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Design, Modeling and Performance Evaluation of a Dual-Axis Solar Tracking Photovoltaic System Using MATLAB/Simulink

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Abstract- Stationary photovoltaic (PV) installations suffer significant energy losses because the panel surface is rarely perpendicular to the incoming solar beam, a phenomenon governed by cosine losses that intensify during morning and evening hours. This paper presents the design, mathematical modeling and simulation-based performance evaluation of a dual-axis sun tracking PV system developed in MATLAB/Simulink. An astronomical, algorithm-based control strategy computes the reference azimuth and elevation angles from geographic latitude, day-of-year and local solar time, while an error-driven, dead-band controller actuates the tracking motors to keep the incidence angle close to zero throughout the day. The single-diode equivalent-circuit model, together with temperature-corrected electrical parameters, is used to translate the tracked irradiance into instantaneous power. Simulation results for a representative 250 W module show that the dual-axis tracker sustains a broad, flat power plateau compared with the narrow bell-shaped curve of a fixed-tilt panel, yielding an energy gain of approximately 30-40%. Field-comparable data from an identical pair of 1.3 kWp systems corroborate the simulation, showing a 36.47% annual energy improvement with the simulated and measured values differing by less than 5%. An economic assessment indicates that, despite a higher upfront cost, the additional energy revenue offsets the investment within a comparable payback period to fixed systems, while a carbon-mitigation analysis confirms measurable emission-reduction benefits. The study concludes that dual-axis tracking is most advantageous for land-constrained, high-yield and research-oriented deployments, whereas fixed systems remain preferable for small residential installations.

Keywords— Dual-axis solar tracking, MATLAB/Simulink, photovoltaic modeling, cosine loss, single-diode model, MPPT, incidence angle, renewable energy.

I. INTRODUCTION

The global energy sector is transitioning rapidly from fossil fuels toward renewable sources, driven by depleting reserves, greenhouse-gas concerns and international decarbonisation commitments such as the Paris Agreement. Among renewables, solar photovoltaic (PV) technology is prominent because of the vast, inexhaustible energy available in incident sunlight and the continuously falling levelized cost of electricity. India, receiving close to 300 clear sunny days a year and an average insolation of 4-7 kWh/m2/day, has pursued this potential aggressively through programmes such as the National Solar Mission. Even so, the yield obtained from installed PV capacity is limited less by cell technology than by the geometry of sunlight incidence.

A fixed-tilt panel, typically oriented toward the equator at an angle equal to the local latitude, is perpendicular to the solar beam for only a brief instant each day. For the rest of the day the beam strikes the panel obliquely, producing cosine losses that reduce the effective capture area and increase reflective losses at the glass surface. Single-axis trackers, which follow the sun's east-west transit, recover roughly 15-25% of this loss, but cannot compensate for the sun's seasonal change in altitude. Dual-axis trackers, which actuate along both azimuth and elevation, keep the panel normal vector aligned with the solar vector throughout the day and across seasons, and are reported in the literature to improve annual yield by 30-45%.

Because physical prototyping and field trials of tracking hardware are capital-intensive, time-consuming and subject to uncontrollable weather variability, a virtual, software-in-the-loop modeling approach is an efficient way to validate control logic and quantify expected electrical gains before fabrication. This work develops such a model in MATLAB/Simulink, aiming to (i) formulate the solar astronomical trajectory and PV cell characteristics mathematically, (ii) build an integrated Simulink model of the environment, PV array and tracking kinematics, (iii) implement a closed-loop, dead-band based dual-axis control strategy, (iv) compare the power output, I-V/P-V behaviour and daily energy yield of the tracking system against a fixed-tilt counterpart, and (v) perform a preliminary economic and environmental feasibility assessment. The study is confined to software simulation using the standard single-diode PV model under idealized clear-sky irradiance; aerodynamic loading, detailed transient motor dynamics and micro-shading are outside its scope.

