one pair of anti-parallel connected photo-resistors or PV solar panels. This pair is electrically balanced by equal illumination intensities and so there is no control signal on the driving motor. For the auxiliary bifacial solar cell active tracker, the bifacial solar cell senses and drives the trackers towards the desired position. The PC controlled date and time based active tracker calculates the angles in terms of date and time by means of algorithms and sends signals to the control unit to manage the positioning system and the driving mechanism so that the tracker is directed to the desired direction (4). The one axis solar trackers can be horizontal or vertical or inclined. Horizontal One Axis Solar Trackers (HOASTs) are widely used in tropical regions where sun is high and day is short. Vertical Axis Solar Trackers (VOASTs) are widely used in regions where sun is low and day is long. One axis solar trackers are used in Parabolic and Linear Fresnel Mirror designs. Two axis solar trackers are very important in Concentrated Solar Power systems (CSP) as solar tower systems because of the errors of the angles due to the long distances between the heliostats and the receiver in the tower structure, and as solar dishes (Sterling engines). Two axis solar trackers are used as well in many applications of Concentrated Photovoltaic systems (CPV) to always position the solar panels normal to the sun’s rays to maximize the power output (1).

4.5 Solar Tracking and Power Output

Tracking improves the efficiency of the PV systems. PV systems without tracking systems are simple and have lower initial investments costs but they produce lower power outputs. The use of tracking systems can boost the collected energy from the sun by 10 to 100% at different times and different geographical conditions. It is not recommended to use solar trackers with small PV panels because of the energy losses in the driving systems which vary from 2% to 3% of the energy increased by the solar trackers (4, 5, & 6). A two axis equatorial based tracking mechanism with computer control was designed, fabricated and tested by Patil et al. (7), a deviation of 3% is determined only all over the day, a 30% increase in power output is calculated, and a small power is consumed to drive the PV modules is calculated as well.

A novel low cost solar tracker suitable for use in equatorial regions around the world was presented by Clifford and Eastwood (8). The passive solar tracker was activated by aluminum/steel bimetallic strips and controlled by a viscous damper. The materials and the manufacturing processes used could be done in the developing world, and replicated and maintained in many regions all over the globe. The efficiency of the tracking PV panel is 23% more than a typical fixed PV panel.

4.6 Comparing the Performance of Solar Trackers

A theoretical model was developed by Helwa et al., (9) to calculate the hourly solar radiation incident on 4 different tracking systems (fixed PV panel facing south and tilted at 40^o, vertical axis tracker tilted at 33^o, one tilted axis tracker with rotating axis in the N-S direction oriented by a tilted angle 6^o with the horizontal, and a two axis tracker) using measured global radiation on a horizontal system, diffuse radiation on a horizontal system, and normal radiation. Then the calculated values were compared with the measured values on-site. It was found that the measured annual average hourly solar radiation incident on the fixed PV panel was 295.04 Wh/m^2, that incident on the vertical axis tracker was 331.15 Wh/m^2, that incident on the one tilted axis tracker was 299.85 Wh/m^2, and that incident on the two axis tracker was 367.65 Wh/m^2. It was calculated that the annual average hourly solar radiation incident on the 4 systems were 310.84 Wh/m^2, 361.2 Wh/m^2, 323.61 Wh/m^2, and 389.65 Wh/m^2 respectively.

A comparison between the performance of a fixed PV panel at altitude 40^o and Zomeworks one axis solar tracker at altitude 30^o was done by Robinson (3). It was found that for total irradiance greater than 1100 W/m^2 “There is statistically significant power increase than the Zomeworks 1-axis tracker compared to a fixed mount ranging from 15% at the lower DBF (50%) to 19% for the upper DBF bins (85%)”. A power increase than the Zomeworks one axis solar tracker was found as well for total irradiance between 900 W/m^2 and 1100 W/m^2 compared to a fixed mounting of a PV panel ranging from 13% for DBF 4% to 24% for DBF 95%. The same was found for the total irradiance between 700 and 900 W/m^2, 500 and 700 W/m^2, 300 and 500 W/m^2, and 100 and 300 W/m^2 ranging from 11% for DBF 35% to 66% for DBF 95%, 11% for DBF 15% to 16% for DBF 85%, 8% for DBF 0% to 23% for DBF 60%, and about 10% for the range of DBF from 0% to 30% respectively.

