SIMULATION OF A DUAL AXIS SOLAR TRACKER FOR ENHANCED ENERGY CAPTURE

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A THESIS SUBMITTED TO THE DEPARTMENT OF ELECTRICAL/ELECTRONIC ENGINEERING, UNIVERSITY OF BENIN, BENIN CITY, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF B.ENG DEGREE IN ELECTRICAL/ELECTRONIC, FACULTY OF ENGINEERING, UNIVERSITY OF BENIN

SUPERVISOR: ENGR. MISS E. C. EKOKO

FEBURARY, 2025

CERTIFICATION

This is to certify that this project was carried out by ALAIGBA JOSHUA AYOMIGBESEMI with matriculation number ENG1905531, EHIMEN JUDE with matriculation number ENG2006255, EMOKPAE PRAISEL with matriculation number ENG1905324, and IHONRE VICTOR EHIZOGIE with matriculation number ENG1905331, in partial fulfillment of the requirements of the award of the Bachelor of Engineering (B.ENG) degree in Electrical Engineering.

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ENGR. PROF. K. O. OGBEIDE	DATE
HOD	

DEDICATION

We dedicate this project to everyone involved in this project, who have been a constant source of inspiration, support and encouragement throughout this journey. Their unwavering belief in my abilities and their valuable insights did play a significant role in shaping the outcome of this project. To our ever supporting supervisor Engr.Miss E. C. Ekoko, your dedication, passion and commitment to excellence have been a source of strength for us. Finally this project is dedicated to anyone who finds inspiration knowledge, or solace within its pages. May it serve as a source of information, motivation, or reflection, and may it contribute in some small way to the greater good.

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ABSTRACT

This project focuses on the simulation of a dual axis solar tracker to enhance solar energy harvesting. Traditional fixed solar panels suffer from inefficiencies due to the sun's movement, limiting their ability to capture maximum solar radiation. The dual axis solar tracker is optimized effectively to rotate both horizontally (azimuth) and vertically (elevation) allowing it to follow the sun's path throughout the day and across seasons thereby enhancing energy absorption and improving photovoltaic (PV) system efficiency.

A simulation-based approach was employed using MATLAB/Simulink to model the system's dynamic response. Key components include a PID controller for optimized system response, virtual sensors mimicking sunlight detection and motors for precise motion control. The performance of the dual axis tracker was analyzed to determine efficiency improvements. The study also explores optimal control strategies, actuator dynamics and environmental adaptability.

The results indicate that the dual axis solar tracker can enhance energy yield by up to 30–40% compared to static systems. The tracker effectively maintains optimal alignment with the sun as confirmed by simulations of panel position, velocity, and motor torque. The findings highlight the potential for increased solar energy efficiency, reduced energy costs and improved sustainability. These insights serve as a foundation for future advancements in solar tracking technology contributing to the broader goal of maximizing renewable energy utilization.

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LIST OF ABBREVIATION

IEA - International Energy Agency
LDR - Light Dependent Resistor
ADC - Analog to Digital Converter
PID - Proportional-Integral-Derivative (Controller)
Kp - Proportional Gain Constant
Ki - Integral Gain Constant
Kd - Derivative Gain Constant
DC - Direct Current
EMF - Electromotive Force
IoT - Internet of Things
CSP - Concentrated Solar Power
J - Rotor Moment of Inertia
R - Resistance (in Ohms)
Nm - Newton Meter (unit of Torque)
I - Armature Current
L - Inductance
KC - Back EMF Constant (volt-seconds per radian)
ω - Angular Velocity (radians per second)
b - Viscous Damping Coefficient
Kt - Torque Constant (N·m/A)
T_L - Load Torque
PV - Photovoltaic
LPWAN - Low-Power Wide-Area Network
UV - Ultraviolet
AI - Artificial Intelligence
ML - Machine Learning

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

With the depletion of fossil fuel reserves and increasing scarcity of non-renewable resources, the need for alternative source has gained significant attention. Renewable sources such as bioenergy, solar, wind, geothermal energy, tidal power and wave power are widely recognized as sustainable replacement for fossil fuel. Solar energy is the most popular used because it is relatively easy to convert to electrical energy. Solar energy (Solar Photovoltaic, PV) is well known as an unrestricted endless source which has emerged as a possible source of renewable source of energy over the past two to three decades and it involves no pollution, filtration or green-house gases emission. It is widely adopted for residential use nowadays because of the low cost of implementation and installation. The International Energy Agency (IEA) worldwide reports that PV capacity has grown out by 49% per year on average source in the early 2000s, making solar power a crucial element of future energy solution.

The solar energy is converted into electrical energy by using solar panel according to the principle of photovoltaic effect. The use of solar panels to convert the sun's energy to electrical energy is very popular, but due to movement of the sun from east to west, the fixed solar panels may not be able to operate ideal energy. Photovoltaic industry has been improving very well and most of the current installed PV system are of the fixed-tilt mounting deign of which the PV modules are tilted at an optimal angle for this type. These PV modules are reduced to severe cosine losses during harvesting of solar energy especially early in the morning and in the late evening. There is need for more advanced technologies to improve the capability of the PV, one of the ways this can be done is through the use of a solar tracker. The solar tracker is a device used for the rotation of the solar panel according to the sun's rays, to utilize the renewable solar energy more efficiently. Research has shown that solar trackers which continuously adjust the orientation of PV panels to face the sun can significantly enhance energy efficiency (Poulek et al., 2016). This project therefore employs a dual solar tracker to harvest more solar power in different angle location at different time interval of the day to get maximum efficiency.

1.2 Statement of Problem

Although solar photovoltaic energy is a promising alternative to traditional power sources, optimizing its efficiency remain a challenge particularly in areas with inconsistent solar radiation. Stationary or fixed solar panels cannot adjust to the sun's changing position leading to suboptimal energy capture. This lead to the introduction of the single axis solar tracker which was developed for rotation of solar panels in east and west direction. While single-axis trackers provide some improvement by allowing either horizontal or vertical movement they fail to fully compensate for the sun's seasonal and daily variations. To overcome this limitation, the dual axis solar tracker is developed to optimize solar energy harvesting by allowing the solar panel to rotate along both horizontal and vertical axes. This enables maximum solar energy absorption thereby improving efficiency and effectiveness. Frequent power outages and rising electricity tariffs in Nigeria severely disrupt daily life, forcing reliance on costly generators that strain household budgets and harm the environment through pollution and emissions. Essential appliances like refrigerators, cooling systems, and electronic devices face constant disruptions, reducing productivity and quality of life. This unsustainable situation highlights the urgent need for reliable and eco-friendly energy solutions.

1.3 Aim

To simulate and optimize a dual axis solar tracker system that can effectively track the sun’s position in both azimuth and elevation directions.

1.4 Objectives

1. To simulate the real-time performance of the dual axis solar tracker using MATLAB/Simulink.
2. To analyze the performance of dual axis solar tracker.
3. To optimize solar panel orientation for maximum efficiency.

1.5 Scope

This project is centered on the simulation and analysis of a dual axis solar tracker that actively adjusts its azimuth and elevation to follow the sun’s trajectory, with the ultimate goal of optimizing energy capture efficiency.

1.6 Methodology

1. Theoretical analysis of the motor equation.
2. The use of MATLAB/Simulink in the simulation of the dual axis solar tracker.
3. Optimization of the dual axis solar tracker using PID controller.

1.7 Significance of the Study

This project on the simulation of a dual axis solar tracker holds significant relevance in addressing the global need for clean, efficient, and sustainable energy sources. As the demand for renewable energy continues to rise, improving the efficiency of solar power systems becomes crucial (Sharma et al., 2022). Unlike traditional fixed solar panels that only capture a limited amount of sunlight during the day, dual axis solar trackers follow the sun’s movement across both horizontal and vertical planes, maximizing energy absorption throughout the day and across different seasons (Mousazadeh et al., 2019). The study demonstrates that solar trackers can significantly enhance energy yield by up to 30–40% compared to static systems (Mahmoud et al., 2021). By simulating the system using advanced tools like MATLAB/Simulink, this project showcases the feasibility of optimizing control algorithms, actuator dynamics, and sensor integration to achieve precise sun tracking. Such precision is crucial for increasing the overall efficiency and reliability of solar power systems (Ghoneim et al., 2020).

Additionally, the insights gained from this project are valuable for guiding the design of future solar energy systems in residential and industrial applications. These findings can help reduce energy costs, lower carbon emissions, and promote a greener environment (Yadav et al., 2023). The study also contributes to technological advancements by exploring control strategies and system responses, which can be adapted for real-world implementations. In the context of sustainable development, this project supports global efforts toward energy transition by providing a practical solution to improve solar energy harvesting (Liu et al., 2021). It aligns with environmental policies aimed at reducing dependence on fossil fuels and encourages the adoption of renewable technologies. Through simulation-based design and performance analysis, this research advances knowledge in the field and serves as a foundation for further technological innovation and development in renewable energy systems.

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical Framework

The dual axis solar tracker is a sophisticated system designed to follow the sun's movement across two axes — azimuth (horizontal) and elevation (vertical). This dynamic orientation ensures that photovoltaic (PV) panels capture maximum solar radiation throughout the day and across different seasons (Chen et al., 2021). The theoretical foundation for this system is rooted in solar geometry and control systems engineering, which enable solar panels to achieve optimal alignment with the sun.