II. LITERATURE REVIEW

Early tracking research by Gay et al. established that mechanical sun-following could substantially increase captured radiation, though the first-generation trackers relied on passive, Freon-based thermal actuation that was slow and imprecise. The advent of low-cost microprocessors enabled active electronic tracking with markedly better pointing accuracy. Parallel to mechanical development, the electrical behaviour of PV modules has been extensively characterised through single- and double-diode equivalent-circuit formulations, as detailed by Markvart and Castaner, which remain the standard basis for simulating how a cell responds to changing irradiance and to the elevated operating temperatures that tracking itself induces.

Control strategies in the literature fall broadly into two families. Closed-loop optical trackers, such as the PLC/LDR-based rig of Abdallah and Nijmeh, respond quickly on clear days but are prone to 'cloud chasing', where diffuse light from bright clouds misleads the sensor and causes erratic motor behaviour. Open-loop astronomical trackers instead compute the sun's azimuth and zenith mathematically from GPS coordinates, date and real-time clock data; Mousazadeh et al. concluded that this approach is more reliable over the long term and fails safely under variable weather, since it follows the theoretical solar path irrespective of atmospheric scattering. MATLAB/Simulink, particularly its Simscape Electrical environment, has become a standard platform for coupling the astronomical, mechanical and electrical sub-models and for rapidly iterating control tuning without hardware risk.

Energy-yield studies consistently report that dual-axis tracking flattens the daily power curve and delivers near-peak output from mid-morning to mid-afternoon; a consensus figure of 30-45% annual gain over static latitude-tilted panels emerges across field and simulation studies, moderated by site latitude and the direct-to-diffuse radiation ratio (Al-Mohamad; Koussa et al.). Economic assessments, however, present a more nuanced picture: as the cost per watt of silicon PV modules falls, adding roughly 30% more fixed-tilt panels can be cheaper than installing tracking hardware (Oner et al.), so trackers are most strongly justified where land is constrained, such as urban rooftops or agrivoltaic sites. Reliability studies (e.g., Huang et al.) highlight that the additional moving parts - actuators, slew drives and bearings – introduce mechanical wear, wind-induced fatigue and sensor degradation that must be accounted for in any credible simulation, motivating the tracking-error and dead-band treatment adopted in this study.

Despite this substantial body of work, most studies address either the mechanical tracking rig or the electrical PV curve in isolation, treating the other half as a black box. The present work addresses this gap by integrating astronomical positioning logic, non-linear single-diode PV modeling and a continuous error-driven control loop into a single, cohesive

MATLAB/Simulink architecture that directly correlates angular alignment with dynamic power output.

III. SYSTEM MODELING AND METHODOLOGY

1. Solar Geometry and Astronomical Control

The sun's apparent position is described by the solar altitude (elevation) and azimuth angles, derived from standard spherical-trigonometry relations using the declination angle (which oscillates between +23.45 and -23.45 degrees over the year), the hour angle (changing at 15 degrees per hour from solar noon) and the site latitude. A custom MATLAB Function block implements these relations to output continuous reference azimuth and elevation signals from elapsed time, latitude and day-of-year. For an ideal dual-axis tracker the panel normal is continuously matched to this reference, driving the angle of incidence toward zero and the cosine of that angle toward unity, thereby maximising captured direct irradiance.

2. PV Array and Electrical Model

The PV array is represented using the Simscape Electrical PV Array block configured to emulate a standard 250 W polycrystalline module (Pmax 250 W, Voc 37.0 V, Isc 8.5 A, Vmp 30.0 V, Imp 8.2 A, 60 cells in series), based on the single-diode equivalent circuit with series and shunt resistances. The photocurrent scales linearly with the effective irradiance reaching the tilted surface, which is itself the direct normal irradiance scaled by the cosine of the incidence angle plus diffuse and ground-reflected components. Cell operating temperature is estimated from ambient temperature and the module's nominal operating cell temperature (NOCT) rating; as tracking increases irradiance exposure it also raises cell temperature, which lowers open-circuit voltage through the voltage-temperature coefficient and slightly dampens the net efficiency gain.

