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MASTER OF SCIENCE IN RENEWABLE ENERGY

TOPIC:
***ASSESSMENT AND OPTIMIZATION OF SOLAR PV TRACKING
SYSTEMS FOR IMPROVED ENERGY HARVESTING EFFICIENCY***

A Thesis submitted to the African Center of Excellence in Energy Studies for Sustainable Development (ACE-ESD) in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN RENEWABLE ENERGY

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Declaration

I, the undersigned, declare that this thesis is my original work and has not been submitted for a degree at any university and all resources used have been thoroughly recognized and cited.

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List of Abbreviations & Acronyms

μP: Microprocessor

AST: Active Solar/Sun Tracker

DAST: Dual Axis Solar/Sun Tracker

CSP: Concentrating solar power

PID: Proportional Integral Derivative

PST: Passive Solar/Sun Tracker

PV: Photovoltaic

RTC: Real Time Chronology

SAST: Single-axis Solar/Sun Tracker

ST: Solar tracker/tracking

STS: Solar tracking system

LCD: Liquid Christal Display

LDR: Light-dependent resistors

Abstract

This project work focuses on the design, optimization, and assessment of a two axis sun tracking systems to the energy harvesting efficiency of solar PV systems. The study further integrates two geared DC motors for accurate panel movement along both axes. The performance of the sun tracker is evaluated through MATLAB simulations, which model the dynamic movement of the tracker, solar panel orientation, and energy output over day. Simulation Results show that the use of a two axis tracker significantly improves energy yield compared to fixed systems, while energy consumption due to motor movement is optimized through control strategies. This project works involves using a photovoltaic conversion panel in an automatic controller-based solar tracker system for efficient energy harvesting. The goal is to design a two axis solar tracker that adjusts its position to follow the sun and optimizing power output. A two axis tracking script made to follow the sun rays in two ways by adding elevation and azimuth. It collects maximum sun rays by watching the sun movement in four different directions. Various technologies for sun tracking systems have been examined, including two axis solar trackers, active solar trackers, chronological trackers, and hybrid trackers. The movement degrees of solar tracking systems of fixed and two axis sun tracking systems have also been examined. It has been discovered that AST with dual axis rotation are suitable for energy harvesting. This project work contributes to the advancement of solar energy technology by proposing solutions that increase harvesting efficiency of solar energy resources.

Chapter 1 INTRODUCTION

1.1. Background

The energy from the sun is a freely available and globally sustainable resource that has demonstrated its potential to be the tipping point in the energy transition from conventional resources dominated by fossil fuels to renewables. Solar to electricity energy conversion is a viable solution to the world energy concerns. Edmund Becquerel discovered in 1839 the photovoltaic effect, is the term for the voltage that is produced when direct light strikes an electrodes in an electrolytic process, till now that is a new way to generate electricity. [1]. Photovoltaic technology was first marketed in 1954 for monitoring satellites in orbit. The demand for PV has increased substantially in recent decades because of their remarkable capacity to generate electricity from sun light [2]. Many research projects have been undertaken in the overall subject of solar energy conversion, as well as in one highly specific sector of that topic, photovoltaics. In this case, creating, improving, and implementing systems using this technology are critical considerations because, when done correctly, they can increase solar energy harvesting. Because optimum efficiency is reached when the incoming light is perpendicular to the solar panels, one way considered is to enhance the quantity of solar radiation caught, this is known as solar tracking[3]. Currently, there is a problem with solar energy harvesting because photovoltaic systems only absorb a small fraction of the solar energy. The orientation and tilt angle of PV cells systems influence how they performance in reference to the sun.

Solar tracking systems are critical for optimal system performance since they orient solar panels towards the sun position at all times of harvesting. A solar tracking device, or tracker, keeps the PV panels perpendicular to the sun rays. ST are devices that boost the performance of solar energy systems by continuously orienting the solar panels towards the optimum angle of sun rays.

1.2. Statement of problem

Initially solar energy is produced by sunrays and can be extracted using different technologies especially solar photovoltaics. There is an issue in solar energy harvesting since photovoltaic only manage to capture a modest percentage of the sun energy due to fixed tilt arrangement that necessitates the strong solar potential to be practical.

However, the assessment and optimization of sun tracking systems for improved energy harvesting efficiency have not widely investigated at both regional and local extent. Effective modeling and simulation of a closed loop active chronological hybrid STS necessitates the use of continuous trackers of the sun position and position the solar photovoltaic perpendicular to the sunlight to ensure the PV panels receive the optimum sun energy over the day resulting in optimal energy harvesting.

1.3. Objective

1.3.1. Main objectives

This thesis major objective is to assess and optimize solar tracking systems for improved PV energy harvesting efficiency.

1.3.2. The Specific objectives

The specific objectives of this research are as follows:

1. To assess types of STS
2. To model and simulate solar tracking system by using worm and gear constraint for improved energy harvesting efficiency.
3. To develop a control algorithm that accurately adjusts the position of the solar PV over the day.

1.4. Research questions

The difficulties mentioned above prompt various concerns about the solar energy harvesting to function effectively. Among these are the following:

1. How do single and two axis solar PV tracking systems function at different solar potential?
2. Can a single axed ST outperform dual?
3. What is the best control strategies for STS?

1.5. Scope of the study

Solar energy harvesting will be used on utility grids and in urban areas for power supply, particularly to improve socioeconomic development. Through simulation techniques, MATLAB Simulink will employ models to analyze historical data and predict solar energy generation patterns, leading to smarter adjustments in both tracking methodologies and train algorithms to anticipate days with varying weather conditions and adjust tracking priorities accordingly. It will also integrate a maintenance system that alerts users when active tracking components (sensors, actuators) require upkeep, ensuring consistent performance of the hybrid tracking system. The simulation will run under various scenarios (different times of day, seasons and different geographical locations) to be sure that there is an improved energy harvesting efficiency.

1.6. Significance of the study

This research has the potential not only to improve the efficiency of sun tracking systems and tilt angle optimization, but also to further the broader acceptance of renewable energy technology. It will underscore the importance of continual innovation and optimization in meeting the growing global demand for energy that is sustainable and clean sources. It aligns with global efforts to enhance renewable energy efficiency and contributes to Rwanda's sustainable development goals.

The study goal is to lower the cost of solar energy, boost energy access, and help the transition to a low carbon economy by optimizing solar PV tracking systems. This supports the need for significant research into solar tracking for innovation and development, which is the fundamental purpose of this thesis research.

Chapter 2 THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Introduction

The energy drives the development and civilization of the society in which we live. While fossil fuels now meet the bulk of the world energy needs, their scarcity and harmful emissions render them unsustainable. Renewable energy sources are critical for lowering emission of greenhouse gases and decreasing reliance on nonrenewable energy.

Solar energy is among the most essential choices for meeting the world growing energy demand in a way that is sustainable. Solar energy is a free, abundant, renewable as well as sustainable source of energy from the sun coming to Earth as light and heat energy. Photovoltaic cells are used for this conversion also called solar harvesting. However, the sun energy potential changes from sun rise to sun set, location to location, daily climatic conditions such temperature, humidity, etc. Mainly solar system performance is influenced by the direction and tilt angle to the sun. To capture the greatest incident beam, the photovoltaic panels must be adjusted to follow the sun. Positioning solar cells to maximize daytime energy extraction is one approach for increasing their performance.

Compared to traditional solar panel placement, which centers panels halfway between West and East with a roughly 30 degree tilt towards the south, a solar tracker aligns a solar PV panel using light or solar sensors attached to a stepper motor, servo motor, gas filled piston, etc., to optimize energy extraction over a day and boost photovoltaic efficiency[4]. New technologies have recently been developed to maximize the quantity of solar radiation that these systems can collect using direct or indirect approaches such as solar trackers (ST) and tilt angle optimization.

2.2. Types of STS Overview

Solar trackers are currently two types based on how they move: double-axis trackers, which revolve around two axes, and single axis trackers, which rotate around only one axis. Although they are less frequent than single and or double axis trackers, there are numerous trackers with significantly more complex designs. Solar tracking systems are designed to keep solar panels at an ideal angle relative to the sun throughout the day.

The disadvantages of these strategies can be mitigated by the solar tracker with proper control and optimization. With the best solar tracker, solar panels systems can perfectly align with sun position and adapt for daily height angle variation, seasonal latitude offset, and other parameters[5].

The azimuth, declination, elevation, inclination, Zenith angles and sun irradiation are all significant considerations when determining where to install a sun tracking system. The sun azimuth angle and height are the primary parameters in determining its position.

Solar tracker systems are three types based on how they govern photovoltaic panel movement: passive, active (single or double axis), and chronological tracking systems[6]. A sensor-based STS uses light sensors like photodiodes or LDRs to directly detect the solar position in the sky and adjust solar PV accordingly, whereas an RTC solar tracking system depends on a Real-Time Clock (RTC) to calculate the sun position based on time and location, allowing the PV to be positioned precisely without the need for constant sensor readings; in essence, sensor-based tracking is more responsive to immediate sun.

Table 2.1: Sensor based versus RTC based solar trackers [6]

Sensor-based ST	RTC-based ST
Extremely unstable	Stable
Closed loop	Open loop
Less accurate	More accurate
Weather dependent	Not weather dependent
Less efficiency	More efficient
Increases efficiency up to 40%	Increases efficiency up to 60%
More Costly	Less costly

Since passive tracking systems rely solely on solar radiation to function, they essentially require no additional power sources. This tracking system is less expensive and sophisticated, but it has poor accuracy and dependence on weather conditions.

While precision is the foundation of active tracking, the tracking mechanism consumes some of the energy produced. Except for particularly foggy days, this technology is fairly accurate. On cloudy days, the sensors have difficulties estimating the solar position in the sky.

Due to this relatively high accuracy, active solar trackers are commonly utilized even if they require extra electricity for sensors, microcontrollers, or motors. Chronological tracking systems consume more power due to the continual spinning of motors or actuators. Additionally, this method is useless when operating on cloudy days. AST systems use sensors and motors to track the sun position and adjust the positions of PV panels, PTS utilize a low boiling point compressed gas or fluid produced solar heat from the sun [7].

Hybrid trackers combine aspects of dual and single axis systems to achieve a balance between price and performance. Advanced control algorithms may be incorporated into these systems to optimize tracking according to particular site conditions. They may also combine both date/time-based and sensor-based approaches to take advantage of the strengths of each method.

2.3. Solar harvesting optimization

A variety of researchers have investigated the effectiveness of photovoltaic systems for increasing solar energy output. In general, three ways to increase photovoltaic system efficiency are boosting solar cell efficiency, improving energy conversion control algorithms, and deploying a tracking system [8]. One of effective ways to increase the energy production PV systems is to install STS, which attempt to optimize the energy gathered by maintaining PV perpendicular to the incident sun rays. The table 2.2 depicts the optimization technics for PV energy harvesting.

Table 2.2: Summary of the techniques used for solar harvesting optimization[9]

MPPT controller	Cooling system	Cleaning system	Solar tracker	Floating PV system
Extract and sustain the maximum power from PV panels at any environmental condition by matching its I-V operating point to the load characteristic via a DC/DC	Cool the PV panels in order to maintain the temperature of the PV cells close to the nominal operating value, which will increase their electrical efficiency and produce more energy	Clean the PV panels of dust, grime, bird droppings, or other pollutants on the surface of the panels, which may cause a loss in their efficiency and thus a decrease in energy production and	Maximize solar energy collection from PV panels by keeping them perpendicular to the incident solar radiation using a movable framework	Installing PV panels on floating structures on water bodies, such as dams and ponds, to take use of the natural water-cooling effect and so improve their efficiency

2.4. Solar geometry

The sun shape and attributes influence the type of energy it releases into space. Solar geometry refers to the position of the sun, its shading, and how beam radiation reaches surfaces of various orientations.

The solar constant G_{sc} estimated at 1367 W/m^2 is the amount of energy received from the sun per unit time on a surface perpendicular to the direction of radiation propagation at the average earth-sun distance outside the atmosphere..

Various angles can be used to characterize geometrically the relationships between a plane of any given orientation with respect to the earth at any given time, regardless of whether the plane is stationary or moving, and the incoming beam of solar radiation, or relatively the position of the sun to that plane.

1. Latitude, (ϕ) the positive north or south angular location; $-90^\circ \leq \phi \leq 90^\circ$.
2. Declination, (δ) the angle of the sun relative to the equator, positive north; $-23.45^\circ \leq \delta \leq 23.45^\circ$. It is measured at solar noon, or when the sun is on the local meridian.
3. The slope or tilt angle, (β) is between the surface plane and the horizontal; $0^\circ \leq \beta \leq 180^\circ$. ($\beta > 90^\circ$ indicates a downward-facing component on the surface.
4. The surface azimuth, (γ) the variation of the normal projection from the local meridian on a horizontal plane, zero due south, east negative, and west positive; $-180^\circ \leq \gamma \leq 180^\circ$.
5. The hour angle, (ω) refers to the angular displacement of the east or west of the local meridian caused by the earth rotation at 15 degrees every hour. Mornings are negative, whereas afternoons are favorable.
6. Angle of incidence, denotes the angle formed by a beam of radiation on a surface relative to its normal.
7. The zenith angle, (θ_z) between the vertical and the line to the sun, indicating the angle of incidence of beam radiation on a horizontal surface.
8. The solar altitude angle, (α_s) between the horizontal and the line to the sun, which is the opposite of the zenith angle.
9. The sun azimuth angle, refers to the angular displacement of the projected beam radiation from south to the horizontal plane. Eastward of south are negative, while westward of south are positive.

2.5. Solar angles calculation

The angle of declination δ determined from the equation 2.1 [10].

$$\delta = 23.45 \left[\frac{360(n+284)}{365} \right] \quad (2.1)$$

The equation below expresses the hour angle for a certain location of L longitude, TL the local time, ET the equation of time, and N the time .

$$\omega = \frac{2\pi}{24} \left(TL - N - 12 \left(\frac{24}{2\pi} \right) L + ET \right) \quad (2.2)$$

$$ET = 9.87 \text{ Sin}(2d) - 7.35 \text{ Cos}(d) - 1.5 \text{ Sin}(d) \quad (2.3)$$

$$d = 2\pi \frac{n+24}{365} \quad (2.4)$$

The angle α_s generated by the solar projection on the horizontal plane of the site is the sun height or solar altitude. It varies between ± 90 degrees and takes value zero at sunset and sunrise, positive during the day, and negative during the night.

$$\mathbf{Sin\alpha s = Cos\delta Cos\varphi Cos\omega + Sin\delta Sin\varphi}$$

(2.5)

The azimuth angle is calculated by projecting the direction of solar radiation onto the southern direction of the location.

$$\mathbf{Cos\theta z = Sin\alpha}$$

(2.6)

The normal of the slanted collecting surface and the path of solar light form an angle of incidence. The angle of incidence, controlled by the sun's location and the angle of inclination (β), dictates how much direct radiation is incident on the surface and estimated as follows (φ the latitude angle) [11].

$$\mathbf{Cos\theta = Cos(\varphi - \beta)Cos\delta + Sin(\varphi - \beta)}$$

(2.7)

The surface spins around two axes simultaneously. Dual-axis trackers provide greater precision and can boost energy absorption by up to 40%. However, they are more complicated and costly. Factors impacting tracking include the axis of rotation, rotational direction and the latitude of the site. Sun trackers can improve the quantity of solar energy collected during the day.

However, they require more care and are prone to damage by wind and the weight of the panels[12]. Figure 2.2 shows a detailed classification of sun tracking systems. Based on freedom, the first option is single axis tracking, moving the solar photovoltaic in horizontal or vertical direction. The second form two axis tracking, which may change in both directions at the same time.

