DEVELOPMENT AND IMPLEMENTATİON OF A DUAL-AXİS TRACKİNG SYSTEM FOR MAXİMİZED SOLAR ENERGY CAPTURE

Husameddin ALLITO[1]/ Sohyb Abdulkarim[2]

[1] Sham University, Electronic Engineering, husamda2@gmail.com, orcid.org/0000-0002-9506-5493

[2] Gaziantep University, Aerospace and Aeronautical Engineering, karim@gantep.edu.tr, orcid.org/0000-0002-3448-9129

ABSTRACT

In this article, we present a method to improve the efficiency of solar panels by based on an electro-mechanical tracking system using an altitude-azimuth tracker that moves along two axes, one to scan the azimuth angle (β) and the other to scan the tilt angle (α). This system is a development of fixed systems, working in two modes: Tracking mode and Fixed mode. We will provide a comparison between the tracking mode and the fixed mode. This system consists of the guidance base carrying the solar panel, two steering motors (‘push-pull’ type), a Control & Driving System for the steering motors, and a Data Acquisition System (DAQ) to store the solar panel data in a Multimedia Card (MMC). This system has been practically implemented and has achieved a 27.6%-29.5% increase in efficiency compared to fixed systems, hence the importance of this system.

Keywords: Solar Panels, Dual-Axis Tracking System, Maximum Power Point Tracking (MPPT), Data Acquisition System (DAQ), Solar Energy Efficiency

ÖZET

Bu makalede, bir yükseklik-azimut izleyici kullanarak iki eksen boyunca hareket eden elektro-mekanik bir takip sistemine dayalı olarak güneş panellerinin verimliliğini artırma yöntemini sunuyoruz. Bu sistem, sabit sistemlerin bir geliştirmesi olup iki modda çalışır: Takip modu ve Sabit mod. Takip modu ile sabit modu arasında bir karşılaştırma sunacağız. Bu sistem, güneş panelini taşıyan bir yönlendirme tabanı, iki yönlendirme motoru, yönlendirme motorları için bir Kontrol ve Sürüş Sistemi ve bir Multimedya Kartı'nda (MMC) güneş paneli verilerini depolamak için bir Veri Toplama Sistemi (DAQ) içermektedir. Bu sistem pratik olarak uygulanmış ve sabit sistemlere göre %27.6-%29.5 oranında bir verim artışı sağlamıştır, dolayısıyla bu sistemin önemi büyüktür.

Anahtar Kelimeler: güneş panelleri, izleyici, azimut açısı, kontrol ve sürüş sistemi, veri toplama sistemi (DAQ), verimlilik artışı, multimedya kartı (MMC).

Anahtar Kelimeler: Güneş Panelleri, Çift Eksenli Takip Sistemi, Maksimum Güç Noktası Takibi (MPPT), Veri Toplama Sistemi (DAQ), Güneş Enerjisi Verimliliği

1. INTRODUCTION

The challenge of enhancing solar energy yield has become increasingly urgent due to the relatively low efficiency of conventional solar cells and the high costs associated with solar energy systems. Currently, standard solar cells achieve efficiency levels between 14% and 22% depending on the type of silicon used in their construction (King, Boyson, & Kratochvil, 2002), making them less economical for widespread use. Research in photovoltaic systems can be categorized into two main areas.

The first area focuses on improving efficiency through advancements in solar cell technology, particularly by exploring alternative semiconductor materials (Green, 2009). These composite materials have demonstrated higher conversion efficiencies, but their high production costs have limited their commercial adoption, and research in this domain is ongoing.

The second research area is dedicated to developing advanced methods for maximizing the performance of solar panels. This involves ensuring that the maximum potential power of a solar panel is transferred to the load through innovative circuit designs aimed at tracking the Maximum Power Point (MPPT) (Chung, Ho, Hui, & Tse, 2006). Additionally, it includes optimizing the orientation of solar panels to maintain direct alignment with the sun, thus achieving the highest possible energy conversion efficiency. These systems, known as dynamic solar tracking systems, form the core focus of this study.