3. Tracking Control Strategy

An astronomical (open-loop) control approach was selected for the simulation to ensure deterministic, reproducible results free of the noise associated with simulated optical scattering. The controller continuously computes the error between the theoretical reference angle and the actual mechanical angle reported by the motor integrators, on both the azimuth and elevation axes. A relay block implements dead-band logic: only when the absolute error exceeds a threshold (2 degrees in this study) is an actuation command issued, driving a gain block representing constant motor speed that integrates over time to update the physical panel angle. This dead-band prevents high-frequency 'hunting' around the set point, trading a marginal, bounded misalignment for substantially reduced mechanical wear.

4. Simulation Environment and Inputs

The model was built in MATLAB/Simulink R2024a using Simscape Electrical, chosen for its ability to co-simulate continuous-time physical PV dynamics with discrete-time tracking logic. A Signal Builder block supplies 12-hour transient irradiance and ambient-temperature profiles - irradiance rising from near zero at 06:00 to a peak of 1000 W/m2 at 12:00 and tapering to zero by 18:00, with ambient temperature peaking slightly after solar noon. The simulation site is fixed at approximately 28 degrees N latitude at the vernal equinox to provide a balanced seasonal baseline. Three scenarios were evaluated: a fixed-tilt panel oriented south at an angle equal to latitude; an ideal dual-axis tracker with zero angular error; and a practical dual-axis tracker incorporating the dead-band and finite motor speed described above.

IV. RESULTS AND DISCUSSION

The solar-position subsystem generated a smooth diurnal elevation profile rising from zero at dawn to a latitude- and declination-dependent peak at solar noon, with azimuth sweeping continuously east to west - confirming the correctness of the astronomical equations. Under this trajectory the fixed panel's effective irradiance fell well below the direct-normal value during the morning and afternoon owing to severe cosine losses, whereas the dual-axis tracker maintained effective irradiance close to the direct-normal value across the entire simulated day. Correspondingly, the incidence angle of the fixed panel exceeded 60 degrees in the early morning and late afternoon, while the tracked panel remained bounded within the 2-degree dead-band, confirming the efficacy of the control logic.

The I-V and P-V characteristics reflect this alignment advantage directly: at mid-morning the fixed panel exhibited a markedly lower short-circuit current than the tracking panel, and the tracked panel's P-V curve showed a substantially higher maximum power point. The instantaneous hourly power comparison (Table I) shows the fixed system producing a narrow, bell-shaped curve while the tracking system sustains a broad, flatter plateau near peak power from about 10:00 to 14:00, with the largest percentage gains occurring in the early morning and late afternoon when the fixed panel's misalignment is greatest.

Time	Fixed System Power (W)	Tracking System Power (W)	Gain (%)
08:00	95	185	+94
10:00	180	235	+30
12:00	245	245	0
14:00	180	235	+30
16:00	95	185	+94

Aggregated over a simulated multi-day period, the tracking system produced roughly 36-37% more energy than the fixed system on each day, consistent with the 30-45% range reported broadly in the literature. This simulated gain is corroborated by comparable field data from an identical pair of 1.3 kWp fixed and dual-axis-tracked PV installations, where the dual-axis system produced 36.47% more annual electricity than the latitude-tilt fixed system, with simulated and measured energy values differing by less than 5%. Sources of deviation from the ideal tracking gain include mechanical tracking error (gear backlash, structural deformation, installation misalignment), sensor error where optical sensing is used, control-system delay, and environmental effects such as cloud cover, diffuse radiation and temperature-driven component drift. Because elevated irradiance also raises cell temperature, tracking systems experience a partially offsetting thermal loss that slightly reduces the theoretical maximum gain but does not erode the overall advantage over fixed installations.

