International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Modeling and Simulation of Model Predictive Control (MPC) and Proportional-Integral-Derivative (PID) for Enhanced Three-Axis Solar Tracking System

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Abstract:
Accurate solar tracking is essential for improving the utilization of solar radiation in photovoltaic systems. Conventional fixed-position solar panels cannot continuously maintain their orientation toward the Sun as its apparent position changes throughout the day. Solar tracking systems address this limitation by adjusting panel orientation according to the desired solar position. This study presents the modeling, simulation, and comparative analysis of proportional–integral–derivative (PID) control and model predictive control (MPC) for a three-axis solar tracking system. The proposed system consists of three independently controlled axes representing hour-angle, azimuth, and altitude movements. Each axis is driven by a DC motor represented by a third-order angular-position transfer function. The PID controller regulates position tracking using proportional, integral, and derivative actions, while MPC determines control inputs through receding-horizon optimization. Both control strategies are implemented in MATLAB/Simulink and evaluated under consistent simulation conditions. The proposed evaluation considers step-reference tracking, transient response, steady-state accuracy, and disturbance rejection. Performance indicators include rise time, settling time, percentage overshoot, tracking error, and integral absolute error. The study aims to identify the relative advantages and limitations of PID and MPC in three-axis solar tracking applications, with particular attention to tracking precision, control stability, and computational requirements.

Keywords: Three-axis solar tracking, proportional–integral–derivative control, model predictive control, DC servo motor, MATLAB/Simulink, tracking accuracy, disturbance rejection

1. Introduction

In recent years, the global transition toward renewable energy has accelerated demand for advanced, efficient solar energy harvesting technologies. Three-axis solar tracking systems have emerged as a promising approach to enhancing solar energy capture by continuously optimizing the orientation of photovoltaic panels in response to the Sun's position. By maintaining optimal alignment throughout the day and across seasonal variations, these systems can potentially increase energy yield by approximately 30–40% compared with conventional fixed-tilt solar panels. However, implementing three-axis solar tracking systems adds considerable complexity because of dynamic environmental conditions, including weather variability and changes in solar position. These challenges highlight the need for intelligent,

adaptive control strategies that ensure high-precision solar tracking, operational reliability, and efficient energy harvesting under real-world conditions.

Myanmar is a Southeast Asian country with very low access to electricity. Yangon, Myanmar's largest city, used to have 24-hour electricity but now experiences at least six hours without power each day. Because Myanmar relies heavily on generators, fuel shortages and high prices have been experienced. To solve this problem, Myanmar should use solar energy. This energy is safe because it does not produce greenhouse gases.

Myanmar has considerable potential for solar energy generation due to its abundant solar radiation throughout the year. Consequently, solar energy has become an increasingly important renewable energy source for meeting the country's growing electricity demand and supporting sustainable energy development. However, most solar photovoltaic (PV) panels installed in Myanmar are mounted in fixed positions, particularly on rooftops, which limits their ability to capture solar radiation efficiently as the Sun moves throughout the day. Solar tracking systems offer a practical solution by adjusting PV panel orientation to follow the Sun's movement, improving solar energy capture and overall power generation. Solar energy originates from the electromagnetic radiation emitted by the Sun and can be converted into electrical energy through photovoltaic technology. As a renewable energy source, solar power offers several advantages, including widespread availability, low operating costs, relatively low maintenance requirements, and versatility across applications. Furthermore, solar PV systems typically have an operational lifespan of approximately 25–30 years, making them a viable long-term option for sustainable electricity generation in Myanmar.

Conventional control methods, particularly proportional–integral–derivative (PID) controllers, are widely used in industrial applications due to their simplicity, cost-effectiveness, and ease of implementation. In solar tracking systems, PID controllers regulate solar panel position by minimizing the error between the desired and actual tracking positions. Although PID controllers are relatively simple to implement, their performance may be limited when dealing with nonlinear system dynamics. Furthermore, the fixed gains and linear structure of conventional PID controllers limit their ability to adapt to external disturbances and changes in operating conditions. As a result, tracking accuracy and control performance may deteriorate under changing environmental conditions, highlighting the need for more advanced, adaptive control strategies.

Model predictive control (MPC) offers a promising approach to overcoming the limitations of conventional proportional–integral–derivative (PID) controllers, particularly in systems with multiple control objectives and time-varying constraints. MPC operates on the principle of receding-horizon optimization, in which a mathematical model predicts future system behavior and determines optimal control actions over a specified prediction horizon. This predictive capability enables MPC to account for changes in operating conditions and external disturbances, making it suitable for dynamic applications such as three-axis solar tracking systems. When MPC is integrated with PID control, the controller parameters can be adjusted dynamically based on predicted system behavior and real-time feedback, potentially improving tracking accuracy, adaptability, and robustness. Furthermore, MPC can incorporate multiple control objectives, including minimizing tracking errors, reducing actuator energy consumption, and limiting excessive actuator movement to reduce mechanical wear. By considering these objectives simultaneously, MPC provides a systematic approach to balancing tracking performance, energy efficiency, and system reliability. This study evaluates and compares the performance of conventional PID and MPC-based control strategies using a simulated three-axis solar

tracking system. The performance of each controller is assessed in terms of tracking error, settling time, overshoot, and disturbance rejection to identify a suitable control strategy for improving the accuracy and reliability of solar tracking systems under varying operating conditions.

The main contribution of this research is a unified simulation and evaluation framework for comparing conventional proportional–integral–derivative (PID) and model predictive control (MPC) strategies under identical operating and environmental conditions. Previous studies have generally examined individual control methods or compared a limited number of controllers, making it difficult to evaluate their relative performance under consistent conditions. To address this limitation, the proposed framework incorporates all three control strategies within a common simulation environment using standardized system parameters, disturbance profiles, and performance indices. This approach enables systematic, consistent comparisons of transient and steady-state responses, including tracking accuracy, settling time, overshoot, and disturbance rejection. The study also considers computational time and hardware implementation requirements to assess the practical feasibility of each control strategy for real-time embedded applications. By combining comparative performance analysis with implementation considerations, this research aims to provide a comprehensive basis for selecting an effective control strategy for three-axis solar tracking systems.

