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Design, Modeling and Performance Analysis of a PD Controller-Based MPPT Scheme for PV Systems

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***Abstract*—Growing worldwide power requirements, coupled with shrinking conventional fuel reserves and escalating environmental concerns, have catalyzed the shift toward sustainable power solutions. Specifically, solar photovoltaic (PV) systems stand out as highly viable options owing to their scalability, eco-friendly nature, and dropping deployment expenses. Nevertheless, PV array efficiency remains highly vulnerable to shifting environmental parameters like insolation levels, thermal changes, partial shading, and fluctuating loads. Such disturbances force the system's operational state away from its optimal threshold, leading to severe power degradation if left unmanaged. To mitigate these issues, implementing robust Maximum Power Point Tracking (MPPT) mechanisms within the power converter stage is critical to maximizing yield.**

This work presents the development and evaluation of a Proportional-Derivative (PD) driven MPPT approach coupled with a DC-DC boost converter, aimed at enhancing PV system responsiveness. Established tracking algorithms like Perturb and Observe (P&O) or Incremental Conductance (INC) suffer from inherent flaws, such as sluggish adaptation during rapid weather shifts and persistent power fluctuations near the peak. Furthermore, standard PI regulators often demonstrate delayed reactions and overshoot due to their lack of predictive derivative action. By integrating a PD controller, the proposed architecture secures a swifter transient response, minimizes oscillatory behavior, and achieves superior stability margins, ultimately optimizing energy extraction.

The system architecture utilizes a single-diode mathematical model to accurately map the non-linear current-voltage (I-V) and power-voltage (P-V) curves of the solar array. A DC-DC boost topology serves as the power-conditioning interface, selected for its robust step-up capabilities and efficiency. The tracking error is fed into the PD control loop, which adjusts the duty cycle of the boost converter's switching component. The derivative element is pivotal in reacting instantly to sudden irradiance drops or spikes, safeguarding operational efficiency under unpredictable atmospheric conditions.

Comprehensive simulations in MATLAB/Simulink demonstrate the viability of this methodology. The framework was tested against abrupt irradiance steps, thermal variations and load alterations. Findings confirm that the PD-based strategy drastically reduces settling times and mitigates steady-state oscillations compared to traditional PI and standalone algorithmic methods. The converter successfully holds a steady voltage output despite external volatility, validating the PD controller as a highly responsive and dependable mechanism for photovoltaic power regulation.

***Index Terms*—Photovoltaic systems, MPPT, PD controller, Boost converter, Single-diode model, Renewable energy, DC-DC converters, Transient response.**

I. INTRODUCTION

Surging electricity demands and the finite nature of carbon-based fuels have pushed the global focus toward green energy alternatives. Solar power is uniquely positioned in this transition due to its adaptability, minimal ecological footprint, and continually dropping infrastructure costs. Despite these promising attributes, solar panels are inherently nonlinear power sources. Their output is profoundly affected by external factors, causing the ideal extraction node—the Maximum Power Point (MPP)—to wander continuously. Without active tracking, a vast portion of available solar energy is wasted.

A. Problem Outline and Environmental Variations

Operational hurdles in solar generation stem primarily from atmospheric inconsistencies. The current and voltage attributes of solar arrays fluctuate drastically in response to passing clouds, temperature shifts, shading from nearby structures, and even surface dust. These variables continuously displace the true MPP. A static system cannot adapt to these shifts, necessitating an agile control layer that can dynamically hunt and lock onto the peak power coordinate under all operational weather states.

B. Limitations of Conventional Techniques

While conventional tracking methods like P&O and INC are widely implemented due to their logical simplicity, they present distinct operational bottlenecks. They rely on fixed-step perturbations, which either slow down the convergence rate or induce heavy steady-state oscillations once the peak is reached. They also struggle significantly under partial shading scenarios.

