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Optimization and Performance Analysis of a Smart Dual-Axis Photovoltaic Tracking Model Using Predictive Control, Neural Networks, and PID-Based Dynamic Selection Framework

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ABSTRACT: The increasing global demand for high-efficiency photovoltaic (PV) systems has intensified research into advanced solar tracking mechanisms capable of maximizing energy harvesting under dynamic environmental conditions. This study presents a smart dual-axis photovoltaic tracking model integrating Model Predictive Control (MPC), Proportional–Integral–Derivative (PID) control, and Artificial Neural Networks (ANN) within a dynamic controller selection framework. The primary objective is to enhance energy capture efficiency by intelligently switching between control strategies based on real-time environmental and system states.

The proposed architecture leverages predictive optimization for trajectory estimation, neural adaptive learning for nonlinear environmental response modeling, and PID-based stability control for fast transient conditions. A comparative synthesis of existing hybrid tracking systems demonstrates that hybridization of control methodologies significantly improves robustness and adaptability in fluctuating irradiance environments (Al-Othman et al., 2023). Furthermore, sensor-driven and sensorless tracking strategies are analyzed to evaluate system responsiveness and energy efficiency trade-offs.

Simulation-based performance evaluation indicates that hybrid MPC–ANN–PID systems outperform conventional single-method controllers in terms of tracking accuracy, energy yield, and dynamic stability. The findings highlight the importance of adaptive control switching mechanisms in modern PV tracking systems. The study contributes a unified optimization framework for intelligent solar tracking systems suitable for large-scale renewable energy applications.

KEYWORDS: Dual-axis solar tracking, Model predictive control, Artificial neural networks, PID control, Hybrid control systems, Photovoltaic optimization, Energy harvesting efficiency, Intelligent control switching, Renewable energy systems.

1. Introduction

1.1 Background and Problem Statement

Solar energy has emerged as one of the most promising renewable energy sources due to its sustainability, scalability, and decreasing installation costs. However, the efficiency of photovoltaic systems is strongly dependent on the angle of incidence of solar radiation. Fixed PV panels suffer from significant energy losses due to suboptimal alignment with the sun's trajectory. Dual-axis solar tracking systems have therefore been widely adopted to maximize incident solar radiation throughout the day.

Despite their advantages, conventional tracking systems based on single control strategies such as PID or rule-based logic often struggle under highly dynamic environmental conditions, including rapid irradiance fluctuations, partial shading, and sensor noise. As a result, researchers have explored hybrid and intelligent control approaches to improve tracking reliability and energy efficiency.

Recent experimental findings demonstrate that hybrid control strategies significantly improve energy harvesting performance by combining complementary control methodologies (Al-Othman et al., 2023). In particular, integrating predictive and adaptive systems allows for improved responsiveness under non-stationary environmental conditions. However, most

existing approaches lack a unified framework capable of dynamically selecting optimal controllers based on system state evolution.

1.2 Research Relevance

The integration of MPC, ANN, and PID controllers within a unified dual-axis tracking framework is motivated by their complementary strengths. MPC provides foresight-based optimization, ANN enables nonlinear pattern learning, and PID ensures fast corrective stability. Previous studies have shown that predictive control strategies improve tracking precision in complex energy systems (Aslam et al., 2023), while ANN-based models enhance adaptability in nonlinear PV behavior (Ngo et al., 2020).

Additionally, PID controllers remain widely used due to their simplicity and robustness in real-time applications (Aung et al., 2020). However, their performance deteriorates in highly nonlinear or uncertain conditions, necessitating integration with intelligent systems.

1.3 Objectives of the Study

The primary objectives of this research are:

1. To design a hybrid dual-axis solar tracking model integrating MPC, ANN, and PID controllers.
2. To develop a dynamic controller selection framework based on real-time environmental inputs.
3. To evaluate the performance improvement in energy harvesting efficiency compared to conventional methods.
4. To analyze system robustness under variable irradiance and partial shading conditions.
5. To establish a scalable optimization framework for intelligent PV tracking systems.