2. Related Works

Recent studies have investigated metaheuristic optimization algorithms, including Genetic Algorithms (GA), and Differential Evolution (DE), to improve the tuning of PID controllers in solar tracking systems. These optimization techniques can improve controller performance by identifying suitable control parameters, reducing tracking errors, and enhancing transient response. However, these methods are often implemented through offline optimization, which may require considerable computational resources and many iterations to achieve satisfactory results. Consequently, applying them directly to real-time control can be challenging, particularly in embedded systems with limited processing capabilities. Conventional PID controllers offer a simple, computationally efficient solution for solar tracking applications, but their fixed control parameters may limit performance under changing operating conditions and external disturbances.

In comparison, model predictive control (MPC) uses a mathematical model to predict future system behavior and determine appropriate control actions while considering system constraints. This predictive capability allows MPC to address multiple control objectives and accommodate variations in operating conditions, although it generally requires greater computational effort than conventional PID control. In this framework, MPC inference adjusts selected control parameters based on system operating conditions. This combination is intended to improve tracking accuracy, disturbance rejection, and control adaptability while maintaining computational requirements suitable for real-time implementation. The performance of the proposed approach is evaluated through simulation to determine its effectiveness and practical feasibility for three-axis solar tracking applications.

Proportional–integral–derivative (PID) controllers are widely used in solar tracking systems because of their simple structure, ease of implementation, and straightforward tuning. They have been widely applied in industrial automation and renewable energy systems, including single-axis, dual-axis, and three-axis solar tracking. PID controllers regulate solar panel position by minimizing the error between the desired and actual tracking positions. Although these controllers perform well under relatively stable operating conditions, their fixed gains and linear structure may limit their effectiveness in systems with

nonlinear dynamics and time-varying characteristics. In particular, external disturbances, such as wind gusts, changes in mechanical loading, and variations in system parameters, can affect tracking accuracy and overall control performance.

In contrast, model predictive control (MPC) is an advanced control strategy based on receding-horizon optimization. MPC uses a mathematical model of the system to predict future behavior and determine optimal control actions over a specified prediction horizon while considering operational constraints. In solar tracking applications, MPC can improve tracking accuracy, control efficiency, and disturbance rejection, particularly in multivariable systems with coupled dynamics and actuator limitations. Its ability to incorporate system constraints and multiple control objectives makes it well suited to more complex tracking applications.

However, MPC generally requires more computational resources than conventional PID control because it must solve an optimization problem at each control interval. Furthermore, its performance depends on the accuracy of the system model, and uncertainties in model parameters, measurement noise, and unmodeled disturbances may reduce prediction accuracy and control effectiveness.

Therefore, selecting an appropriate control strategy requires consideration of tracking performance, computational complexity, and practical implementation requirements. The primary objective is to develop and evaluate a MATLAB/Simulink model for comparing PID and MPC in a three-axis solar tracking system. The specific objectives are to:

- Develop a mathematical model of the DC servo motor used in the hour-angle, azimuth, and altitude tracking mechanisms.
- Design conventional PID and MPC controllers for angular-position regulation.
- Implement both controllers in MATLAB/Simulink using consistent motor parameters and operating conditions.
- Evaluate tracking error, rise time, settling time, overshoot, steady-state accuracy, and disturbance rejection.
- Compare controller performance and computational requirements to assess their suitability for three-axis solar tracking applications.

3. Methodology for the System

Solar energy is harvested by converting sunlight into electrical and thermal energy. Solar panels are usually made of semiconductor materials like silicon. When exposed to sunlight, photons release electrons, producing electricity. Photovoltaic (PV) cells produce Direct Current (DC) power, which is collected by the wiring within the solar panels. An inverter converts this to AC power.

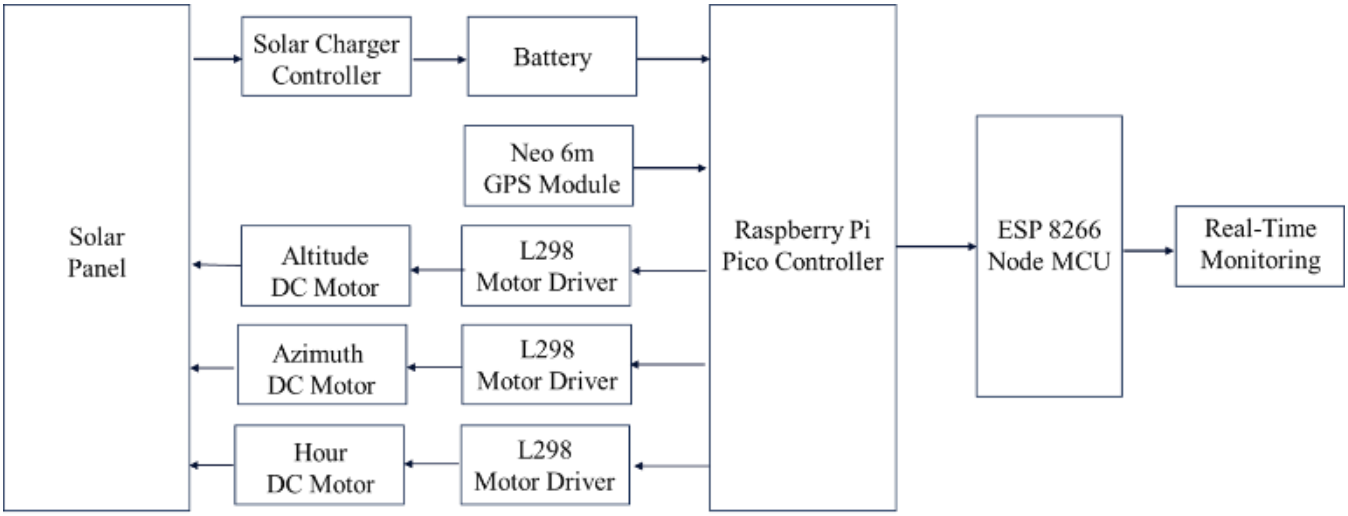


Figure.1. Block Diagram of the System

The block diagram illustrated in Figure 1, represents the entire design and working principle of the proposed solar tracking system. In the proposed system, the solar panel receives sunlight and uses a converter to transform solar energy into electrical energy. The converter converts solar energy into usable electric power, which is then regulated by the voltage regulator and finally stored in a rechargeable battery. The solar inverter converts the DC output power from the PV solar panel to AC so it can power electrical devices or connect to the grid. The main components in the block diagram include the photovoltaic solar panel, rechargeable battery, battery charger controller, microcontroller, signal conditioner circuits, motors and motor driver circuits, and GPS module. The solar panel is the main power source, while the battery stores power.