Control-loop strategies utilizing Proportional-Integral (PI) and Proportional-Derivative (PD) mechanisms have been introduced to refine this process. PI controllers, while robust in steady-state, often struggle with the nonlinearities of PV sources, displaying sluggish recovery and excessive overshoot during swift irradiance changes. Conversely, PD control excels in dynamic environments by reacting to the rate of error change, granting a much faster transient response. The challenge lies in tuning the PD setup to ignore high-frequency noise while exploiting its rapid reaction time.

C. Research Objectives

The core aims of this study include:

1) Formulating an accurate mathematical representation of a PV module utilizing the single-diode equivalent circuit.
2) Structuring a DC-DC boost converter that maintains continuous conduction and reliable voltage elevation.
3) Deploying a PD-driven MPPT loop to eliminate steady-state power ripples and drastically cut down transient recovery times.
4) Simulating the integrated system against harsh environmental dynamics, including step-changes in solar intensity and temperature.
5) Laying a modular groundwork where the fast-acting PD loop can eventually be paired with intelligent systems like fuzzy logic for hybrid control.

II. LITERATURE REVIEW

Maximizing the energy yield from solar arrays heavily relies on the applied tracking algorithm. Over the years, the industry has transitioned from basic heuristic methods to sophisticated mathematical and AI-driven control models to handle unpredictable weather anomalies.

A. Conventional MPPT Methods

Foundational MPPT techniques largely relied on direct hill-climbing methodologies. The P&O strategy operates by adjusting the voltage and checking if the output power increased, continuing the perturbation in that direction. While highly prevalent, this logic creates a permanent oscillation around the exact MPP, inherently wasting power. Additionally, it can easily track in the wrong direction during rapid weather shifts. Incremental Conductance solves the directional confusion by comparing instantaneous conductance to incremental conductance, but it requires higher computational overhead and is still constrained by fixed step-size dilemmas.

B. Linear Control-Based MPPT (PI, PID, and PD)

Standard PI regulators are frequently deployed for converter management due to their steady-state reliability; yet, they tend to exhibit sluggish reactions and overshoot under dynamic solar conditions. Because the PV power curve is heavily nonlinear, static PI tuning often fails to adapt to all environmental operating regions.

Recent scholarly work emphasizes the utility of PD action for rapid solar tracking. The derivative component actively predicts the trajectory of the error, allowing the system to arrest sudden voltage collapses when a cloud passes over the panel. PD systems boast a lighter computational footprint than complete PID systems while resolving the fundamental speed limitations of P&O and PI combinations.

C. DC-DC Boost Converter Studies

The integration of step-up (boost) converters is crucial for elevating the low output voltage of solar panels to usable levels for inverters and storage banks. However, these converters introduce nonlinear switching dynamics. Ensuring stable operation requires careful inductor and capacitor sizing to avoid slipping into the discontinuous conduction mode (DCM) during low-sunlight hours, which complicates the MPPT controller's job.

D. Intelligent Based MPPT Techniques and Gaps

Recent trends point toward artificial intelligence, utilizing Neural Networks and Fuzzy Logic Controllers (FLC), to bypass the need for exact mathematical plant models. These methods handle partial shading exceptionally well. However, a noticeable gap exists: fully intelligent algorithms can be computationally heavy, while traditional algorithms are too slow. This paper uses the PD controller to bridge this gap, utilizing its high-speed derivative response as a reliable baseline that is fully compatible with future intelligent hybrid expansions.

III. PHOTOVOLTAIC SYSTEM FUNDAMENTALS

The capacity of a solar array to generate electricity is dictated by a combination of atmospheric inputs and inherent electrical limits.

A. Environmental Factors

- **Insolation and Irradiance:** Irradiance refers to the instant solar power per unit area (W/m^2), whereas insolation represents the accumulated solar exposure over a specific timeframe, often quantified in Peak Sun Hours.
- **Physical Alignment and Obstructions:** Panel tilt and azimuth determine the baseline capture efficiency. More severely, physical obstructions causing partial shading force bypass diodes to activate, creating complex, multi-peak P-V curves that confuse basic tracking logic.

