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Remote Triggered Single-Axis Solar PV Tracking System with Varying Angle of Incidence

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Abstract- With the increasing number of remotely accessible laboratories, technical education is reaching student communities in more versatile and flexile ways. This work describes the design and implementation of a remotely operable, single-axis photovoltaic tracking system with two degree resolution through an online, real-time, Virtual Laboratories environment. The tracking system is shown to accurately calculate the sun's position and orient the attached photovoltaic (PV) module to face the sun either directly or at an angle of incidence selected by the user. The laboratory experiment covers topics such as the efficiency of the PV panel, the angle of incidence and how these specific variables contribute to the power extracted from the panel. In particular, the remote experiment teaches how to calculate cosine losses, which are of fundamental importance to the efficient and cost effective implementation of solar installations, and the calculation of the variation in power production as a function of the angle of incidence. The graphical user interface (GUI) allows users to experimentally determine the angle at which the maximum power is generated. The novelty of this work includes teaching power extraction from renewable, solar photovoltaic energy sources without confining the students or instrumentation to classroom walls or physical laboratories.

Keywords: Angle of incidence, Cosine loss, Photovoltaic solar cell, Remote trigger lab, Single axis tracking, Solar energy, Solar position algorithm.

1. Introduction

With rapidly growing demand for renewable energies worldwide, augmenting the teaching of renewable energy technologies with experimental laboratory demonstrations is critical to responding to the inquisitiveness of students and creating awareness, appreciation, and ultimately the ability to implement such systems. Broad objectives in renewable energy education include providing functional knowledge and understanding of the necessary facts, concepts and technologies for harnessing renewable sources of energy [1]. However, the cost of installing and setting up high quality laboratories and a lack of experienced faculty are key factors for the reduced effectiveness of teaching renewable energy technology in many locations worldwide [2]. Virtual laboratories are viable alternatives [3, 4] that provide high-quality, remotely accessible labs that can be used by multiple institutions simultaneously for teaching and learning purposes, thereby overcoming the need for local, individual installations.

Solar energy is one of the most abundant, popular, cleanest, easiest to access, and simplest to convert alternative energy sources available in today's energy scenario [5, 6]. Understanding the factors that affect energy conversion efficiency and how to optimize energy production is imperative for any student of energy studies. Improving the efficiency of solar systems [7] by enhancing solar energy conversion and storage processes are focal areas of research in the scientific community. The main objectives are to more efficiently utilize available solar energy resources and to lower the per unit cost of electricity (LCOE - levelized cost of electricity), leading to increased adoption. Electricity production from solar photovoltaic (PV) cells can be greatly increased by using solar tracking [8, 9] (orienting the solar PV panel to always face the sun) which consequently reduces the angle of incidence and the associated cosine losses [10], continuously keeping the conversion efficiency near its peak. Tracking is achieved by implementing algorithms to control mechatronics hardware to move the solar PV panel, in a pre-determined fashion, to follow the sun's position throughout the day and year.

This paper describes the design, development and optimization of a remotely triggered solar PV tracking system for use as a real-time, online laboratory to teach key concepts related to solar energy. The user can change the angular orientation of the panel, which in turn changes the angle of incidence of the sunlight on the solar panel, an important parameter in photovoltaic energy conversion. Since the experiment is hosted online, users can access it from any part of the world during daylight hours within the Indian Standard Time (IST) zone. This interactive experiment process enhances the engagement and interest amongst students, by providing real-time, hands-on learning, creating the environment for a deeper, lasting learning experience.

2. Prior and Related Works

A PV panel is composed of a multitude of photovoltaic cells connected together which can produce direct current primarily from visible light and infrared (IR) radiation of solar spectrum, where the wavelength is in the range of 400-1150 nm [10]. Solar tracking systems, or solar trackers, are used in conjunction with photovoltaic systems to orient the PV panels towards the sun in order to maximize power production. There are a multitude of developed devices that track the sun in such a manner that the cosine losses are minimized and the conversion efficiency is optimum. Trackers are most commonly used in commercial solar PV applications where the extra cost is more than offset by the increased power production and in places where the energy production needs to be maximized for a given set of PV modules like forests, mountains, and high latitude areas. They are also required, essential equipment for most commercial solar thermal energy systems. Tracking can be achieved by a variety of methods: purely mechanical systems, a sun sensor, a sensor that senses the amount of electricity produced, a solar position algorithm (SPA), or a combination of these [11, 12].

Sun sensors are a simple way of positioning the PV cells for reducing the angle of incident light or radiation. The sensors continually measure the sunlight, providing feedback to the control system to determine the direction the tracking system should move to increase energy production and send actuating pulses to the motor control unit [13].

A very basic algorithm for tracking the sun is to rotate the tracker at 15 degrees an hour, after fixing the initial position for the latitude and longitude of the location, and keeping the panels at a fixed angle in the dawn and dusk hours [14].