The sun's azimuth and altitude angles are calculated based on time, date, and geographical location. The microcontroller analyzes this information to generate the control signals needed to operate the motors through the motor driver circuit. The motors will make changes to the position of the panels along the three-axis of rotation to make sure they are perfectly positioned in relation to the position of the sun. When the sun's position indicates that the solar panels are optimally positioned, the system remains in that position. The sun's position changes with the Earth's rotation and revolution, and the microcontroller continuously updates the tracking angles. This system comprises three components: solar radiation calculation; motion planning and three-axis solar tracking system design; and data transmission and system monitoring.

The solar tracker will be designed using principles to accurately describe the Sun-Earth geometric relationship. The parameter should be calculated and measured latitude, longitude, angle of incidence, light intensity, tilt angle (the angle between the positive - Z direction of the reference frame and the positive - Z direction of the body frame: the number of degrees from the horizontal plane), hour angle (the angular distance, measured west ward along the celestial equator, with 360 degree corresponding to 24 hours), solar azimuth angle (the compass direction, measured clockwise from north of the sun's position in the sky), solar altitude angle (the angular height of the sun above the horizon, measured from an observer's perspective: local horizon), declination angle (the angular distance of a celestial object like the sun north or south of the celestial equator, measured along the hour circle passing through the object) are direction of solar tracking system.

4. Control Method

This section describes the design and implementation of the control strategies considered in this study, namely proportional–integral–derivative (PID) control and model predictive control (MPC). The performance of each controller is evaluated in terms of tracking accuracy, stability, and disturbance rejection to determine its effectiveness in achieving precise three-axis solar tracking under nonlinear and dynamically varying operating conditions.

The PID controller is a staple in industrial control applications due to its simplicity and general effectiveness.

$$u(t)=K_p(t)+K_i\int e(t)dt+K_d\frac{de(t)}{dt} \quad (1)$$

In the proposed three-axis solar tracking system, proportional–integral–derivative (PID) controllers independently regulate the hour-angle, azimuth, and altitude motors. Although PID controllers are relatively simple to tune and implement, their performance may degrade under nonlinear system dynamics and varying environmental conditions, potentially causing excessive overshoot, prolonged settling times, and reduced tracking accuracy. These limitations mainly stem from the linear control structure and fixed proportional, integral, and derivative gains (Kp, Ki, and Kd) of conventional PID controllers. As a result, their ability to respond effectively to significant changes in system dynamics and unexpected external disturbances, such as sudden variations in wind loading, may be limited. Therefore, more advanced control strategies may be required to improve tracking precision, stability, and disturbance rejection under varying operating conditions.

Model Predictive Control (MPC) has recently become a significant control method in a wide variety of applications. In this control strategy, the controller calculates optimal control moves by minimizing a cost function related to the system dynamics while accounting for constraints. At every control move, the MPC controller measures or estimates the current state of the process. Then, using the internal plant model, it calculates an open-loop optimal control sequence over the prediction horizon to minimize the cost function. In accordance with the receding horizon concept, only the first control move in this sequence is applied to the plant, and the remaining moves are not implemented.

Using a predictive model of the plant allows prediction of future system output over a prediction horizon (N) at every time step t. The predicted output is a function of the historical input/output data up to time t and the future control actions (u) that are determined by the system. The optimal control action vector u is found through minimization of the objective (cost) function. This objective function usually includes a penalty for the difference between the model-predicted output and the desired reference trajectory. The internal model estimates the system's future behavior based on historical and current state-variable values. Today, MPC theory development is driven by applications, with manufacturing technology making an important contribution, often with challenging requirements for reliability, constraints, and time. The work should inspire non-control experts to join the effort and develop new use cases, pushing the boundaries of technological limitations.

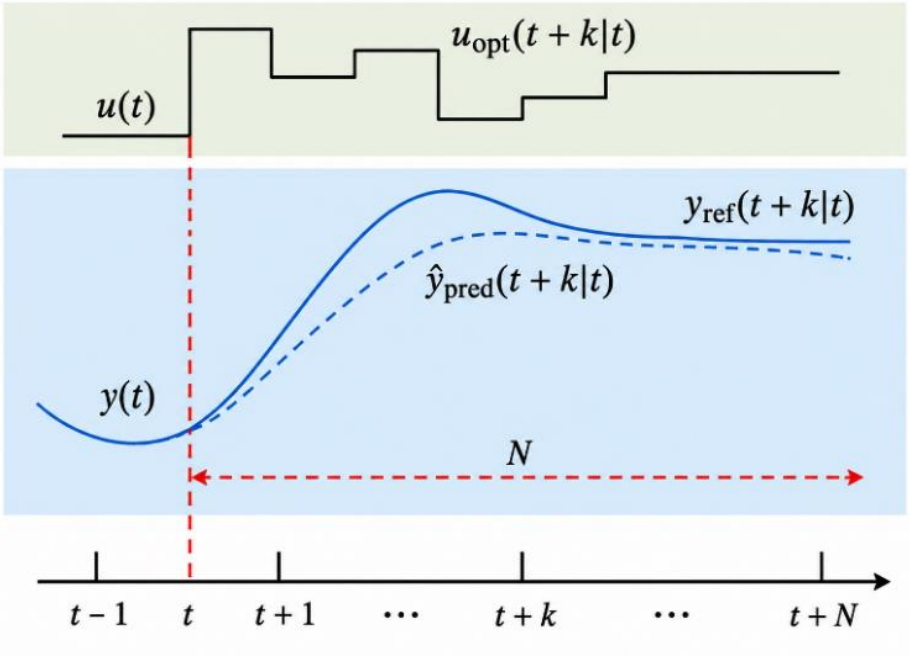


Figure.2. MPC Control System Operation

$$\mathbf{x}(\mathbf{k}+\mathbf{1}) = \mathbf{A_d}\,\mathbf{x}(\mathbf{k}) + \mathbf{B_d}\,\mathbf{u}(\mathbf{k})$$

$$\mathbf{y}(\mathbf{k}+\mathbf{1}) = \mathbf{C}\,\mathbf{x}(\mathbf{k}) \qquad (2)$$