Importance and Objectives of the Research: The significance of this research lies in the growing necessity for renewable energy sources, particularly solar energy, as fossil fuel reserves continue to diminish. Solar energy is abundant, clean, and available throughout daylight hours, making it an essential alternative. As such, advancing research in this area is critical to harnessing its full potential. This study has several key objectives:

1. Evaluate the efficiency of the solar tracking system compared to traditional fixed systems.
2. Analyze changes in the panel's output resistance at the maximum power point positions.

3. Investigate the impact of temperature variations on the solar panel's capacity.
4. Develop a data acquisition system, along with a control and command system, to collect and store operational data in MMC memory.
5. Construct a fully integrated system capable of operating independently from a computer for extended periods.

This research aims to create a reliable and efficient solar energy system that maximizes energy yield while maintaining operational autonomy.

2. THEORETİCAL BACKGROUND

Solar energy, one of the most abundant renewable energy resources, has become a key focus for addressing global energy demands while reducing environmental impacts. Photovoltaic (PV) technology is widely used to convert sunlight into electrical energy; however, its efficiency remains constrained by several factors, including material properties, environmental conditions, and system design.

2.1 Photovoltaic System Basics

A photovoltaic system converts sunlight into electricity using semiconducting materials. The core of the system is the solar cell, which generates a voltage when exposed to light through the photovoltaic effect. Silicon, the most common material for solar cells, offers efficiencies ranging from 14% to 22%, depending on its type and manufacturing quality (Green, 2009). Advanced materials such as perovskites and tandem cells have demonstrated efficiencies exceeding 25%, though they are still in the experimental phase and face challenges in scalability and cost (King, Boyson, & Kratochvil, 2002).

The efficiency of solar cells is further affected by external factors such as shading, temperature variations, and suboptimal orientation. Thus, improving the performance of solar energy systems requires strategies that go beyond material enhancements.

2.2. Solar Tracking Systems

Solar tracking systems are an effective solution to maximize energy capture by maintaining optimal alignment of the solar panel with the sun's position throughout the day. These systems can be categorized into single-axis and dual-axis trackers. Single-axis trackers adjust the panel's angle along a single dimension (e.g., east-west), while dual-axis trackers allow movement along both the azimuth and altitude angles, ensuring maximum exposure to sunlight (Chung, Ho, Hui, & Tse, 2006). Dual-axis tracking systems are more efficient but come with increased complexity and cost.

Dynamic solar tracking systems employ control mechanisms such as stepper motors and feedback systems, which use sensors to monitor sunlight intensity and adjust the panel's position accordingly. These systems have been shown to significantly increase the energy output of PV panels, with gains of up to 30% compared to fixed systems (Shraif, 2002). However, the additional mechanical and electrical components introduce challenges in terms of maintenance and reliability.

2.3. Maximum Power Point Tracking (MPPT)

In addition to optimizing panel orientation, ensuring that the solar panel operates at its Maximum Power Point (MPP) is essential for efficiency. The MPP is the point at which the panel produces its maximum electrical power under specific environmental conditions. MPPT algorithms continuously adjust the load on the panel to ensure operation at this optimal point, even as sunlight intensity and temperature vary. Techniques such as Perturb and Observe (P&O), Incremental Conductance, and Artificial Neural Networks are commonly used for MPPT (King, Boyson, & Kratochvil, 2002). These approaches differ in terms of response time, complexity, and robustness to changing conditions.

2.4. Integration of Data Acquisition and Control Systems

Modern tracking systems integrate Data Acquisition (DAQ) and Control Systems to monitor performance and adjust operations in real time. DAQ systems collect data on panel orientation, sunlight intensity, temperature, and electrical output, which are processed to optimize the tracking system's performance. Multimedia Cards (MMCs) are often used to store these datasets for analysis and improvement (Shraif, 2002). Advanced microcontrollers and sensors further enhance the precision and efficiency of these systems, paving the way for smart solar tracking solutions.