B. Electrical Characteristics, P-V and I-V Curves

Standard solar cells yield an open-circuit voltage (V_{oc}) hovering between 0.5V and 0.6V without a connected load. The true operational capability is defined by current-voltage (I-V) sweeps under Standard Test Conditions (STC).

As seen in Fig. 1, the relationship between current, voltage, and power is explicitly nonlinear.

The theoretical maximums are bounded by the Short Circuit Current (I_{sc}) and Open Circuit Voltage (V_{oc}). The true objective of the control system is to find and hold the Maximum Power Point (P_{max}), mathematically expressed as:

$$P_{max} = I_{max} \times V_{max} \tag{1}$$

Thermal dynamics also play a major role; cell heating severely degrades the output voltage, making continuous tracking not just beneficial, but mandatory for system viability.

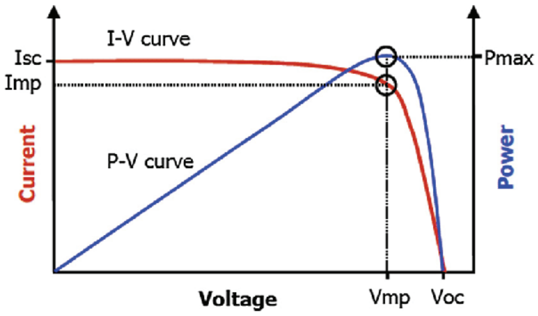


Fig. 1. Typical Current-Voltage (I-V) and Power-Voltage (P-V) curves of a PV module demonstrating the Maximum Power Point (P_{max}).

IV. PROPOSED CONTROL ARCHITECTURE

Given the volatile nature of solar energy capture, a robust intermediate control layer is mandatory. The architecture detailed in this paper utilizes a PD algorithm to govern the switching behavior of a DC-DC boost topology.

A. System Components

The entire generation and control pipeline is modeled cohesively within MATLAB/Simulink, visually represented in Fig. 2.

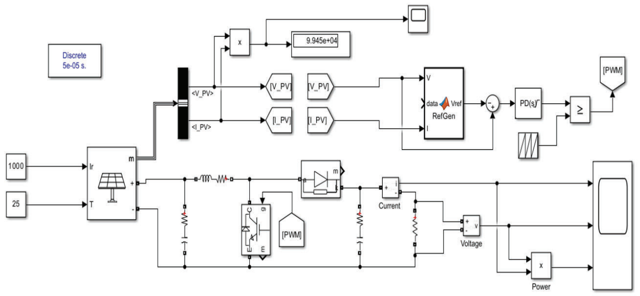


Fig. 2. Complete MATLAB/Simulink Block Diagram of the Proposed PV System, Boost Converter, and PD Controller.

1) **Photovoltaic (PV) Array Model:** Driven by dynamic irradiance (G) and temperature (T) inputs to simulate shifting weather. It outputs the raw system Voltage (V_{PV}), Current (I_{PV}), and Power (P_{PV}).
2) **Signal Acquisition:** Terminal sensors feed real-time electrical metrics back to the central logic unit for continuous calculation.
3) **Reference Trajectory Generator:** Analyzes the incoming electrical data to compute the instantaneous target voltage (V_{ref}) corresponding to the peak power.
4) **PD Controller:** Processes the deviation between the target and actual voltage. The proportional band corrects immediate gaps, while the derivative term dampens extreme fluctuations.
5) **Boost Topology and PWM:** The physical interface that elevates the source voltage. The controller manipulates the PWM duty cycle to physically hold the panel at the desired electrical operating state.

B. Advantages of the PD-Based Approach

By acting on the rate of error change, the PD logic prevents the massive voltage collapses typical when heavy clouds suddenly obscure the sun. It stabilizes the PWM signal much faster than integral-based controllers. To safeguard against high-frequency sensor noise—a common weakness of derivative controllers—the system is designed with appropriate signal filtering, ensuring clean PWM generation.