Another method of solar tracking is by installing PV panels and sensing the amount of electricity produced. The system is continually adjusting the orientation of the panels and searching and maintaining for an orientation which produces more power from the system.

A maximum power point tracking (MPPT) [15, 16] algorithm can be incorporated in order to optimise the efficiency of a PV system by extracting the maximum possible power from the PV panel. These algorithms are used in almost all medium to large size solar photovoltaic installations. However, the implementation cost of such a system is relatively high for small, low-cost systems [17] and varying weather conditions could influence the working of PV sensors. MPPT algorithms are used in combination with a tracking system to increase solar PV power output.

There are different solar position algorithms available for determining the sun's position for any time of the day, day of the year and location on the Earth's surface. The sun's position is calculated based on the time and date, latitude and longitude, and the elevation and azimuth angles of the location [11, 12, 18].

The design of an intelligent controller [19, 20, 21] which uses multiple methods will circumvent problems with sun sensors arising due to cloudy skies and weather changes and control complications arising from open-loop solar position algorithms. However, the design of an intelligent controller can become more expensive. If an intelligently controlled PV tracker is not working, it may not have a backup option for manual control [22].

3. Theoretical Aspects

3.1. Solar Tracking

Solar tracking experiments can be conducted by using either a fixed panel or single or multiple axis trackers. An example of a performance comparison between a fixed solar panel and a single axis tracker [13] is shown in Fig. 1. The curve plots the measured power over a 15 hour window between 5.00 AM and 8.00 PM. Although in the example given in Fig. 1, the magnitude of peak power is slightly higher with a fixed panel, the single axis tracker is still superior due to the higher power yield over a wider range of time [13].

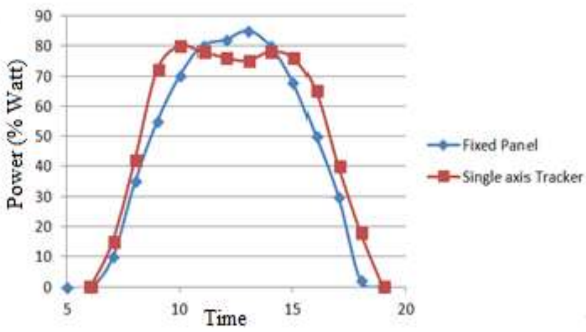

Fig. 1. Example of performance comparison graphs between fixed panel and single axis tracker [13].

The single axis solar PV tracker designed and implemented by the authors for the virtual lab (VL) experiment, shown in Fig. 2, allows a student to remotely study how the power production varies with respect to the solar angle of incidence on the PV module.

Fig. 2. Solar PV tracker setup installed by the authors at their university.

The photovoltaic panel is fixed on a single-axis mechanical tracking assembly as shown in Fig. 2. It is actively positioned by the solar position algorithm using a stepper motor. The tracker axis is oriented in the north-south direction, causing the panel to face directly east in the morning and directly west in the evening. Since the university is near to the equator, East-West tracking provides the most energy throughout the year. Some common definitions of parameters and naming conventions are given below [10]:

1. The declination angle, δ, is the angle between the earth's equatorial plane and a line drawn from the centre of the earth to the centre of the sun, on a given day of the year and is given by,

$$\delta = \sin^{-1}[0.39795\cos[0.98563(N-173)]] \quad (1)$$

where, N is the number of days, counting from January 1st, and the argument of cosine is in degrees.

2. The hour angle, ω, is the angular displacement of the sun east or west of the local meridian, due to the rotation of earth on its own axis at 15° per hour. Alternately, it can be defined as the angular distance between the meridian of the observer and the meridian whose plane contains the sun.

3. The solar elevation or altitude angle, α, is the angle between the central ray from the sun, and a horizontal plane containing the observer. The altitude angle is given by,

$$\alpha = \sin^{-1}(\sin\delta\sin\phi + \cos\delta\cos\omega\cos\phi) \quad (2)$$

where ϕ is the latitude at the measurement site, δ is the declination angle and ω is the hour angle.

4. The zenith angle or the sun's altitude, θ_z, is the complement of the elevation angle, and is given by,

$$\theta_z = 90 - \alpha \quad (3)$$

5. The azimuth angle, *A*, is measured on the horizontal plane (tangential to the earth's surface) and is defined as the clockwise angle between due north [10] and the projection of the sun's central ray on the earth's surface.

$$A = \cos^{-1}\left[\frac{(\sin\delta\cos\phi) - (\cos\delta\cos\omega\sin\phi)}{\cos\alpha}\right] \quad (4)$$

6. The tracking angle for an east-west tracking system (north-south axis), ρ_t, is then determined by taking the east-west component of the vector between the centre of the tracker's pivot axis and the sun. The tracking angle is then given by,

$$\rho_t = \frac{\sin A}{\tan\alpha} \quad (5)$$

An example diagram of panel position vs. tracking angles is shown in Fig. 3.