According to Liu et al., (2020), solar tracking systems can significantly enhance the efficiency of PV panels by maintaining an optimal angle of incidence for sunlight. The performance of such systems is governed by solar altitude and azimuth angles, which vary throughout the year due to Earth's axial tilt and orbital movement. Control strategies for dual-axis solar trackers typically involve feedback mechanisms driven by sensors, such as light dependent resistors (LDRs), combined with algorithms like Proportional Integral Derivative (PID) control and heuristic models (Mohamed et al., 2019). These strategies ensure that the solar panels adjust continuously to the sun's changing position.

2.2 Overview of Solar Tracking System

Solar tracking systems are mechanisms designed to optimize the orientation of solar panels toward the sun to maximize energy capture. By adjusting the position of the solar panels throughout the day, these systems ensure that the panels receive direct sunlight, enhancing energy efficiency (Chen et al., 2020). The integration of such systems into renewable energy solutions has led to significant improvements in power generation, especially in large-scale photovoltaic installations.

Solar tracking systems have revolutionized solar energy technologies by significantly improving the efficiency of photovoltaic (PV) panels and concentrating solar power (CSP) systems. These systems align solar modules to follow the sun's movement throughout the day, ensuring that solar panels maintain an optimal angle of incidence for sunlight. This optimization reduces energy losses and maximizes power output compared to fixed solar panels (Chen et al., 2020). The introduction of solar tracking systems is particularly crucial in areas with high solar irradiance, where they can substantially increase the daily energy yield. Studies have shown that using a solar tracker can improve energy generation by 10% to 25% for single-axis systems and up to 40% for dual-axis systems, depending on geographic location and weather conditions (Kalogirou, 2018).

Solar tracking systems are used across various applications, including utility-scale solar farms, residential solar installations, and research facilities. These systems are vital for optimizing the performance of photovoltaic (PV) modules and concentrated solar power (CSP) systems, which rely on the precise alignment of mirrors or lenses to focus sunlight onto a receiver. With the increasing global demand for renewable energy, solar tracking systems have gained widespread attention as they bridge the gap between traditional fixed solar panels and the need for higher efficiency and reliability. The advancements in automation, artificial intelligence, and machine learning have further improved the accuracy and cost-effectiveness of solar tracking systems, making them a preferred choice for energy providers (Sharma et al., 2021). In addition to their technical benefits, solar trackers have a positive economic impact. By boosting the efficiency of solar panels, they reduce the land area required for energy generation, thereby lowering associated costs for large-scale solar installations. Furthermore, the enhanced energy yield ensures a faster return on investment (ROI), making solar trackers a financially viable option for solar energy projects (Ravi et al., 2022). Despite these advantages, the implementation of solar tracking systems is not without challenges. Factors such as initial capital costs, maintenance requirements, and exposure to environmental conditions like wind and snow must be carefully considered during system design and deployment. However, ongoing innovations in materials and tracking algorithms are addressing these issues, paving the way for wider adoption of solar tracking technologies globally (Lee et al., 2019).

2.3 Timeline of Advancements in Solar Tracking Systems

Solar tracking systems have evolved from simple manual methods to advanced mechanical and automated solutions. Early approaches involved passive solar alignment for heating and lighting, while the 19th century saw the introduction of manually adjustable solar collectors for maximizing sunlight capture. Although lacking automation, these methods laid the groundwork for more precise and efficient mechanical tracking systems, which later integrated electronics and control technologies for superior solar energy harvesting.

2.3.1 Mechanical Solar Trackers (pre-electronics era)

The concept of solar tracking dates back to the early 20th century, with basic mechanical trackers designed to follow the sun's path. These early systems were manually operated or relied on rudimentary mechanisms such as clock-driven motors. While innovative for their time, these systems were limited in precision and required frequent human intervention to adjust their orientation (Sharma et al., 2021).

Mechanical solar trackers were typically used in experimental setups or small-scale applications, with their performance constrained by the lack of real-time adaptability and automation. Despite these limitations, they laid the groundwork for the development of more advanced systems.

2.3.2 Integration of Electronics and Automated Tracking (Early 2000s)

The early 2000s marked a significant transition in solar tracking technology, driven by the integration of electronics and automation. The use of light sensors such as photodiodes and light-dependent resistors (LDRs) allowed trackers to detect the sun’s position more accurately. These sensors, combined with microcontrollers, enabled automated adjustments, reducing the reliance on manual operations (Chen et al., 2020). During this period, astronomical algorithms began to gain popularity. These algorithms used geographical coordinates and time data to predict the sun’s position, ensuring precise tracking even during cloudy conditions. This development significantly improved the efficiency and reliability of dual axis solar trackers, making them suitable for larger-scale applications such as photovoltaic (PV) power plants.

2.3.3 Modern Dual axis Trackers with Advanced Control Systems

In the past decade, dual axis solar trackers have evolved into highly sophisticated systems incorporating advanced control technologies. Modern trackers use artificial intelligence (AI) and machine learning (ML) to optimize their performance. These systems analyze real-time data and historical weather patterns to predict sunlight availability, enabling proactive adjustments and maximizing energy capture (Gupta and Kumar, 2020). IOT-enabled devices now allow for remote monitoring and control of solar trackers, further improving operational efficiency and reducing maintenance costs. Additionally, advancements in actuator technology, such as hydraulic and piezoelectric systems, have enhanced the precision and durability of these trackers (Patel et al., 2023).

2.4 Fundamentals of Solar Trackers

Solar trackers are mechanical devices designed to orient solar panels or mirrors toward the sun to maximize energy capture. By adjusting their orientation throughout the day, solar trackers ensure that the incident sunlight hits the solar surface at the optimal angle, enhancing energy generation efficiency (Sharma et al., 2021).

2.4.1 Working Principle of Solar Tracker

The fundamental working principle of solar trackers is based on the concept of solar geometry, which involves understanding the sun's path across the sky throughout the day and across seasons. The sun's movement is influenced by the Earth's rotation and its tilt relative to the orbital plane, making it necessary for solar trackers to account for these variations when adjusting the position of solar panels (Chen et al., 2020).

2.4.2 Types of Solar Tracking Systems

Solar trackers can be broadly classified into two categories: single-axis and dual axis trackers.

2.4.2.1 Single-Axis Solar Trackers

Single-axis trackers rotate around a single axis, either horizontally or vertically. They are simpler in design and cost-effective but offer lower efficiency compared to dual axis trackers (Ravi et al., 2022).

2.4.2.2 Dual-Axis Solar Trackers

Dual axis trackers, on the other hand, can adjust both the vertical and horizontal orientations of the panels, making them more efficient. These systems are especially beneficial in capturing maximum solar radiation throughout the year, regardless of seasonal (Gupta et al., 2020).

2.4.2.2.1 Principles of Dual-Axis Solar Trackers

Dual axis solar trackers operate by following the sun's movement across two planes: azimuth and elevation.

2.4.2.2.1.1 Azimuth Tracking

This refers to the horizontal rotation of the tracker to align with the sun’s position from east to west. Azimuth tracking ensures that the solar panels maintain an optimal angle with the sun as it moves across the sky during the day (Sharma et al., 2021).

2.4.2.2.1.2 Elevation Tracking

This involves vertical adjustments to account for the sun’s height in the sky, which changes throughout the day and across seasons. Elevation tracking ensures optimal solar alignment during sunrise, sunset, and variations in solar altitude (Chen et al., 2020). By combining these two tracking mechanisms, dual axis trackers achieve near-perpendicular alignment with the sun's rays throughout the day, significantly increasing energy absorption compared to single-axis or fixed systems.

2.4.2.2.2 Operational Efficiency Improvements of Dual-Axis Solar tracker over Single-Axis Trackers

Dual axis solar trackers offer significant operational advantages over single-axis systems In terms of:

2.4.2.2.2.1 Higher Energy Yield

By adjusting to both azimuth and elevation angles, dual axis trackers capture up to 40% more solar energy than fixed systems and approximately 10-20% more than single-axis trackers, depending on location and weather conditions (Patel et al., 2023).

2.4.2.2.2.2 Enhanced Adaptability

Dual axis trackers are effective in regions with high solar variability, as they can adjust to the sun’s movement more precisely than single-axis systems.

2.4.2.2.2.3 Optimized Land Use

The higher energy yield per unit area allows for smaller installations to achieve the same output, making dual axis systems particularly suitable for land-constrained applications. Despite these benefits, dual axis systems are more complex and costly than single-axis trackers. However, advancements in materials, automation, and control technologies continue to bridge this gap, making dual axis trackers a viable choice for high-efficiency solar energy systems.

2.4.2.2.3 Control Strategies for Dual-Axis Solar Trackers

Control strategies for dual-axis solar trackers have advanced from simple manual adjustments to sophisticated automated systems. Early methods relied on pre-programmed movements without feedback, while modern systems use techniques such as sensor-based feedback and PID controllers. These approaches ensure precise real-time tracking, adaptability to environmental changes, and optimized solar energy capture throughout the day.

2.4.2.2.3.1 Traditional Control Methods for Dual -Axis Solar Trackers

Control methods for solar tracking systems are broadly categorized into open-loop and closed-loop systems. These systems are selected based on performance requirements, environmental conditions, and system complexity.

2.4.2.2.3.1.1 Open-Loop Control Systems

An open-loop control system operates without real-time feedback. The system adjusts the solar tracker based on a fixed algorithm, which determines the position of the solar panels using pre-programmed data such as the time of day, geographical location, and date. Since it does not rely on external sensors, this method assumes predictable, static conditions.