$\boldsymbol{A_d} \in \mathbb{R}^{\boldsymbol{n\,x\,n}}$ and $\boldsymbol{B_d} \in \mathbb{R}^{\boldsymbol{n}}$ are discrete-time state-space matrices using the exponential hold discretization method as follows:

$$parent\,A_d(t) = e^{AT}$$

$$B_d(t) = \left(\int_0^T e^{A\lambda}\,d\lambda\right) B \qquad (3)$$

$$e^{AT} = I + AT + \frac{1}{2!}A^2T^2 + \ldots.. + \frac{1}{n!}A^nT^n + \ldots..$$

The MPC problem can be solved as an optimization problem by minimizing the objective function J and the constraints x, y, and u:

$$\text{Min U(k) J (k)}$$

$$x(k+1) = A_d x(k) + B_d u(k)$$

$$y(k+1) = C_d x(k) + D_d u(k)$$

$$u_{min} \le u(k+j-1/k) \le u_{max}$$

$$x_{min} \le x(k+i/k) \le x_{max}$$

$$\text{i} = 1, \ldots., \text{P}$$

$$\text{j} = 1, \ldots\ldots \text{M} \qquad (4)$$

Positive values of the declination angle indicate that the Northern Hemisphere is facing the Sun (summer). On the other hand, negative values indicate that the Southern Hemisphere is facing towards the Sun (winter).

$$\delta = 23.45^{\circ}\sin\left[\frac{2\pi}{365}(n+284)\right] \quad (5)$$

where n = the day number over the year.

The latitude angle formed between a particular place on Earth and the equator. It will be positive in the Northern Hemisphere. It will be negative in the Southern Hemisphere. Myanmar's latitude varies from 9°32'N to 28°31'N. Longitude is the angle between a particular place on Earth and the Greenwich line. Longitudes west of the Greenwich line have negative values, whereas those easts of the Greenwich line are positive. Myanmar's longitude lies between 92°10'E and 101°11'E. Hour angle replaces temporal hours with spatial angles. It is the difference between a particular point's position at a given time and its position at solar noon.

$$h = 15(ST - 12) \quad (6)$$

where ST denotes the solar time in 24-hour format, starting from 0 to 12 before solar noon and 13 to 24 in the afternoon.

It is difficult to apply solar time to the official time in regions with different longitudes within one country. There are 24 standard time zones on the planet Earth. One time zone (TZ) has a single time that is approximately the same across the whole TZ and valid for the whole country. The time applied in a certain TZ is named the local time (LT). It is necessary to take the difference between the solar and local time into account in solar energy calculations;

$$EQT(EoT) = 9.87\sin(2\beta) - 7.53\cos\beta - 1.5\sin\beta \quad (7)$$

where; β = the displacement of time from standard time

$$\beta = \frac{(n-1)\times 360}{365} \quad (8)$$

$$\text{The Solar Time}, ST = LT + \frac{L_{ong} - TZ}{15} + \frac{EoT}{60} \quad (9)$$

The solar noon is the midpoint in time between sunrise and sunset.

$$\cos(h_s) = -\tan(L)\tan(\delta) \quad (10)$$

where L = latitude, h = hour angle and □ = declination angle

The total time between sunrise and sunset is called daytime length.

$$DL = \left(\frac{2}{15}\right)\cos^{-1}[-\tan(L)\tan(\delta)] \quad (11)$$

Solar radiation intensity refers to the amount of solar power (energy per unit time) received per unit area on the Earth's surface. It is usually expressed in watts per square meter (W/m²).

$$I_o = I_{sc}\left[1 + 0.033\cos\left(\frac{2\pi n}{365}\right)\right] \quad (12)$$

$$I_H = I_o\sin(\alpha) \quad (13)$$

$$H_o = \left(\frac{24\times 3600}{\pi}\right) I_o\left[\frac{\pi}{180}h_s\sin(L)\sin(\delta) + \cos(L)\cos(\delta)\sin(h_s)\right] \quad (14)$$

where I_{sc} = solar constant (1360.8 ± 3.5%), I_o = surface perpendicular to solar beam and I_H = surface parallel to ground.

5. Simulation and Results of Three-Axis Solar Tracking System

Accurate solar tracking in three-axis systems depends largely on the precision and response characteristics of the actuator control system. A mathematical model describing the dynamic behavior of the DC motor and associated mechanical components is essential for effective controller design, simulation, and performance evaluation. This section presents the derivation of the DC motor transfer function, the mathematical modeling of the azimuth and altitude tracking angles, and the overall system architecture of the proposed three-axis solar tracking system.

For the comparative evaluation, both control strategies use the same DC motor model, simulation duration, initial conditions, and reference inputs. A step input is applied to investigate transient response characteristics, including rise time, settling time, overshoot, and steady-state error. Additional reference trajectories and external disturbances may be introduced to evaluate tracking performance under varying operating conditions. The motor shaft position is measured and fed back to the controller to maintain closed-loop operation.

The simulation results are recorded and analyzed using MATLAB tools. Controller performance is assessed through angular-position responses and quantitative error indices. This common simulation framework enables a systematic comparison of PID and MPC control strategies while minimizing differences caused by simulation settings or plant parameters.