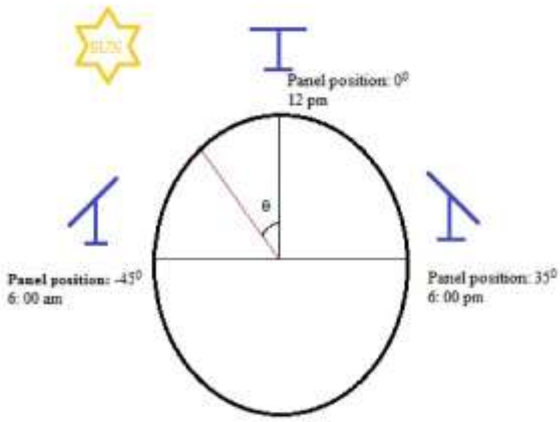

Fig. 3. Panel positioning illustration.

7. The reduction in power that occurs when the solar panel is not oriented perpendicular to the sun's rays (i.e., when the panel's surface normal is not parallel to the sun's direct rays) is commonly known as the cosine loss. Cosine losses can be one of the most significant performance constraints of a PV system. Cosine losses represent the difference between the amount of energy falling on a surface of fixed area with its normal pointing directly at the sun and a surface with the same area, oriented parallel to the earth's surface. In other words, the energy received over a unit area of the earth's surface is reduced by the cosine of the angle between the earth's surface normal at that location and the direction of the sun's rays [10]. Whenever the panel is not oriented to directly face the sun, such as with fixed or single axis tracking, there will be cosine losses and a consequent reduction in power. The cosine factor is the number by which the peak possible power is multiplied to get the final power output.

With the tracking axis oriented in the north-south direction [10], the cosine factor is given by:

$$\cos(\theta_i) = \sqrt{1-\cos^2(\alpha)\cos^2(A)} \quad (6)$$

where θ_i is the solar incidence angle, α is the solar elevation angle, and A is the solar azimuth angle.

The cosine loss over a unit area [23] is then calculated as,

$$P = E_b \times \cos(\theta_i) \qquad (7)$$

where E_b is the irradiance in W/m^2 and θ_i is the angle of incidence, as shown in Fig. 4.

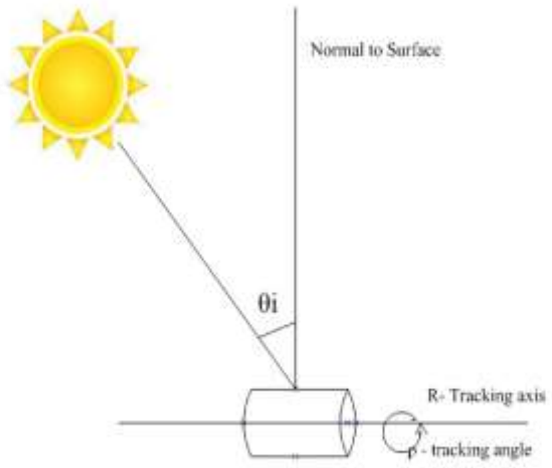

Fig. 4. Diagram illustrating angle of incidence.

3.2. Solar Positioning

The NREL (National Renewable Energy Laboratory) solar positioning algorithm [11, 12] is implemented using LabVIEW to calculate the tracker position angle. The sun's position is normally determined by a number of factors such as the solar elevation angle, solar azimuth angle, latitude and longitude of the location, and the time and date. The algorithm for the solar tracker experiment is shown in Fig. 5. When starting the experiment, the solar PV panel is moved to its initial, horizontal position by a stepper motor. A threshold voltage feedback signal is given from a limit switch to the data acquisition unit to let the system know when the panel is at its initial orientation.

The PV tracker can be operated in two modes: In automatic mode, the tracking angle for the time of the day is calculated using the NREL algorithm and the panel is turned to the calculated position. The voltage and current at the present position are then measured. Tracking continues until the experiment is stopped. In manual mode, the user is allowed to choose the orientation angle of the panel. As the user moves the panel away from its optimum angle, the power produced reduces. In this way, the user can manually determine the optimum angle for the solar panel to produce the maximum power. The user can also work through the solar position algorithm calculations to determine the optimum tracking angle. The optimum angle determined by the user in these two methods should give the same result.