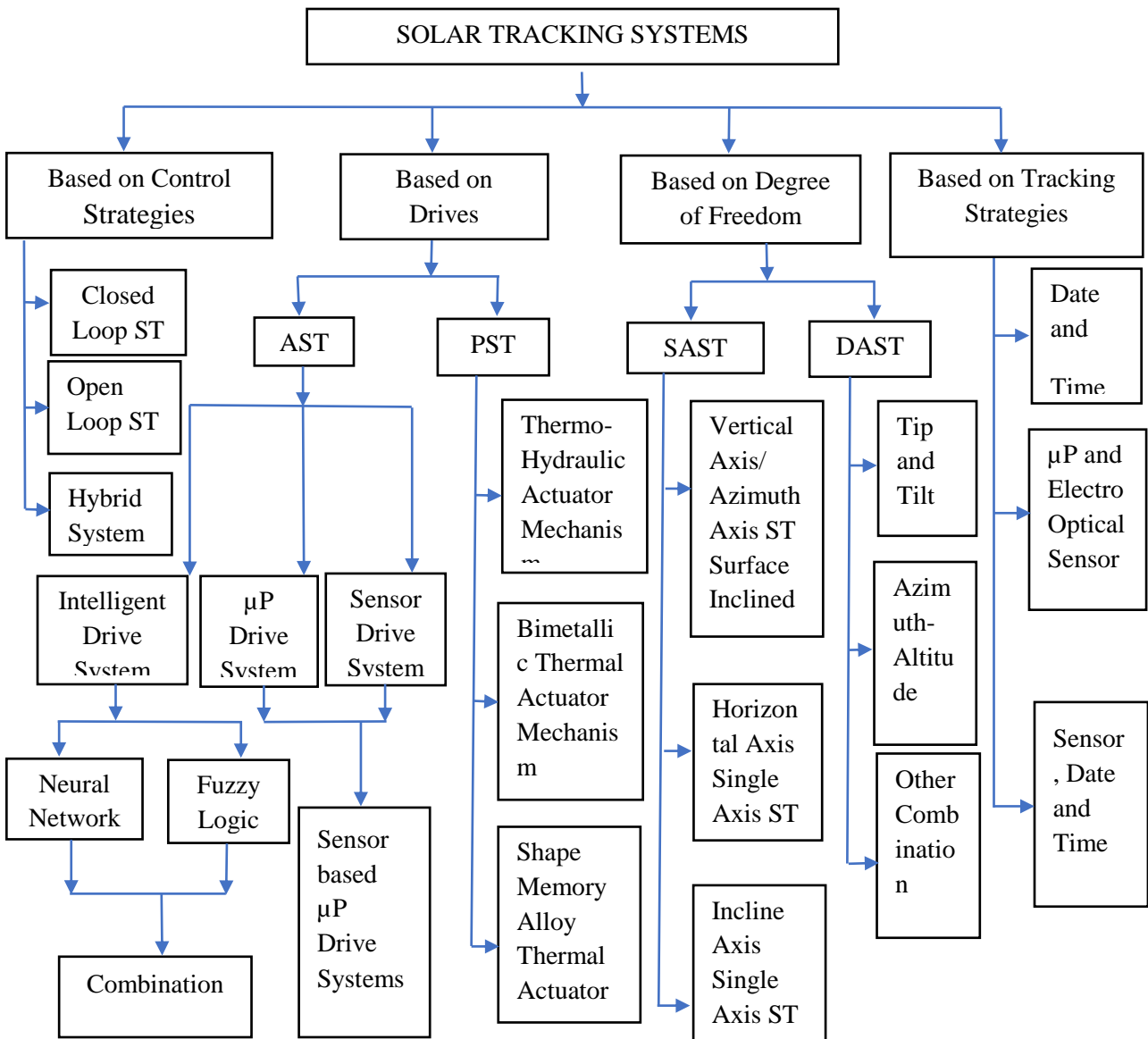


Figure 2.1: Classification of solar tracking systems[13][14][15]

2.6. Solar tracking systems working principle

Throughout the day, the sun travels continuously, whereas a solar panel remains stationary. When a solar panel is attached to the ground and oriented in the direction of the northern hemisphere, its energy yield is not consistent throughout the day; at the beginning and end of the day, the incorrect inclination angle of the panel reduces its electricity production. A solar tracker turns the solar panel towards the sun while maintaining an optimal angle of incidence of solar radiation (about 90°). The tracker will continue to circle until the difference is roughly equal, that is, when the light intensity on the east, West, North and South LDR are equal. It should be noted that a threshold value is commonly employed in this sort of controller (on-off) to ensure smooth rotation of the tracker motors [9].

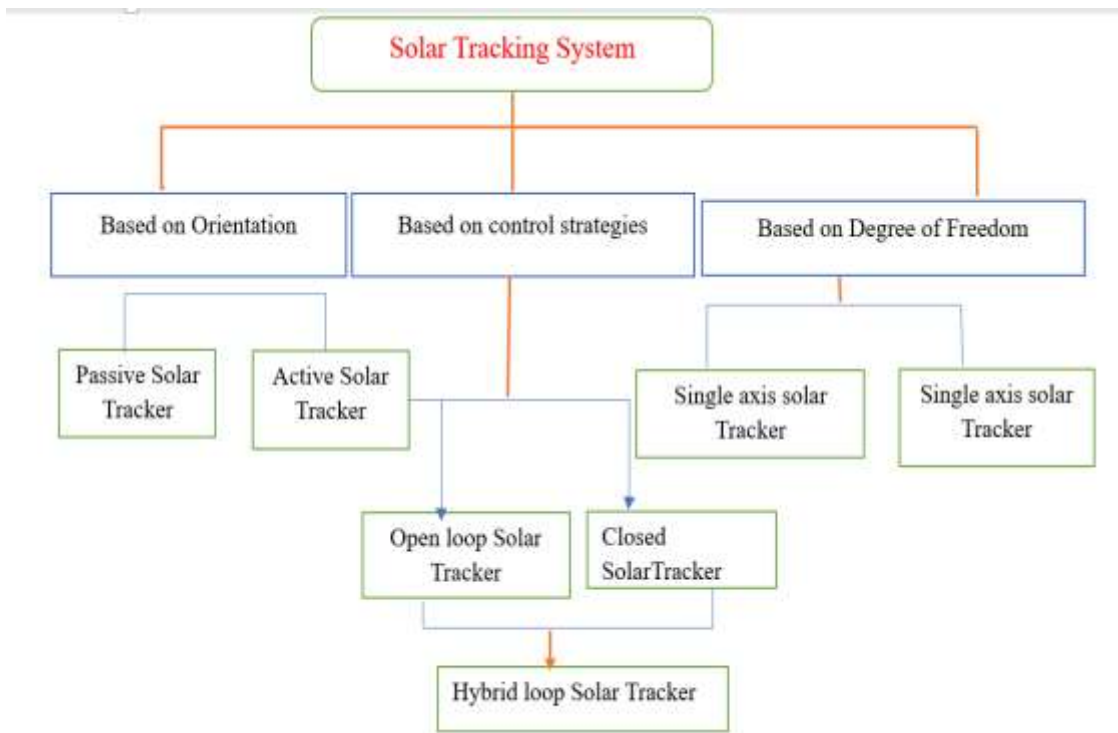


Figure 2.2: Solar tracker systems classification

For some additional applications using closed loop tracking systems, a camera serves as a sun position sensor. The camera catches real-time photographs of the sun and feeds them back to the controller, which then processes the images using software to determine the center of gravity of each shot.

The processing of results allow us to calculate the angle difference between the sun position and the PV panel. The controller then provides the necessary control signal to the tracker actuators to correct this disparity and align the PV panel with the sun rays[16].

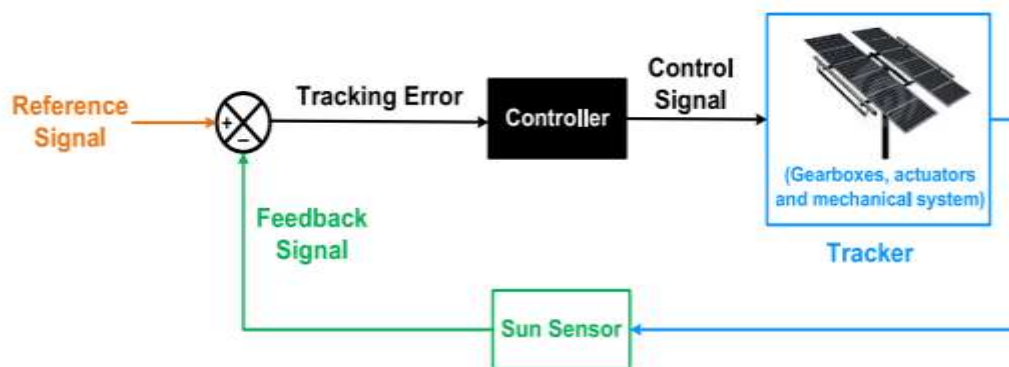


Figure 2.3: Block diagram of the closed-loop control[16]

2.7. Solar Tracker Fundamentals

A device that tracks the sunlight and points a solar PV panel toward the sun. The sun travels across the sky over the day and seasons, depending on its height. Devices that are powered by solar energy are most efficient when they are aligned with the sun. Sun tracker can improve the efficiency of solar panels, but it may also increase system complexity. Solar trackers range in price, quality, and performance. The most prevalent type is heliostats, which employ a moving mirror to redirect the sun position to a certain location[17].

2.8. Types of Solar Trackers

The solar tracking systems may be classified according to the extent of its rotating movement. STS are categorized into two groups based on their degrees of rotation: single axis and two axis solar trackers. SAST go along a single axis, usually east-west, tracking the sun movement through the sky. While these systems increase efficiency relative to fixed panels, they do not capture the full potential of sunlight, especially at higher latitudes[18].

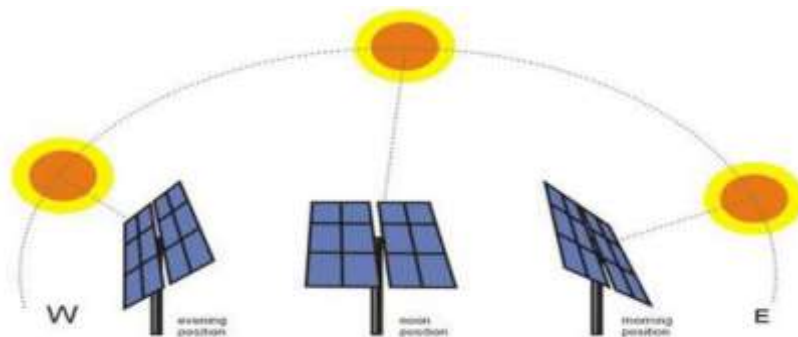


Figure 2.4: Single Axis Solar tracking

Two axis solar tracking devices can move both horizontally and vertically, allowing them to track the sun location more accurately throughout the day and season. These systems provide a higher energy production because they can account for both the sun horizontal movement and vertical angle owing to seasonal fluctuations. The brief details for the preceding types are detailed below.

2.8.1. The Single Axis Solar Trackers

The single axis solar trackers shown in Figure 2.6 can track the sun as it moves from east to west during the day. It is vital to note that a single axis refers to the tracker adjustment along one dimension to follow the sun course. The single axis tracker does not account for the sun changing location over the seasons. Notably, a single axis tracker can generate substantially more energy than a fixed axis system. Single axis solar trackers can increase energy output by up to 20% when compared to stationary flat PV systems[19].

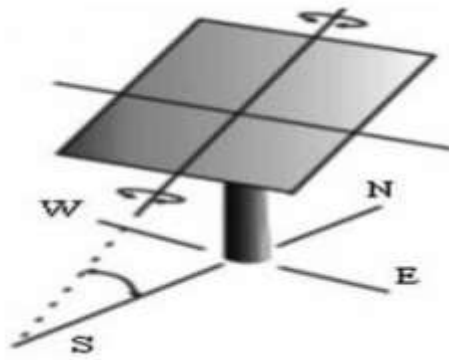


Figure 2.5: Single Axis Solar Tracker[17]

2.8.2. Dual Axis Solar Trackers

The two axis tracker can follow the movement of the sun both during the day and over the course of a year. Figure 2.7 shows a two axis solar tracker.

Unlike the daily east to west motion, the sun position shifts from north to south and east to west as the seasons change. The two axis tracker minimizes the angle between the sun's beams and the screen by efficiently tracking the sun's two-dimensional movement. Compared to single and fixed axis trackers, this allows for maximum solar absorption, which could result in better energy output. When compared to stationary flat PV panels, two axis trackers offer superior performance, achieving better efficiencies with energy benefits ranging from 20% to 50%. [20].

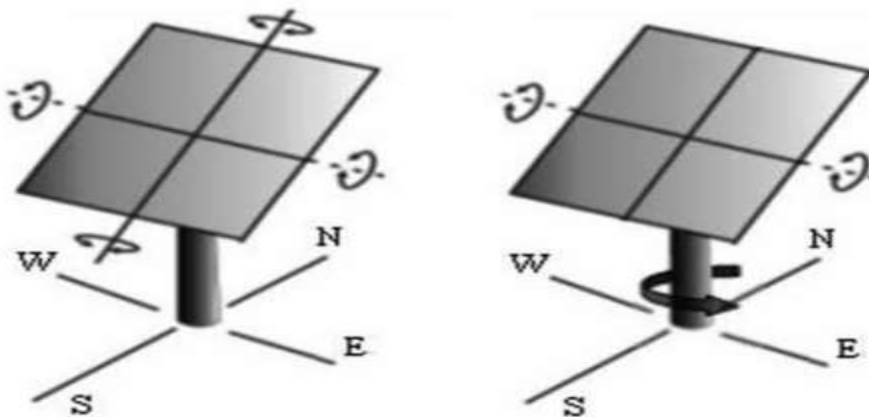


Figure 2.6: Dual Axis Solar Tracker[17]

There are types of solar tracking techniques. Furthermore, tracking is classified into three types: active, passive, and chronological tracking. In an active solar tracking system, sensors continuously measure the location of the sun the whole day. Sensor then helps to actuate motor, ensuring that the panel faces the sun over the day.

2.8.3. Active Tracking

The active solar energy tracking system uses existing sensors to continuously determine the position of the sun over the day[21]. The sensor will activate the motor or actuator, causing the fixture to move in response to sunlight. Once the sunlight is not perpendicular to the tracker, one light sensor will have different illumination than another.

This difference can be used to estimate the direction in which the tracker must be aimed to be perpendicular to the sun [22]. Based on their tracking strategies, AST can be microprocessors, electro-optical sensors based on date and time, auxiliary bifacial PV cells, and a combination of the three types above[23].

2.8.4. Passive Tracking

Passive solar trackers can position their sensor units into the direction of the solar radiation beam without utilizing any mechanical drives[24]. Most of these kinds of trackers are made up of two actuators packed with expandable gas or an on-shape memory alloy. This system makes use of the concept of thermal expansion, or an imbalance in pressure between two places at each end of the tracker. When the PV panel is perpendicular to the sun, the two sides are in balance. When the sun moves, one side is heated, which causes one side to expand and the other to come into contact, causing the PV panel to rotate [25].

2.8.5. Chronological Tracking

A chronological tracker is a timer controlled tracking system. The structure moves at a consistent rate over the day because the sun moves across the sky at a constant rate of around 15 degrees an hour. This approach is more appropriate for single axis tracking without sensors. For two axis tracking, a modified version. The program running on the controller module may compute and set the sun position over the day. The sun tracker spins in response to data transmitted from the control unit memory of prestored data or calculated using a predefined formula[26].

2.9. Summary

The authors in[2] , Research on the design and manufacture of a solar panel incorporating a sun position tracker. The adoption of SPT technology significantly improved the performance of the PV system. The maximum improvement of a single axis sun position tracker over fixed systems is 56%, whereas the average increment is roughly 28.5%. Whenever the day started in the morning, all of the board components were turned to face the East, and the panels were shifted to the left side. The panels moved from the bottom to the top based on the time set in the control unit.

The publication [3], The authors focused on the design and simulation of a solar tracking system for PV. They determined that in order to maximize efficiency from photovoltaic panels, it was required to address the problem of PV orientation, this necessitates the use of a solar tracker in conjunction with the photovoltaic system. A solar tracker will follow the sun over the day and alter the angle of the solar panel such that the sun remains normal and consistent with the solar panels at all times.

There are two approaches to optimize the useable energy rate: by maximizing the conversion and degree of absorption, and by boosting the incident radiation rate through mechanical steering devices.

The authors [8], M. E. H. Chowdhury, A. Khandakar, B. Hossain, and R. Abouhasera, Develop a low cost closed-loop solar tracking system, based on the sun position algorithm.

Closed loop solar trackers are the most popular type of dual-axis tracker since they are simple to use and inexpensive. STS can boost energy production by 10% to 50% over standard PV systems mounted at a fixed angle. With two degrees of freedom to follow the sun location using azimuthal and elevation angles, algorithm based trackers outperform fixed and optical trackers by 13.9% and 2.1%, respectively.

The authors in [13] , Describe the critical role of PV, they discovered that technologies for RE generation; SAT system with proper control systems can enhance electrical power by 22% to 56% as compared to fixed solar systems.

In [9], A. El Hammoumi, S. Chtita, S. Motahhir, and A. El Ghzizal work on Solar PV energy: From material to use, and The most often utilized ways to maximize the power output of PV systems are: A concentration on solar trackers and floating solar panels. According to their findings, PV systems have recently become one of the most popular energy producing solutions around the world.

Despite the fact that the PV energy market is rapidly developing globally, many countries, particularly those with congested urban regions, are running out of room.