3. METHODOLOGY

In this study, we followed the steps outlined below as follow: 1. Description of the Electro-Solar Tracking System., 2. Description of the Data Acquisition System., 3. Presentation of the Results., 4. Analysis of the Obtained Results., 5. Recommendations.

3.1. Description of the Electro-Solar Tracking System:

The electro-solar tracking system consists of the following components:

1. Mechanical Base: A mechanical movement base that supports the solar panel.
2. Solar Panel Steering Motor.
3. Control and Command Circuit.
4. Measured Parameters.

5. Operating Principle of the Tracking System.

Mechanical Movement Base: The mechanical base supports the solar panel and allows it to move in two directions: the horizontal direction (associated with the Azimuth Angle) and the vertical direction (associated with the Tilt Angle). This type of tracking system is known as the altitude-azimuth tracker [1].

Tilt Angle Control: The tilt angle is controlled by rotating the solar panel around a horizontal axis fixed at one end of the panel, allowing vertical movement (up and down) using a telescoping arm attached at the opposite end of the frame, as shown in Figure 1 and Figure 2.

Azimuth Angle Control: The azimuth angle is controlled by rotating the solar panel around a pivot point at the center of the panel, perpendicular to the previous axis. The rotation is automated through a "push-pull" motor that receives commands from the control circuit. Figure 1 and Figure 2, illustrates the mechanism for controlling the azimuth angle.

The tilt angle (α) is adjusted once every season, as the tilt of the sun relative to the Earth changes gradually during each season. The azimuth angle (β) is adjusted throughout the day from sunrise to sunset, due to the Earth's rotation and the sun's shifting position.

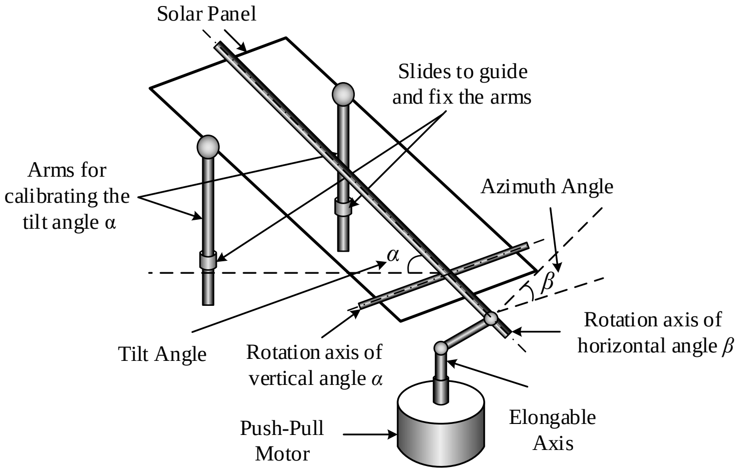

Figure 1: Mechanism for moving the panel according to the azimuth angle β and tilt α

Figure 2: Real-life implementation of the manufactured solar tracking system.

Steering Motor: This motor is used to adjust the solar panel's azimuth angle (β). It is a DC motor (push-pull type) consisting of a 3W DC motor, a gearbox that reduces the speed by approximately 16 times, and a push mechanism with a maximum length of 10 cm.

3.2- Control and Driving Circuit:

The control circuit consists of an AVR microcontroller (ATMega16) and an integrated analog-to-digital converter (ADC), which includes eight analog channels. The system also includes an MMC data storage, a real-time clock (RTC) for time and date tracking, and a driving circuit for the steering motor, along with a keyboard and LCD display for calibration and system settings. The solar panel is mounted on the mechanical base and equipped with measurement sensors. The circuit adapts the sensor signals for the ADC, as shown in Figure 3.