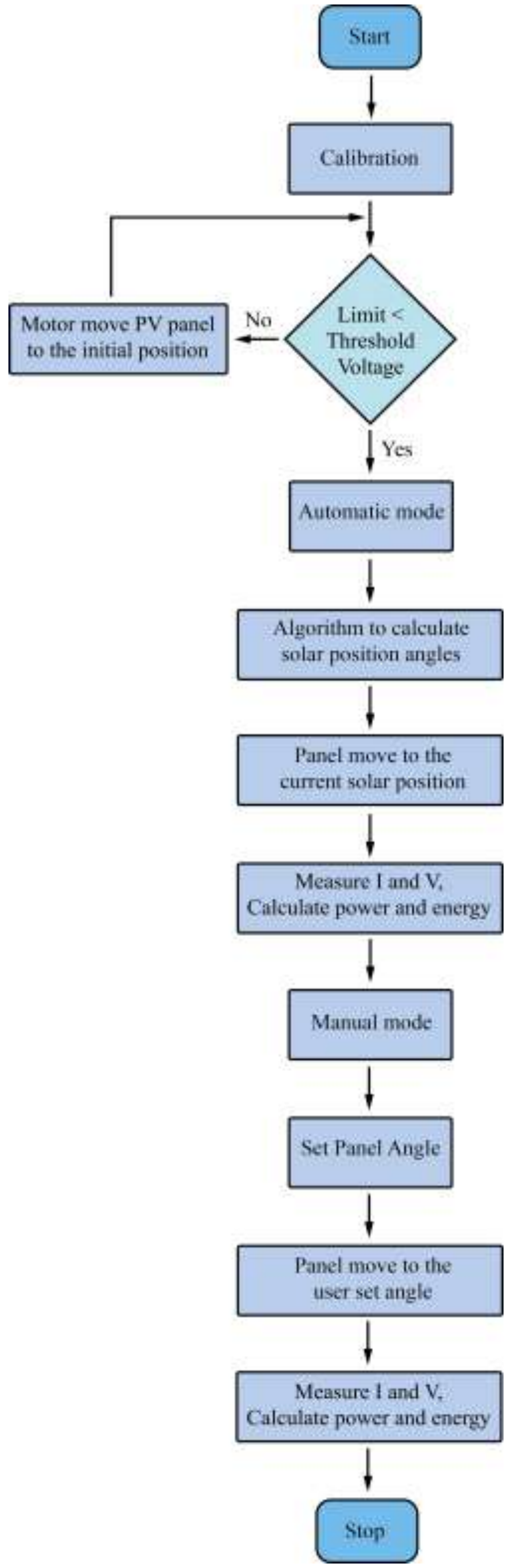

Fig. 5. Algorithm for the operation of the solar PV tracker experiment.

4. Methodology and System Design

The experimental hardware set up consists of a polycrystalline solar panel, a 12V DC unipolar stepper motor, a GSM2 stepper motor driver card, a LabJack UE9

Pro for data acquisition, a compact DC voltage and current sense PCB, relays, and two 3W LED bulbs as the load.

The stepper motor is controlled using the stepper motor driver card. The control signals for the driver card are sent from the data acquisition unit and interfaced to the LabVIEW based control software which runs the solar position algorithm and the user GUI. From the computer interface, the data is transferred via internet to a web server and is made accessible for anyone using the experiment. The solar position algorithm and experiment control algorithms are on the LabVIEW host server, whereas the GUI is hosted on a separate HTTP server. Communication between the user and the host HTTP server and between the host HTTP server and the data acquisition card takes place over Ethernet.

4.1. Hardware Setup

The photovoltaic solar panel is attached to a steel frame which pivots about an axis pointing in the north – south direction, as shown in Fig. 6. The PV panel frame has an external ring gear attached to it, which meshes with the gear attached to the stepper motor. When the stepper motor rotates, it causes the PV panel frame to rotate about its axis.

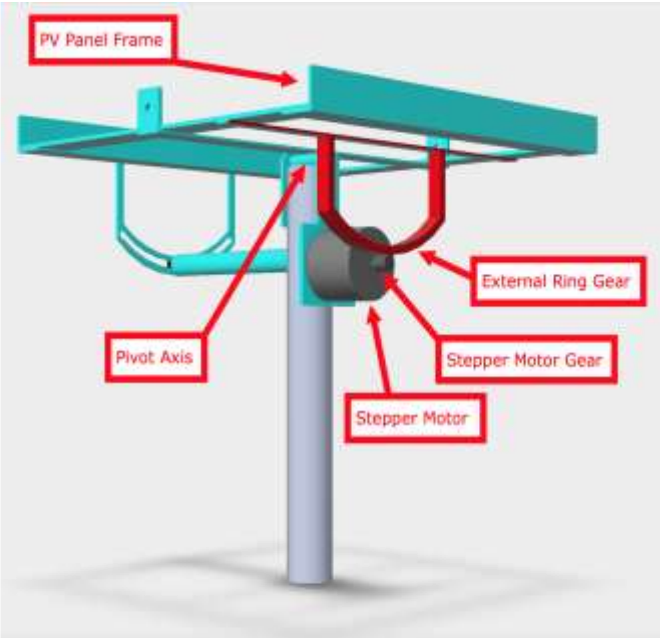

Fig. 6. Mechanical assembly of the tracker.