In [27], K. Melo, M.. Kitayama da Silva, J. Lucas de Souza Silva, T. Costa, and M. Villalva, work on improvement for the energy yield of PV installations by using bifacial modules and tracking systems. Improving solar photovoltaic installation energy yield using bifacial modules and a tracking system: an analytical method. They discovered that bifacial PV technology can be combined with sun tracking devices to increase solar energy production. The bifacial technology can reach up 3.78% to 8.16%, and the tracker gain ranges from 13.40% to 18.20%, depending on weather conditions and system parameters. The total benefit from using bifacial modules and trackers ranges between 19.39% and 27.39%. Another option for PV increased energy collection and efficiency is to combine these technologies to improve the technical and economic feasibility of solar plants.

2.10. Research Gaps

The Solar tracking systems are one way to maximize the power output of these solar panels. An automatic solar tracking system maximizes solar power generation by continuously adjusting PV orientation to keep the Sun perpendicular to the panel, which is only natural for a few hours and is the main problem for fixed solar panel systems.

Solar tracking with two degrees of freedom is more efficient than systems with only one axis and are stationary.

They do, however, necessitate a high level of maintenance, more complex design and control mechanisms due to the presence of moving components, and high operational and energy consumption is still key main gap to achieve desired energy demand and efficiency.

2.11. Project Arrangement

Chapter one: Introduction provides the background, problem statement, objectives, scope, and structure of the dissertation, chapter two: Literature review: reviews previous research on solar tracking systems, photovoltaic technology, and existing control strategies.

Chapter three: Methodology describes the design, simulation, and data collection, chapter four: designs and simulates results and presents the results of the design simulations and analysis of system performance, chapter five: results and discussion discusses the simulation results, energy output comparison, and system performance evaluation and chapter six: conclusion and recommendations summarizes the findings and provides suggestions for future work in the field.

Chapter 3 METHODOLOGY

3.1. Introduction

The STS are intended to increase the efficiency of PV systems by altering their orientation to match the passage of the sun across the sky.

3.2. Research steps

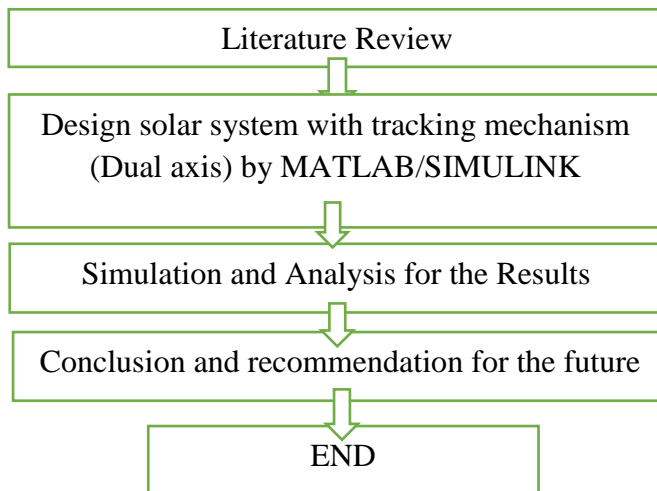


Figure 3.1: Research Chronological steps

Through simulation techniques, MATHLAB Simulink will employ models to analyze historical data and predict solar energy generation patterns, leading to smarter adjustments in both tracking methodologies and train algorithms to anticipate days with varying weather conditions and adjust tracking priorities accordingly. It will also integrate a maintenance system that alerts users when active tracking components like sensors and actuators require upkeep, ensuring consistent performance of the hybrid tracking system. The simulation will run under various scenarios i.e. different times of day, seasons and different geographical locations) to be sure that there is an improved energy harvesting efficiency.

Literature Review: A comprehensive review of existing studies on PV tracking systems, focusing on design and performance.

Simulation and Modeling: Using software tools like MATLAB/SIMULINK, simulate the performance of SA and DA tracking systems under various climatic scenarios similar to Rwanda. Parameters such as solar irradiance, temperature, and shading effects will be incorporated. The solar tracking system primary components include typical PV, deep cycle rechargeable battery, its charge controller, microprocessor, signal processing circuits, a motor, and a motor drives.

The motor module includes a stepper motor and a motor drive. The motor module produces mechanical movement of rotation in terms of angles.

3.3. Solar Tracking Platform Components

The solar monitoring platform is a system component that allows solar collector movement and tracking control, such as a dual axis cross-coupled controller. Typically, the entire integrated system includes the following:

1. Transmission/actuator mechanical drive subsystem includes the positioning system that turns the reflector towards the sun includes linear actuators, worm gears, linear drives, slew drives, and planetary gear drives. Electric motors: DC or AC electric motors used to power mechanical drives via current, frequency, or speed control; battery storage serving as a backup battery system for power storage and startup power requirements.
2. The motion sensing subsystem uses linear or rotational shaft encoders, tilt sensors, inclinometers, photodiodes, and photosensitive resistors to monitor the present location of the dish as it moves to the target position. Solar Position Algorithm calculates of sun vector (γ_s , θ_s), solar azimuth and elevation angles, and finally control unit subsystem: Programmable device to coordinate the modes of operation and the control strategy to position the system based on the solar position algorithm or sensor coordinates[28].

3.4. Data collection

The implementation of a dual axis solar tracking algorithm using azimuth and altitude angles. To maximize solar irradiance, solar position must be calculated (using date, time, and location coordinates) and PV panel orientation adjusted. This data will be imported into software (Latitude $-1^{\circ}56'37.34''S$ and Longitude $29^{\circ}52'50.08''E$). Rwanda's latitude is -2.00000000 , and its longitude is 30.00000000 . Geographic coordinates are a method of expressing the location of a place on Earth by utilizing a pair of numbers to indicate a latitude and longitude.

These coordinates are used to denote the location of a point on the Earth surface, with latitude representing the distance north or south of the equator and longitude representing the distance east or west of the prime meridian. Using these coordinates, one can locate the exact location of a spot on the globe.

3.5. Specifications and Methods

This project presents a method for controlling solar panel orientation with stepper motors. The script has been written to take all sensor output as input and then, using the algorithm, determine the direction and speed of the stepper motor and generate the output to be sent to the stepper motor block.

The parameters required include solar panel specifications, a DC motor for tracking, and sensors. The PV requires Elevation Angle that Received from the Tracking Motors, Azimuth Angle:

Received from the Tracking Motors, Solar Irradiance that Represents the sunlight intensity on the array (optional for this project work, use a constant value) Temperature that Represents the operating temperature of the PV array (optional for advanced models). The table 3.1 describe the Solar panel specifications (Advance Power API-M265), allows for the modeling of a range of preset PV modules from the NREL System Advisor Model (January 2014), as well as user defined PV modules. Input 1 = Sun irradiation, in W/m², and input 2 = Cell temperature, in degrees Celsius.

Table 3.1: PV modules available on market

Items	Rating and Unit
Parallel string	80
Connected series string par module	20
Maximum power	264.96W
Cell par module	72
Open circuit Voltage (Voc)	44.42V
Short-circuit current (Isc)	8.11A
Maximum voltage at maximum power point (vmp)	36
Current at maximum power point (Imp)	7.36A
Temperature coefficient of Voc(%/deg.c)	-0.3244
Temperature coefficient of Isc(%/deg.c)	0.053317

Table 3.2: Motor specifications

Items	Rating and Unit
Number of Sliders	1
Size	650 x 64 x 50 mm
Slide Width	78mm
Horizontal Load	56 kg
Vertical Load	15 kg
Current	1.2 A
Voltage	12 V
Resistance	3.2 Ohms
Step Angle	1.8°
Torque	45 N.cm
Accuracy	0.1 mm

3.6. The tracking mechanism

The tracking mechanism in a dual-axis solar tracker system involves mechanical components (such as motors, gears, and actuators) that adjust the panel's position throughout the day. There are various mechanisms for implementing dual-axis tracking:

- ❖ **Geared DC Motors:** DC motors, particularly those with gears, are often used in solar tracking systems due to their precise control over movement. They can move the solar panel incrementally, allowing for small adjustments that optimize energy capture.
- ❖ **Step Motors:** These motors provide even finer control of movement than DC motors, allowing for very precise angular adjustments. However, they are generally more expensive and complex to integrate.
- ❖ **Linear Actuators:** These devices provide linear motion to adjust the tilt of the solar panel, although they are less common in dual-axis systems compared to rotational motors. In this research, geared DC motors configuration is chosen for their affordability and adequate precision, which is suitable for an effective dual-axis solar tracker system.

3.7. Control Systems for Solar Trackers

The efficient tracking system requires a controller to manage the movement of the solar panel based on input from sensors and converters. Control systems can be divided into two categories like Open-Loop Control: In this type of system, the controller moves the tracker based on a predetermined algorithm, such as calculating the sun's position based on time and geographical location. While this approach is simpler and less expensive, it lacks the ability to respond to environmental factors like cloud cover.

The Closed loop control: This system uses sensors e.g., light sensors or GPS to continuously monitor the position of the sun and adjust the tracker in real time. This approach ensures the tracker stays aligned with the sun despite changes in weather or atmospheric conditions. Most modern dual axis solar trackers utilize closed-loop control systems, as they provide more accurate tracking and maximize energy output by responding to real-time conditions.

The control algorithms used can vary as PID control: A common control method that adjusts the tracker's position based on a weighted combination of the error, the integral of the error, and the rate of change of the error, in this project works, a PID control strategy will be implemented for simplicity and effectiveness in adjusting the dual-axis tracker's position.

3.8. System Simulations

The Simulink model will include input block for reading solar angles (elevation and azimuth), Controller Block for calculating motor control signals based on angle differences they are connected on input signal as yaw and pitch signals PV Array block:

Simulate PV panel behavior using Sim's cape Electrical and Visualization: Plot solar irradiance and power output

3.8.1. Physical Model

The simulation consists of four modules: sun tracking cells, signal processing circuit, controller and a motor. An AST, changes the orientation of solar panels using an electric actuator with a motor and gears.

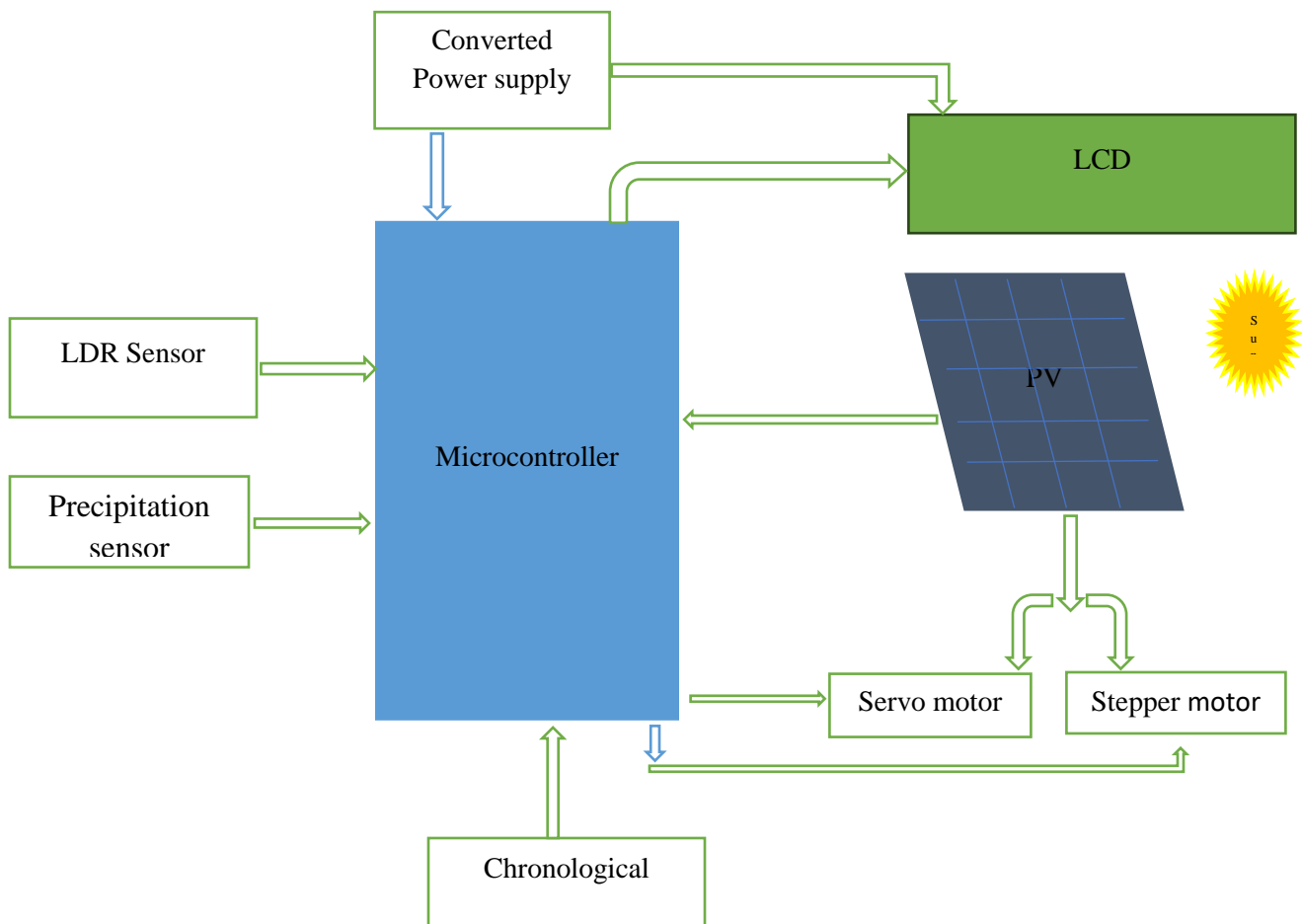


Figure 3.2: Physical model of dual axis trackers

DAT will be chosen to be used as these systems have two axes of rotation, one for east-west movement and another for north-south tilt. This enables them to optimize energy production and harvesting by tracking the sun's course more precisely throughout the day and year. The device constantly adjusts the panels to maintain the correct angle with respect to the sun. This requires turning the panels in both elevation and azimuth directions.

Sensors and motors will adapt the panel alignment using preprogrammed automatic tracking to detect the position of the sun and vary the panel's orientation accordingly, as well as change the angle based on the time of day and geographic location.

This ATS will use sensors to detect the angle of sunlight and the sun's position in real time; actuators that can adjust solar panel orientation based on input from sensors ensuring the optimal alignment with the sun all along the day and control algorithm to process sensor data to adjust panel position dynamically, enhancing the energy capturing during peak sunlight hours and LCD displaying the energy harvested during simulation.

3.8.2. Modelling and Simulation

Modeling and simulating a closed loop active chronological hybrid solar tracking system in MATLAB Simulink, a model that combines aspects of both active and chronological solar tracking methodologies to optimize energy harvesting efficiency.

The Chronological Tracking System will employ an algorithm to determine the sun's position depending on geographical location, date, and time. This can provide a baseline of optimal angles for solar panels at various times of day and year. It will also employ a fixed time schedule: the panels can be adjusted to established optimal angles, avoiding the need for constant motor operations and preserving energy, and seasonal adjustment will adapt the angle settings periodically to account for changes in sun position throughout seasons. The hybrid control logic will combine inputs from both the active tracking sensors and the chronological algorithm.

The model should prioritize active tracking during peak daylight hours when quick adjustments can yield the highest energy gains, during cloudy days or low light periods, the tracker will be controlled by chronologically based on the date and time and rely more on chronological adjustments to conserve battery and mechanical wear and during heavy rain; the tracker will be controlled by precipitation sensor and active sensor to stop the mechanism, as well as during night, the chronological will stop the mechanism based on sunrise and sunset.

To model the DAST system, simulate the movement of the solar panel based on the position of the sun, and evaluate energy harvesting efficiency as a function of panel orientation.

The solar positioning modeled the position of the sun relative to Earth surface, tracker movement simulate the movement of the solar panel based on the position of the sun using a dual axis tracker and energy harvesting efficiency that calculate the energy harvested based on the panel orientation and sun incident angle.

3.8.3. Solar Positioning Model

Location of the sun is described by two angles, the solar azimuth angle (θ_a) and solar elevation angle (θ_e) which are angle in the horizontal plane measured from the south and the angle from the horizon represent the sun height above or below the horizon, respectively.

These angles are determined by time, latitude, and the day of the year. In this scenario, we use simple equations to determine these angles at each time step of the day.

The formulas for solar angles are based on standard solar geometry calculations which are solar declination (δ) is a function of the day of the year (n) and hour angle (ω) is the difference between the time of day and solar noon[29].

$$\text{Solar declination } (\delta) = 23.44^\circ * \sin\left(\frac{360}{365} * (n - 81)\right) \quad (3.1)$$

Where: n is the day number of the year, (1 to 365).

