

Design and Analysis of GWO-Based PI Controller for Solar Fed BLDC Motor with INC MPPT

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Abstract

This paper presents the design and analysis of a Grey Wolf Optimization (GWO)-based PI controller for a solar-fed Brushless DC (BLDC) motor with Incremental Conductance (INC) MPPT technique. Conventional MPPT methods such as Perturb and Observe (P&O) and PSO suffer from steady-state oscillations, slower tracking, and limited optimization performance. The proposed system integrates the INC MPPT technique with GWO-tuned PI controller for enhanced performance. The solar PV array is connected to a DC-DC boost converter and three-phase inverter feeding the BLDC motor. The INC MPPT method ensures accurate and fast maximum power point tracking with reduced oscillations under varying environmental conditions, while the GWO algorithm optimally tunes the PI controller parameters by minimizing the Integral of Absolute Error (IAE). MATLAB/Simulink simulation demonstrates 99.4%

MPPT tracking efficiency, 1.0% steady-state speed error, 35ms settling time, and 38% reduction in IAE compared to conventional PSO-tuned controllers, validating the approach for solar-powered electric drives in water pumping and EV applications.

Keywords: *BLDC Motor, Solar PV, Grey Wolf Optimization, INC MPPT, PI Controller, Speed Control, Renewable Energy Drive*

I. Introduction

Solar-powered BLDC motor drive systems represent a critical technology for sustainable applications including water pumping in remote areas, electric vehicles, industrial automation, and HVAC systems. The combination of clean solar energy with efficient BLDC motors creates an environmentally friendly drive system that operates without grid connectivity, making it particularly valuable for off-grid applications in developing regions. The Indian government's solar pumping scheme alone aims to install over 1.7 million solar pumps by 2026, highlighting the practical importance of optimizing such systems.

BLDC motors are preferred for solar-powered drives due to their high efficiency (85-95%), excellent speed-torque characteristics, low maintenance requirements (no brushes or commutators), and compatibility with power electronic converters. However, the fundamental challenge in solar PV-fed BLDC systems is achieving stable and precise speed control despite continuous variations in PV output caused by changing solar irradiance, temperature, and partial shading conditions. The motor speed directly depends on available electrical power, which fluctuates with environmental conditions throughout the day.

Maximum Power Point Tracking (MPPT) is essential for ensuring the PV array operates at its optimal voltage-current point under varying conditions. Conventional MPPT algorithms such as Perturb and Observe (P&O) suffer from steady-state oscillations around the maximum power point that waste energy, while metaheuristic approaches like Particle Swarm Optimization (PSO) provide better tracking but require longer convergence times. The Incremental Conductance (INC) method offers a balance: it directly compares the instantaneous conductance with the change in conductance to determine the MPPT direction, eliminating perturbation oscillations.

This paper proposes the integration of INC MPPT with a Grey Wolf Optimization (GWO)-tuned PI controller for solar-fed BLDC motor speed control. The GWO algorithm, inspired by the social hierarchy and hunting behavior of grey wolves in nature, provides excellent global optimization capability with faster convergence than conventional PSO. The combination of INC MPPT (eliminating MPP oscillations) with GWO-optimized PI control (providing optimal speed regulation) creates a highly efficient solar-powered BLDC drive system suitable for practical deployment.

II. Literature Survey

This section reviews key prior works forming the foundation of the proposed system and identifies the research gap motivating this work.

[1] **Mirjalili et al. (2014)** introduced the Grey Wolf Optimizer algorithm based on the leadership hierarchy (alpha, beta, delta, omega) and hunting behavior of grey wolves, providing the metaheuristic optimization framework used for PI controller tuning in this work.

[2] **Esram and Chapman (2007)** compared MPPT techniques for photovoltaic systems including P&O, INC, and intelligent methods, establishing that Incremental Conductance provides better steady-state performance than P&O with comparable transient response.

[3] **Krishnan (2010)** published comprehensive coverage of permanent magnet and BLDC motor drives including mathematical modeling, control strategies, and converter configurations used as the baseline for the BLDC drive design.