2.4.2.2.3.1.1.1 Advantages of Open Loop Systems

1. Open-loop systems are straightforward to design and implement, using minimal components such as microcontrollers and timers.
2. Since they do not require sensors or complex feedback mechanisms, open-loop systems are less expensive to construct, making them ideal for basic applications where precision is not critical.
3. Without the need for constant monitoring or sensor feedback, open loop systems tend to consume less power, which is beneficial in off-grid or remote applications where energy consumption is a concern (Sharma et al., 2021).

2.4.2.2.3.1.1.2 Limitations of Open Loop Systems

1. Since the system operates without feedback, it cannot compensate for variations in environmental conditions, such as changes in cloud cover, temperature, or atmospheric pressure. This can lead to suboptimal solar panel orientation, reducing energy capture (Lee et al., 2019).

2. Open-loop systems cannot adjust to real-time changes, making them unsuitable for dynamic environments where solar radiation is highly variable.
3. Open-loop control does not account for real-time errors or unexpected environmental changes, which may cause misalignment with the sun, especially during the day.

2.4.2.2.3.1.2 Closed-Loop Control Systems

A closed-loop control system incorporates feedback from sensors to adjust the position of the solar tracker in real time. Common sensors used in closed-loop systems include light dependent resistors (LDRs), potentiometers, and encoders, which provide data on the solar panel’s orientation relative to the sun. The controller continuously adjusts the tracker’s position to minimize the error between the desired and actual position of the panel.

2.4.2.2.3.1.2.1 Advantages of Closed Loop Systems

1. Closed-loop systems can accurately track the sun’s position by making real-time adjustments based on feedback, improving energy efficiency by ensuring optimal alignment of the panels throughout the day.
2. By maintaining accurate alignment with the sun, closed loop systems maximize the solar panel's exposure to sunlight, thus increasing energy yield (Patel et al., 2023).
3. These systems can adjust to fluctuating weather conditions, such as cloud cover, shading, or changes in the solar radiation intensity, enhancing their reliability under variable conditions (Sharma et al., 2021).

2.4.2.2.3.1.2.2 Limitations of Closed Loop Systems

1. Closed-loop systems require sensors, feedback loops, and real-time data processing, making them more complex to design and implement compared to open-loop systems.

2. The inclusion of sensors, actuators, and controllers increases the overall cost of closed-loop systems, making them more expensive to build and maintain.

3. Due to the additional components, closed-loop systems may require more frequent maintenance, especially to calibrate the sensors and ensure system accuracy.

2.4.2.2.3.1.3 PID Control

The Proportional-Integral-Derivative (PID) controller is a widely used method for controlling dual axis solar trackers in a closed-loop system. The PID controller works by adjusting the position of the tracker to reduce the error (difference between the desired and actual position of the solar panel). It uses three components:

1. Proportional (P): The proportional term adjusts the error by an amount that is directly proportional to the magnitude of the error. Larger errors result in greater corrections.
2. Integral (I): The integral term accumulates past errors, helping to correct small, persistent deviations that may not be corrected by the proportional term alone.
3. Derivative (D): The derivative term anticipates future errors based on the rate of change of the error, helping to reduce overshooting and improve system stability.

The PID controller’s ability to finely adjust the solar panel’s position ensures that the tracker follows the sun as accurately as possible, improving tracking performance and energy efficiency. However, the PID controller requires precise tuning of its parameters (Kp, Ki, and Kd) to avoid issues such as overshooting or oscillations (Patel et al., 2023).

2.5 Current Trends and Innovations in Dual-Axis Solar Trackers

The evolution of dual axis solar trackers has been marked by significant innovations in their design, materials, operation, and integration with advanced technologies. These innovations aim to increase the efficiency, reliability, and cost-effectiveness of solar energy systems, addressing the growing global need for sustainable energy solutions. Key trends include miniaturization, the use of novel materials, autonomous systems, and the application of digital twin technologies. This section delves into these current trends, their operational benefits, and the advancements driving them.

Miniaturization and lightweight design are becoming increasingly important in the development of dual axis solar trackers, as they contribute to reducing installation costs and improving system efficiency. Lighter systems are not only more cost-effective but also more adaptable, making them suitable for a wider range of applications, including residential, commercial, and remote installations. Miniaturization helps reduce the use of materials and simplifies the manufacturing process, contributing to cost savings. It also makes installation easier, especially in locations where space is constrained or when dealing with lightweight installation teams (Noghabi et al., 2020). By utilizing smaller, more efficient components, such as compact motors and drive systems, modern dual axis trackers become more energy-efficient while maintaining optimal performance.

The choice of materials used in the construction of dual axis trackers plays a crucial role in enhancing their durability and efficiency. The use of lightweight yet stronger materials has enabled the development of trackers that can withstand extreme environmental conditions while maintaining high performance. Recent developments have focused on materials such as titanium alloys and aluminum composites, which offer a high strength-to-weight ratio, thus improving the structural integrity of the trackers (Zhao & Liu, 2016). Additionally, advanced coatings and composite materials are being used to protect solar trackers from environmental factors such as corrosion, UV radiation, and mechanical wear. Materials like flexible solar panels, made from organic photovoltaic (PV) and perovskite solar cells, offer a promising future for lightweight, efficient, and cost-effective dual axis trackers. These materials have led to the development of solar panels that are not only lighter but also more efficient, capturing more solar energy by reducing reflective losses (Tian et al., 2021).

The integration of autonomous systems in dual axis solar trackers is a growing trend that reduces the need for human intervention in their operation and maintenance. Autonomous trackers are equipped with advanced sensors and smart algorithms that allow them to self-adjust based on real-time solar irradiance and other environmental factors. These autonomous trackers help reduce maintenance costs by minimizing the need for manual interventions. Additionally, they ensure that the solar panels are always positioned for optimal performance, improving the overall energy efficiency of the system. By integrating with the broader smart grid infrastructure, autonomous trackers can adapt to changes in energy demand, improving the reliability and stability of the energy grid. The development of dual axis solar trackers has been an area of intense research, with numerous studies contributing to the improvement of efficiency, durability, and control systems for solar tracking technologies. Over the years, various studies have contributed to understanding and improving the performance of dual axis solar trackers. These landmark studies can be categorized into three major themes: mechanical design, control strategies, and performance optimization.

Early studies in solar tracker development focused on the mechanical designs, examining how tracking systems could optimize the orientation of photovoltaic panels. Hottel et al., (1974) proposed the first theoretical models of solar tracking systems, emphasizing the potential for increased energy yield with dual axis trackers. These early models laid the groundwork for subsequent studies on how mechanical components could be designed to follow the sun's path accurately. With advancements in electronics and automation, more studies began to focus on the integration of control systems. Krantz et al., (2014) explored the development of adaptive control algorithms, allowing the system to adjust tracking behavior based on real time solar positioning data. This development was further refined by studies on the integration of closed-loop control systems, which significantly enhanced tracking accuracy and system reliability Bishop et al., (2017). In more recent years, research has shifted towards optimizing the performance of solar trackers by taking into account environmental factors, such as wind loads, temperature variations, and shading effects. Moghaddam et al., (2020) investigated how wind-induced forces affect the structural integrity of dual axis systems, leading to innovations in material selection and structural reinforcement for enhanced stability. Studies by Zhang et al., (2018) explored the impact of environmental factors on solar irradiance, concluding that accurate simulation models could account for these variations, thereby improving performance predictions for tracking systems.

2.6 Significance of Solar Power in Global Energy Demand

Solar power plays a pivotal role in addressing the global energy demand. As a clean and renewable energy source, it contributes to reducing greenhouse gas emissions and dependency on fossil fuels. With advancements in technology, the adoption of solar power is expected to increase, further aiding the global transition to sustainable energy (IEA, 2021). The use of solar tracking systems is justified by their ability to enhance the efficiency of solar panels, thereby maximizing energy output. This increased efficiency translates to cost savings and a higher return on investment, making solar tracking an essential component of modern solar energy solutions Patel et al., (2023).

2.7 Review of Related Studies

Smith et al., (2014) used simulation tools to compare the performance of fixed photovoltaic panels with dual axis solar tracking systems. The study focused on quantifying the increase in energy capture provided by the dual axis configuration over traditional fixed systems. Simulated data revealed that dual axis trackers captured significantly more solar energy by dynamically adjusting to the sun's position, thereby reducing shading and reflection losses. The researchers found that even slight improvements in tracking precision resulted in marked increases in overall energy output. This comparative analysis underscores the advantages of dual axis solar trackers in maximizing energy harvest. The findings support the adoption of dynamic tracking systems as a viable solution for enhancing the efficiency of solar installations across various scales.

Singh et al., (2024) utilized simulation tools to evaluate the performance of advanced controllers in dual axis solar trackers. The study focused on fine-tuning the controller's parameters to achieve precise tracking and reduced energy losses during movement. The simulations indicated that advanced controllers significantly improved tracking precision by minimizing overshoot and oscillations. The researchers found that this led to higher energy capture efficiency and a reduction in the energy consumed during adjustments. This research demonstrates the importance of optimizing control strategies such as tuning, in enhancing the performance and reliability of dual axis solar trackers making them more suitable for real-world renewable energy applications.