Solar elevation (θ_e) and azimuth (θ_a): The calculation of the solar elevation angle depends on the latitude and the solar declination.

$$\text{Solar elevation } (\theta_e) = \sin(\text{Latitude}) \sin \delta + \cos \text{Latitude} \cos \delta \cos \omega \quad (3.2)$$

$$\text{Azimuth } (\theta_a) = \arctan 2[\sin \omega \cos \omega \sin \text{Latitude} \tan \delta \cos \text{Latitude}] \quad (3.3)$$

3.8.4. Tracker movement

The dual axis tracker changes the solar panel's orientation to optimize the amount of solar energy incident on it. We need to replicate the panel's movement in both azimuth and elevation directions. Assume the tracker adjusts its position according to the calculated azimuth and elevation angles.

3.8.5. Energy Harvesting Efficiency

The energy harvested is directly related to the amount of sunlight incident on the panel, which depends on the angle between the solar radiation and the panel surface. The efficiency can be calculated using the equation (3.3).

$$P_{\text{harvested}} = I * A * \cos(\theta) * \eta \quad (3.4)$$

Where: P is the harvested power (in watts), I is the solar irradiance (W/m^2), which we model as a function of time. A is the panel area (m^2), θ is the angle between the panel's surface and the incoming sunlight and η is the efficiency of the panel, the parameter required are summarized in table 3.3

Table 3.3: Required Parameters

Parameters	Descriptions	Unit
Solar Irradiance	Average solar radiation received	W/m ²
Panel Tilt Angle	Angle of solar panel orientation	Degrees
Tracking Type	Fixed, Single-Axis, Dual-Axis	N/A
Energy Output	Total energy generated	kWh

3.8.6. Understanding Azimuth and Elevation

The azimuth is the angle formed by measuring north clockwise around the observer's horizon and a celestial body (sun, moon). It determines the orientation of a celestial body. Celestial bodies have azimuths of 0 degree due to north, 90 degrees due to east, 180 degrees due to south, and 270 degrees due west.

The elevation is the vertical angular distance between a celestial body (sun or moon) and the observer's local horizon, also known as the observer local plane[30]. For us, the sun's elevation is the angle formed between the direction of the geometric center of the sun's visual disk and the observer's local horizon. The sun/moon is at elevation of 12 degrees when its geometric center is located 12° above the observer's local horizon or plane.

The azimuth is measured eastward (clockwise) from geographic north to the projected satellite path on a (locally) horizontal plane at the earth station. Elevation angle for measuring upward from the local horizontal plane at the Earth station to the satellite Path[31].

3.8.7. Mathematical modelling of solar photovoltaic array

The technical characteristics of the photovoltaic modules used for this model are listed in Table 3. 3. The computationally equivalent circuit for the solar module in figure 4.2 was designed under a solar cell block that is already built in the MATLAB/Simulink library[32].

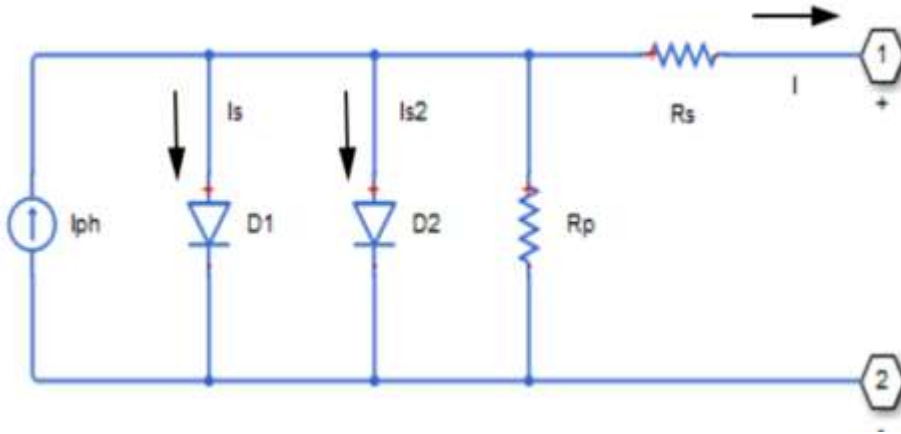


Figure 3.3: Equivalent Circuit of a Photovoltaic

The output current I is

$$I = I_{ph} - I_s * (e^{(V+I*R_s)/(N_1 * V_t)} - 1) - I_{s2} * (e^{(V+I*R_s)/(N_2 * V_t)} - 1) - (V+I*R_s)/R_p \quad (3.5)$$

Where: I_{ph} is the current induced by the sun

$$I_{ph} = I_{ph0} * I_r / I_{r0} \quad (3.6)$$

The solar cell has series, R_s and parallel or shunt, R_{sh} resistances, this prompted the IV characteristics of solar cells to diverge from the ideal photovoltaic model in equation (3.5), resulting in the characteristic given in equation (3.6).

$$I = I_{ph} - I_d = I_{ph} - I_0 (e^{qV/RT} - 1) - I_d \quad (3.7)$$

$$I_{rs} = \frac{I_{sc}}{\frac{qV_{oc}}{\exp(N_s A K T_0)} - 1} \quad (3.8)$$

The reverse saturation current at reference temperature I_0 is given by equation

$$I_0 = I_{rs} \left(\frac{T_0}{T_r}\right)^3 \exp\left[\frac{q * E_{g0}}{A_k} \left(\frac{1}{T_r} - \frac{1}{T_0}\right)\right] \quad (3.9)$$

Hence the diode saturated current depends on temperature

$$I_{pv} = N_p * I_{ph} - N_p * I_0 \left[\exp\left(\frac{qV_{pv}}{N_s A K T}\right) - 1 \right] \quad (3.10)$$

$$P = I_{pv} * V_{pv} \quad (3.11)$$

I_{ph} : Photocurrent (ampere) , N_p : Cells interconnected in parallel

I_{sc} : Short-circuit current (Ampere) , K : Boltzmann's constant (1.38×10^{-23} Joule/Kelvin)

K_i : Cell short-circuit current temperature coefficient (ampere /kelvin) , V_{pv} : Output voltage of a PV module

(A)

T_0 : Cell operating temperature (kelvin) , T : the temperature of p-n junction, T_r : Cell is reference temperature in degree (kelvin)

I_{rs} : reverse saturation current of the diode , S : solar irradiance (Watt/meter square)

q : Electron charge (1.602×10^{-19} Coulomb) , V_{oc} : Open circuit voltage (Volt)

N_s : Cells interconnected in series , A : Ideality factor

I_{PV} : Output current of a PV module (A) , I_0 : PV module saturated current (A)

E_{go} : band gap for silicon

The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc} so

$$FF = \frac{P_{max}}{V_{oc}I_{oc}} = \frac{V_{mp}I_{mp}}{V_{oc}I_{oc}} \quad (3.12)$$

The efficiency η of the module is the ratio of output power to input power

3.8.8. Mathematical Modeling of solar Tracking motor

The design of a two-axis photovoltaic panel (solar tracking) system is a challenging undertaking. The efficiency and cost of a tracking system should be optimized. In contrast to fixed systems, tracking systems are concerned with energy use. This is a factor that influences the system's efficiency. To reduce this effect, literature is reviewed, and a DC motor with a gear system (damper motor) with low energy consumption is discovered to be the best option[33]. The dual axis tracker must be able to track both the sun's azimuth and altitude angles. Two servomotors will impart torque to the azimuth & elevation axes to seek the sun position. In a two axis tracker, the system adjusts both the azimuth angle (ϕ) and elevation angle (θ) to track the sun's location more precisely[29]. This can be done by tracking the source for its whole range of motion. By taking Variation in the solar declination angle (δ) ranges from +23.50 to -23.50 during earth's revolution around the sun, this variation can be described by equation[34]. The motor's torque is given by

$$T_m = k_m * I \quad (3.13)$$

k_m is the motor constant (related to the motor type) and I is the current supplied to the motor. The torque must overcome the moment of inertia (I panel) of the solar panel and any resistive forces (friction, wind, etc.) to move the panel. The net torque required to move the solar panel is:

$$T_{net} = T_m - T_{load} \quad (3.14)$$

Where T_{load} : load accounts for any resistive torques

The rotational motion of the panel can be described using the rotational form of Newton second law as given

$$I_{panel} \frac{d^2\theta}{dt^2} = T_{net} \quad (3.15)$$

Where I_{panel} : is the moment of inertia of the solar panel, $\frac{d^2\theta}{dt^2}$: is the angular acceleration and θ is the angular position of the solar panel.

In real world scenarios, there will be resistive forces such as friction or air resistance that oppose the motion. These can be modeled as a damping term in the equation of motion and given as

$$T_{friction} = b \frac{d\theta}{dt} \quad (3.16)$$

Where b is the damping coefficient (related to friction). Using equation 3.16 and 3.14 into equation 3.15

$$I_{panel} \frac{d^2\theta}{dt^2} + b \frac{d\theta}{dt} = T_m - T_{load} \quad (3.17)$$

Chapter 4 RESULTS AND DISCUSSION

4.1. Simulation Model

The Simulink model include Input block for reading solar angles (elevation and azimuth), controller block for calculating motor control signals based on angle differences. PV Array block: Simulate PV panel behavior using Sim's cape Electrical and Visualization: Plot solar irradiance and power output on scope block.

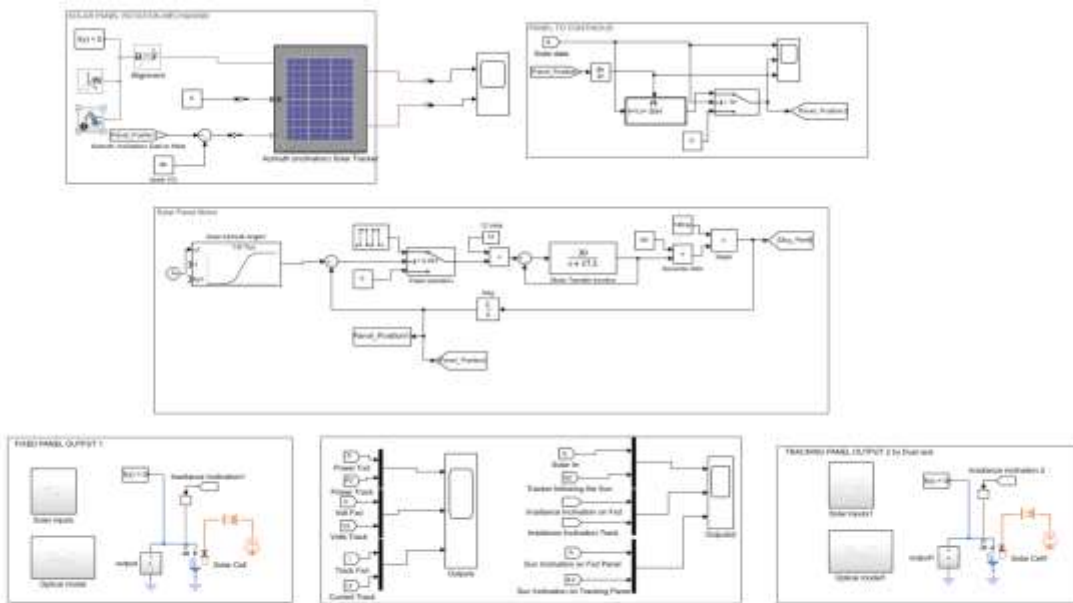


Figure 4.1: Simulated model in Simulink

The above dual axis solar tracking algorithm based on azimuth and altitude angles. This requires solar position calculation using date, time, and location coordinates to adjust PV panel orientation to maximize solar irradiance. Feedback loops for providing actual PV orientation back to the tracking motors subsystem have been identified, resulting in more realistic behavior. The geared dc motors were chosen for their cost and adequate precision, making them ideal for a dual axis solar tracker system. Most current dual axis solar trackers use closed loop control systems, which allow more precise tracking and maximize energy output by adapting to real-time conditions.

Among the different types of panels are available for example, monocrystalline, polycrystalline, amorphous and hybrid. Here in this project, we use polycrystalline solar panel. The figure 4.2 depicts Sun path diagram

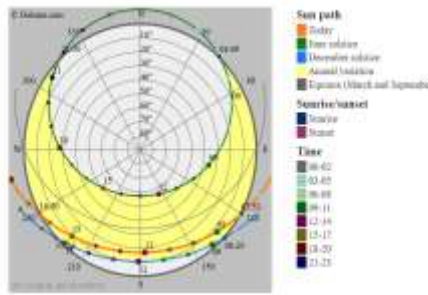


Figure 4.2: Sun path diagram of Karlskrona [35].

The sun path diagram depicts the sun's passage across the sky. This path is generated by plotting the sun's azimuth and elevation angles on a given day. It is a useful method for tracking the sun's direction over time in this project task. The MATLAB script was created to provide updated panel Azimuth as 80.79 degrees and updated panel elevation as -18.41 degrees. After providing the required input at different time of the day from 06:00 am to 6:00pm, and the readings were recorded in the scope and display has used to extract the results of incidence of solar rays, voltage, current and power for fixed panel and movable solar panel.

4.2. Input data and sun position calculation

To accurately track the sun, we first need the sun's position at any given time of the day, which can be determined using the solar position algorithm based on parameters such as time of day (date and time), geographical location (latitude and longitude), tilt angle of the solar panel, and azimuth angle of the solar panel[35]. The sun position method determines two key angles: solar zenith angle (θ_z). Solar azimuth angle (θ_a) is the angle formed by the sun and the vertical axis (straight up). The sun's horizontal angle relative to true north. These angles are needed to calculate the solar panel's orientation.

4.2.1. The Control Algorithm

The control algorithm is done in three step which are to determine desired angles for the solar panel. Here for a given the calculated solar position, the desired tilt (elevation) and azimuth of the solar panel can be computed as follows: desired Tilt (θ_t): the tilt angle at which the solar panel should be positioned to be perpendicular to the solar rays and desired azimuth (θ_a):

The horizontal orientation of the panel to face the sun. Secondly compare current position to desired position. The current position of the panel (tilt and azimuth angles) is compared with the desired position derived from the sun's position[36].

$$\text{Tilt Adjustment } (\Delta\theta_t) = \text{desired Tilt} - \text{current Tilt} \quad (4.1)$$

$$\text{Azimuth Adjustment } (\Delta\theta_a) = \text{desired azimuth} - \text{current Azimuth} \quad (4.2)$$

Finally apply actuators (motors) to adjust the position. The system will then apply the necessary adjustments using servo motors or stepper motors to change tilt and azimuth of the panel to the desired angles.

To ensure smooth operation, the system might use a PID controller for both axes, which will minimize oscillations and ensure that the panel moves toward the desired position efficiently.

4.2.2. PID Controller for Positioning

The PID controller is used for both tilt and azimuth control to adjust the position smoothly and accurately. This controller minimizes errors and adjust the panel's position gradually[37]. Also, it adjusts the motor speed and direction to minimize the error and bring the panel to the desired tilt and azimuth position. The equation 5.1 and 5.2 are for PID parameters[38].

$$P_{\text{tilt}} = K_p e_{\text{tilt}} + K_i \int e_{\text{tilt}} dt + K_d \frac{de_{\text{tilt}}}{dt} \quad (4.3)$$

$$P_{\text{azimuth}} = K_p e_{\text{azimuth}} + K_i \int e_{\text{azimuth}} dt + K_d \frac{de_{\text{azimuth}}}{dt} \quad (4.4)$$

Where

e_{tilt} and e_{azimuth} are the errors in tilt and azimuth (desired position - current position).

K_p, K_i, K_d are the proportional, integral, and derivative gains.

To ensure the panel does not exceed its maximum physical tilt range or azimuth range. The tilt should be restricted between 0° and 90° for a typical panel. The azimuth should be restricted between 0° and 360° (for the east west tracking system)[39].

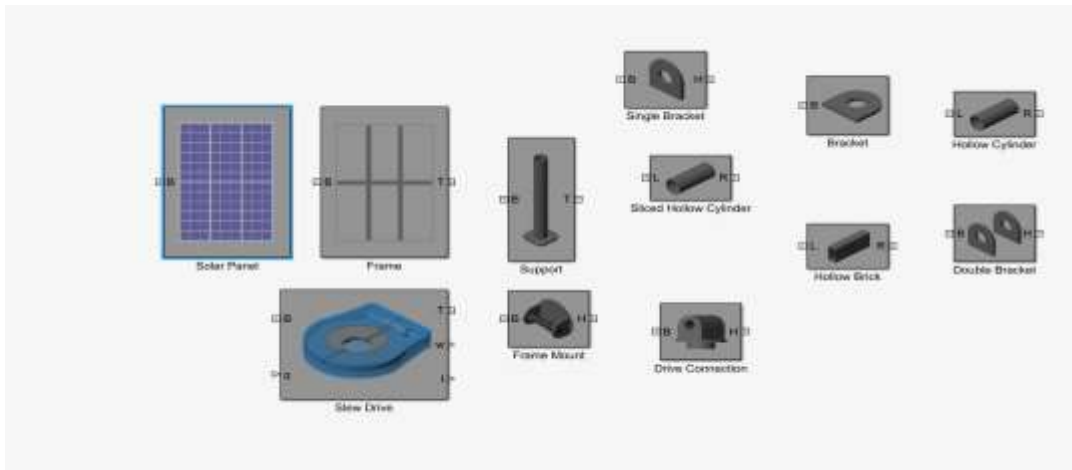


Figure 4.3: Library for mechanical system

The efficiency of photovoltaic (PV) systems can be greatly increased by using a dual-axis tracking device. This technology guarantees that the solar panels retain their best orientation towards the sun throughout the day, optimizing energy capture. The scope and display have used to monitor real-time power output variations as the tracking system adjusts panel orientation. Here the PV array maintains an optimal position relative to the sun, ensuring higher energy generation compared to fixed solar panels.