1.4 Scope and Significance

This study focuses on the design, simulation, and analytical evaluation of a hybrid control architecture for dual-axis solar tracking systems. The scope includes controller integration, decision logic formulation, and performance benchmarking against existing approaches. The significance lies in providing a scalable and adaptive control framework capable of improving photovoltaic system efficiency in both industrial and residential applications.

2. Literature Review

2.1 Evolution of Solar Tracking Control Systems

Early solar tracking systems primarily relied on simple geometric calculations of solar position using astronomical models. MATLAB-based implementations demonstrated the feasibility of angle-based solar tracking, but lacked adaptability to environmental disturbances (Jha et al., 2020). Subsequent developments introduced sensor-based systems to improve real-time responsiveness.

Dousoky et al. (2012) highlighted energy efficiency improvements achieved through optimized radiation tracking mechanisms, emphasizing the importance of control precision. However, these early systems remained limited in handling nonlinear environmental variations.

2.2 PID-Based Solar Tracking Systems

PID controllers have been extensively used in solar tracking due to their simplicity and ease of implementation. Modified tuning approaches, such as Ziegler–Nichols adaptations, have been proposed to enhance system response (Aung et al., 2020). Nevertheless, PID-based systems face limitations in handling nonlinear dynamics and time-varying disturbances.

A survey of PID applications in dynamic systems confirms their widespread use in robotics and UAV control, but also emphasizes performance degradation under uncertainty (Lopez-Sanchez & Moreno-Valenzuela, 2023). This limitation has motivated hybrid integration with intelligent controllers.

2.3 Model Predictive Control in Solar Energy Systems

MPC has emerged as a powerful optimization-based control strategy capable of handling multivariable systems with constraints. In solar tracking applications, MPC enables predictive adjustment of panel orientation based on future irradiance estimation.

Ikhwan et al. (2018) demonstrated MPC-based dual-axis tracking using MATLAB simulations, showing improved accuracy compared to conventional methods. Similarly, clustering-based MPC approaches have been applied in solar thermal systems, enhancing operational efficiency under varying environmental conditions (Chanfreut et al., 2023).

2.4 Neural Network-Based Solar Tracking Approaches

Artificial Neural Networks (ANNs) have been widely adopted for modeling nonlinear relationships in photovoltaic systems. ANN-based solar trackers provide adaptive learning capabilities for predicting optimal sun positioning under uncertain conditions (Ngo et al., 2020).

Masoumi et al. (2023) further demonstrated that ANN models combined with online optimization improve tracking accuracy and energy output. Feedforward neural networks have also shown effectiveness in nonlinear mechanical and energy systems modeling

(Mouloodi et al., 2022).

2.5 Hybrid Control and Intelligent Switching Systems

Hybrid control systems combining multiple strategies have gained significant attention in recent years. A key advancement involves switching between PID and ANN controllers to improve precision and adaptability in dual-axis systems (Away et al., 2023). This approach enhances robustness under varying environmental conditions.

Research on optimal control strategy selection further confirms that hybrid systems outperform standalone controllers in photovoltaic tracking applications (Palomino-Resendiz et al., 2023). Additionally, predictive hybrid neural control frameworks demonstrate strong performance in dynamic systems with uncertainty (Meng & Fan, 2023).

2.6 Sensor-Based and Sensorless Tracking Innovations

Sensor-based systems, such as UV sensor-driven tracking mechanisms, have improved accuracy in real-world implementations (Jamroen et al., 2021). Conversely, sensorless approaches using particle filters provide cost-effective alternatives with reduced hardware dependency (Pirayawaraporn et al., 2023).

These developments indicate a trend toward intelligent, adaptive, and low-cost solar tracking systems.

2.7 Research Gap Identification

Despite significant advancements, several gaps remain:

1. Lack of unified hybrid frameworks combining MPC, ANN, and PID in a single architecture.
2. Limited development of dynamic controller switching mechanisms.
3. Insufficient real-time adaptability under rapidly changing environmental conditions.
4. Lack of comprehensive comparative performance analysis across hybrid control strategies.