Li et al. (2013) developed advanced control algorithms for dual axis solar trackers and evaluated their performance through simulation. Their study aimed to refine the control mechanisms to ensure the tracker maintained optimal alignment with the sun throughout the day. The simulation results demonstrated that the enhanced control strategies significantly improved tracking accuracy, reducing energy losses during adjustment phases. Li et al., showed that precise, real-time control adjustments lead to a more stable and efficient energy capture process. This research highlights the critical role of robust control systems in optimizing the performance of dual axis solar trackers. By integrating improved control strategies, designers can achieve higher energy efficiency and reduce maintenance costs associated with mechanical wear.

Alexandru et al., (2010) used simulations to study the energy use of dual axis solar tracking systems. They focused on finding the best times to move the tracker in steps rather than continuously. This method aimed to balance maximum sunlight capture with minimal energy needed for movement. The simulations showed that by timing the tracker movements with the sun’s path, energy use could be greatly reduced while still capturing enough sunlight. The researchers found that step-by-step tracking not only cuts down on energy costs but also decreases mechanical wear, extending the system’s lifespan. This study highlights the importance of analyzing energy consumption when designing solar tracking systems. Using simulation tools, engineers can develop strategies to improve net energy output, making these systems more efficient and cost-effective for both small and large solar installations.

A notable study by Shufat et al., (2019) in Turkey focused on the modeling and design of an azimuth-altitude dual axis solar tracker aimed at optimizing energy generation. The researchers employed MATLAB/Simulink for the system's modeling and simulation, providing a comprehensive framework for evaluating its performance under varying solar conditions. The results of the simulation highlighted a substantial improvement in solar energy absorption when compared to fixed solar systems. By dynamically adjusting the azimuth and altitude angles, the tracker ensured that the solar panels remained perpendicularly aligned to incoming sunlight, thereby maximizing energy capture throughout the day and across different seasons. Shufat et al. demonstrated that the use of MATLAB/Simulink not only facilitated accurate system modeling but also allowed for iterative design improvements to enhance tracking performance. The study underscored the potential of azimuth-altitude tracking configurations to significantly boost the efficiency of solar energy systems, making them a viable solution for both residential and commercial applications.

A study by Mulcahy et al., (2014) investigated the integration of dual axis tracking systems in solar-powered EV charging stations across various locations in the United States. The research found that by dynamically adjusting the solar panels to follow the sun's path throughout the day and year, dual axis trackers substantially increased the amount of solar energy harvested compared to fixed systems. This increase in energy output directly contributed to higher charging capacity, enabling stations to meet the growing demand for electric vehicle charging while reducing reliance on grid power. The study emphasized the practical benefits of using dual axis trackers in locations with varying sunlight conditions, such as regions with seasonal fluctuations or partial cloud coverage. By optimizing the solar panels' alignment, dual axis systems improved the reliability and efficiency of charging stations, making them a more viable solution for large-scale EV infrastructure. Mulcahy et al.'s research demonstrates that integrating advanced tracking technologies, like dual axis trackers, into solar-powered EV charging stations can significantly enhance energy production, supporting the transition to clean, renewable energy for transportation. As the EV market expands, these innovations will play a crucial role in creating a sustainable and resilient charging infrastructure.

Pande et al., (2016) conducted a comprehensive study on the implementation of dual axis solar tracking in water pumping systems across rural India. The study revealed notable improvements in energy capture and system reliability compared to fixed-axis setups. The increased solar energy harvest ensured sufficient power for operating water pumps even during periods of lower sunlight intensity. Furthermore, the research emphasized the potential of dual axis systems to reduce maintenance costs and extend the lifespan of pumping components by providing a stable and consistent energy supply. The integration of dual axis tracking technology in solar water pumping systems is a promising advancement for agricultural sustainability. It offers an efficient and eco-friendly solution to support irrigation needs, particularly in regions with limited access to conventional power sources. As India continues to invest in renewable energy technologies, the adoption of dual axis trackers is likely to play a crucial role in transforming rural agricultural practices.

A recent study by Alexandru et al., (2023) employed simulations to analyze the performance of a dual axis solar tracking mechanism in photovoltaic (PV) systems. The research examined the system’s efficiency in capturing solar radiation across various seasonal and weather conditions. The results demonstrated the effectiveness of the dual axis configuration in maximizing energy capture compared to fixed and single-axis systems. Moreover, Alexandru’s study emphasized the importance of simulation tools in predicting system behavior, identifying operational inefficiencies, and guiding design improvements. The use of computational models allowed for the testing of multiple configurations without the need for costly physical prototypes. The findings highlighted that simulation-based evaluations could accelerate the development of more efficient and reliable solar tracking systems, contributing to advancements in renewable energy technology. The insights gained from performance simulations underscore the potential of dual axis solar trackers to significantly enhance energy generation in PV systems. As renewable energy technologies evolve, simulation-driven performance evaluations are expected to remain a cornerstone of system innovation and optimization.

2.8 Research Gap

While numerous studies have explored the design and simulation of dual-axis solar trackers, most of them focus on either single-axis systems or dual-axis systems with limited control strategies often relying on basic open-loop or closed-loop control mechanisms. Additionally many existing studies emphasized on theoretical modeling without sufficient emphasis on real-time dynamic response optimization or the integration of advanced control like PID controllers for precise sun tracking. Thus, below are the gaps of the study:

1. Advanced Control Strategy Integration: Unlike many related studies that use basic control methods, this project employs a Proportional-Integral-Derivative (PID) controller to optimize the dynamic response of the dual-axis solar tracker. The PID controller is fine-tuned to minimize tracking errors, reduce overshooting, and ensure precise alignment with the sun’s position in real-time. This level of control precision is not extensively covered in existing literature, especially in the context of dual-axis systems.
2. Comprehensive Simulation Approach: While some studies have simulated dual-axis solar trackers, they often focus on specific components (e.g., motor dynamics or panel orientation) without integrating all system components into a cohesive simulation. This project, however, provides a holistic simulation that includes sun position calculation, PID control, motor dynamics, and solar panel output, offering a more comprehensive understanding of the system’s performance
3. Focus on Energy Efficiency and System Optimization: Many studies highlight the energy yield improvements of dual-axis trackers but do not delve deeply into the energy consumption of the tracking system itself. This project not only simulates the energy capture efficiency but also analyzes the energy consumption of the motors and control systems, ensuring that the energy gain from tracking outweighs the energy used by the system.
4. Real-Time Environmental Adaptability: While some studies consider environmental factors like shading or weather conditions, they often do so in a static or simplified manner. This project incorporates real-time

feedback mechanisms using virtual sensors to simulate how the system adapts to dynamic environmental changes such as sudden cloud cover or variations in solar irradiance.

5. Simulation-Based Design for Future Prototyping: Unlike studies that either focus solely on simulation or on physical prototypes, this project bridges the gap by using simulation as a foundation for future physical prototyping. The simulation results are designed to inform the construction of a physical prototype, addressing potential real-world challenges such as motor imperfections, sensor calibration, and environmental factors.

CHAPTER THREE

METHODOLOGY

3.1 Methods

In this chapter, the methodology and design principles for the simulation of the dual axis solar tracker are outlined. The simulation is built using MATLAB/Simulink to model the entire system, including the calculation of the sun’s position, the design of the PID controller, the simulation of motor dynamics, and the solar panel behavior. Each component of the system is modeled individually and then integrated to assess the overall performance and optimize energy generation. The objective of the dual axis tracker is to continuously adjust the solar panel’s orientation to the sun thus maximizing the solar energy harvested throughout the day.

The primary goal of this project is to simulate a real-time control system that can effectively track the sun’s position in both azimuth and elevation directions. The key components involved include:

1. Sun Position Calculation: A model that computes the solar angles based on geographic location and time of year.
2. PID Controller: A feedback control system that adjusts the panel’s position based on real time errors
3. Motor Dynamics: The model for the motors driving the panel’s movement in two axes.
4. Solar Panel Output: A model that shows the solar panel's power output based on its angle relative to the sun.

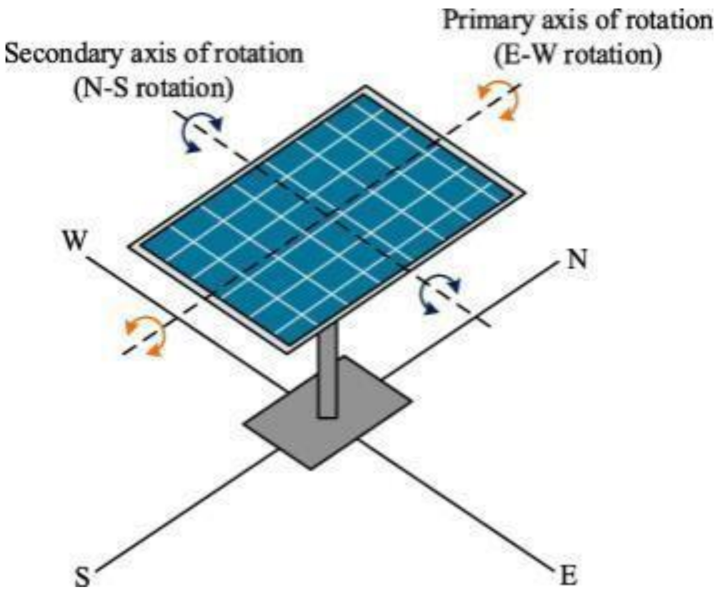

Figure 3.1: Image of a dual axis solar tracker

A solar panel tracking the sun using Light Dependent Resistors (LDRs) is a common approach in solar tracking systems, particularly for simple and cost-effective designs. LDRs are light sensitive resistors whose resistance decreases as the intensity of light increases. Here's how the system works:

3.2 Basic Principle of LDRs in Solar Tracking

Light Sensing: The solar panel uses multiple LDRs to detect the intensity of sunlight falling on different parts of the panel.