4.7 Solar Tracking Errors and Accuracy

Different Sun positions and weather conditions all over the year makes it difficult to determine the tracking accuracy. In addition, the array outputs like electrical power and electrical current are not enough to determine the tracking accuracy because there are other parameters that have an effect on the accuracy as DNI, ambient and cell temperatures, wind speeds and directions, and the deflection across the array itself due to weight or wind loading. Moreover, the lack of standards that describe the tracker performance makes it difficult to evaluate the performance of a solar tracker and therefore it's difficult to compare the performance of various solar trackers. "These challenges call for a method for accurately characterizing both absolute and relative tracking accuracy in the field, under a variety of weather conditions" (2).

The tracking pointing errors are determined by two angles (azimuth and altitude angles, or hour and declination angles). The pointing error that the system can tolerate without significant loss in power output is called the acceptance angle. Stafford et al. (2) presented data on solar tracking errors collected over a period of months from on-site commercial CPV power plants. The relation between the fraction of available energy that could be captured by the CPV system and the acceptance angle was graphed as well. It was shown that as the acceptance angle increases the more available energy fraction could be captured. Another graph was drawn to show the relation between the wind frequency and the total tracking error. The graph showed a normal distribution between the total tracking error and the wind frequency.

"A key component of the motion controller of trackers is the software, where flexibility easy-of-use and integration with other I/O ports are parameters for consideration" (5). Cost effective software such as the Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) was demonstrated by Oh et al. (5). LabVIEW was used for developing a tracking algorithm of a modeled two axis azimuth/altitude solar tracking system application and developing the application program by calculating the solar azimuth angle, the solar altitude angle, and the times of sunrise and sunset, and by determining the motor steps to send them to the controller, the device responsible for sending the relevant steps to the axis and motors for the purpose of driving and positioning the tracker towards the Sun. The changes in the solar altitude and solar azimuth angles were compared with the results of Korea Astronomy and Space Science Institute (KASI). It was found that the maximum error of the solar altitude angle was 0.0371^o at 4 am (Korea Local Time) and the minimum error was 0.0006^o at 10 am (Korea Local Time). It was found as well that the maximum error of the solar azimuth angle was 0.0823^o at 1 am (Korea Local Time) and the minimum error was 0.0012^o at 5 pm (Korea Local Time).

In a patent application publication (10), Mark Mcdonald determined the solar tracking error of the solar collector by determining the differences between the power of the feedback signal and the former signal. He reached as well that the solar collector responds late by 0.5^o, and that the servo feedback signal corrects the solar collector position by 2.65^o.

5. METHODOLOGY

This research is an experiment to measure the elevation angle and the azimuth angle of a non-algorithm based two axis solar tracker and the azimuth angle of the non-algorithm based passive one axis solar tracker in the ASU Solar Research laboratory, and compare them to those calculated by the celestial calculation algorithm of the meteorological station tracker in the laboratory. From this comparison, the accuracies of tracking of those types of solar trackers will be determined. In this paper, the azimuth angle of the non-algorithm based passive one axis solar tracker is measured, then compared to the angle calculated by the celestial calculation. By this way, the accuracy of the non-algorithm based passive one axis solar tracker is determined.

5.1 Instrumentation

The azimuth angle of the non-algorithm based passive one axis solar tracker is measured in the laboratory. The DNI, the global diffuse radiation, the wind speed, the wind direction, and the power output of the passive one axis solar tracker are already being measured in the laboratory. The azimuth angle of the passive one axis solar tracker is measured by a 6" linear potentiometer. The DNI is being measured by Hukesflux DR-1 Pyrheliometer (first class) pointed at the sun by a Minitrack II Solar Tracker (celestial based algorithm). The global diffuse radiation is being measured by Hukesflux SR-11 Pyranometer (first class). The albedo is not considered until the current time of the experiment. The wind speed is being measured by a Met-1 034 b Wind Set. Two enPhase M190 micro-inverters were used. AC electrical powers are being measured by Ohio Semitronics power transducers.

5.2 Calibration of the 6" linear potentiometer

The idea of mounting a 6" linear potentiometer on the non-algorithm based passive one axis solar tracker came from the occurrence of relative motion between components of the damper, as shown in Figure 5, and the maximum distance traveled through this motion is 6". The calibration was done in order to get a relation between the output of the potentiometer and the actual azimuth angle of the tracker. The output of the linear potentiometer mounted is "$V_{potentiometer}/V_{excitation}$", where $V_{excitation}$ is 2500 mV for the potentiometer used. The equation is as shown in Figure 6:

$$Az^o = -1591.7(BrHalf)^2 + 1840.3(BrHalf) - 296.85$$

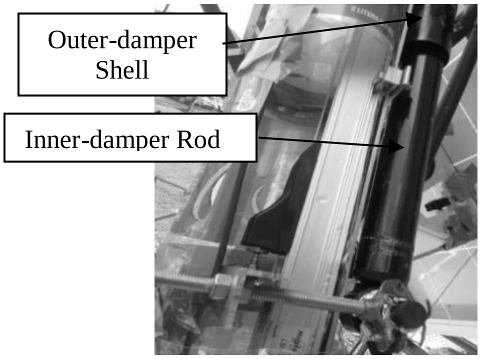

Fig. 5: Components of the damper, and the 6” linear potentiometer.