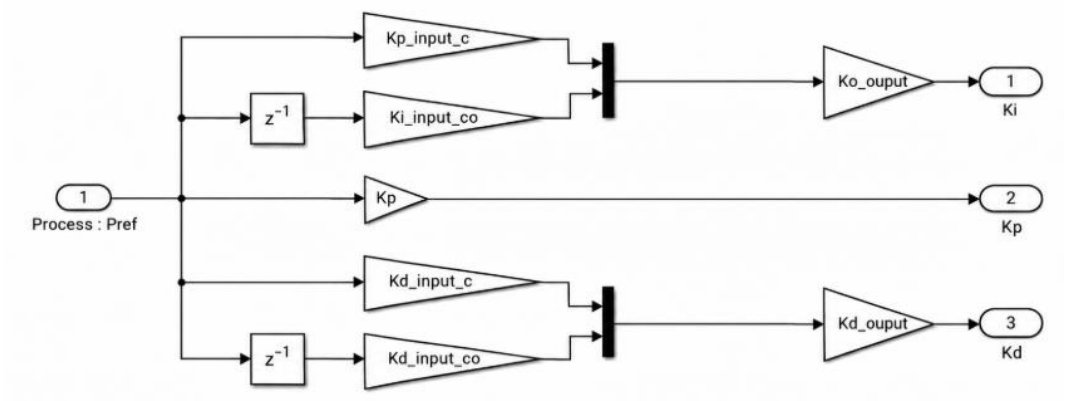


Figure.3. MATLAB Simulink Block Diagram of PID Controller

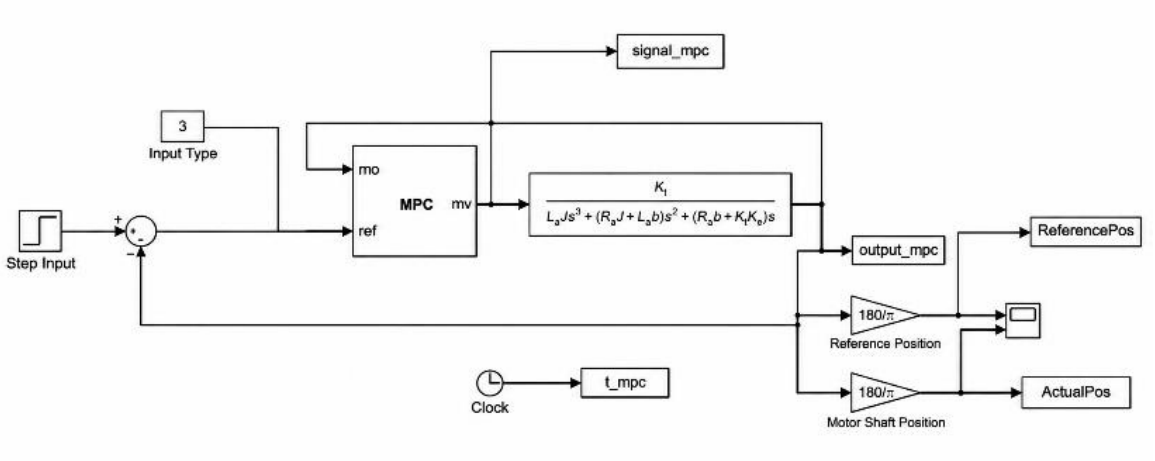


Figure.4. MATLAB Simulink Block Diagram of MPC Controller

6. Performance Evaluation and Comparative

The performance of PID and MPC controllers is compared using the angular-position responses of the hour-angle, azimuth, and altitude motors. The evaluation focuses on transient response, steady-state tracking accuracy, disturbance rejection, and computational requirements. Conventional PID control is expected to provide a relatively simple, computationally efficient solution, whereas MPC offers the additional capability to predict future system behavior and incorporate operating constraints into its control calculations. However, the relative performance of the two strategies depends on the selected controller parameters, motor dynamics, and simulation conditions.

The comparison uses identical reference inputs and plant models to ensure consistency. Step-response analysis evaluates rise time, settling time, and overshoot, while steady-state error and integral absolute error quantify tracking accuracy. Disturbance-rejection tests examine each controller's ability to maintain the desired angular position under changing operating conditions. Computational performance is also evaluated to determine whether the additional optimization requirements of MPC are justified by improvements in tracking behavior. The resulting analysis provides a basis for assessing each controller's suitability for three-axis solar tracking applications.