The entire assembly is mounted on a pole and oriented to face the PV panel due east in the morning and due west in the evening, which is the most effective single axis tracking for a solar photovoltaic installation near to the Earth's equator.

Even though the stepper motor has continuous 360^0 rotation capability, the panel rotation is limited to approximately -45 to +35 degrees for solar tracking.

4.2. Panel Rotation Equipment

The PV frame is rotated by a six wire, unipolar stepper motor [24] with minimum step angle of 1.8 degrees and an angular rate of movement of 4 degree/sec. A stepper motor driver card [25] is used to drive the stepper motor. Various modes of operation, direction and speed can be selected by adjusting the logic connections as can be seen on Fig. 7. The speed of the motor can be varied with the adjustable potentiometer in the driver card. The motor driver card has two terminal blocks and a trimmer pot. The motor and power supplies are connected to the first block and the second block is used for control logic connection.

4.2. Solar Panel Specifications

The polycrystalline panel used in this work is 230×350×25 mm in dimension, with a peak power of 10W, 18V maximum peak power voltage and 0.56A maximum peak power current. The open circuit voltage (V_{oc}) for the panel is 21.8 V, with a short circuit current (I_{sc}) of 0.61A.

4.3. Transducers

A Hukseflux LP02 pyranometer [26] is used to measure the Global Horizontal Irradiance (GHI) i.e. the solar radiation incident upon the horizontal plane. GHI is an important parameter for two reasons: 1) to determine the amount of solar power the PV panel is capable of extracting for a given amount of sunlight, and 2) to calculate variations in the power produced by the panel as a function of the time of day. The LP02 pyranometer can measure irradiance up to $2000W/m^2$ in the temperature range of -40 to 800 C, with $15\mu V/ (W/m^2)$ sensitivity and was chosen due to its high quality, high sensitivity irradiance measurement, and reasonable cost.

A compact printed circuit board (PCB) is used for sensing the DC current and voltage of the PV module [27]. The PV module's current is determined by measuring the differential voltage drop across a shunt resistor located on the board. This differential voltage is then converted on the PCB into an analog voltage output associated with an external load resistor divider with gain ranging from 1 to 100. Voltage sensing is accomplished by scaling the raw solar panel voltage to the 0-3.3V range using a precision resistor divider. Final conversions used for the sensor are 242.3mV / Volt and 73.20mV / Amp. The power and energy are calculated from the measured voltage and current.

4.4. Data Acquisition and Control (DAQ)

A LabJack UE9 Pro data acquisition and control (DAQ) card [28], shown in Fig. 8, is used to collect data from the pyranometer and the current and voltage sense PCB. It also provides the electronic control signals for the stepper motor drive. The DAQ card communicates with the host computer over Ethernet. This device was chosen for its ease of use, inbuilt Ethernet port, analog inputs with 20-bit resolution and digital inputs and outputs.

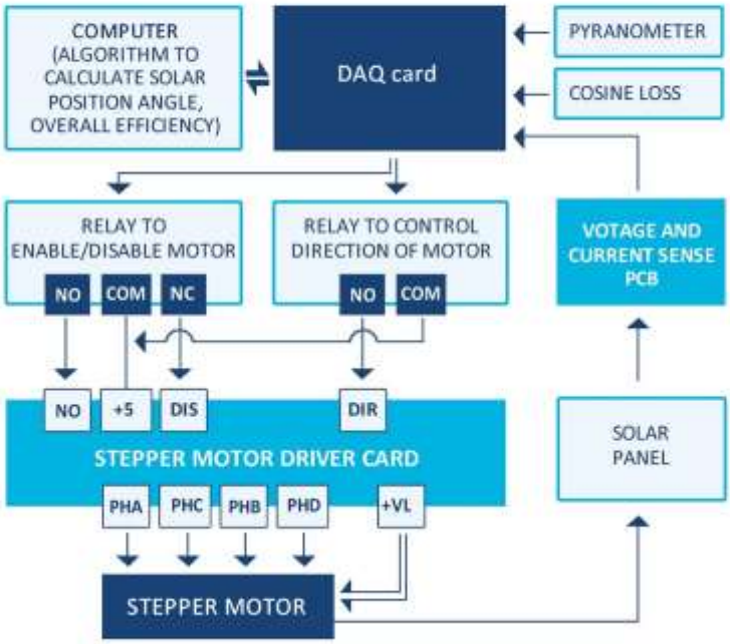

Fig. 7. Block diagram of the solar PV tracker.

Fig. 8. PV Tracker control and load circuit.

4.5. Control Software

A computer based control system was developed using LabVIEW software to perform the data acquisition and control tasks. The LabVIEW application on the control server communicates with the GUI, through which the user can remotely perform the experiment. Solar Position Algorithm calculations [12] are incorporated using LabVIEW as shown in Fig. 9.