LDR Placement: Typically, two LDRs are placed on opposite sides of the solar panel and one is used for each axis of rotation (azimuth and elevation). For a dual axis system, this means using 4 LDRs (two for the horizontal axis and two for the vertical axis).

Resistance Change: As sunlight hits each LDR, its resistance changes in proportion to the intensity of light. When sunlight is directly aligned with the panel, both LDRs will receive equal amounts of light resulting in equal resistance on both sides.

3.3 Working of the Tracking System

I. Comparing LDRs: The two LDRs (for each axis) are connected to a control circuit, usually involving an analog-to-digital converter (ADC) that converts the resistance values to a usable signal.

II. Light Intensity Imbalance: If the sunlight is not directly aligned with the panel, one LDR will receive more light, and its resistance will decrease more than the other. This imbalance is used to determine which direction the panel needs to move.

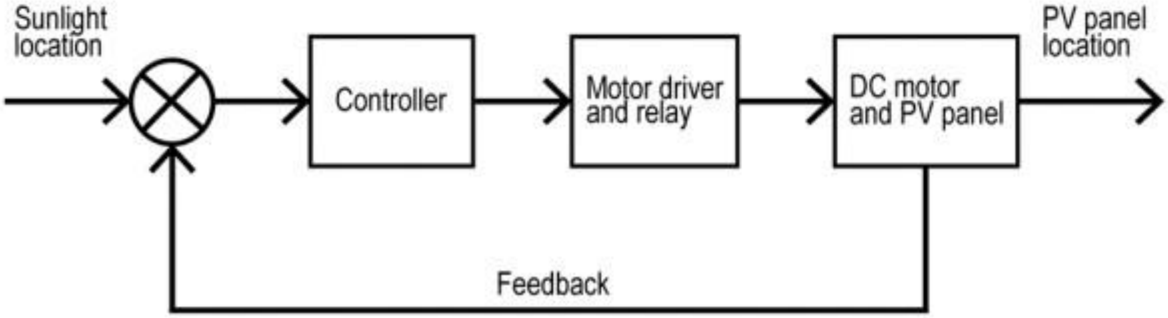

Figure 3.2: Block diagram of Dual axis solar tracker

3.3.1.1 The building Blocks of Dual-Axis Solar Tracker

The dual axis solar tracker is composed of several essential components that work together to optimize solar energy capture by ensuring continuous alignment with the sun's movement. These building blocks includes:

3.3.1.1 Reference Generation

This account for the sunlight location at every point in time. This provides the desired azimuth and tilt angles based on solar position algorithms or pee-calculated solar paths. These reference signals serve as the target angles for the control system and thus ensures the solar panel is aligned with the sun for maximum efficiency.

3.3.1.2 PID Controller

The PID (Proportional-Integral-Derivative) controller is a crucial component in the dual axis solar tracker, ensuring precise and efficient alignment of the solar panel with the sun. Its primary purpose is to minimize the error between the reference angles (desired azimuth and tilt angles) and the actual angles of the solar panel by generating appropriate control signals for the DC motors. By continuously adjusting these signals, the PID controller ensures that the solar panel remains optimally oriented for maximum energy absorption throughout the day.

Kp: Proportional gain for reducing steady-state error.

Ki : Integral gain for eliminating accumulated error over time.

Kd: Derivative gain for minimizing overshoot and improving system stability.

In the dual axis solar tracker, the PID controller dynamically drives the DC motors responsible for adjusting both the azimuth (horizontal orientation) and tilt (vertical orientation) angles. By continuously responding to real-time feedback from sensors, the controller compensates for external disturbances such as wind or mechanical resistance, ensuring the solar panel remains accurately aligned with the sun. This precision in tracking significantly improves the overall efficiency of the solar energy system, making the PID controller an indispensable part of the dual axis solar tracker.

I. Motor: The motor is a critical component in a dual axis solar tracker as it facilitates the movement of solar panels to align with the sun's position. This alignment maximizes solar energy capture and enhances the overall efficiency of the system. The motors are strategically placed to handle Azimuthal Rotation: The horizontal movement of the solar panel to follow the sun from east to west.

II. Elevation Adjustment: The vertical movement to adjust the tilt based the sun’s height in the sky.

III. The motor is controlled by a micro-controller through a motor driver circuit but in this. The control system is programmed to adjust the panel’s position based on input from light intensity.

IV. Input Signal Processing: Light sensors or time-based algorithms provide feedback on sun position.

V. Motor Activation: The motor driver receives signals to rotate the motor in small increments for precise alignment.

Electrical equation

$$V = L\frac{dI}{dt} + RI + KC\omega$$

Where:

V: Input voltage (volts) □ L: Inductance (henries)

R: Resistance (ohms)

I: Armature current (amperes)

KC: Back EMF constant (volt-seconds per radian)

ω: Angular velocity (radians per second)

Mechanical equation

$$J\frac{dw}{dt} + b\omega = \mathrm{KtI} - T_L$$

Where:

J: Rotor moment of inertia (kg·m^2)

b: Viscous damping coefficient (N·m·s/rad)

Kt: Torque constant (N·m/A)

T_L: Load torque (N·m)

3.3.1.3 Panel rotation

A dual axis solar tracker allows the solar panel to follow the sun's movement both horizontally (azimuthal rotation) and vertically (altitudinal rotation), ensuring optimal solar exposure throughout the day and across seasons. The azimuthal rotation, which tracks the sun's movement from east to west, typically uses a motor-driven gear or rotary actuator mounted on a vertical pole or base. For altitudinal rotation, the system employs a linear actuator or a motor with a gear system to adjust the panel's tilt angle. This mechanism is usually attached to the back of the panel frame. Proper weight distribution and structural integrity are essential to handle the wind and the weight of the panels. Additionally, the tracking system consumes energy for its operation, so it must be efficient to ensure that the energy gain from increased solar capture outweighs the system's energy usage. Durability is also crucial, as the system must withstand various weather conditions, including wind, rain, and temperature fluctuations.

$$\frac{d^2\,\theta}{dt^2} = \frac{1}{j}\left(T - K_d\frac{d\,\theta}{dt}\right)$$

3.3.1.3 Feedback Mechanism

In a dual axis solar tracker, the feedback mechanism ensures precise alignment of the solar panel with the sun by continuously monitoring and adjusting the panel's position. This mechanism typically involves a combination of sensors, controllers, and actuators working in a closed loop system to track the sun's movement and respond to environmental changes. The feedback mechanism operates in real time, ensuring continuous alignment as the sun moves throughout the day. This dynamic response enhances the system's efficiency by maximizing solar energy capture. Moreover, the closed-loop design minimizes errors caused by mechanical tolerances or environmental disturbances, making it an essential component of a dual axis solar tracker.