Power output variations can be monitored using Simulink scopes. The proposed PV panel is given as on figure 4.4 below and simulated by using Simulink software at different irradiance.

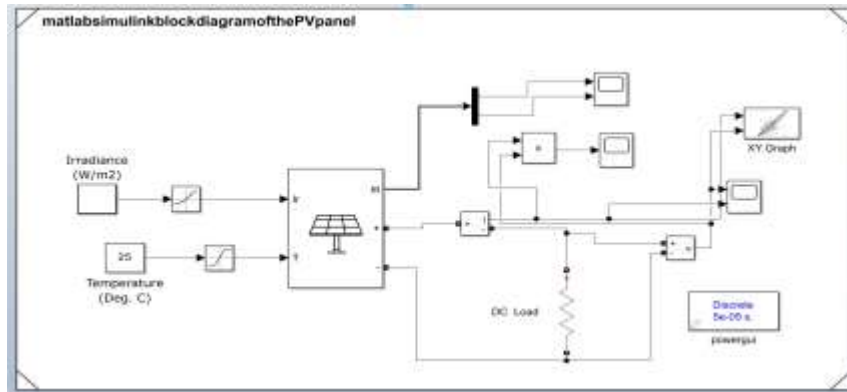
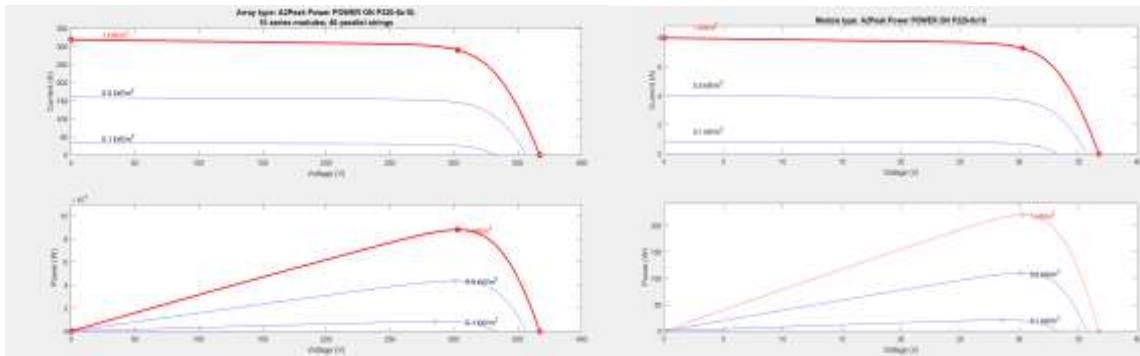


Figure 4.4: SIMULINK block diagram of PV panel

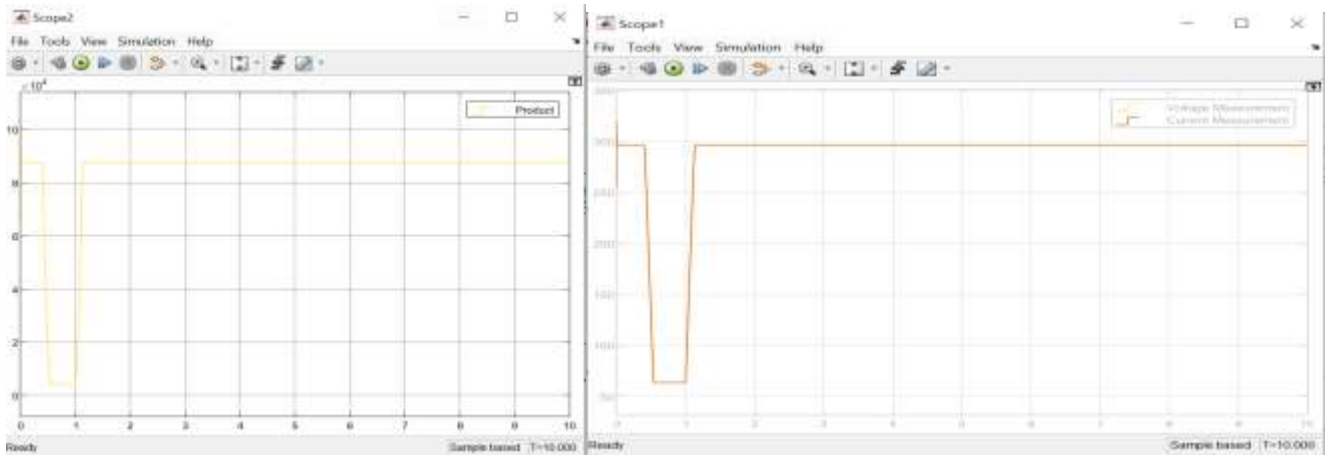
To implement a PV array made up of strings of PV modules connected in parallel. Each string is made up of modules connected in sequence. Allows for the modeling of a range of preconfigured PV modules from the NREL System Advisor Model, as well as user defined PV modules. Input 1 is sun irradiance in W/m², and input 2 is cell temperature in degrees Celsius, both of which are available in the MATLAB library. This module consists of 54 monocrystalline silicon cells with a maximum output of 200 watts. The characteristic of selected PV module are shown as



(a) Peak power and current at different illumination (b) Peak power and current at different temperature

Figure 4.5: Peak power and current at different illumination and temperature

When considering a photovoltaic cell (solar cell), both peak power and current decrease with increasing temperature while significantly increasing with higher illumination levels; essentially, higher light intensity generates more current, while elevated temperatures reduce the cell's efficiency, leading to lower peak power and current at a given illumination level.



(a) Power that can be generated by this PV panel (b) Current and voltage Measurement

Figure 4.6: Expected Power, voltage and current that can be generated by this PV panel.

The above explains that solar irradiations, for peer review led to an increase in power corresponding to the maximum power points (PMPP). The influence of temperature is smaller compared to that of solar irradiance, but it is no longer negligible on the IV characteristic of a PV module. For a change in the temperature value, we can see that the voltage variation changes much more than that of the current, which varies very slightly.

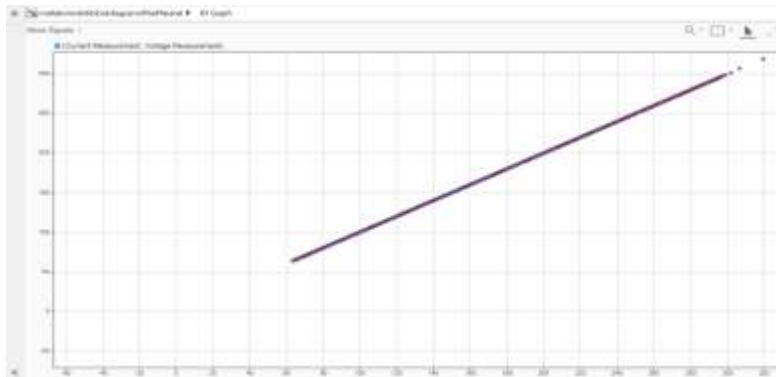


Figure 4.7: Both current and voltage measurement on XY graph

The XY graph block in the Simulink Sinks library is an alternative configuration of the record block that visualizes two input signals on an XY plot (in our case voltage and current). The first input port provides the voltage data for the XY plot.

The second input port provides the current data. The XY graph block supports logging and visualizing data for non-scalar inputs. However, the XY visualization does not support multidimensional data. When you connect non scalar signals to the XY graph block

4.3. Results and Analysis

The Solar power generation is significantly influenced by factors such as the orientation of solar panels and the time of day. With the simulated data, we analyze the performance of two types of solar panels:

Dual axis or moving panel as panel that adjusts its orientation both horizontally and vertically to track the sun and fixed panel that remains stationary at a fixed angle.

This analysis includes the power, voltage, and current generated by both panels across different times of the day, with a 10 seconds interval for precision. The power is recorded at each hour for both case as the figure 4.8 depicts.

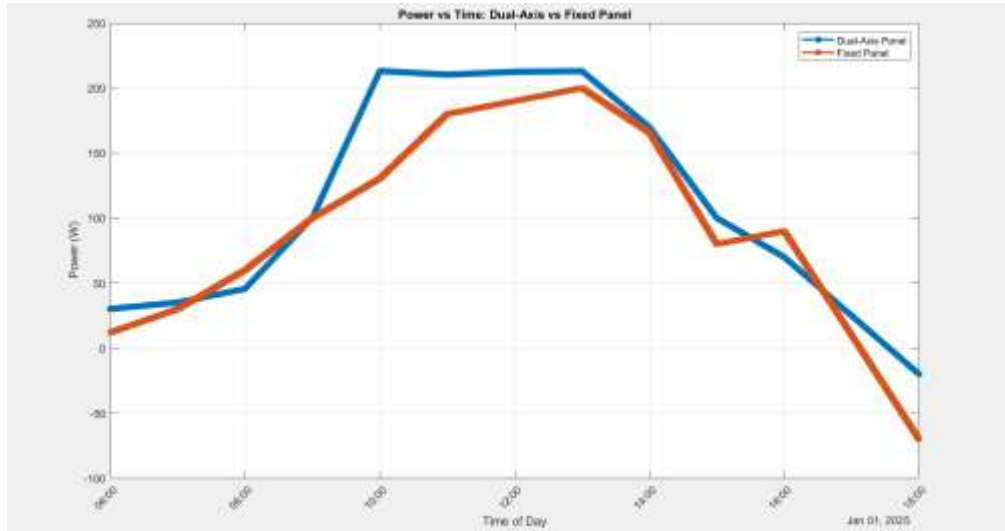


Figure 4.8: Results for output power versus time for both fixed panel and moving panel

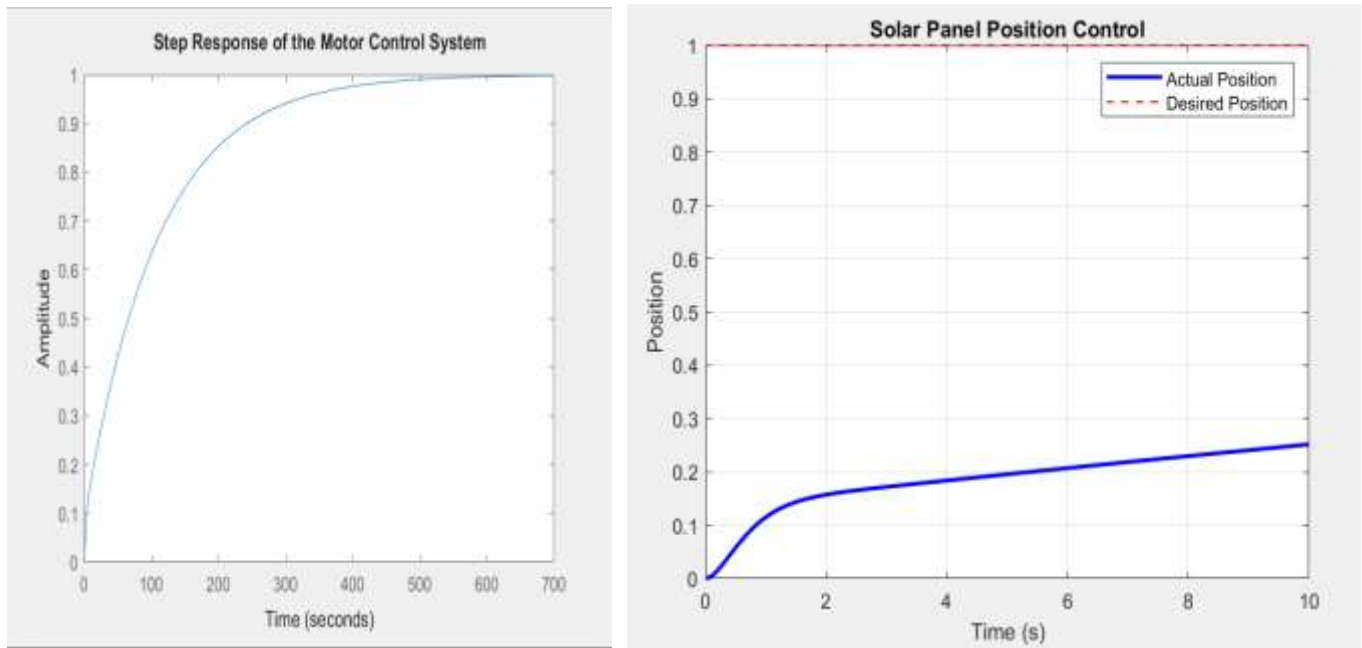
By the analysis, it is clear that the dual axis solar tracking panel provides better performance than the fixed panel, both in terms of power and efficiency. The ability of the dual axis panel to track the sun vertically and horizontally allows it to capture more sunrays throughout the day, leading to higher energy output. The fixed panel, while simpler, is less efficient due to its static orientation as shown on figure 4:8, this highlights the importance of tracking solar technologies, which can maximize energy capture, especially in regions with varying sun angles.



Figure 4.9: Output voltage and current vs time for both fixed panel and moving panel

Both panels show similar trends in voltage, with a slight increase during the midday when the angle of solar rays is more direct. The voltage for the dual-axis panel is generally higher due to better alignment with the sun throughout the day. Also, the current produced by the panel dual axis tracker follows the same trend as the power, peaking when the sun is highest in the sky.

The fixed panel current fluctuates more, showing lower values compared to the moving panel. The above results are against time but also Solar energy generation depends significantly on various factors, including the orientation and tracking capabilities of the solar panel.



(a) Step response for motor control (b) Solar panel position

Figure 4.10: Step Response of the Motor control.

The step response of the motor control system illustrates the system's behavior when subjected to a unit step input. The response shows a gradual increase in amplitude, asymptotically approaching a steady-state value of 1. The system exhibits no significant overshoot, indicating a well-damped response.

The time required to reach steady state suggests a relatively slow system, likely due to high inertia or low control gains. The response characteristics provide insight into system stability and settling time, which are crucial for optimizing motor control parameters. Figure 4.10 (b) presents the performance of a solar panel position control system. The desired position (red dashed line) remains at 1, indicating the target tracking position. However, the actual position (blue solid line) exhibits a slow and underdamped response, failing to reach the desired set point within the observed time frame.

This suggests that the controller may require parameter tuning to improve the response speed and accuracy. The presence of a steady-state error indicates that additional compensation, such as integral control action, may be necessary to enhance tracking performance.

4.4. Optimization of Energy Harvesting

During the simulation, the software records the voltage, current and power at different time of the day angle position of the solar ray at the day.

The MATLAB script was created to be simulated by optimizing the output. Since the records is taken on the whole day, the software uses linear interpolation for both case and the figure 4. 11and 4:12 depicts the results after optimization.

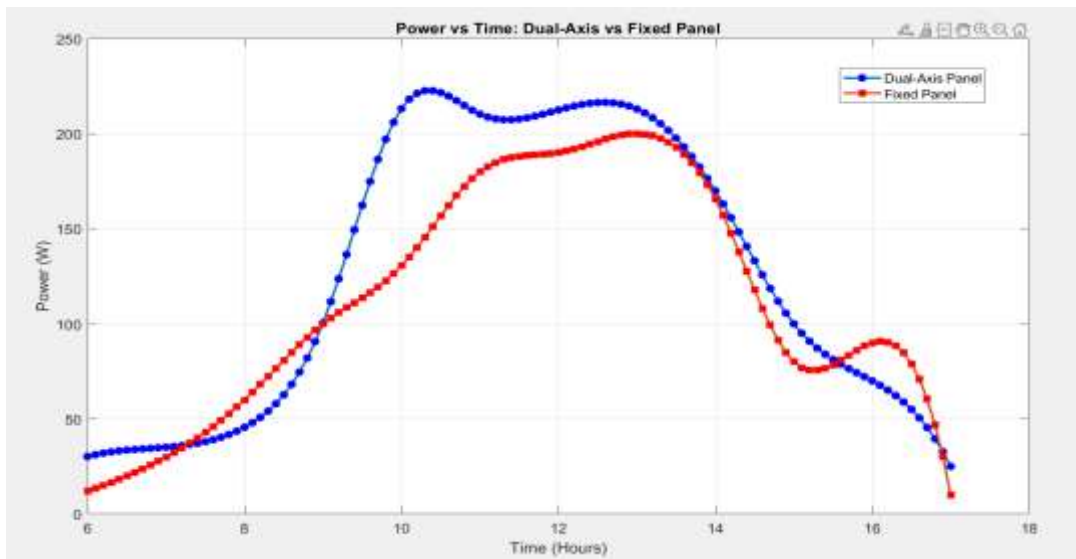


Figure 4.11: Optimized output power versus time for both fixed panel and moving panel

The software originally recorded at hourly intervals but for optimization, the software was extended to finer time intervals using a 0.1-hour like 6-minute interval.