Importantly, experimental evidence highlights the superiority of hybrid control approaches in maximizing energy harvesting efficiency in real-world PV systems (Al-Othman et al., 2023), reinforcing the need for integrated frameworks.

3. Methodology

3.1 System Architecture Overview

The proposed smart dual-axis photovoltaic tracking system is designed as a multi-layer intelligent control architecture integrating Model Predictive Control (MPC), Artificial Neural Networks (ANN), and Proportional–Integral–Derivative (PID) control within a dynamic switching framework. The architecture is structured into four functional layers: sensing and environmental acquisition, prediction and modeling, controller execution, and decision-based switching logic.

The sensing layer acquires solar irradiance, temperature, panel orientation, and angular deviation data. In advanced configurations, sensorless estimation techniques inspired by particle filtering methods can be incorporated to reduce hardware dependency while maintaining accuracy (Pirayawaraporn et al., 2023). The prediction layer uses ANN models to estimate optimal solar angles based on nonlinear environmental inputs, while MPC computes future trajectory optimization under constraints.

The control layer consists of PID for fast response correction, ANN-based adaptive adjustment, and MPC-based predictive optimization. The switching layer determines the most suitable controller in real time based on performance indices such as tracking error, irradiance variability, and system stability.

3.2 Mathematical Modeling of Dual-Axis Tracking System

The dual-axis solar tracker is modeled using spherical coordinate transformation of solar azimuth and elevation angles. The panel orientation vector is continuously adjusted to minimize the angular error between sun position and panel normal vector.

The solar position is computed using deterministic solar geometry models, similar to MATLAB-based tracking frameworks (Jha et al., 2020). The tracking error function is defined as:

$$E(t) = |\theta_s(t) - \theta_p(t)| + |\varphi_s(t) - \varphi_p(t)|$$

where θ represents elevation and φ represents azimuth angles.

The control objective is to minimize E(t) over time while maximizing irradiance incidence.

3.3 Model Predictive Control (MPC) Formulation

MPC is implemented as an optimization-based controller solving a finite horizon problem:

$$min\, J = \Sigma\, [E(t+k)\text{^}2 + \lambda u(k)\text{^}2]$$

subject to system dynamics and actuator constraints.

The predictive model estimates future solar position changes using irradiance trends and weather variability patterns. MPC is particularly effective in handling multivariable constraints and has been successfully applied in solar energy systems and parabolic trough

tracking applications (Chanfreut et al., 2023).

3.4 Artificial Neural Network (ANN) Model Design

The ANN component is designed as a feedforward multilayer perceptron with input features including irradiance, temperature, time index, and historical tracking error. The network outputs optimal angular correction values.

The ANN is trained using backpropagation with supervised datasets derived from optimal solar tracking trajectories. Similar ANN-based photovoltaic optimization frameworks have demonstrated high accuracy in nonlinear energy prediction tasks (Ngo et al., 2020; Mouloodi et al., 2022).

The ANN enhances system adaptability by learning nonlinear relationships between environmental conditions and optimal tracking angles.

3.5 PID Controller Design

The PID controller provides real-time corrective action based on instantaneous tracking error:

$$u(t) = KpE(t) + Ki\int E(t)dt + Kd(dE/dt)$$

Tuning is performed using modified Ziegler–Nichols rules adapted for solar tracking dynamics (Aung et al., 2020). PID ensures fast stabilization, particularly during sudden irradiance changes or mechanical disturbances.

3.6 Dynamic Controller Selection Framework

The core contribution of this research is the dynamic switching mechanism that selects the optimal controller among MPC, ANN, and PID.

A decision function D(t) is defined as:

$$D(t) = arg\,min\,\{w1E(t), w2\Delta I(t), w3S(t)\}$$

where ΔI represents irradiance fluctuation and S represents system stability index.

Switching logic:

- MPC is activated during highly variable weather conditions.
- ANN is selected for nonlinear prediction-dominant scenarios.
- PID is used for fast transient correction and steady-state refinement.

Hybrid switching approaches have shown improved precision in dual-axis systems compared to static controllers (Away et al., 2023).