3.4 Simulation of Dual Axis Solar Tracker

I. Panel Equation

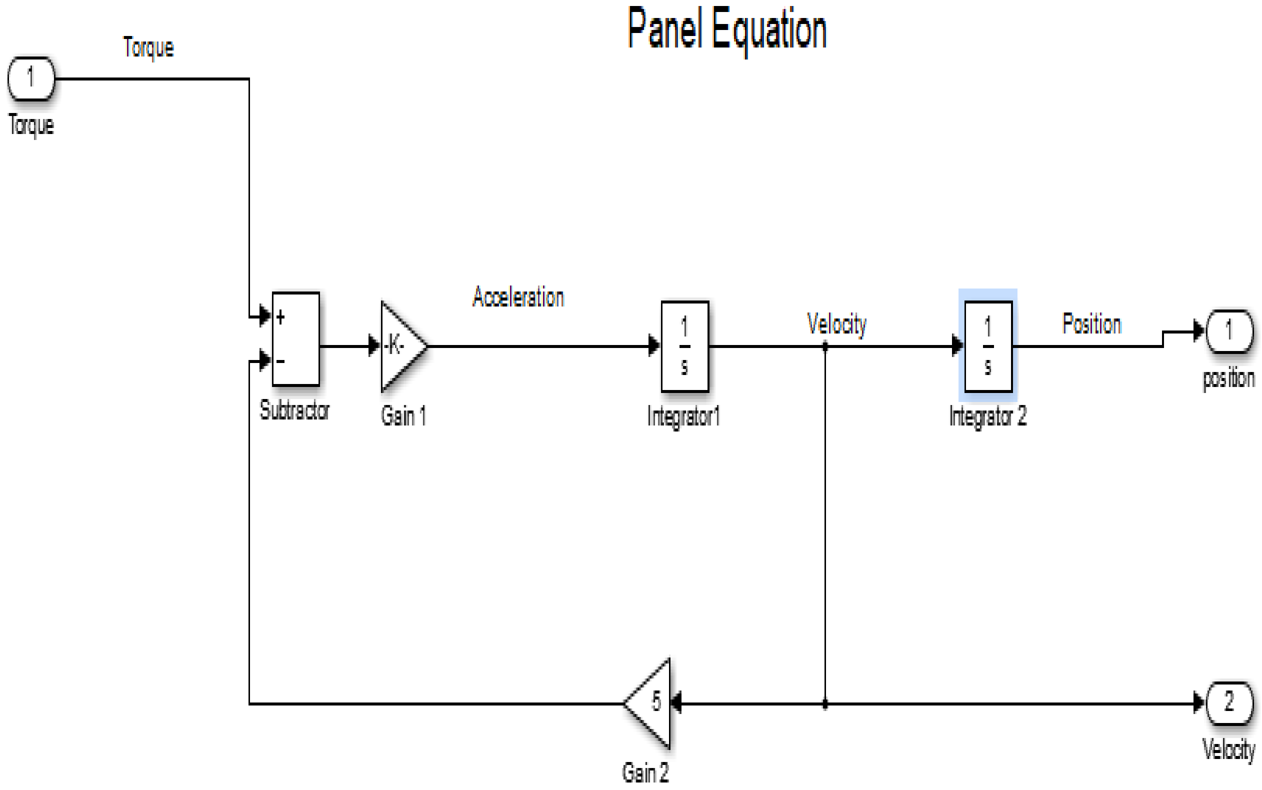

Figure 3.3: Diagram of Panel Equation

II. Motor Design

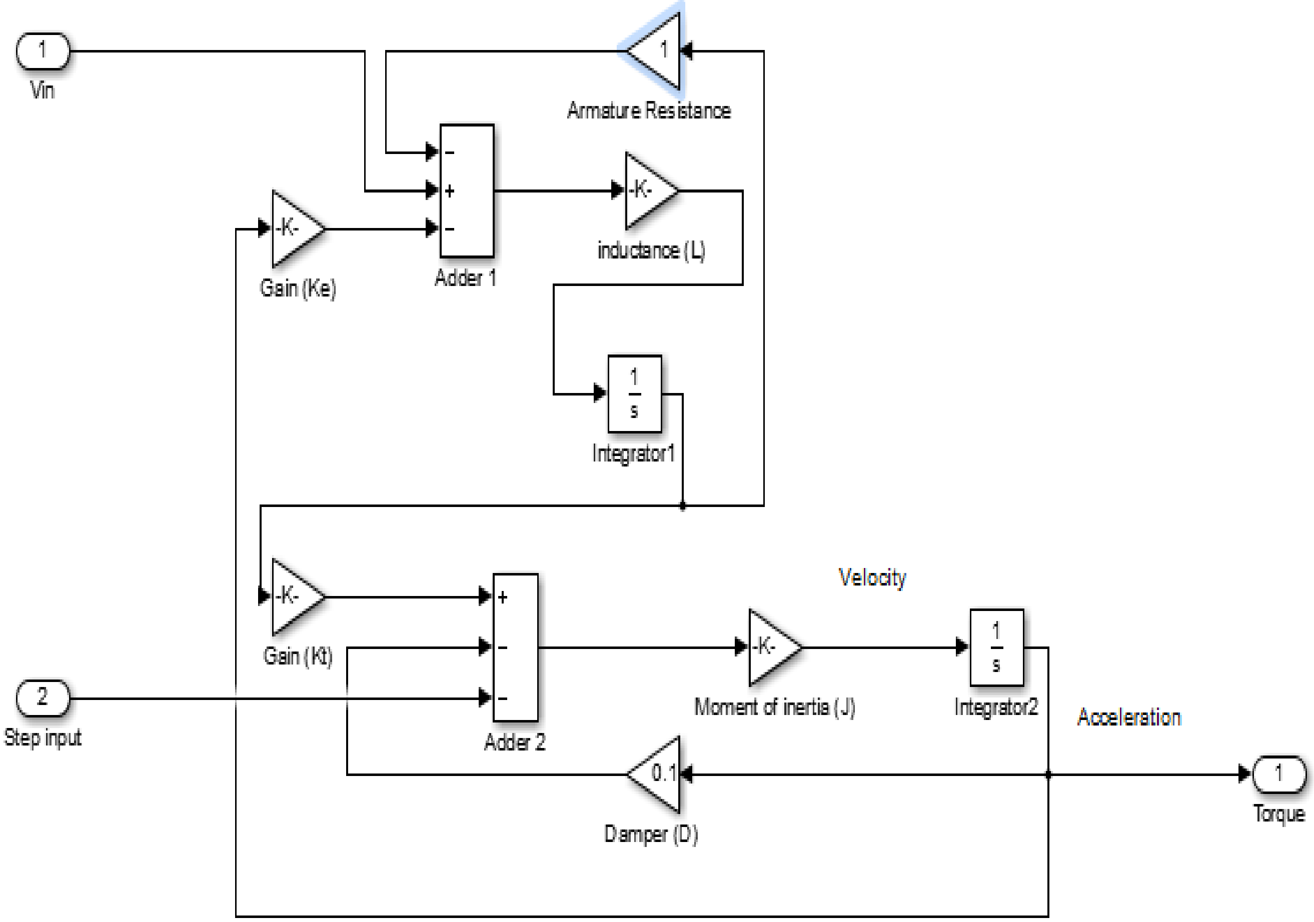

Figure 3.4: Diagram of the Motor

III. Tracker System

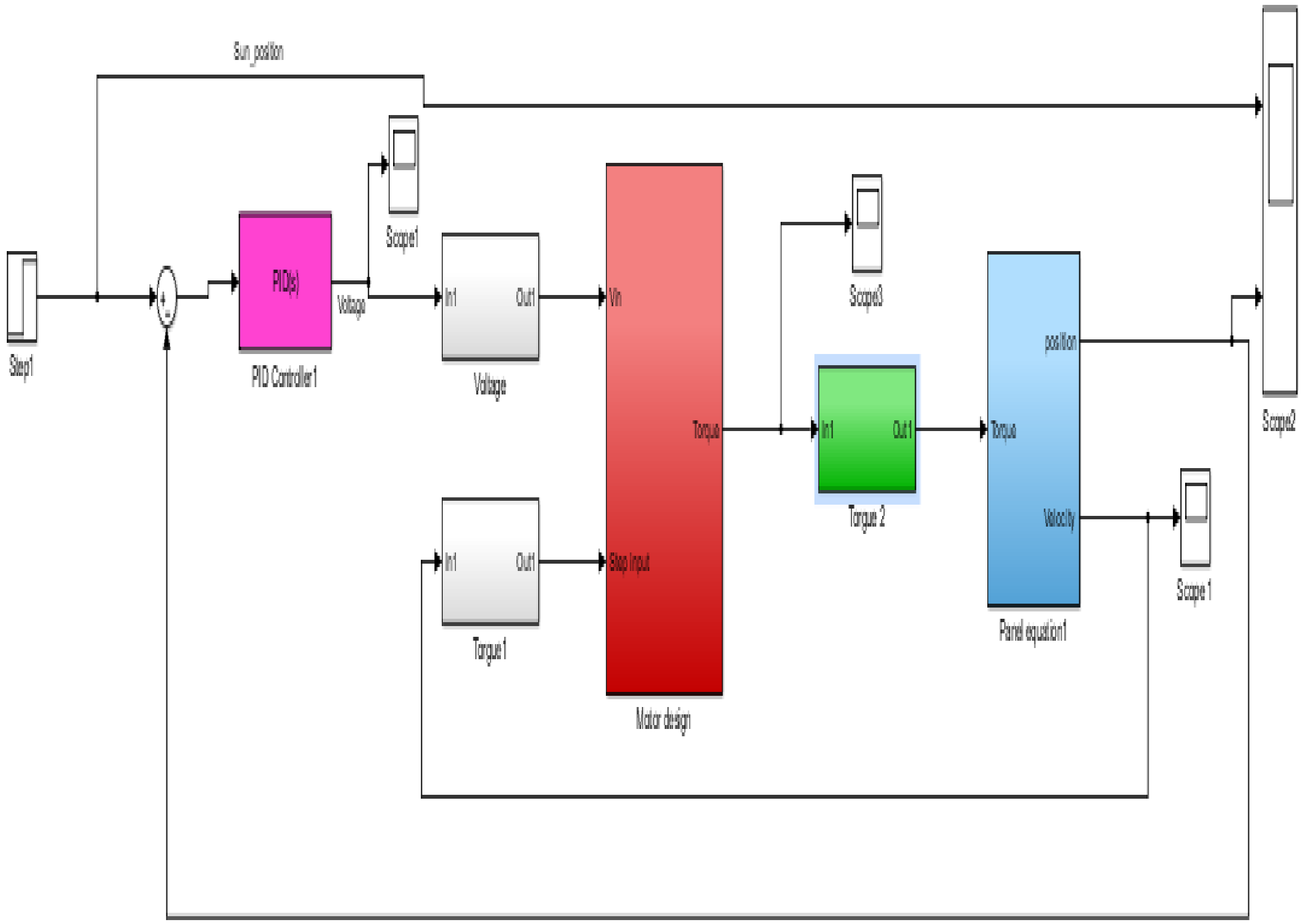

Figure 3.5: Diagram of the Tracker System

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Results

The results from the panel position, panel velocity, motor torque and tracker system are presented in this section.