This finer time resolution provides a more detailed view of the panel performance throughout the day by adjusting its position throughout the day, ensures optimal alignment with the sun, leading to a steady and high power output. This results in better energy harvesting across the entire day, especially during the midday period.

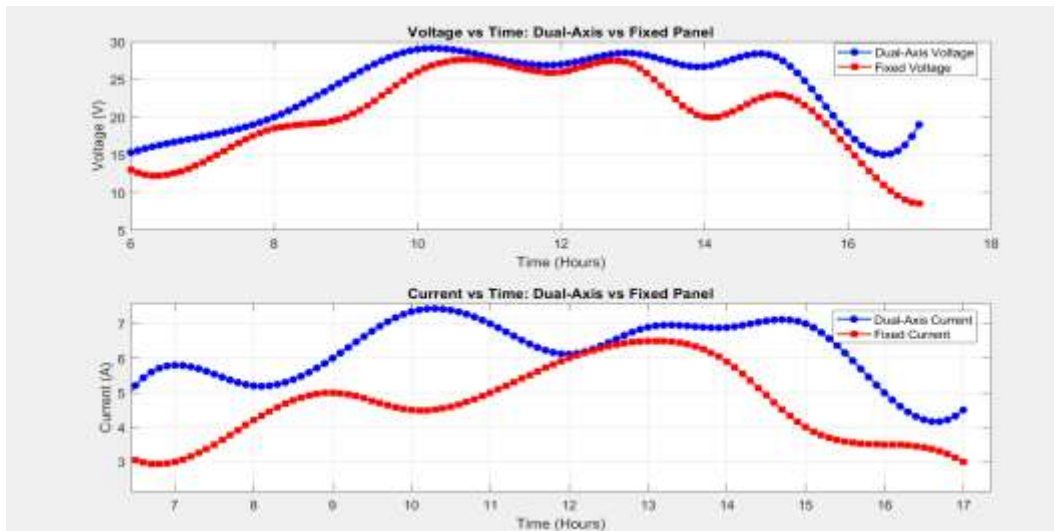


Figure 4.12: Optimized output voltage and current vs time for fixed and moving panels

The optimized voltage and current analysis confirm the superiority of dual axis panels over fixed panels in terms of overall energy generation. By continuously tracking the sun, the dual-axis panel maintains optimal orientation throughout the day, ensuring steady and higher electrical outputs. In contrast, the fixed panel's efficiency is lower due to its fixed orientation, which results in significant misalignments during certain hours. Total energy harvested is 4542.2743Wh and average energy harvested per hour is 189.2614Wh as figure depict.

4.5. Solar Elevation and Energy Harvesting

The solar elevation angle represents the height of the sun above the horizon at each hour of the day. It is crucial because it directly influences how much sunlight the solar panel receives, the fig 4.13 how the elevation angle varies from sunrise to sunset, reaching its peak at solar noon (when the sun is highest in the sky). This peak is typically around noon for a given location.

The elevation angle starts at 0° (sunrise), increases to a maximum value around midday (solar noon), and then decreases back to 0° by sunset. The pattern follows the sun's natural path in the sky. The dual-axis tracker aims to adjust the solar panel to match this variation, maximizing energy capture when the sun is at its highest elevation.

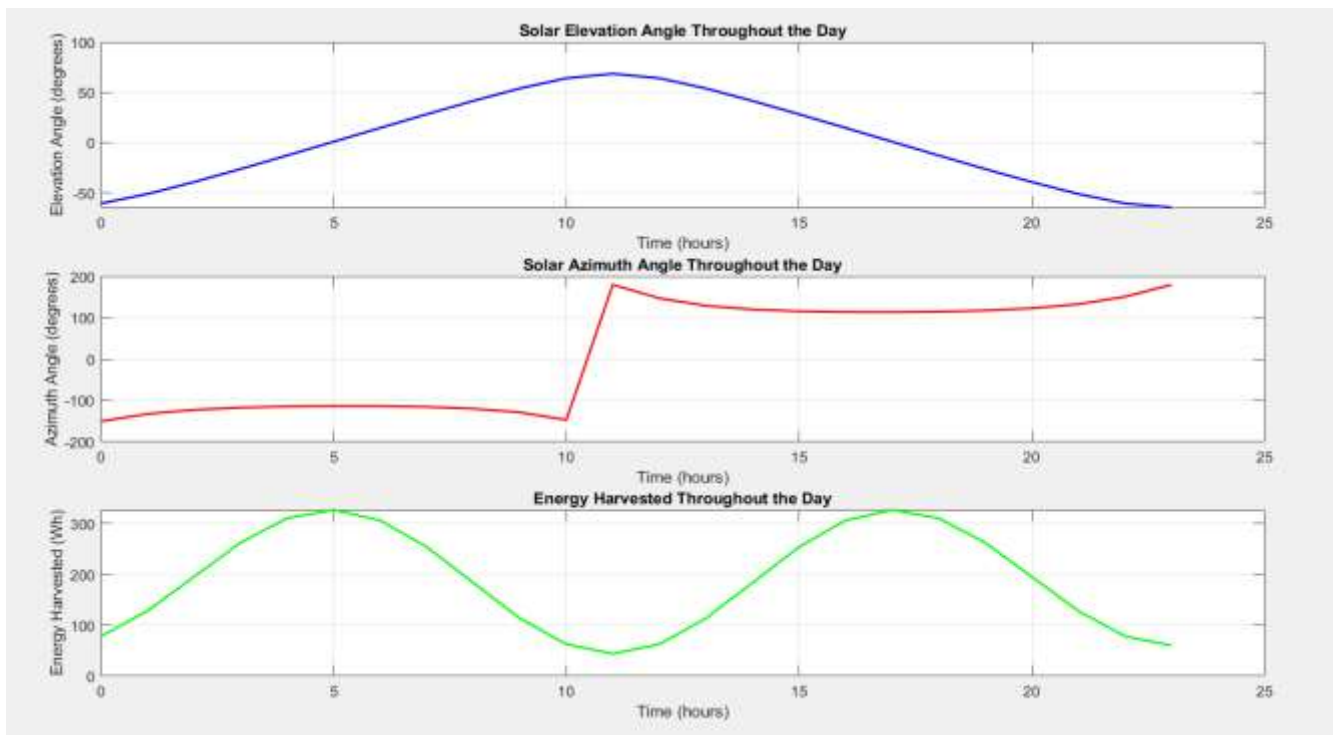


Figure 4.13: Elevation, azimuth and energy harvesting

The solar azimuth angle represents the sun position in the horizontal plane (the direction relative to the north, measured clockwise). This angle varies from east to west as the day progresses. The sun rises in the east, moves toward the south (in the northern hemisphere), and sets in the west. The azimuth angle is negative in the morning (east) and becomes positive as the sun moves westward throughout the day. The dual-axis tracker also adjusts the solar panel to track the sun azimuth, ensuring that the panel is oriented toward the sun's horizontal position, regardless of time.

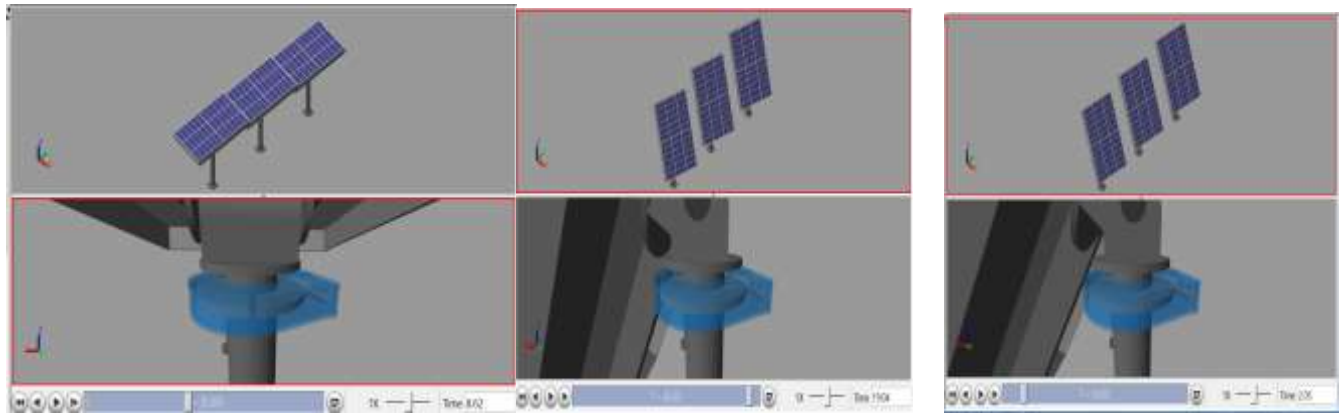
The energy harvested by the solar panel at each hour of the day as it is a function of the solar irradiance, panel area, panel orientation, and efficiency. As the solar elevation and azimuth angles change throughout the day, the tracker adjusts the panel's position, thus optimizing the energy capture.

The fig 5.14 shows how much energy the system collects at each time step. The energy harvested starts at zero at sunrise, increases to a peak around midday when solar irradiance and panel orientation are optimal, and decreases as the sun sets. Fig 4.13 how the dual-axis tracker effectively maximizes energy capture during daylight hours by continuously adjusting the solar panel's orientation.

4.6. Panel Orientation

To ensure precise movement of the solar panels, the tracking system can utilize mechanical components such as gears and worm drives. The gear constraints provide a mechanical advantage by converting motor torque into controlled angular motion, the gear ratio determines the speed and force applied to the tracking system.

Also worm mechanism within system allows for smooth and controlled movement, preventing back-driving due to external forces such as wind. This mechanism ensures stability and precision in solar tracking. The motors drive the worm gear or gear train, adjusting the elevation and azimuth angles as calculated by the tracking controller.



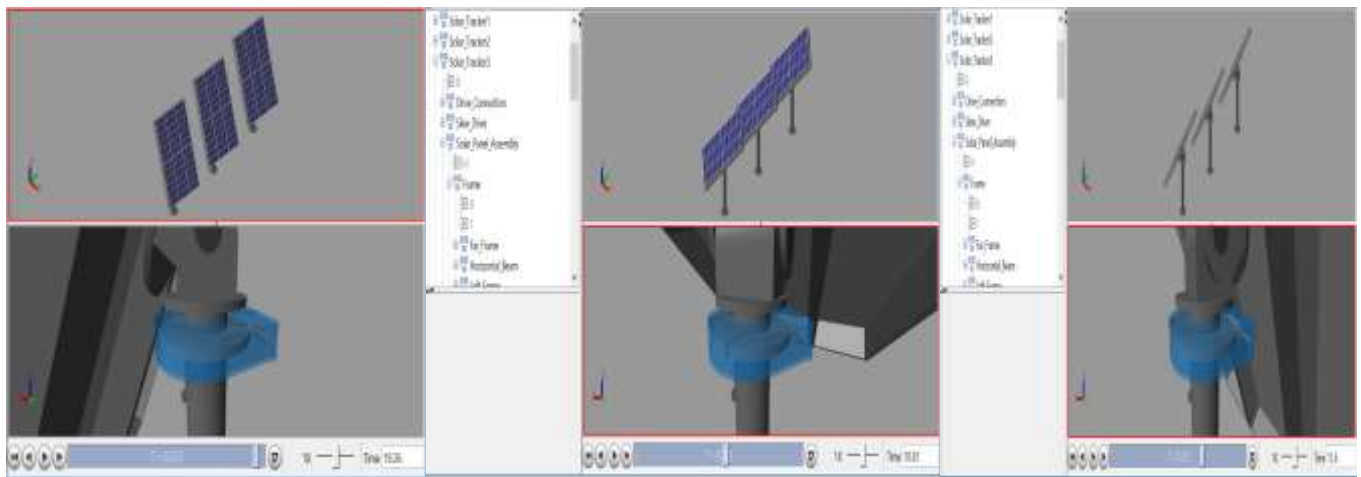
(a) Morning

(b) noon

(c) Afternoon

Figure 4.14: Daily Clockwise Rotation of solar panel

The Encoders and sensors measure the actual position of the panels, ensuring alignment with the desired angles computed by the tracking algorithm. By integrating these mechanical components, the dual-axis tracking system achieves enhanced accuracy, stability, and efficiency in solar panel orientation



(a) Morning

(b) Noon

(c) Afternoon

Figure 4.15: Daily Anticlockwise Rotation of solar panel

By implementing the dual-axis tracking system, the PV array maintains an optimal position relative to the sun, ensuring higher energy generation compared to fixed solar panels. Power output variations can be monitored using Simulink scopes.

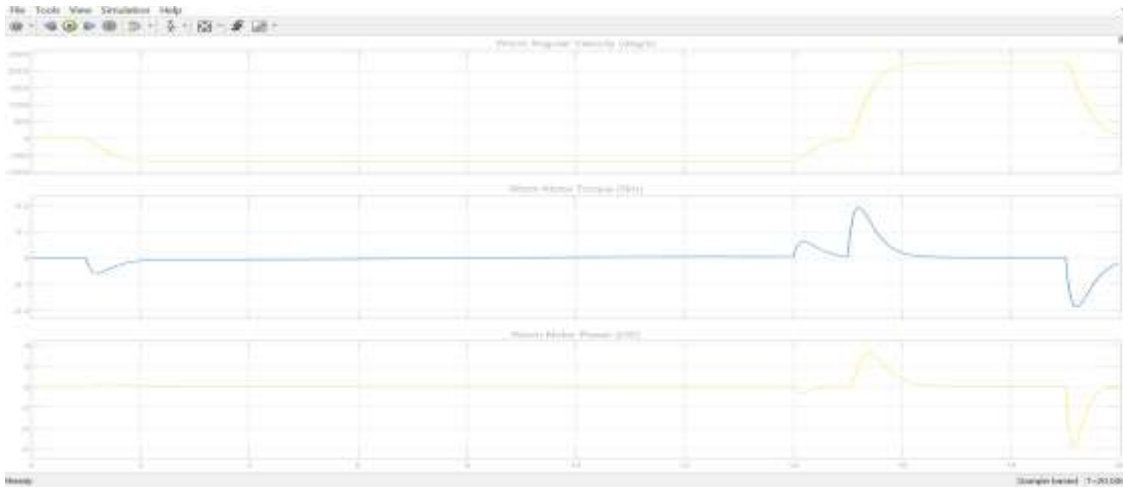


Figure 4.16: Output power; Torque and angular velocity for tracking

The speed at which the panel moves due to the worm and gear constraint are determined by angular velocity, however torque generated by the worm gear to adjust the position of the panel. The Worm Power determines the total power used by the worm drive to maintain panel orientation and are varying according to the panel movement.

4.7. Active, Chronological and Hybrid solar tracking

Data was collected on both sunny and gloomy days to evaluate the effectiveness of active, chronological, and hybrid algorithms for solar tracking. The solar tracker was positioned in an open field where it would get sunlight throughout the day. Voltage readings were taken at 60 minute intervals from 6:30 a.m. to 18 p.m. Readings from conventional fixed-mount solar panels were also used to create a baseline voltage. Following that, a research was conducted to determine how much energy the hybrid solar tracker generated, consumed, and received. The microprocessor estimates the sun's position and instructs motors to move the solar panel towards it at predetermined time intervals using prescribed azimuth and elevation angles. The azimuth angle in the horizontal plane is measured from true north to the horizontal projection of the sun's light, as given in Equation 4.5 and 2.2

$$\text{Azimuth angle} = \tan^{-1} \left[\frac{\sin \theta}{(\cos \theta \sin \phi) - (\tan \phi \cos \delta)} \right] \quad (4.5)$$

Where ϕ is the latitude of the location, δ is the solar declination angle, and θ denotes the hour angle. The elevation angle changes throughout the day depending on the day of the year and latitude of that particular location, as given in Equation 4.6.

$$\text{Elevation angle} = \left[(\sin \delta \sin \phi) - (\cos \delta \cos \phi \cos \theta) \right] \quad (4.6)$$

The figure depicts the diagram representing the hybrid algorithm for solar tracking from 6:00 up to 6:00pm within 7 days for both cloud days and sunny days.