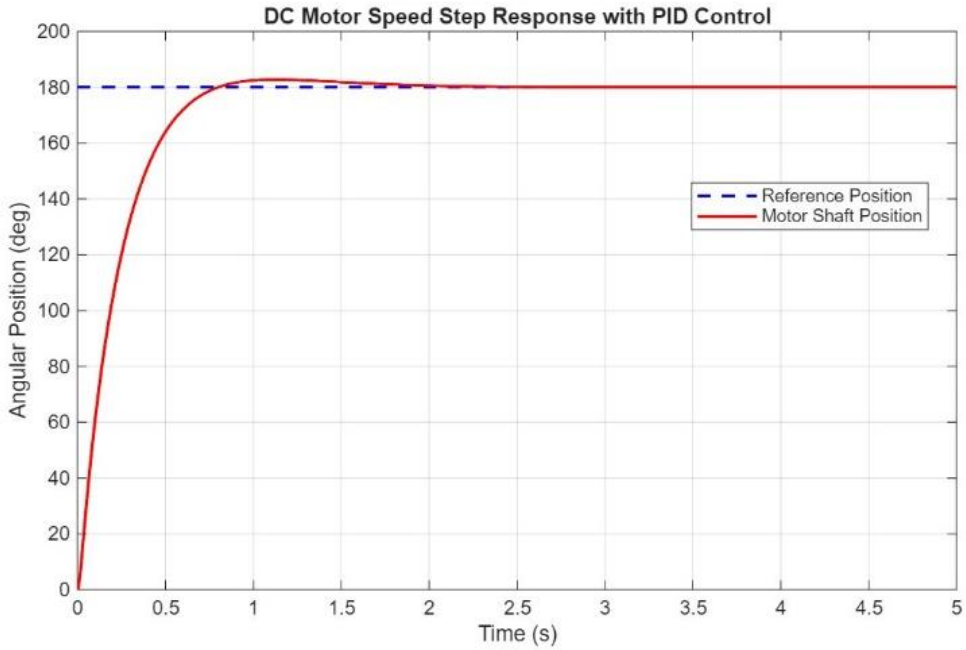


Figure.5. Step Response of DC Motor PID Controller

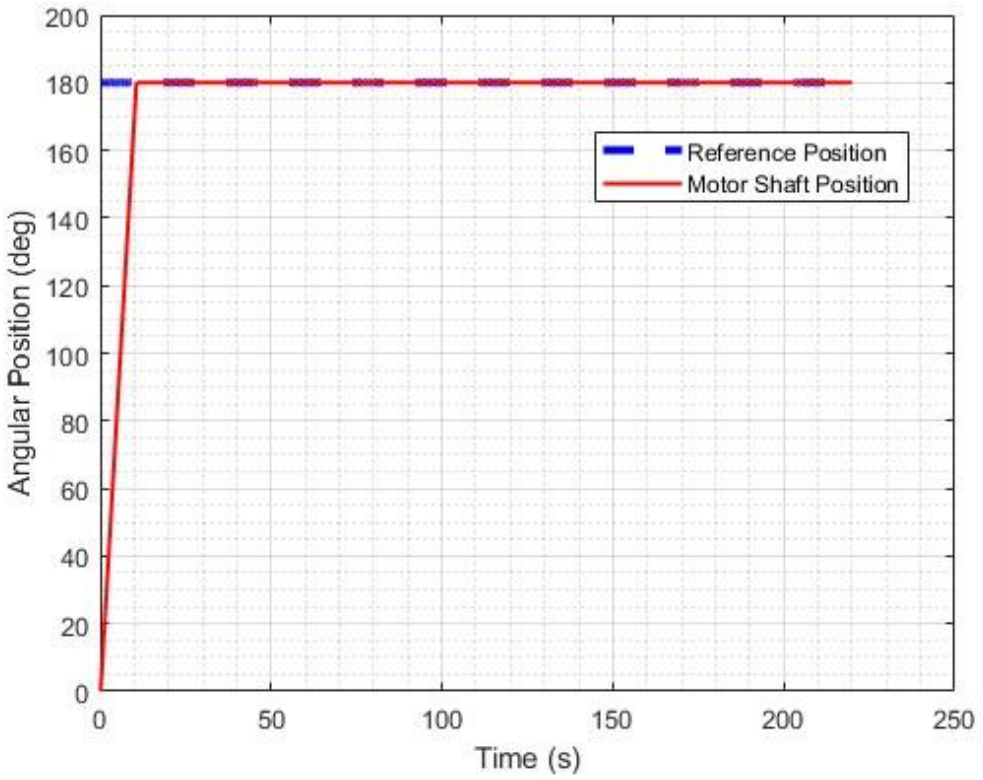


Figure.6. Step Response of DC Motor MPC Controller

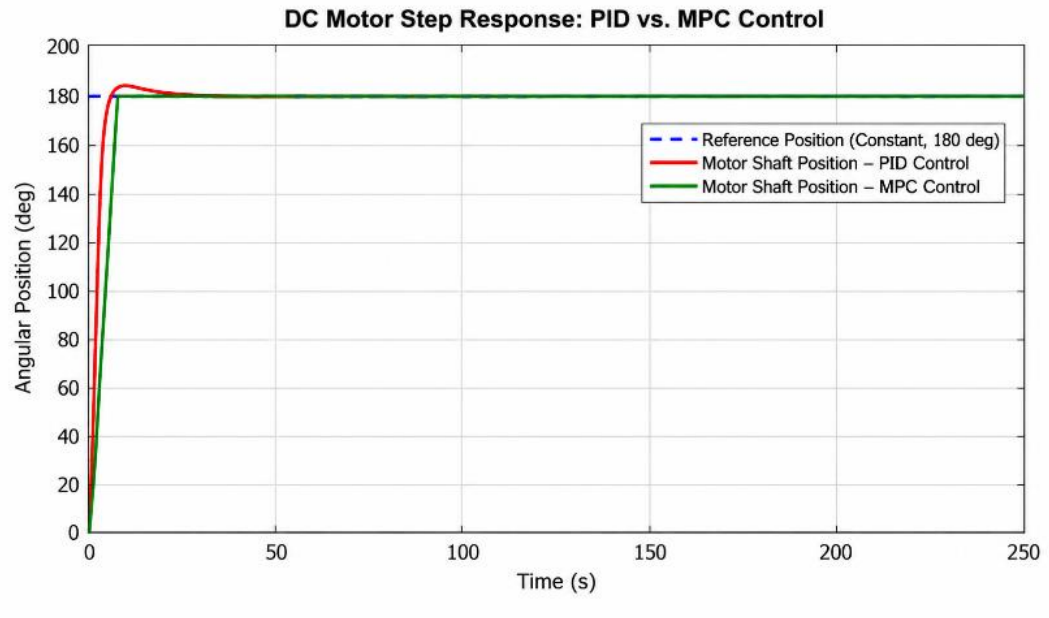


Figure.7. Performance of DC Motor Step Response

Figure 7. illustrates the step-response characteristics of the DC motor angular position under proportional–integral–derivative (PID) and model predictive control (MPC), with a constant reference position of 180°. Both controllers successfully track the desired position and achieve negligible steady-

state error. However, their transient responses differ, particularly in rise time, maximum overshoot, and settling time.

The PID controller exhibits a rapid initial response, reaching approximately 90% of the reference position within 0.5 s. The motor shaft position subsequently exceeds the reference value, reaching a maximum of approximately 183°, corresponding to an overshoot of about 1.7%. Following this peak, the response gradually decreases toward the desired position and settles at approximately 2.5 s. This behavior indicates that the PID controller provides a relatively fast response, although it shows a small overshoot and a longer settling period.