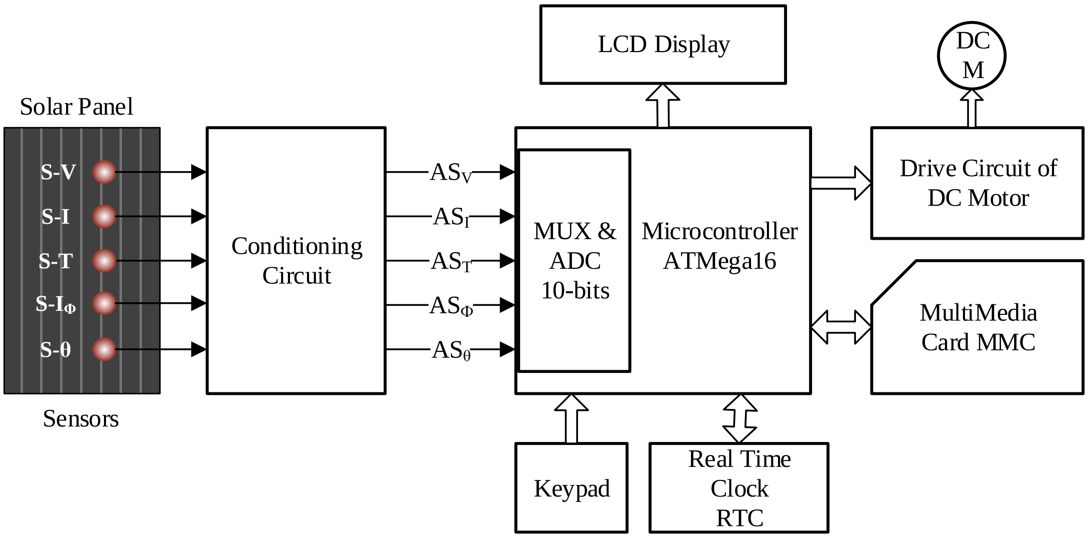

Figure 3: Control, Driving and Data Acquisition Circuit Diagram

Measured Parameters:

- Open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) of the solar panel.
- Maximum power output (P_{max}, calculated).
- Azimuth angle (β).
- Temperature and light intensity (T_p, I_{ph}).
- Time and date from the RTC.

3.3- Operating Principle of the Tracking System:

Before the tracking system is operational, the following initial settings are configured: Tracking Start time (T_{Start}), Tracking End time (T_{End}), Tracking interval ($T_{Interval}$), Power reading frequency (τ), Maximum stop error (err_{max}).

These settings are stored in the microcontroller's EEPROM. When the tracking system is activated, it begins tracking from T_{Start}, adjusting the panel's position at intervals of $T_{Interval}$ to search for the maximum power point. If the power increases, the panel continues in the same direction; if it decreases, the direction is reversed. The cycle continues until the maximum power point is achieved, and the panel's data is stored in the MMC.

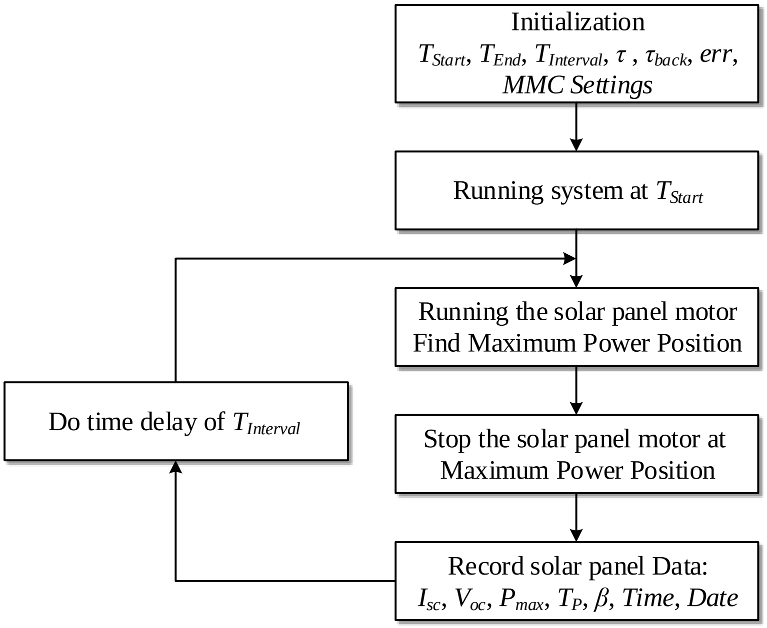

Figure 4: Block diagram of the tracking system

3.4- Data Acquisition System (DAQ):