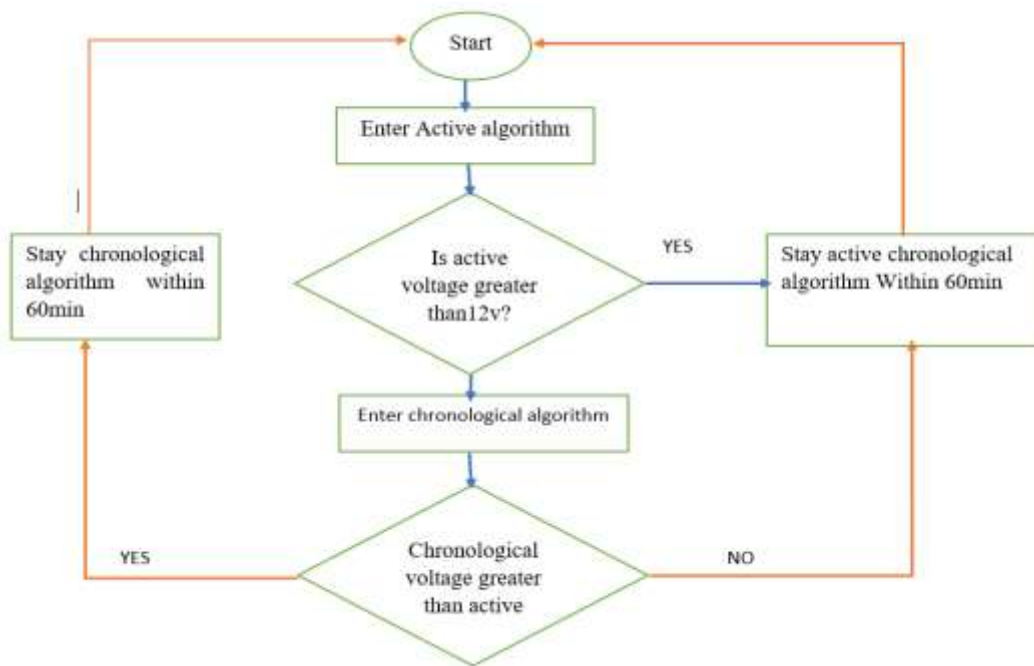
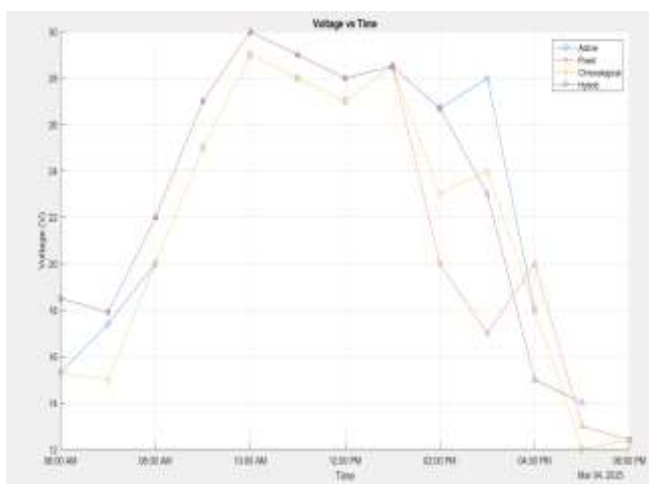


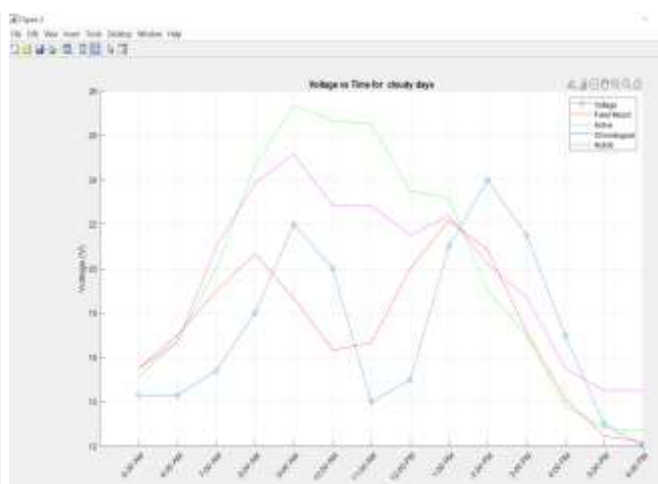
Figure 4.17: The expected hybrid algorithm

Active employment of sensors and motors provides more accurate and efficient tracking of the sun's position, despite the fact that it consumes more power and is less accurate on cloudy days, as illustrated in figure 4.18 (a).

Chronological tracking is a timed based tracking system that rotates at 15° per hour beginning at 30° . This has negligible energy losses and low tracking error, but continuous rotation demands more energy and needless effort on cloudy days, as shown in figure 4.18 (b).



(a) Average voltage readings for sunny days



(b) Average voltage readings for cloudy days.

Figure 4.18: Average voltage readings for both sunny days and cloud days

This figure (a) illustrates the variation of voltage over time for different solar panel configurations: Active, Fixed, Chronological, and Hybrid. The trends in the graph show how solar panel output voltage changes throughout the day under normal weather conditions.

In the early morning (around 6:00 AM), the voltage starts at a low level due to minimal sunlight exposure. As the sun rises, the voltage increases steadily, reaching its peak around noon when solar irradiance is at its maximum. After noon, the voltage gradually declines as sunlight intensity reduces in the afternoon and approaches evening. The differences between the curves indicate how each solar panel configuration responds to sunlight. The active and hybrid models generally exhibit better voltage performance compared to the fixed model, as they adjust their orientation to maximize sunlight absorption.

The chronological model follows a time-based adjustment mechanism, which may not be as efficient as real-time tracking mechanisms.

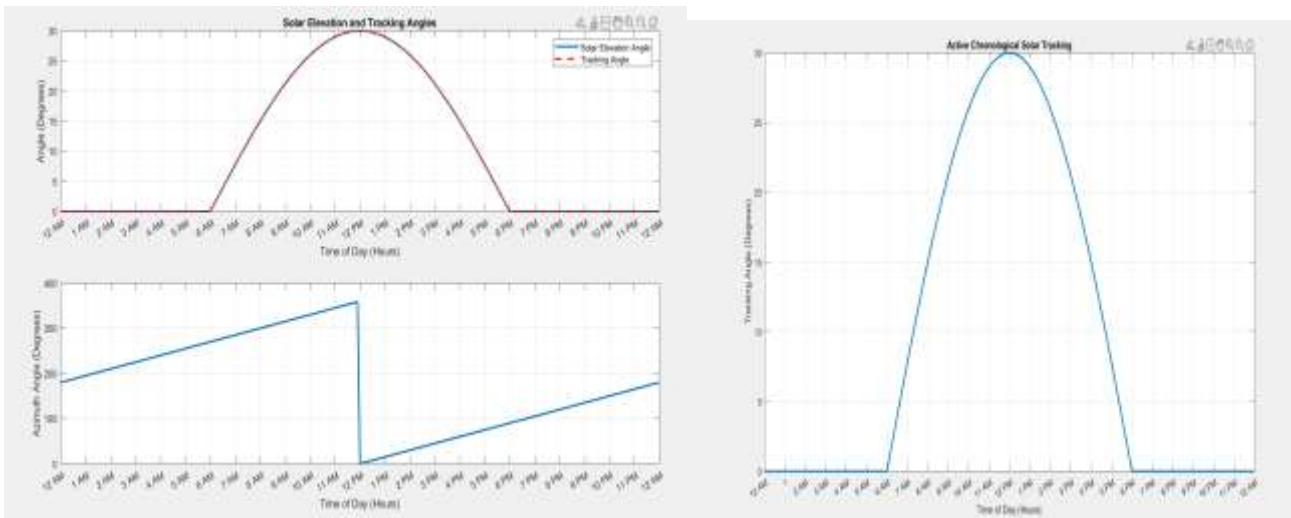
This graph highlights the advantages of dynamic solar panel configurations, such as active tracking and hybrid models, over static (fixed) mounting, leading to improved voltage output and overall efficiency.

The figure 4.18 (b) presents the voltage variation over time for different solar configurations under cloudy weather conditions similar to 4.9 (a), however, the voltage trends appear more irregular due to the presence of clouds affecting solar irradiance.

During early morning hours (6:00 AM – 8:00 AM), the voltage starts low and increases gradually, similar to the normal weather scenario, however, the midday voltage peak is lower compared to (a) due to cloud interference, which reduces the available sunlight.

The voltage fluctuations throughout the day indicate the transient nature of cloud cover, causing periodic dips in solar generation. The active and hybrid tracking systems still show higher efficiency in capturing available sunlight compared to the fixed system, as they adjust their orientation to optimize exposure to diffused solar radiation. The fixed mount configuration exhibits the lowest voltage output since it cannot adapt to changing light conditions.

It demonstrates the impact of cloudy weather on solar panel performance, emphasizing the importance of tracking mechanisms in mitigating efficiency losses due to variable sunlight conditions.



(a) Solar elevation and azimuth

(b) Chronological tracking angle

Figure 4.19: Solar elevation, azimuth and chronological tracking angle

From above the figure 5.19. (a) One is for the solar elevation and motor angles, and another for the solar azimuth angle, providing a comprehensive view of the sun's position and the motor's adjustments throughout the day. To verify the effectiveness of this design, we compared the motor angle and sun angle over the course of a day when the panel was stationary versus when it was attached to our prototype dual-axis tracker. Our system begins recording data as the sun rises at 6:00 a.m. and continues until sunset. Figure 4.20 illustrates how the solar tracker device maximizes solar irradiance by maintaining the solar module's active surface vertical at the sun's angle. From midday to sunset, the fixed panel loses a significant amount of solar radiation.

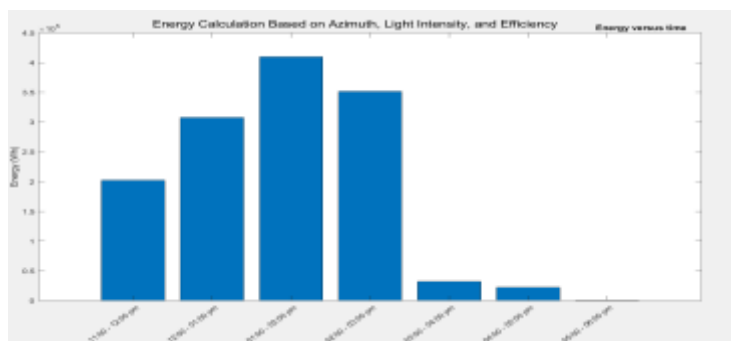


Figure 4.20: Energy generated during a day

The figure 4.20 represents the energy generation of a solar system over different time intervals, considering azimuth angle, light intensity, and system efficiency. The x-axis denotes the time intervals throughout the day, while the y-axis represents the amount of energy produced in watt-hours (Wh). The bars indicate the energy output during each specific time period. The most energy generated was about 4000 kWh, which occurred in the afternoon at 1 P.M and 2pm. when the sunlight intensity is the strongest.

On the other hand, the least energy generated was about 250 kWh at evening, the scenarios to discuss are described as the following:

At morning Hours (11:00 AM – 12:00 PM): Energy production starts at a moderate level as sunlight intensity increases. The system begins to generate more power as the sun moves higher in the sky, improving the incident angle of sunlight on the solar panels.

At Peak Solar Hours (12:00 PM – 03:00 PM): The highest energy production occurs between 12:00 PM and 03:00 PM, reaching a peak between 01:00 PM and 02:00 PM. This is because the sun is at its highest position, maximizing irradiance and panel efficiency. The azimuth angle is optimal, and light intensity is at its maximum, allowing for the highest energy conversion.

At Afternoon Decline (03:00 PM – 06:00 PM) after 03:00 PM, the energy output starts decreasing. The drop in solar radiation due to the sun's lower position results in reduced power generation.

By 05:00 PM – 06:00 PM, the energy production is minimal as sunlight intensity diminishes as figure 4.21 highlights the relationship between solar panel orientation (azimuth), light intensity, and efficiency in determining energy production.

It emphasizes the importance of tracking systems or optimized panel positioning to maximize energy yield during peak hours.

The sharp decline in the evening suggests the need for energy storage (batteries) or grid integration to maintain power supply after sunset. Total energy harvested is 48613.3895Wh and Total motor power consumption is 4.8wh.

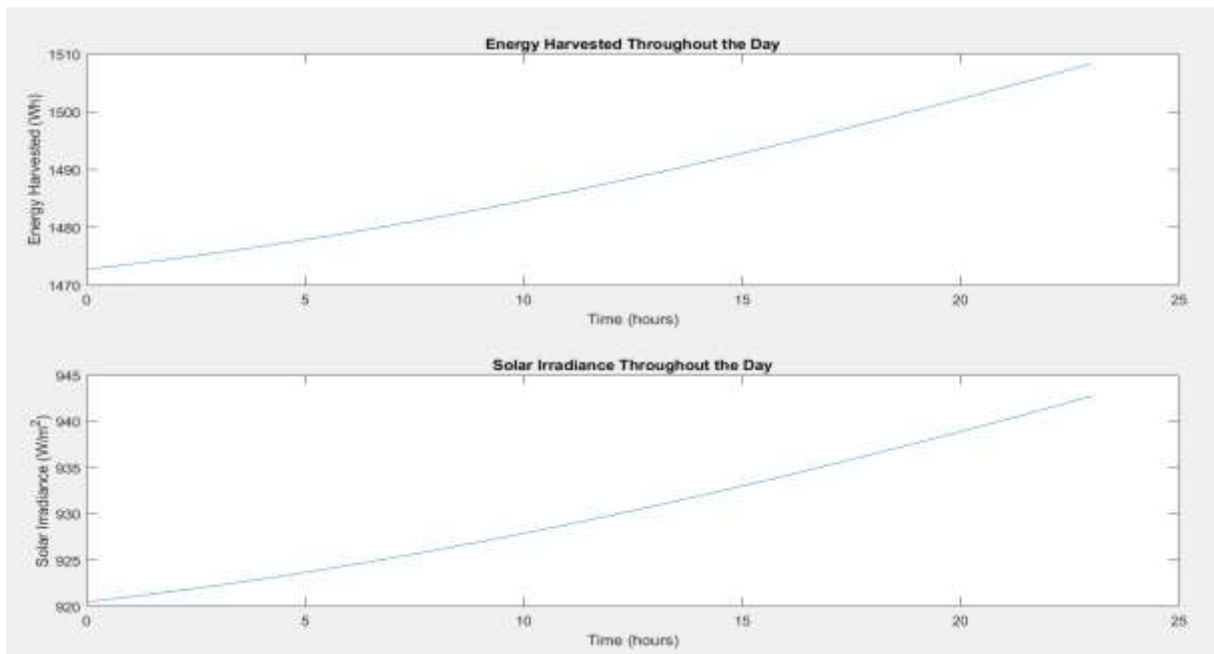


Figure 4.21: Energy harvested and solar Irradiance

The energy harvested represents the energy (in watt-hours) captured by the solar panel at each hour throughout the day. It is computed based on the solar irradiance (the amount of sunlight) at each time step, the panel area, and the time step (1 hour). The tracking system is assumed to optimize the panel's orientation to always capture the maximum solar irradiance, meaning the panel adjusts to follow the sun's movement to maximize energy capture.

The energy harvested varies as the solar irradiance changes over the course of the day. It starts at zero at sunrise (when the sun is at a very low angle) and gradually increases as the sun rises higher in the sky. The energy harvested is highest around solar noon when the sun is at its peak (maximum elevation angle). During this time, the panel receives the most direct sunlight, and the energy harvested is maximized. After solar noon, the energy harvested gradually decreases as the sun moves towards the horizon (sunset)

The solar irradiance plot shows the amount of solar radiation (in watts per square meter, W/m^2) received by the solar panel at each hour of the day. As the elevation angle increases, the panel receives more sunlight, and as it decreases (either at sunrise or sunset), the irradiance decreases.

The figure 5.21 follows the expected behavior of solar irradiance throughout the day, starting from zero at sunrise (early morning), increasing to a peak around solar noon (when the sun is highest in the sky), and then decreasing towards zero at sunset. The irradiance values are highest when the sun is directly overhead (around noon), and the values gradually reduce as the sun moves towards the horizon.

Chapter 5 CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The dual axis tracking system enhances solar PV efficiency by continuously aligning the panel with the sun's movement. The Simulink model demonstrates the feasibility and effectiveness of this approach, making it a viable solution for improving solar energy harvesting. The optimized analysis of Power vs Angle and time for both dual axis and fixed solar panels reveals a marked improvement in energy generation when solar panels are equipped with tracking technology. The dual-axis panel consistently outperforms the fixed panel, particularly during off peak hours when the fixed panel is misaligned with the sun. This project underscores the effectiveness of solar tracking systems in optimizing solar energy generation, suggesting that the higher initial investment in tracking systems is justified by the increased energy output. The process of sizing and maximizing the efficiency of a PV solar panel is always an important stage during installation. The dual axis solar tracker system increases energy harvesting efficiency by aligning the panel with the sun's shifting position throughout the day. The graphs show how the system tracks the elevation and azimuth angles to maximize solar irradiation, resulting in best energy generation. The energy harvested graph shows the expected increase in energy production as the sun moves across the sky, with the system providing efficient tracking across the entire day.