5. The Remotely Triggerable Experiment

The Solar PV experiment is hosted on the internet as a remote triggered laboratory, as part of the Solar Energy Labs, Mechanical Engineering, Amrita University Virtual Labs (http://amrita.vlab.co.in) [29, 30]. The website and experiment pages, including the theory, procedure, self-evaluation, feedback and other pages are open to anyone who has access to the internet.

However, for security reasons [3], access over the internet is only granted with a free, one-time registration and a log-in. As the hardware is shared between users, only one user will be able to access the experiment at a given time. A scheduler allows users to schedule the experiment at their preferred time. After a successful login, users are advised to go through the theory, procedure and self-evaluation tab folders before selecting the Remote Trigger (RT) tab. The 'RT' Tab has the user interface for controlling the hardware for the remote-trigger operation and conducting the experiment. There is an option for the user to select between 'graphic view' of the experiment setup that displays the rotation of the panel as an animation using real-time data or the real time video. The animation is especially useful when internet connectivity is slow due to low bandwidth, as can be the scenario for higher educational institutes that are located in rural parts of developing countries.

Fig. 10 shows the interactive web page. In order to start the experiment, user should click on the 'Start &Calibrate' button, which brings the panel to the initial position. After calibration, when the user selects the 'Automatic' switch from the 'Select Tracking Mode' option, the panel turns to the current solar position angle so that the panel faces the sun as directly as possible for a single axis tracker. The voltage at the current position along with the power and efficiency of the panel is recorded on the graph. The panel's absolute angular position gets updated every minute, which is reflected on the screen and animation.

When the user selects 'Manual' mode in the 'Select Tracking Mode' option, an option to change the tracking angle to any desired value in a range of -45 to +35 degrees, gets activated on the display. It can be observed from the real-time graph of the acquired data, available on the GUI, that the power produced by the panel decreases with an increase in the angle of incidence. The selected position can be verified from the graphical view and real time video options available on the GUI.

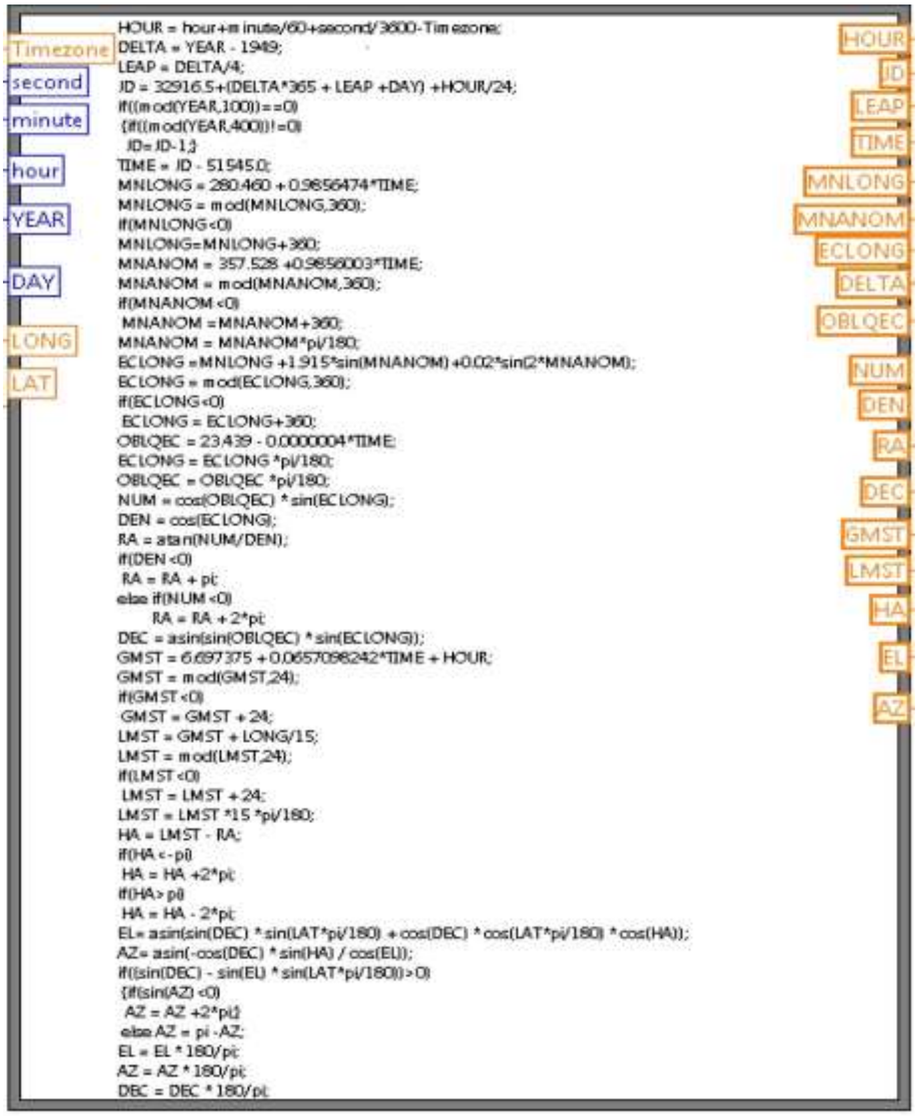

Fig. 9. LabVIEW code for solar position control algorithm.