V. MATHEMATICAL MODELING

Constructing accurate state-space and circuit models is required to validate the controller's effectiveness and to calculate exact inductor and capacitor sizing for the boost stage.

A. PV Mathematical Model

The fundamental building block is modeled using the single-diode equivalent circuit. The terminal current I is defined as:

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_s)}{AkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \tag{2}$$

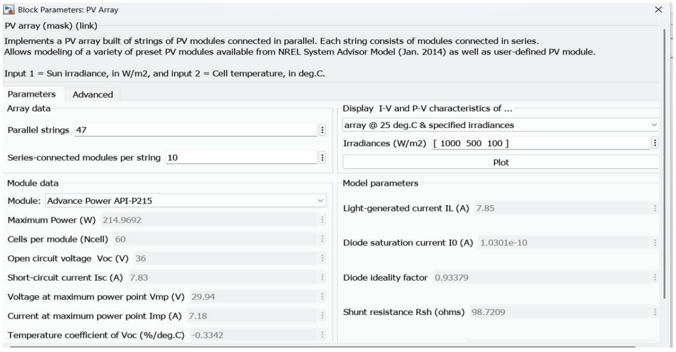
The generated photocurrent (I_{ph}) shifts proportionally with solar irradiation (G) and ambient heat (T):

$$I_{ph} = (I_{sc,ref} + K_i(T - T_{ref})) \frac{G}{G_{ref}} \tag{3}$$

The aggregate power delivered by the terminals is:

$$P_{PV} = V_{PV} \times I_{PV} \tag{4}$$

Simulink parameters are matched to these mathematical constraints, as shown in Fig. 3.



PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Array data

Parallel strings: 47
Series-connected modules per string: 10

Display I-V and P-V characteristics of ...: array @ 25 deg.C & specified irradiances
Irradiances (W/m2): [1000 500 100]

Module data

Module: Advance Power API-P215
Maximum Power (W): 214.9692
Cells per module (Ncell): 60
Open circuit voltage Voc (V): 36
Short-circuit current Isc (A): 7.83
Voltage at maximum power point Vmp (V): 29.94
Current at maximum power point Imp (A): 7.18
Temperature coefficient of Voc (%/deg.C): -0.3342

Model parameters

Light-generated current IL (A): 7.85
Diode saturation current I0 (A): 1.0301e-10
Diode ideality factor: 0.93379
Shunt resistance Rsh (ohms): 98.7209

Fig. 3. Block Parameters configuration for the simulated PV Array in MATLAB/Simulink.

B. Boost Converter State-Space Model

Assuming operation within the continuous conduction mode (CCM), the voltage transfer ratio linking output (V_o) to the panel input ($V_{in} = V_{PV}$) is governed by the duty cycle (D):

$$V_o = \frac{V_{in}}{1 - D} \tag{5}$$

TABLE I
PARAMETERS OF THE PV MATHEMATICAL MODEL

Symbol	Description
I_{ph}	Photo current (depends on irradiance)
I_0	Diode reverse saturation current
R_s	Series resistance of the cell
R_{sh}	Shunt resistance of the cell
A	Ideality constant of the diode
T	Operating cell temperature (Kelvin)
q	Electron charge (1.602×10^{-19} C)
k	Boltzmann constant (1.38×10^{-23} J/K)
G	Solar Irradiance (W/m^2)

The transient states of the inductor current (i_L) and output capacitor voltage (V_o) are defined via standard differential relationships:

During switch ON state:

$$\frac{di_L}{dt} = \frac{V_{PV}}{L} \tag{6}$$

During switch OFF state:

$$\frac{di_L}{dt} = \frac{V_{PV} - V_o}{L} \tag{7}$$

Capacitor Voltage Dynamics:

$$\frac{dV_o}{dt} = \frac{I_L - I_o}{C} \tag{8}$$

These derivations strictly dictate the sizing of L and C to prevent unwanted discontinuous operations and to suppress output voltage ripple.