5.2. Recommendations

Given the performance advantages of dual axis tracking, it is recommended that solar installations in regions with high solar availability consider incorporating such systems to maximize energy production. Although fixed panels are less expensive and easier to install, their lower efficiency during certain times of the day can significantly reduce the overall energy yield. Further research can explore other types of tracking systems, such as single-axis tracking, and their efficiency in different geographical locations. The regions with high solar availability like Rwanda and other global region is recommended to install PV panel with dual axis solar tracking mechanism for maximizing energy harvesting.

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Appendix

MATLAB script for PV CELL

```
function Ir2 = optics2(S2, Incl)
```

```
%This function computes the reflection, absorption and transmission in  
%the glass to compute the irradiation to the PV cells, the heat absorbed  
%in the glass and the radiation power absorbed in the PV cells,  
%it is based on Fresnel's laws, depending on the incident angle
```

```
Ncell = 72;  
Acell = 0.0225;  
ng = 1.52;  
absg = 0.2;  
dg = 0.01;  
rpv = 0.15;
```

```
% Fresnel equations 1st boundary
```

```
r1p = ( ng^2*cos(Incl) - sqrt(ng^2 - sin(Incl)^2) )^2/( ng^2*cos(Incl) + sqrt( ng^2 - sin(Incl)^2 ) )^2;
```

```
%P polarization
```

```
r1s = ( cos(Incl) - sqrt(ng^2 - sin(Incl)^2) )^2/( cos(Incl) + sqrt( ng^2 - sin(Incl)^2 ) )^2; %S polarization
```

```
r1 = 0.5*(r1p + r1s); %Effective reflectance
```

```
t1 = 1-r1;
```

```
nga = 1/ng; %refractive index glass -> air
```

```
th2 = asin(sin(Incl)/ng); %Snell's law to compute angle of incidence on 2nd boundary
```

```
% Fresnel equations 2nd boundary
```

```
r2p = ( nga^2*cos(th2) - sqrt(nga^2 - sin(th2)^2) )^2/( nga^2*cos(th2) + sqrt( nga^2 - sin(th2)^2 ) )^2 ;
```

```
r2s = ( cos(th2) - sqrt(nga^2 - sin(th2)^2) )^2/( cos(th2) + sqrt( nga^2 - sin(th2)^2 ) )^2 ;
```

```
r2 = 0.5*(r2p + r2s); %Effective reflectance
```

```
t2 = 1 - r2;
```

```
taug = exp(-absg*dg/cos(th2));
```

```
%Total coefficients for infinite reflections between 2 parallel boundaries
```

```
Transg = t1*taug*t2/(1 - r1*r2*taug^2);
```

```
Reflg = r1 + (t1^2*taug^2*r2)/(1 - r1*r2*taug^2);
```

```
Absg = 1 - Transg - Reflg;
```

```

Ir2 = S2*Transg; %Irradiation to the PV cells
heatg = Acell*Ncell*Absg*S2; %heat absorbed in the glass
powAbspv = Acell*Ncell*Transg*(1-rpv)*S2; %radiation power absorbed by PV cells. Part of it
transforms in electrical power

```

```
end
```

MATLAB script for energy harvesting

```
% Solar Tracker Simulation - Dual-Axis Tracker
```

```
% Parameters
```

```
latitude = 1.945; % Rwanda latitude in degrees
```

```
longitude = 29.868; % Rwanda longitude in degrees
```

```
panel_area = 1.6; % m2 (assumed panel area)
```

```
solar_constant = 1000; % W/m2, average solar irradiance at Earth's surface
```

```
time_step = 1; % time step for simulation in hours
```

```
hours_in_day = 24; % total hours in a day
```

```
% Create arrays for time, angle, and power
```

```
time = 0:time_step:hours_in_day-1;
```

```
solar_irradiance = zeros(1, hours_in_day);
```

```
azimuth_angle = zeros(1, hours_in_day); % Angle in horizontal plane
```

```
elevation_angle = zeros(1, hours_in_day); % Angle from horizon
```

```
% Solar angle calculations for each time step (simple model)
```

```
for t = 1:hours_in_day
```

```
    % Assuming a simple model where the sun's angle changes based on time of day
```

```
    % Elevation angle (tilt from horizontal plane)
```

```

elevation_angle(t) = 23.44 * sin(deg2rad((360/365) * (t - 81))); % Rough estimate (simplified)

% Azimuth angle (rotation in horizontal plane)
azimuth_angle(t) = 15 * (t - 12); % Sun moves 15 degrees per hour

% Solar irradiance based on time of day (simplified model)
solar_irradiance(t) = solar_constant * cos(deg2rad(elevation_angle(t)));

end

% Energy harvested per hour (assuming tracking panel maximizes solar irradiance capture)
energy_harvested = solar_irradiance .* panel_area * time_step; % in Wh

% Energy consumed by motors (simplified: assume constant consumption per axis)
motor_power = 0.1; % DC motor power consumption in watts
total_motor_power = motor_power * 2 * hours_in_day; % Two motors running all day

% Total energy harvested throughout the day (in Wh)
total_energy_harvested = sum(energy_harvested);

% Output results
disp(['Total energy harvested (Wh): ', num2str(total_energy_harvested)]);
disp(['Total motor power consumption (Wh): ', num2str(total_motor_power)]);

% Plot results
figure;
subplot(2, 1, 1);

```

```

plot(time, energy_harvested);

title('Energy Harvested Throughout the Day');

xlabel('Time (hours)');

ylabel('Energy Harvested (Wh)');

```

```

subplot(2, 1, 2);

plot(time, solar_irradiance);

title('Solar Irradiance Throughout the Day');

xlabel('Time (hours)');

ylabel('Solar Irradiance (W/m^2)');

```

Simulation for dual axis solar tracking

```

% Simulation of Dual-Axis Solar Tracker System

% Parameters

latitude = 1.945; % Latitude for Rwanda in degrees

panel_area = 1.6; % m^2 (area of the solar panel)

solar_constant = 1361; % W/m^2 (solar irradiance constant)

efficiency = 0.15; % Assumed efficiency of solar panel (15%)

time_step = 1; % Time step for simulation in hours

hours_in_day = 24; % Number of hours in a day

% Solar Declination for each day (simplified model)

day_of_year = 172; % Example: Day 172 of the year (June 21st)

delta = 23.44 * sin(deg2rad((360/365) * (day_of_year - 81))); % Solar Declination in degrees

% Arrays to store results

time = 0:time_step:hours_in_day-1;

solar_irradiance = zeros(1, hours_in_day);

```

```

elevation_angle = zeros(1, hours_in_day); % Elevation angle (degrees)
azimuth_angle = zeros(1, hours_in_day); % Azimuth angle (degrees)
energy_harvested = zeros(1, hours_in_day); % Energy harvested each hour
% Simulation for solar positioning and energy harvesting
for t = 1:hours_in_day
    % Hour Angle ( $\omega$ )
    omega = 15 * (t - 12); % Sun moves 15 degrees per hour, from solar noon (12:00)
    % Solar Elevation Angle ( $\theta_e$ )
    sin_elevation = sin(deg2rad(latitude)) * sin(deg2rad(delta)) + ...
        cos(deg2rad(latitude)) * cos(deg2rad(delta)) * cos(deg2rad(omega));
    elevation_angle(t) = rad2deg(asin(sin_elevation)); % Elevation angle in degrees

    % Solar Azimuth Angle ( $\theta_a$ )
    azimuth_angle(t) = atan2d(sin(deg2rad(omega)), ...
        cos(deg2rad(omega)) * sin(deg2rad(latitude)) - ...
        tan(deg2rad(delta)) * cos(deg2rad(latitude))); % Azimuth angle

    % Solar Irradiance (simplified model)
    solar_irradiance(t) = solar_constant * cos(deg2rad(elevation_angle(t))); % W/m^2

    % Energy Harvested ( $P = I * A * \cos(\theta) * \eta$ )
    angle_to_sun = elevation_angle(t); % Assuming the panel is tracking the sun perfectly
    energy_harvested(t) = solar_irradiance(t) * panel_area * cos(deg2rad(angle_to_sun)) * efficiency
* time_step; % Wh
end

```

```

% Total Energy Harvested

total_energy_harvested = sum(energy_harvested); % Total energy harvested in Wh

% Display Results

disp(['Total energy harvested (Wh): ', num2str(total_energy_harvested)]);
disp(['Average energy harvested per hour (Wh): ', num2str(mean(energy_harvested))]);

% Plot Results

figure;
subplot(3, 1, 1);
plot(time, elevation_angle, 'b', 'LineWidth', 1.5);
title('Solar Elevation Angle Throughout the Day');
xlabel('Time (hours)');
ylabel('Elevation Angle (degrees)');
grid on;

subplot(3, 1, 2);
plot(time, azimuth_angle, 'r', 'LineWidth', 1.5);
title('Solar Azimuth Angle Throughout the Day');
xlabel('Time (hours)');
ylabel('Azimuth Angle (degrees)');
grid on;

subplot(3, 1, 3);
plot(time, energy_harvested, 'g', 'LineWidth', 1.5);
title('Energy Harvested Throughout the Day');

```

```

xlabel('Time (hours)');
ylabel('Energy Harvested (Wh)');
grid on;

Active solar tracking
% Active Solar Tracking
time = 0:0.1:24; % Time from 0 to 24 hours
solar_irradiance = 1000 * sin(pi * time / 12); % Simulated solar irradiance

% Initialize tracking angle
active_angle = zeros(size(time));

% Calculate active tracking angle
for i = 1:length(time)
    if solar_irradiance(i) > 0
        active_angle(i) = mod(time(i) * 15, 360); % Angle based on time
    end
end

% Plot results
figure;
plot(time, active_angle, 'g', 'DisplayName', 'Active Tracking Angle');
xlabel('Time (hours)');
ylabel('Angle (degrees)');
title('Active Solar Tracking');
legend;

```

```
grid on;
```

Chronological Tracking

```
% Chronological Solar Tracking
```

```
time = 0:0.1:24; % Time from 0 to 24 hours
```

```
chronological_angle = zeros(size(time));
```

```
% Define fixed angles for different times of the day
```

```
for i = 1:length(time)
```

```
    if time(i) < 6 || time(i) > 18
```

```
        chronological_angle(i) = 0; % Nighttime
```

```
    elseif time(i) < 12
```

```
        chronological_angle(i) = 30; % Morning angle
```

```
    else
```

```
        chronological_angle(i) = 60; % Afternoon angle
```

```
    end
```

```
end
```

```
% Plot results
```

```
figure;
```

```
plot(time, chronological_angle, 'b', 'DisplayName', 'Chronological Tracking Angle');
```

```
xlabel('Time (hours)');
```

```
ylabel('Angle (degrees)');
```

```
title('Chronological Solar Tracking');
```

```
legend;
```

```
grid on;
```

Hybrid tracking

```

% Hybrid Solar Tracking

time = 0:0.1:24; % Time from 0 to 24 hours

solar_irradiance = 1000 * sin(pi * time / 12); % Simulated solar irradiance

fixed_angle = 30; % Fixed angle

hybrid_angle = zeros(size(time));

% Calculate hybrid tracking angle

for i = 1:length(time)

    if solar_irradiance(i) > 0

        active_angle = mod(time(i) * 15, 360); % Active tracking logic

        hybrid_angle(i) = (fixed_angle + active_angle) / 2; % Average of fixed and active

    else

        hybrid_angle(i) = fixed_angle; % Default to fixed angle when no sunlight

    end

end

% Plot results

figure;

plot(time, hybrid_angle, 'm', 'DisplayName', 'Hybrid Tracking Angle');

xlabel('Time (hours)');

ylabel('Angle (degrees)');

title('Hybrid Solar Tracking');

legend;

grid on;

Control System Algorithm for Solar Position

% Define system parameters

```

```

Kp = 1; % Proportional gain
Ki = 0.1; % Integral gain
Kd = 0.01; % Derivative gain

% Create a PID controller
pidController = pid(Kp, Ki, Kd);

% Define the solar panel dynamics (example transfer function)
num = [1]; % Numerator coefficients
den = [1, 5, 6]; % Denominator coefficients
solarPanelSystem = tf(num, den);

% Create a closed-loop system
closedLoopSystem = feedback(pidController * solarPanelSystem, 1);

% Simulate the response to a step input (desired position)
t = 0:0.01:10; % Time vector
stepInput = ones(size(t)); % Step input for desired position
[y, t] = step(closedLoopSystem, t);

% Plot the results
figure;
plot(t, y, 'b', 'LineWidth', 2);
hold on;
plot(t, stepInput, 'r--', 'LineWidth', 1);
xlabel('Time (s)');

```

```

ylabel('Position');

title('Solar Panel Position Control');

legend('Actual Position', 'Desired Position');

grid on;

```

Formulas for scripts development

$\delta = 23.45360n + 284365$	7
<u>(2.1)</u>	
$\omega = 2\pi 24TL - N - 12242\pi L + ET$	7
<u>(2.2)</u>	
$ET = 9.87 \sin 2d - 7.35 \cos d - 1.5 \sin(d)$	<u>(2.3)</u> 7
$d = 2\pi n + 24365$	
<u>(2.4)</u>	
$\sin \alpha = \cos \delta \cos \varphi \cos \omega + \sin \delta \sin \varphi$	<u>(2.5)</u> 7
	8
$\cos \theta_z = \sin \alpha$	<u>(2.6)</u> 8
	8
$\cos \theta = \cos \varphi - \beta \cos \delta + \sin(\varphi - \beta)$	<u>(2.7)</u> 8
Solar declination (δ) = $23.44 \circ \sin 360365 * n - 81$	
<u>(3.1)</u>	22
Solar elevation (θ_e) = $\sin(\text{Latitude}) \sin \delta + \cos \text{Latitude} \cos \delta \cos \omega$	<u>(3.2)</u> 22
	22
Azimuth (θ_a) = $\arctan 2[\sin \omega \cos \omega \sin \text{Latitude} \tan \delta \cos \text{Latitude}]$	<u>(3.3)</u> 22
Phaversted = $I * A * \cos \theta * \eta$	
<u>(3.4)</u>	22
$I = I_{ph} - I_s * (e^{(V+I*Rs)/(N*Vt)} - 1) - I_{s2} * (e^{(V+I*Rs)/(N2*Vt)} - 1) - (V+I*Rs)/R_p$	<u>(3.5)</u> 24
	24
$I_{ph} = I_{ph0} * I_r / I_{r0}$	<u>(3.6)</u> 24
	24
$I = I_{ph} - I_d = I_{ph} - I_0 (e^{qV/RT} - 1) - I_d$	<u>(3.7)</u> 24
	24
$I_{rs} = I_s \exp(qv_0cNsAKT_0) - 1$	
<u>(3.8)</u>	24
$I_0 = I_{rs}(T_0/T_r)^3 \exp[q * E_{g0} A_k (1/T_r - 1/T_0)]$	
<u>(3.9)</u>	24
$I_{pv} = N_p * I_{ph} - N_p * I_0 [\exp(qv_{pv}NSAKT) - 1]$	
<u>(3.10)</u>	24

P = I_{pv} * V_{pv}	
(3.11)	24
FF = P_{max}V_{oc}I_{oc} = V_{mp}I_{mp}V_{oc}I_{oc}	
(3.12)	25
T_m = k_m*I	(3.13)
	25
T_{net} = T_m – T_{load}	
(3.14)	25
I_{panel}d²θ/dt² = T_{net}	
(3.15)	25
T_{friction} = b dθ/dt	
(3.16)	26
I_{panel}d²θ/dt² + b dθ/dt = T_m – T_{load}	
(3.17)	26
Tilt Adjustment (Δθ_t) = desired Tilt - current Tilt	(4.1)
	28
Azimuth Adjustment (Δθ_a) = desired azimuth - current Azimuth	(4.2)
	28
P_{tilt} = K_{petilt} + K_{ietilt}dt + <u>K_dd²tilt/dt²</u>	
(4.3)	29
P_{azimuth} = K_{peazimuth} + K_{ieazimuth}dt + <u>K_dd²azimuth/dt²</u>	
(4.4)	29
Azimuth angle = tan – 1 sinθ cosθ sinφ – tanφ cosδ	
(4.5)	38
Elevation angle = sinδ sinφ – cosδ cosφ cosθ	(4.6)
	38