3.7 Performance Evaluation Metrics

The system is evaluated using:

- Tracking Accuracy (TA)
- Energy Harvesting Efficiency (EHE)
- Mean Absolute Error (MAE)
- Response Time (RT)
- Stability Index (SI)

These metrics are used for comparative benchmarking against traditional solar tracking systems.

4. Results / Findings

Simulation results demonstrate that the proposed hybrid MPC–ANN–PID framework significantly improves dual-axis solar tracking performance under varying environmental conditions. The system consistently maintains lower angular tracking error compared to standalone PID and ANN-based systems.

The MPC module provides superior performance during periods of rapid irradiance fluctuation, particularly under partially cloudy conditions. ANN-based prediction improves steady-state tracking accuracy by effectively capturing nonlinear relationships between environmental parameters and optimal panel orientation. PID control contributes to rapid error correction during transient disturbances.

Quantitatively, the hybrid system achieves higher energy harvesting efficiency compared to conventional tracking systems reported in experimental studies (Al-Othman et al., 2023). The improvement is attributed to adaptive switching, which ensures that the most effective controller is active at any given time.

Tracking accuracy analysis indicates a reduction in mean angular error across both azimuth and elevation axes. The system also exhibits improved response time, particularly when transitioning between environmental states with sudden irradiance variation.

Stability analysis confirms that the dynamic switching framework does not introduce oscillatory behavior, provided that hysteresis thresholds are properly configured. This ensures smooth transitions between controllers without control conflict.

Overall, results confirm that hybridization of MPC, ANN, and PID yields a synergistic effect, enhancing both robustness and adaptability in real-world solar tracking conditions.

5. Discussion

The findings highlight the effectiveness of integrating predictive, adaptive, and classical control strategies within a unified solar tracking framework. The MPC component enhances foresight-based decision-making by anticipating future solar position changes, which is

critical in environments with rapid weather variability. ANN contributes significantly by modeling nonlinear dependencies between environmental variables and optimal tracking angles, improving long-term accuracy.

PID control remains essential for ensuring system stability and immediate corrective response. However, its standalone performance limitations are overcome when embedded within the hybrid structure. This aligns with prior studies indicating that PID controllers are most effective when combined with intelligent augmentation systems (Lopez-Sanchez & Moreno-Valenzuela, 2023).

The hybrid switching mechanism plays a crucial role in optimizing performance. Unlike static control systems, the proposed framework dynamically adapts to environmental conditions, ensuring optimal controller selection. This approach is consistent with hybrid control findings in solar tracking literature, where switching between PID and ANN has demonstrated improved precision (Away et al., 2023).

Comparative analysis with experimental hybrid control systems confirms that integrated architectures achieve higher energy efficiency in real-world PV applications (Al-Othman et al., 2023). The improvement is particularly significant under unstable irradiance conditions, where single-method controllers typically fail to maintain optimal alignment.

Despite these advantages, several limitations exist. The system complexity increases computational overhead due to simultaneous evaluation of multiple controllers. Additionally, ANN training requires high-quality datasets, which may not always be available in practical installations. Another limitation is the sensitivity of switching thresholds, which must be carefully tuned to avoid oscillatory behavior or controller conflicts.

From a practical perspective, the proposed system is highly suitable for smart grid integration and large-scale solar farms where maximizing energy yield is critical. The framework also has potential for extension into hybrid renewable energy systems and autonomous energy management platforms.

6. Conclusion

This study presented a smart dual-axis photovoltaic tracking model integrating Model Predictive Control, Artificial Neural Networks, and PID control within a dynamic selection framework. The proposed architecture successfully combines predictive optimization, nonlinear learning, and real-time correction to enhance solar tracking efficiency.

Results demonstrate that hybrid control significantly improves energy harvesting performance, tracking accuracy, and system stability compared to conventional methods. The dynamic switching mechanism ensures optimal controller utilization based on environmental conditions, making the system robust under variable irradiance and partial shading scenarios.

The research contributes a unified intelligent control framework for next-generation photovoltaic systems, supporting the transition toward more efficient renewable energy infrastructures. Future work may focus on hardware implementation, edge-computing optimization, and integration with IoT-based smart energy networks.

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