The system consists of sensors, a sensor-conditioning circuit, an ADC integrated into the microcontroller, and a memory card (MMC) for storing data. The system measures the following parameters: time, date, solar panel voltage, current, temperature, rotation angle, and light intensity. The maximum power is calculated using the voltage and current measurements (Figure 5). The data is stored in indexed fields (data structures) in the MMC memory.

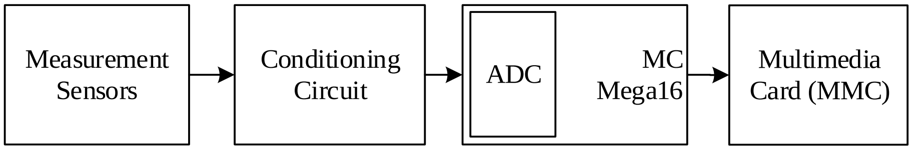

Figure 5: Data Acquisition System

3.5- Data Transfer:

At the end of the day, the stored data is transferred from the MMC to a computer for analysis. The data is transferred via a serial communication system and processed using a program developed in C#.NET, which allows for data analysis, chart plotting, and reporting (Figure 6).

The software enables the user to:

1. Read, write, and erase data from the MMC.
2. Analyze and sort the data for voltage, current, rotation angle, and temperature.
3. Store the data in binary (BIN) or text (TXT) files.
4. Plot curves for current, voltage, resistance, and power relative to time and temperature.
5. Save the curves as image files (bmp, emf, jpg) for further analysis.

The graphical user interface GUI of the software is shown in Figure 7, displaying the measurement data retrieved from the MMC memory.

4. EXPERİMENTAL RESULTS

The results obtained and verified practically are summarized through the curves shown in the following figures(8, 9,10). These figures display the maximum power, maximum voltage, maximum current, and output resistance of the solar panel over time for both the tracking system (curves in red) and the fixed system (curves in blue).