4.1.1 Result from the Panel Position

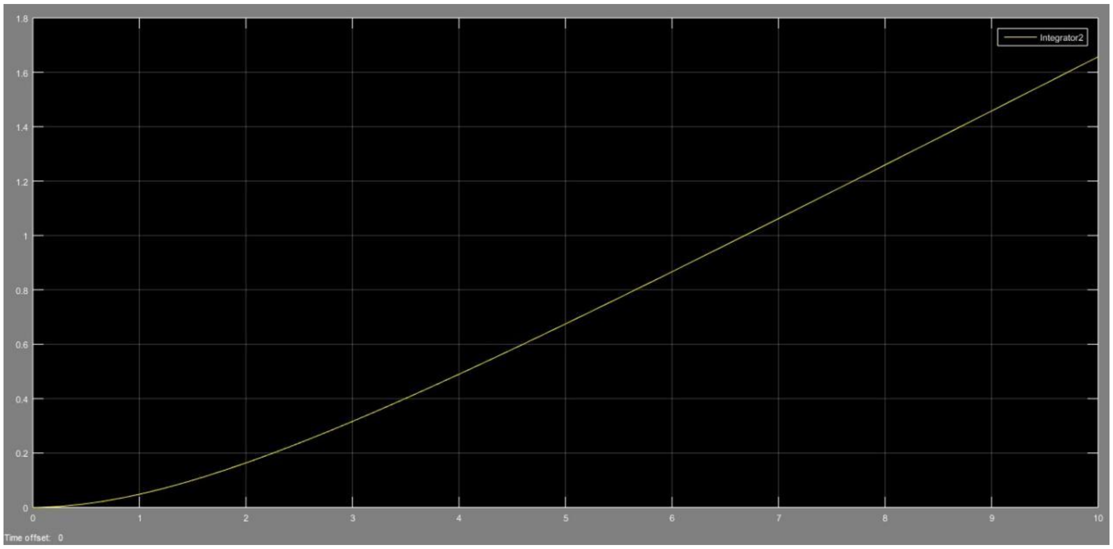

Figure 4.1: Graph of the Panel Position

The graph of the panel position displays a smooth and continuous increase over time, representing the angular displacement of the solar panel as it tracks the sun’s movement across the sky. The gradual rise indicates that the panel adjusts its orientation steadily to follow the sun’s trajectory from east to west throughout the day. The linear trend suggests that the panel position changes at a relatively constant rate, reflecting the predictable motion of the sun during daylight hours. This behavior highlights the effectiveness of the dual axis tracker in maintaining optimal alignment with the sun, maximizing solar energy capture. The smoothness of the graph also indicates the absence of abrupt shifts, implying that the control algorithm operates efficiently to track the sun without oscillations or delays in movement.

4.1.2 Result from the Panel Velocity

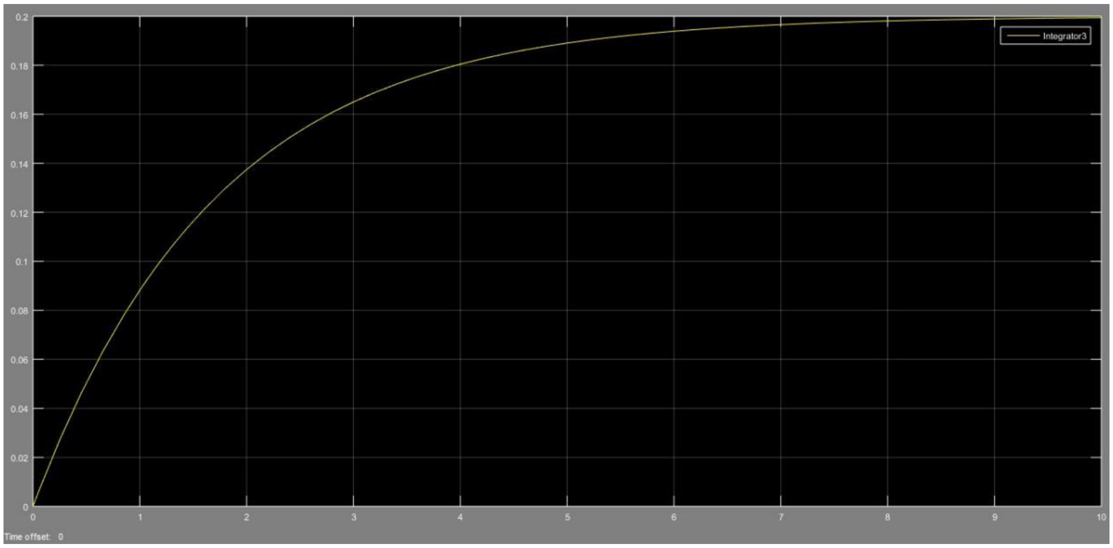

Figure 4.2: Graph of the Panel Velocity

The graph of the panel velocity illustrates the rate of angular change in the panel's position over time. It shows a rapid initial increase in velocity, which corresponds to the panel's need to quickly adjust its orientation during sunrise when the sun's position changes more sharply. As time progresses, the velocity curve flattens, indicating a slower rate of angular change around midday when the sun is near its peak elevation, and its apparent motion becomes less dramatic. This pattern reflects the system's responsiveness to variations in the sun's movement speed, ensuring accurate tracking without unnecessary energy consumption. The smooth transition in velocity further suggests that the tracker employs a closed-loop control system that dynamically adjusts the speed based on real time feedback, enabling precise and stable tracking performance throughout the day.

4.1.3 Result from the Motor Torque

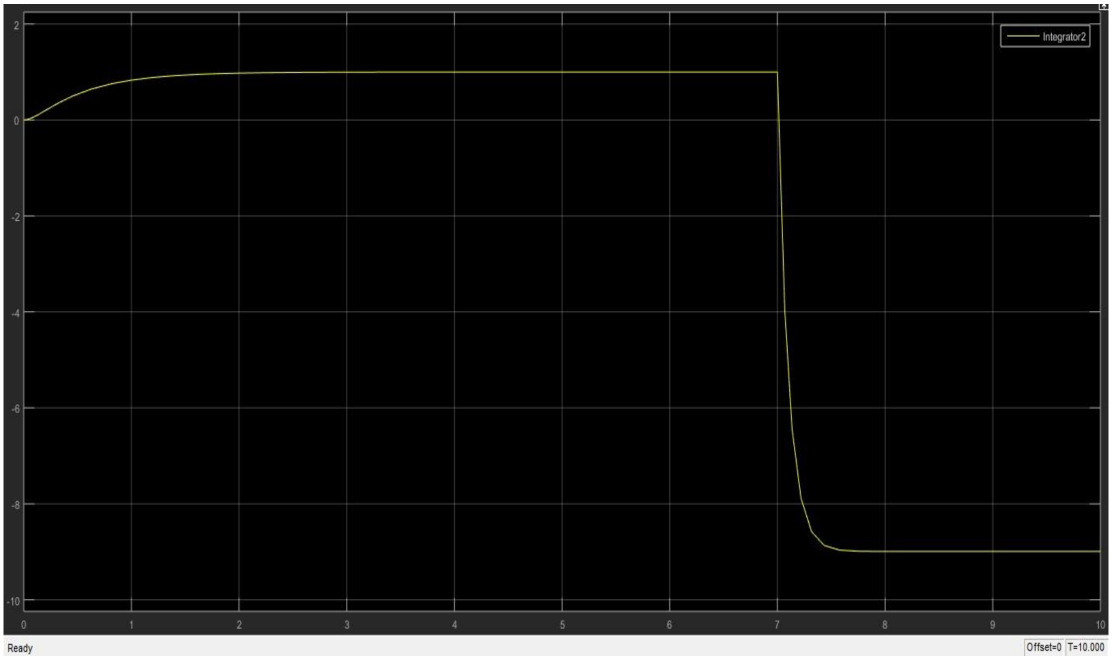

Figure 4.3: Graph of the Motor Torque

This graph illustrates the motor torque response over time, which is a critical parameter in controlling the dual axis solar tracker. Initially, the torque increases rapidly, reflecting the motor’s effort to overcome inertia and align the panel with the sun’s position. It then stabilizes at a nearly constant value, indicating that the motor maintains the required force to track the sun smoothly. Around 7 seconds, the torque decreases sharply, showing that the motor has achieved its desired position and reduces its output to maintain stability. This behavior highlights the system’s efficiency in dynamically adjusting torque to avoid unnecessary energy consumption while ensuring precise control of the panel orientation.