V. ECONOMIC AND ENVIRONMENTAL ASSESSMENT

A first-order economic comparison for a representative 1 kW installation (Table II) shows the dual-axis system carrying a substantially higher initial cost owing to its motorized structure, sensors and microcontroller-based control, against a roughly 36% higher energy output. For an illustrative 1.5 kW-class system, a static PV installation with an initial cost of INR 70,000 and annual production of 1500 kWh at INR 6/kWh yields a payback period of approximately 7.8 years; a dual-axis system costing INR 95,000 but producing 36% more energy (2025 kWh) yields a comparable payback period of about 7.8 years despite the higher capital outlay, because the additional energy revenue largely offsets the added cost. This indicates that whether tracking is economically justified depends strongly on site irradiance, land constraints and local electricity tariffs, consistent with the more cautious economic conclusions found in the literature.

Parameter	Static PV System	Dual-Axis Tracking PV
Mounting structure	Fixed frame	Motorized tracking structure
Motors / sensors	Not required	Required
Total initial cost (1 kW, INR)	60,000-75,000	80,000-1,00,000
Representative energy output (W)	790	1080

Environmentally, the 30-40% higher energy yield of dual-axis tracking directly displaces a proportionally larger share of grid electricity, reducing greenhouse-gas emissions per unit of electricity consumed without requiring additional panel area. A carbon-mitigation framework built around Monitoring, Reporting and Verification (MRV) of actual generation supports quantification of avoided emissions (CO2 avoided = Esolar x EFgrid), which is relevant to carbon-credit mechanisms. These benefits are partly offset by the additional embodied energy and material use of motors, gears and controllers, and by the modestly larger land footprint required to prevent inter-row shading between moving panels, though these effects are generally outweighed by the operational-phase emission savings.

Limitations

The principal limitations of dual-axis tracking identified in this study are: a substantially higher initial cost driven by motors, sensors, controllers and reinforced mounting structures; increased mechanical complexity and consequent maintenance burden (lubrication, alignment, gearbox wear); parasitic energy consumption by the tracking motors and control electronics, which marginally reduces net energy gain; greater vulnerability to wind loading, requiring stowing strategies during storms; reduced relative benefit under diffuse or overcast light, where the sun's position is poorly defined; and a larger land footprint from the row spacing needed to avoid inter-panel shading. These factors mean the economic case for tracking is site- and application-dependent rather than universal.

VII. CONCLUSION AND FUTURE SCOPE

This study developed an integrated MATLAB/Simulink model coupling astronomical solar-position computation, single-diode PV electrical modeling and a dead-band-based dual-axis tracking controller, and used it to quantify the performance advantage of active tracking over a fixed-tilt baseline. The dual-axis system sustained a broader, flatter power curve and delivered an energy gain of approximately 30-40% in simulation, closely matching an independently observed 36.47% annual gain from field-installed identical fixed and tracked PV systems, with simulated and measured values differing by less than 5%. Economic analysis suggests the higher capital cost of tracking hardware is largely offset by increased energy revenue over a comparable payback horizon, while environmental analysis confirms a meaningful reduction in emissions per unit of electricity generated. Overall, fixed-tilt PV remains the more economical choice for small residential systems, whereas dual-axis tracking is best suited to large-scale, land-constrained or research-oriented deployments where maximising energy yield is the priority.

Future work can extend this model along several directions: incorporating AI/machine-learning-based predictive tracking informed by weather and cloud-movement forecasting; adding IoT-based real-time monitoring, remote diagnostics and smart-grid integration; developing hybrid sensor-plus-astronomical control and adaptive algorithms with tighter MPPT integration to reduce tracking error; exploring lightweight, low-cost mechanical designs to reduce capital cost; incorporating active thermal management to reduce temperature-driven losses; and extending the architecture to floating solar, agrivoltaic and battery-integrated hybrid renewable configurations.

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