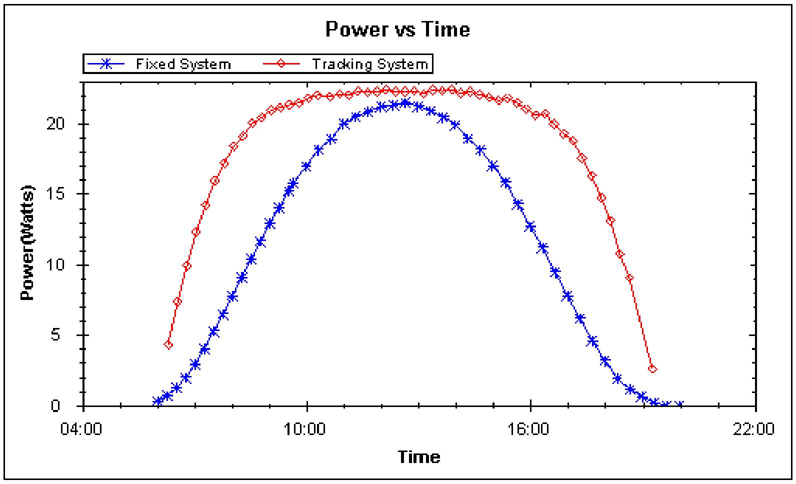

Figure 8: Maximum power curves for the fixed and tracking system

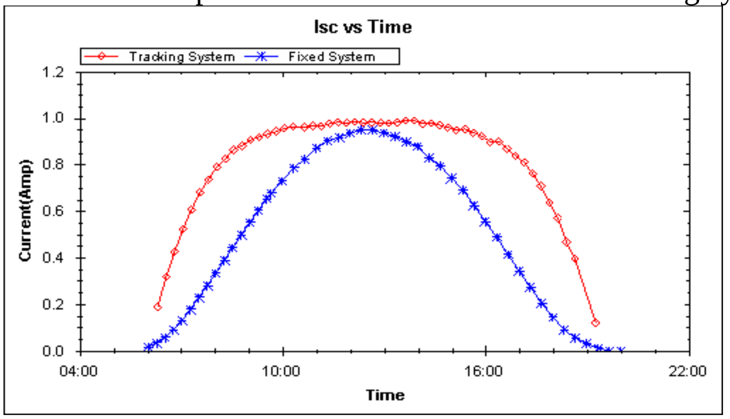

Figure 9: Maximum current curves I_{SC} for the fixed and tracking system

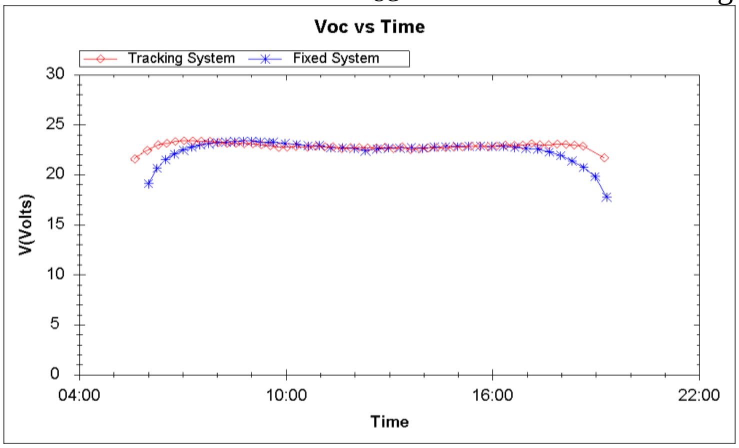

Figure 10: Maximum voltage curves V_{OC} for the fixed and tracking system

5. RESULTS DİSCUSSİON

From the previous figures (curves), we can conclude the following:

1. The tracking system achieves an increase in efficiency of approximately 29.5% compared to the fixed system, as shown in Figure (8).
2. The current, and consequently the power of the solar panel, is primarily dependent on the solar radiation intensity Φ, which is the main determinant of the solar panel's conversion efficiency, as shown in Figures (8, 9).
3. The power curves resemble the shape of the current curves, indicating that the current is the primary determinant of the maximum power of the solar panel, while the impact of voltage is minimal, as suggested by conclusion 2 and confirmed by Figures (8, 9, 10).
4. In the tracking system, the solar panel's power is at its maximum from approximately 8:30 AM to 5:00 PM, giving a period of maximum power of 8.5 hours. In contrast, in the fixed system, the solar panel's power is at its maximum from about 11:00 AM to 2:00 PM, with a period of maximum power of only 3 hours.

6. CONCLUSION

This research has demonstrated that the Tracking System achieves an approximately 30% increase in efficiency compared to the Fixed System, which is a significant improvement. It is noteworthy that the energy consumption required to move the solar panel, along with the system's cost and maintenance, does not exceed 5% of the efficiency gain. In other words, the net energy gain from the tracking system is about 25%, making this system a practical and advantageous solution.

The system can be further optimized by integrating different tracking techniques, combining mechanical tracking with Maximum Power Point Tracking (MPPT). This would create a comprehensive system capable of achieving maximum conversion efficiency through mechanical tracking while delivering the full power output of the solar panel to the load via MPPT.

The integrated system suggested in point 2 could also be connected to the main electrical grid using electronic circuits that meet grid connection requirements.

This system could be expanded to incorporate multiple energy sources, such as wind power or others, thereby creating a hybrid energy system, which would result in even higher efficiency.

Understanding the output resistance of the solar panel can be beneficial for determining the appropriate load to connect to the panel's output to harness its full power (Figure 11). Based on this, an electronic system could be developed to ensure the complete transfer of the solar panel's power to the load.

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