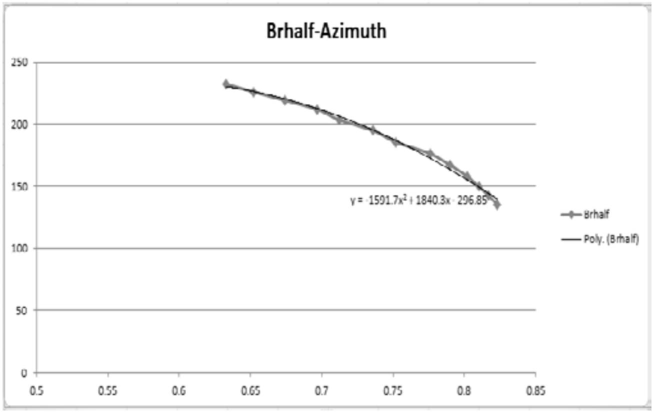

Fig. 6: Calibration of the 6” linear potentiometer.

5.3 Data Collection

The measurements of the azimuth angle of the non-algorithm based passive one axis solar tracker, the DNI, the global diffuse radiation, the wind speed, the wind direction, the power output of the passive one axis solar tracker, and the magnitude of the algorithm calculated azimuth angle of the of the non-algorithm based passive one axis solar tracker are collected by means of the Data Acquisition System in the ASU Solar Research laboratory.

5.4 Data analysis

After the azimuth angle of the non-algorithm based one-axis solar tracker was recorded by Logger-Net software, it is compared to that calculated by the celestial algorithm of the meteorological station tracker. Using Microsoft Excel and the Logger-Net software, the relations between the accuracy of the non-algorithm based one-axis solar tracker and the power output, the Direct Beam Fraction (DBF), the total irradiance, the wind speed, and the time of the day are determined.

6. RESULTS

The results shown are made on February 9, 2013. This day was very sunny and clear in Boone, North Carolina, where the ASU Solar Research Facility Laboratory is located.

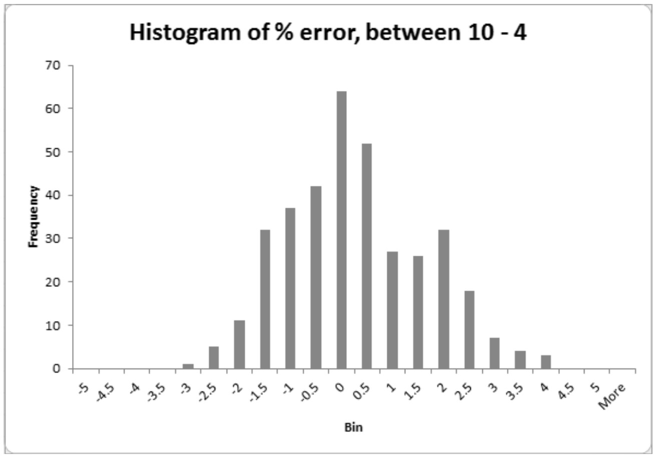

Fig. 7: Histogram showing the tracking error percentage of the non-algorithm based passive one axis solar tracker.

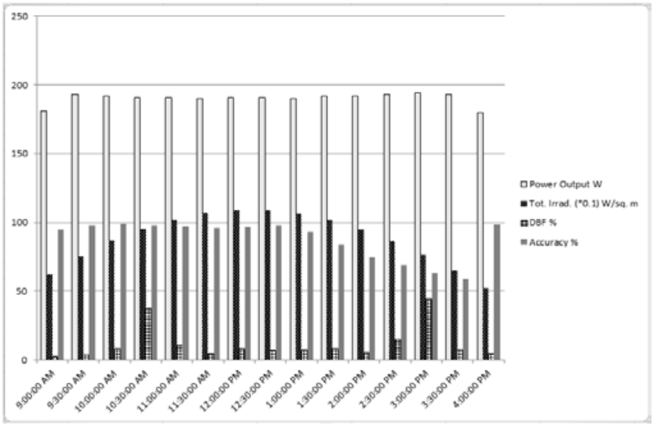

Fig. 8: The power output, total irradiance, DBF and the accuracy percentages (from 9 am to 4 pm).