The graph has provisions for the user to interact with the plotted data. The user can select a point on the efficiency plot from the 'Efficiency, Power vs. Angle' graph, which will highlight the corresponding power in the 'Power Vs. Angle' graph plotted against the tracking angle. This can be used to find the maximum power transfer characteristics of the panel. When the user selects a point from the power plot of the 'Efficiency, Power vs. Angle' graph, the corresponding voltage in the 'Voltage vs. Angle' graph gets highlighted. This can be used to find the maximum voltage transfer characteristics of the panel and tracker for the given solar irradiance and load.

The "Station status" section on the GUI displays a variety of relevant, real time data during the experiment, such as the date, local time, solar elevation, solar azimuth, tracking angle, efficiency, GHI, and voltage. Upon completing the experiment, all collected data can be exported for further verification, calculation and analysis by clicking on the 'Export' button. Clicking the 'Stop' button will end the session.

The last tab folder on the GUI, 'Dataset,' has pre-recorded data for the solar tracker. This data is made available, to give a feel of the plot when the experiment is performed correctly and to download data for conducting the experiment offline when the experiment is unavailable or to gain additional understanding by perusing sample graphs from earlier experiments and exporting the associated data for further analysis. Sample graphs for the automatic tracking mode from the dataset folder are shown in Fig. 11 and 12. The graph for maximum power produced by the solar PV tracker can be obtained by conducting the experiment during different times of the day. From the exported data, the user can manually calculate the cosine losses at various data points, as enumerated in section 3, Eq. (7).