In comparison, the MPC controller produces a response with negligible overshoot and reaches the reference position without noticeable oscillations. The response appears to settle rapidly and remains stable at approximately 180° throughout the remaining simulation period. This behavior suggests that MPC provides smoother transient performance and better overshoot suppression under the illustrated operating conditions. However, the displayed graph's extended time scale prevents reliable determination of the MPC response's precise rise time and settling time.

Overall, both controllers demonstrate satisfactory steady-state tracking performance. The PID controller provides a rapid initial response but exhibits a small overshoot and a relatively longer settling time. In contrast, MPC demonstrates a smoother response with minimal overshoot. These observations suggest that MPC may offer advantages in angular-position regulation, particularly when limiting overshoot is an important control objective. Nevertheless, a quantitative comparison using the original MATLAB/Simulink simulation data is required to accurately establish the relative performance of the two controllers.

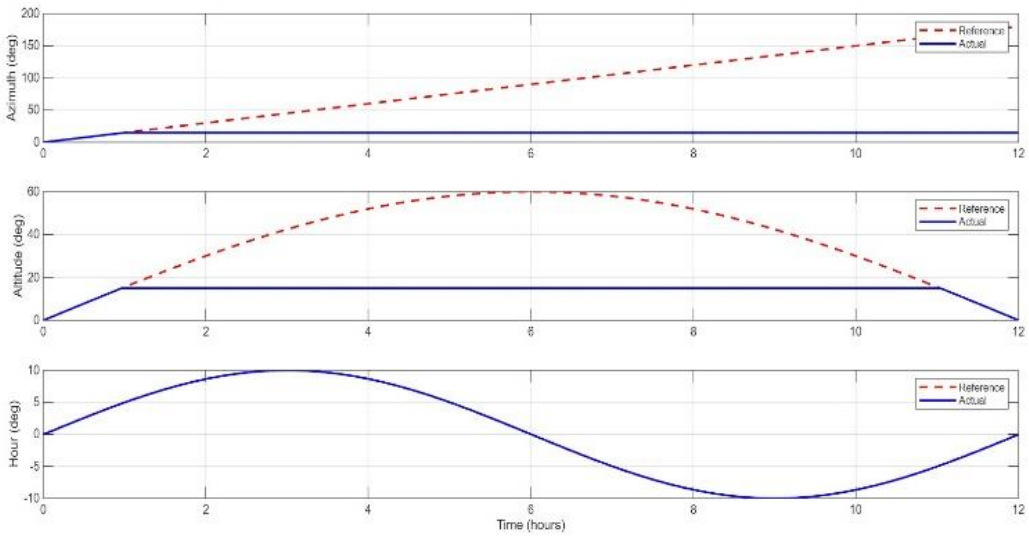


Figure.8. PID Control Performance of Three-Axis Solar Tracking System

Figure 8 shows the reference and actual angular positions of the three-axis solar tracking system, comprising the azimuth, altitude, and hour-angle axes, over a 12-hour simulation period. The responses show differences in tracking performance across the three axes under the applied reference trajectories.

The azimuth-angle response shows a gradual increase in the reference position from approximately 0° to 180° throughout the simulation period. However, the actual position initially increases, then remains nearly constant at approximately 20°. This indicates that the azimuth actuator cannot follow the

continuously increasing reference trajectory, resulting in a growing tracking error over time. The deviation suggests limitations in the control response, which may be associated with actuator constraints, controller tuning, or the implementation of the tracking mechanism.

In contrast, the altitude-angle response demonstrates close agreement between the reference and actual positions. The altitude reference follows a smooth trajectory, increasing from approximately 0° at the beginning of the simulation to a maximum of about 55° at 6 hours before gradually decreasing toward 0° at 12 hours. The actual altitude position closely follows this reference throughout the simulation period, with no significant deviation or oscillation visible. This indicates satisfactory tracking accuracy and stable control performance for the altitude axis under the simulated operating conditions.

Similarly, the hour-angle response exhibits close agreement between the desired and actual angular positions. The reference follows a sinusoidal-like trajectory, increasing from approximately 0° to 10° during the first 3 hours, decreasing to approximately −10° at 9 hours, and returning toward 0° at the end of the simulation. The actual response closely matches the reference trajectory, indicating that the controller can follow changes in the hour-angle command with minimal visible tracking error.

Overall, the simulation results indicate that the altitude and hour-angle control systems achieve satisfactory reference tracking, whereas the azimuth control system exhibits a considerable deviation from its desired position. Although the altitude and hour-angle responses demonstrate stable tracking behavior, the increasing azimuth error indicates that further investigation and controller adjustment are necessary. Improving the azimuth control response is essential for achieving consistent tracking performance across all three axes of the proposed solar tracking system.