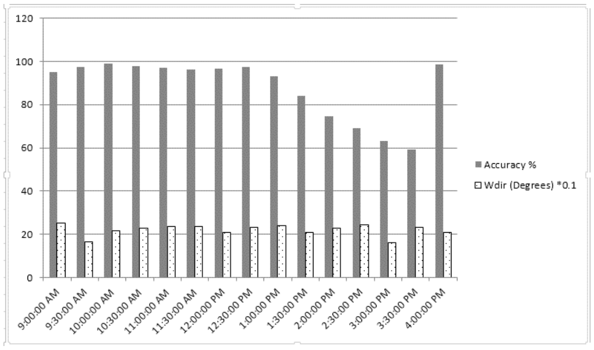

Fig. 9: The accuracy percentage and wind direction (from 9 am to 4 pm).

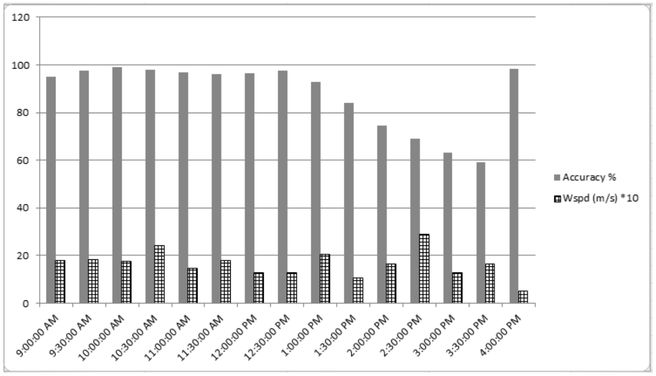

Fig. 10: The accuracy percentage and wind speed (from 9 am to 4 pm).

7. CONCLUSION

From the figures in the previous section, it is concluded that:

a) From Figure 7, a curve to check tracking errors between -4% and +10% was applied on that sunny and clear day. It is found that errors lie between -3% and +4%. In addition, it is found that most of the errors are from -1.5% to 0.5%. Moreover, it is found that tracking error 0% has the highest occurrences as well.

b) From Figure 8, the power output and accuracy don't behave the same behavior. At 2:30 pm, power output is 193 watts (> power output at 2:00 pm, 192 watts). However, accuracy at 2:00 pm is 74.6% (> accuracy at 2:30 pm, 68.9%). The DBF doesn't behave the same as the power output. The reason of this is that the direction of the tracker (i.e. accuracy) doesn't behave as the power output. The total irradiation is normally distributed all the day from 9 am to 4 pm, and the highest is around noon (according to the local time of Boone city where the experiment is done). Both the total irradiation and the DBF don't behave as each other as expected because the diffusion radiations changes from time to time, in addition to that the power output and accuracy are neither directly proportional nor inversely proportional.

c) From Figure 9, it is shown from 12:30 pm to 3:30 pm that the wind direction affects the accuracy of the tracker when the wind directions are in the same directions of azimuth of the surface of the tracker. This attributes to that the tracker looks towards the true south (180^o) at 12:39 pm in the location of the lab, which is Boone, North Carolina. Hence, the tracker looks towards the eastern half of the sky (azimuth angle<180^o) before that time. On the contrary, the tracker looks towards the western part of the sky (azimuth angle>180^o) after that time.

d) From Figure 10, there is very weak effect of low wind speeds on the tracking accuracy.

8. SUMMARY

This thesis research and the experiment explained are part of the efforts done in the ASU Solar Research Facility Laboratory to determine the economic values of solar trackers. A previous research is done to compare the performance of solar trackers and fixed panels according to their power outputs. A current research is pursuing the previous one. This thesis research aims to provide well understanding to the interrelation between the power outputs and the accuracies of the solar trackers in order to ultimately provide the laboratory to carry out comprehensive researches on the economic values of solar trackers.
In this thesis research, which this paper is the first publication of, new and inexpensive equipment were used to detect the solar trackers motions and directions. By using this new equipment and calibrating them, the laboratory was able to understand the relation of motion versus accuracy versus power output of both active and passive solar trackers. This contribution in the solar research discipline is valuable because it provides well experimenting and analyzing approaches to further investigate in the technology of solar tracking. Moreover, the results of the done experiment provide different aspect in solar tracking technology, which is the trackers accuracy.

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