4.1.4 Result from the Tracker System

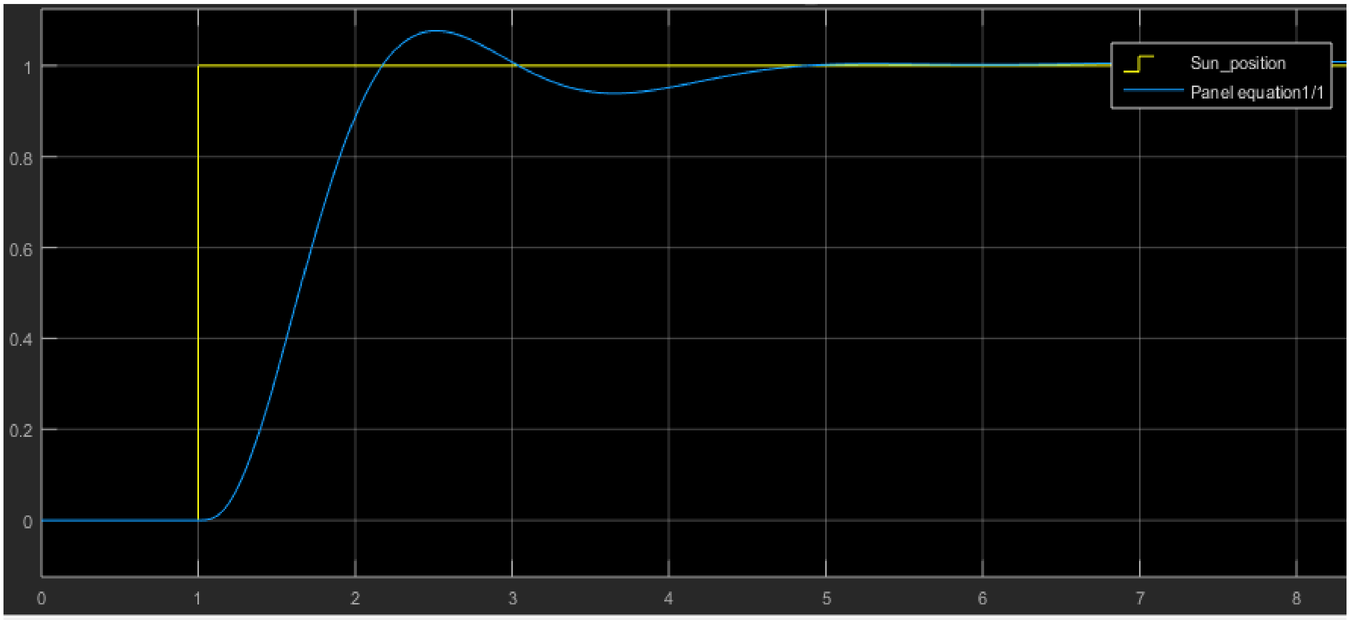

Figure 4.4: Graph of the Tracker System

This graph demonstrates the performance of the tracker system by comparing the panel position (blue line) to the sun's position (yellow line). The blue line shows a gradual increase, closely following the yellow line, which represents the sun's trajectory. The alignment between the two lines indicates that the panel effectively adjusts its orientation to track the sun throughout its movement. Initially, the panel takes some time to accelerate and align with the sun, but it quickly converges, minimizing the tracking error. The smooth and synchronized curves reflect the accuracy and responsiveness of the control system, ensuring optimal solar energy capture by keeping the panel aligned with the sun's path.

4.2 Discussion

In this section, a highlight of the results obtained based on panel position, panel velocity, motor torque and tracker system is discussed.

4.2.1 Discussion on Results for the Panel Position

Figure 4.1 illustrates the positioning of the solar panel over time, showing a graph that depicts the panel's angular position as it adjusts to track the movement of the sun. The graph reveals a consistent and steady increase in the panel's angular position, which reflects the continuous effort of the system to align the panel with the sun's trajectory throughout the day. This smooth and gradual increase in the panel's angle signifies that the system is operating efficiently, with minimal fluctuations or errors. Such linear progress not only suggests a high level of accuracy in the tracking mechanism but also highlights the effectiveness of the control system in maintaining synchronization with the sun's changing position in the sky. By carefully adjusting the panel's angle to follow the sun's path, the system ensures optimal exposure to sunlight, thereby maximizing energy capture. The minimal deviation observed in the graph indicates that the control system is functioning as designed, successfully minimizing tracking errors and ensuring that the panel maintains precise alignment with the sun at all times. This behavior underscores the reliability and precision of the tracking system, demonstrating its capability to respond dynamically to environmental changes while maintaining an efficient performance throughout the solar tracking process.

4.2.2 Discussion on Results for the Panel Velocity

Figure 4.2 presents a graph that illustrates the dynamic behavior of the panel’s movement over time, showing an initial rapid increase in its angular velocity, followed by a gradual leveling off. This pattern highlights two distinct phases: an acceleration phase at the beginning, followed by a stabilization phase as the panel approaches its optimal speed. The rapid increase at the start represents the system's ability to quickly accelerate the panel to the necessary speed required for efficient tracking. During this phase, the control system ensures that the panel adjusts swiftly to align with the sun's position, minimizing the time it takes to reach the target angle. Once the required speed is achieved, the graph shows a smooth transition into a slower, more controlled pace, where the angular velocity gradually levels off. This gradual deceleration is critical for ensuring that the panel does not overshoot its target angle or experience any oscillations. By slowing down as it approaches the correct position, the system avoids any sudden movements that could lead to inaccuracies in alignment. The leveling off phase ensures that the panel stabilizes and maintains precise positioning, allowing for continuous tracking without the risk of overcorrecting. In summary, the behavior depicted in the graph demonstrates the efficiency and precision of the control system. It ensures that the panel accelerates quickly to the required speed and then decelerates smoothly to fine-tune its position, maintaining optimal tracking accuracy throughout the process without any unnecessary overshooting or fluctuations. This results in a stable and reliable tracking system, capable of ensuring optimal solar panel performance throughout its operation.

4.2.3 Discussion on Results for the Motor Torque

Figure 4.3 provides a graphical representation of the motor torque over time, illustrating the motor's performance during the panel's movement. Initially, the graph shows a sharp increase in torque which corresponds to the motor's effort to generate the necessary force to move the panel from its starting position. This sharp rise indicates that the motor is working at its full capacity to overcome inertia and initiate movement, ensuring that the panel reaches its desired angle in a timely manner. Once the panel begins moving, the torque gradually stabilizes. This phase represents the motor's ongoing effort to sustain the movement, maintaining the appropriate level of torque to keep the panel in motion at the required speed. The steady torque at this stage demonstrates the motor’s efficiency in sustaining the panel’s movement with minimal fluctuation, ensuring a smooth and precise tracking process. After the panel reaches its target position, the torque drops significantly, indicating that the motor no longer needs to exert force to maintain movement. The drop in torque signifies the successful completion of the movement and the stabilization of the panel at the correct angle. The reduction in torque also highlights the motor’s efficiency in minimizing energy consumption once the task is completed, avoiding unnecessary power expenditure while still ensuring precise alignment. In conclusion, the behavior depicted in the graph reflects the motor’s effectiveness in efficiently managing energy usage throughout the tracking process. The sharp rise in torque at the beginning ensures rapid movement while the stabilization phase maintains smooth tracking and the significant drop in torque after reaching the target position which emphasizes the motor’s ability to minimize energy use while maintaining high precision in the system. This efficiency is crucial for optimizing the solar panel’s performance while reducing operational costs.

4.2.4 Discussion on Results for the Tracker System

Figure 4.4 presents demonstrates the performance of the tracker system, a comparison between the solar panel’s position represented by the blue line and the sun’s position depicted by the yellow line. The graph clearly shows how closely the two curves aligns highlighting the high level of accuracy and responsiveness of the tracker system in adjusting the panel’s position to match the sun’s movement across the sky. Throughout the graph, the minimal deviation between the blue and yellow lines indicates that the tracking system is effectively following the sun’s path. The close alignment signifies that the panel is continuously adjusting its position with great precision, ensuring that it remains oriented toward the sun for maximum exposure. This precision is essential for maintaining optimal solar energy capture, as even small misalignments can result in a reduction in energy efficiency. The responsiveness of the system is also evident in the way the panel adjusts its position in real-time to follow the sun’s trajectory without significant lag or overshooting. The tracker’s ability to rapidly and accurately reposition the panel ensures that it stays aligned with the sun for the duration of the day regardless of the sun’s changing position in the sky. In summary, the graph in Figure 4.4 demonstrates the effectiveness of the solar tracker system in maintaining precise synchronization with the sun’s movement. The close correlation between the panel’s position and the sun’s position throughout the day highlights the system’s efficiency in capturing solar energy, ensuring that the panel is always optimally aligned for maximum energy generation. This behavior emphasizes the reliability of the tracking system in optimizing solar panel performance over time.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The simulation of the dual axis solar tracker system demonstrates the potential for significantly enhancing solar energy harvesting. The project carried out successfully modeled a system that dynamically adjusts to the sun's position in both azimuth and elevation using a PID controller, virtual sensors, and motor dynamics. The results of the simulation as illustrated by the graphs of panel position, velocity, and motor torque, show that the system can effectively track the sun's movement. The tracker is able to maintain optimal alignment with the sun thereby maximizing energy capture. This simulation-based approach allowed for the analysis and optimization of control algorithms and system responses providing valuable insights into the design of future solar energy systems. The successful tracking performance demonstrated by the close alignment of the panel's position with the sun's trajectory confirms that dual axis trackers are a viable solution for increasing solar energy output compared to fixed systems. Thus, this project contributes to the broader effort of developing sustainable and efficient renewable energy sources.

5.2 Recommendations

1. Physical Prototype Development: It is highly recommended to move from simulation to the development of a physical prototype. This will help in understanding real-world issues, validating simulation results, and testing the system's resilience and durability.
2. Advanced Environmental Modeling: Future work should include more advanced modeling of environmental factors, such as wind, rain, snow, and shading. This can be achieved by

incorporating more complex environmental data into the simulation to more realistically assess how the system will perform in various conditions.

3. Sensor Calibration and Integration: Investigate the integration of actual sensors in the physical prototype to evaluate the accuracy of sensor calibration and performance in real-time conditions.
4. Material Testing: Testing of different materials for the physical prototype to ensure structural integrity of the design and durability, for instance by considering lightweight and durable options like titanium alloys and aluminum composites.
5. Cost-Benefit Analysis: A thorough cost-benefit analysis should be conducted that takes into account initial investment costs, energy generation benefits, and maintenance expenses for a physical system.
6. Integration of IoT: Explore the integration of Internet of Things (IoT) devices for remote monitoring and control to improve operational efficiency.
7. Improved System Realism and Component Testing: Future work should incorporate real-world environmental conditions, such as wind loads, temperature fluctuations, and mechanical tolerances, into the simulation models. Additionally, physical testing of motors, sensors, and structural materials should be conducted to ensure accuracy, reliability, and durability in real-world applications.

By implementing these recommendations, the project can be advanced to a stage where the dual axis solar tracker can become a reliable and efficient solution for real-world renewable energy applications.

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