C. MPPT and PD Controller Law

The primary tracking logic identifies the target voltage (V_{mpp}) and issues a reference command:

$$V_{ref}(t) = f_{MPPT}(V, I) \tag{9}$$

The instantaneous deviation $e(t)$ between the physical panel voltage and the target is found by:

$$e(t) = V_{ref}(t) - V_{PV}(t) \tag{10}$$

This error is fed into the continuous-time PD algorithm to compute the necessary restorative action $u(t)$. Simulation parameters for this block are shown in Fig. 4.

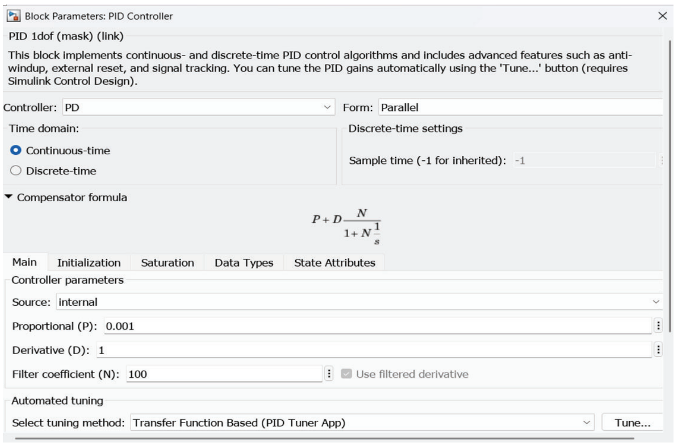
The mathematical core of the PD operation is:

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} \tag{11}$$

Here, K_p drives the system toward the target, while K_d acts as a braking mechanism against erratic changes. The duty cycle sent to the converter switch is updated via:

$$D(t) = D_0 + u(t) \tag{12}$$

By anticipating the error trajectory, the derivative term is solely responsible for truncating the settling time and flattening the perpetual oscillations that hinder standard algorithmic tracking.



Block Parameters: PID Controller

PID 1dof (mask) (link)

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PD
Form: Parallel

Time domain:
● Continuous-time
○ Discrete-time

Discrete-time settings
Sample time (-1 for inherited): -1

Compensator formula

$$P + D\frac{N}{1+N\frac{1}{s}}$$

Controller parameters
Source: internal
Proportional (P): 0.001
Derivative (D): 1
Filter coefficient (N): 100
☑ Use filtered derivative

Automated tuning
Select tuning method: Transfer Function Based (PID Tuner App)

Fig. 4. PID Controller Block Parameters configured specifically for PD operation.

VI. SIMULATION AND PERFORMANCE EVALUATION

The full schematic, linking the PV source, power electronics, and control algorithms, was subjected to rigorous testing inside MATLAB/Simulink. The model encapsulates the physical parameters of the solar array, the exact component values of the boost circuit, and the discretized PD logic generating the high-frequency PWM switching signal.

A. Dynamic Response to Irradiance Variations

To simulate real-world weather turbulence, the model was forced to react to severe step-changes in solar density (e.g., an instant plummet from $1000W/m^2$ to $500W/m^2$). The data reveals that the PD-driven system locks onto the new peak exponentially faster than standard PI setups. The K_d variable detects the steep drop in the power derivative and immediately commands a duty cycle correction. This proactive response averts deep voltage sags and allows the generation curve to stabilize seamlessly.

B. Oscillation Reduction

A major operational flaw in standard algorithmic tracking is the permanent perturbation required to confirm the MPP location, which bleeds potential power through steady-state ripple. The implementation of the PD logic effectively cures this phenomenon. By precisely driving the error margin $e(t)$ to absolute zero without overshoot, the derivative braking effect produces a remarkably flat, stable power yield once the peak is acquired.