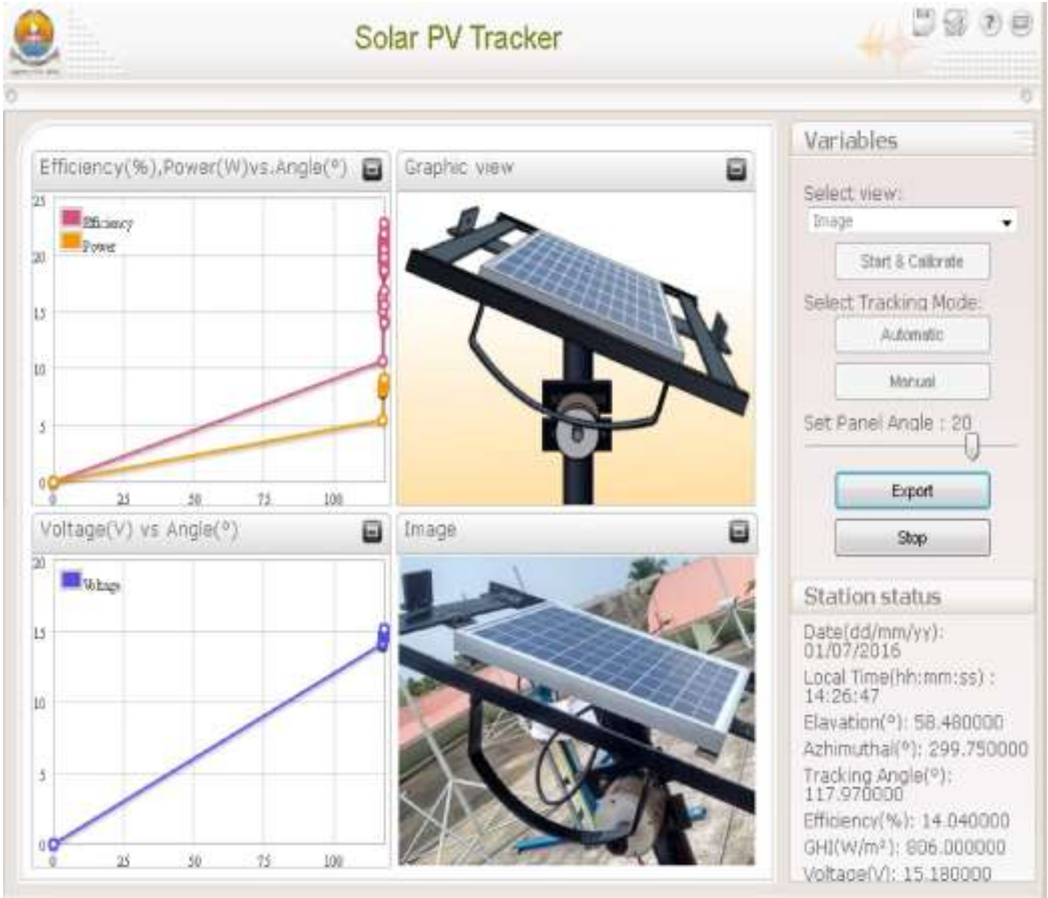

Fig. 10. GUI of Remote triggered solar PV tracker experiment

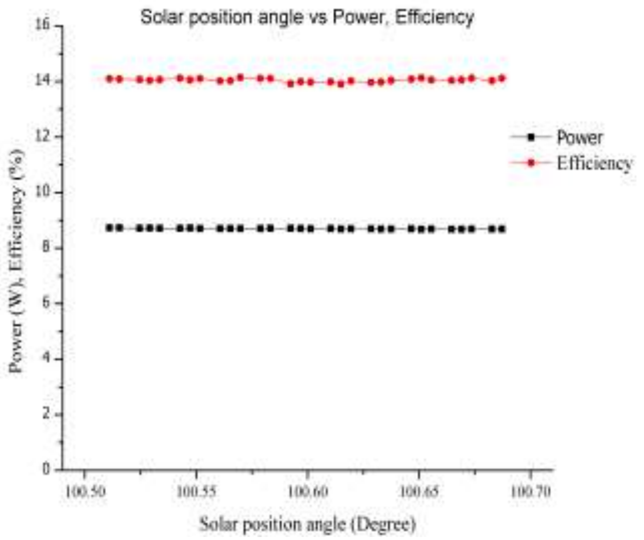

Fig. 11. Power, Efficiency vs. Angle plot from dataset

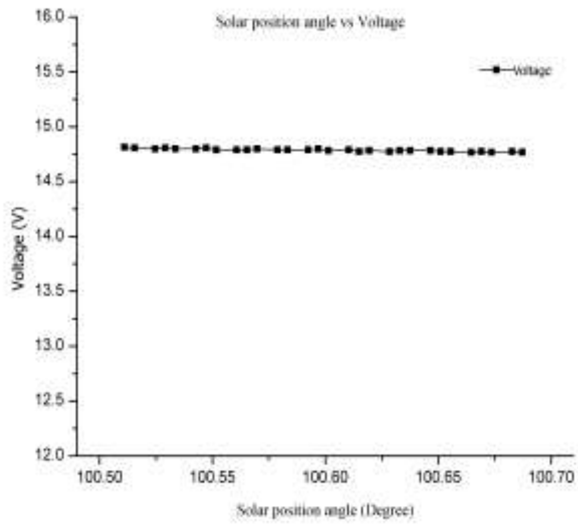

Fig. 12. Voltage vs. Angle plot from dataset

5.1. Virtual Lab User Feedback

The remote triggered solar PV tracker experiment has been accessed by around 4000 users from around the world. A part of the feedback submitted by the users is shown in Fig. 13. The feedback response shows the experience of the students in performing remote triggered virtual lab.

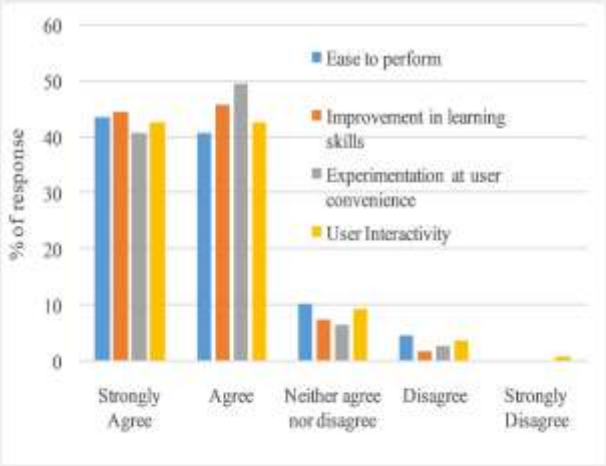

Fig. 13. Feedback survey response.

6. Conclusion and Future Work

The Amrita Virtual Lab experiment for single axis PV tracking has been successfully designed, deployed and tested with a two degree resolution. The design of the single axis tracker, the interfacing required for a remote user to control the solar PV tracker, and other aspects have been accomplished as part of this study. This remote triggered experiment has been accessed and benefited by more than 4000 students from various institutes.

The online, real-time experiment setup can be used to learn important parameters such as cosine losses and the effects of the angle of incidence, which are crucial for setting up PV systems to harness solar energy. These parameters help determine the optimum angle to install a solar PV system to maximize power production. The efficiency of the solar panel is calculated from the effective power produced by the panel compared to the total available solar radiation, as measured by the pyranometer. Cosine losses are calculated from the angle of incidence and solar radiation data. The experiment is currently setup for polycrystalline panels and could be extended to monocrystalline, thin film or other types of panels, allowing a comparative study of multiple PV module chemistries, efficiencies, and the impact of variations in the angles of incidence. This work illustrates the importance and necessity of augmenting learning, for emerging topics such as renewable energy, to learners who do not have access to physical laboratories.

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