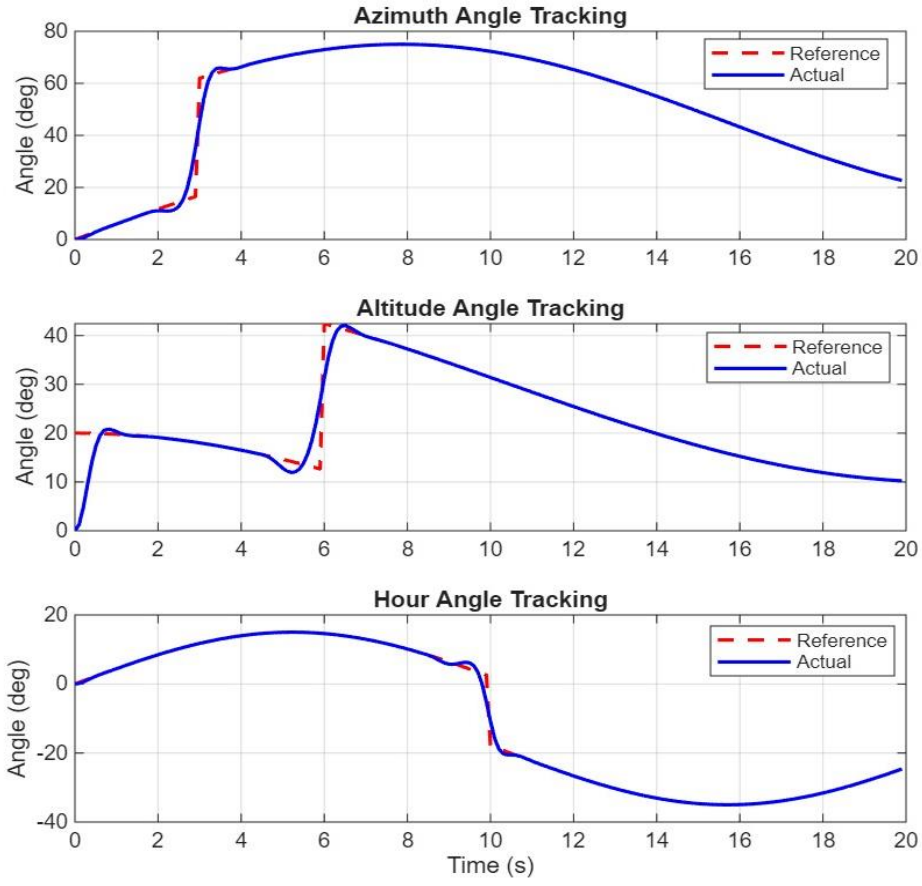


Figure.9. MPC Control Performance of Three-Axis Solar Tracking System

Figure 9 presents the MPC control angular-position responses of the three-axis solar tracking system, comprising the azimuth, altitude, and hour-angle axes, over a 20-second simulation period. The reference and actual angular positions are compared to evaluate the tracking accuracy and dynamic response of each axis. Overall, the results show that the actual positions closely follow the reference trajectories, although small deviations occur during rapid changes in the reference signals.

The azimuth-angle response shows a gradual increase from 0° during the initial tracking period, followed by a rapid change in the reference position to approximately 63° at around 3 s. The actual position follows this transition with a slight delay and a small overshoot before approaching the reference trajectory. The azimuth angle subsequently increases to a maximum of approximately 75° at 8 s and gradually decreases to about 22° at the end of the simulation. Throughout this period, the actual position remains close to the reference, indicating satisfactory tracking accuracy. The small transient deviation observed during the rapid reference change suggests that the controller can respond to sudden changes in the desired position while maintaining a relatively smooth output.

The altitude-angle response exhibits several changes during the simulation period. Initially, the angle increases rapidly from 0° to approximately 20°, followed by a gradual decrease to around 15° at 5 s. A significant change in the reference position occurs at approximately 6 s, when the desired altitude increases to about 40°. The actual response follows this sudden increase with a small overshoot, reaching approximately 41° before returning toward the reference trajectory. After this transient period, the altitude angle gradually decreases to approximately 10° at 20 s. The close agreement between the reference and actual positions indicates that the controller provides satisfactory tracking performance, although a short transient deviation is observed during the abrupt change in the reference signal.

The hour-angle response follows a smooth trajectory during the initial simulation period, increasing from 0° to approximately 15° at around 5 s before gradually decreasing. At approximately 10 s, the reference signal undergoes a rapid decrease to about −20°. The actual hour-angle position follows this transition with a slight delay and limited deviation. Following this change, the angle continues to decrease, reaching approximately −35° at 16 s before increasing to about −25° at the end of the simulation. The actual response remains closely aligned with the reference trajectory, demonstrating satisfactory tracking accuracy throughout most of the simulation period.

Therefore, the simulation results demonstrate that the three tracking axes are capable of following their respective reference trajectories under the simulated operating conditions. Small transient errors and overshoots are observed during abrupt changes in the reference positions, particularly in the azimuth and altitude responses. However, these deviations decrease as the actual positions approach their corresponding reference trajectories. The results indicate stable reference-tracking behavior without sustained oscillations. Further quantitative analysis of rise time, settling time, maximum overshoot, and tracking error is required to determine the control performance of each axis more precisely.

7. Conclusion

This study presented the modeling, simulation, and comparative evaluation of proportional–integral–derivative (PID) and model predictive control (MPC) strategies for a three-axis solar tracking system using MATLAB/Simulink. The proposed system consists of three independently controlled axes representing azimuth, altitude, and hour-angle movements. The investigation focused on the angular-position responses of the DC motor and the tracking performance of each axis under the selected simulation conditions.

The DC motor step-response results showed that both PID and MPC controllers were capable of achieving the desired reference position of 180° with negligible steady-state error. The PID controller exhibited a rapid initial response, with a maximum overshoot of approximately 1.7% and a settling time of about 2.5 s. In contrast, the MPC controller produced a smoother response with negligible visible overshoot and no sustained oscillations. These observations suggest that MPC may provide improved transient-response characteristics, particularly in applications where overshoot reduction and smooth actuator movement are important.

The three-axis tracking simulations further demonstrated differences in the performance of the two control strategies. Under PID control, the altitude and hour-angle axes closely followed their reference trajectories, whereas the azimuth axis exhibited a considerable tracking error. In comparison, the MPC simulation showed close agreement between the reference and actual angular positions across all three axes, with only minor transient deviations during rapid reference changes. These results indicate that MPC is a promising approach for maintaining accurate angular-position tracking under the simulated operating conditions. However, because the two tracking simulations used different reference trajectories and time scales, additional tests under identical conditions are required to confirm the relative advantages of MPC.

The findings provide a basis for further investigation of predictive control in three-axis solar tracking applications. While PID control remains attractive because of its simple structure and low computational requirements, MPC offers greater flexibility in handling system constraints and optimizing control actions. Future work should focus on evaluating both controllers using identical tracking trajectories, external disturbance profiles, and quantitative performance indices. Experimental validation using a physical tracking mechanism, DC motor actuators, position sensors, and an embedded controller is also recommended to assess real-time computational feasibility and practical tracking accuracy. Further investigation of actuator energy consumption and photovoltaic power generation would help establish the overall benefits of the proposed control strategy for solar energy applications.

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