C. Future Enhancements: Fuzzy Logic Integration

Even with exceptional transient handling, pure mathematical controllers possess vulnerabilities to sensor noise and extreme nonlinearities caused by complex partial shading. The next evolutionary step for this architecture is the integration of a Fuzzy Logic Controller (FLC). Because FLCs rely on rule-based linguistic structures rather than rigid equations, merging an FLC with the high-speed PD backbone will yield a hybrid controller capable of instantaneous reaction times and total immunity to multi-peak shading conditions.

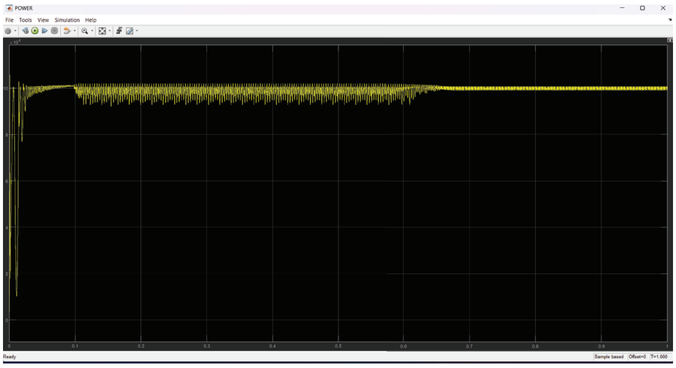


Fig. 5. MATLAB/Simulink scope output illustrating the simulated power transient response and steady-state oscillation reduction over time.

VII. CONCLUSION

This paper outlines the successful design, mathematical derivation, and simulated validation of an advanced Maximum Power Point Tracking (MPPT) framework utilizing a PD controller and a DC-DC boost topology. By employing a highly accurate single-diode equivalent circuit for the PV array and precise state-space modeling for the converter, the research establishes a reliable virtual testbed for analyzing power conditioning systems.

Simulation outputs verify that replacing basic heuristic logic or standard PI controllers with a properly tuned PD loop drastically elevates tracking efficiency. The controller demonstrates superior agility during severe atmospheric step-changes, drastically shrinking the transient recovery window. Furthermore, the derivative action successfully eliminates the chronic steady-state power oscillations that typically plague conventional tracking methods, ensuring that the maximum possible energy is smoothly transferred to the load.

Ultimately, this study proves that PD-augmented control is a highly effective, low-overhead solution for stabilizing renewable energy generation. The modularity of the developed Simulink model also provides an excellent foundation for future research, paving the way for advanced intelligent hybrid systems, such as neuro-fuzzy PD controllers, to tackle even more complex environmental anomalies.

REFERENCES

[1] A. Chauhan, R.P. Saini, “A review on Integrated Renewable Energy System based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control,” *Renewable and Sustainable Energy Reviews*, Volume 38, 2014.

[2] M.A. Eltawil, Z. Zhao, “Grid-connected photovoltaic power systems: Technical and potential problems-A review,” *Renewable and Sustainable Energy Reviews*, Volume 14, Issue 1, 2010.

[3] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, “Optimization of perturb and observe maximum power point tracking method,” *IEEE Transactions on Power Electronics*, vol. 20, no. 4, pp. 963-973, 2005.

[4] Solar Photovoltaic Technology and Systems A Manual for Technicians, Trainers and Engineers, IIT Bombay & MNRE, 2011.

[5] S. Rehman, M. Mahbub Alam, J.P. Meyer, “Feasibility study of a wind-PV-diesel hybrid power system for a village,” *Renewable Energy*, Volume 38, Issue 1, 2012.

[6] T. Esram and P. L. Chapman, “Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques,” *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439-449, June 2007.

[7] B. N. Alajmi, K. H. Ahmed, S. J. Finney, and B. W. Williams, “Fuzzy-Logic-Control Approach of a Modified Step-Size P&O MPPT Algorithm Implementing Fast Convergence Design,” *IEEE Transactions on Industrial Electronics*, vol. 26, no. 4, pp. 1112-1120, April 2011.