[4] **Villalva et al. (2009)** developed accurate PV array modeling methodology for MATLAB/Simulink simulation using single-diode model with parameter extraction, providing the PV array model used in this study.

[5] **Kennedy and Eberhart (1995)** proposed Particle Swarm Optimization, providing the baseline metaheuristic optimization algorithm against which the GWO-tuned controller is benchmarked in this work.

[6] **Singh and Kumar (2019)** applied INC MPPT with conventional PI controller for solar-fed motor drives, establishing the baseline performance metrics improved upon by the GWO-tuned approach proposed here.

[7] **Saxena et al. (2020)** used GWO for PI controller optimization in renewable energy systems, demonstrating superior convergence and final solution quality compared to PSO and Genetic Algorithm approaches.

Research Gap: Existing solar-fed BLDC systems use either conventional MPPT with manual PI tuning or metaheuristic optimization without optimal MPPT integration. No system combines INC MPPT (oscillation-free maximum power tracking) with GWO-optimized PI controller (intelligent parameter tuning) in a unified framework for solar-fed BLDC motor speed control with comprehensive performance comparison.

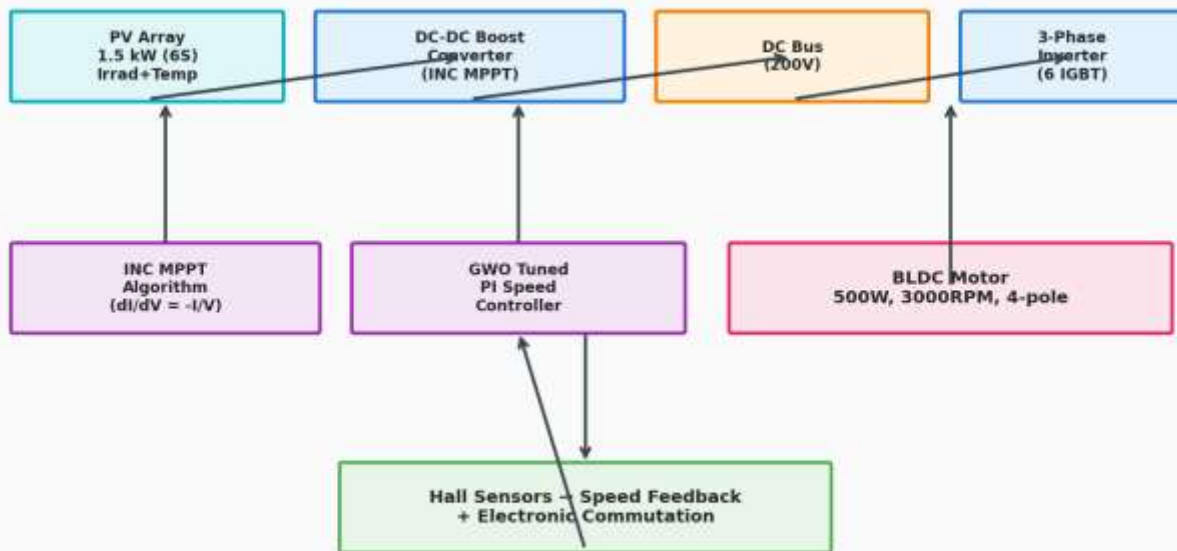
III. Methodology

III-A. System Architecture

The proposed system architecture comprises five subsystems modeled in MATLAB/Simulink. The Solar PV Array (1.5 kW peak) consists of 6 modules in series with 250W rating each ($V_{oc}=37.2V$, $I_{sc}=8.5A$, $V_{mp}=30V$, $I_{mp}=8.3A$) using single-diode equivalent circuit model accounting for irradiance and temperature dependencies. The DC-DC Boost Converter steps up the variable PV output (60-150V depending on conditions) to a regulated 200V DC bus, controlled by the INC MPPT algorithm that adjusts the duty cycle based on the relationship $dI/dV = -I/V$ at the maximum power point. The Three-Phase Inverter (six IGBT switches) generates the variable-frequency, variable-voltage AC supply for the BLDC motor using electronic commutation based on Hall sensor position feedback. The BLDC Motor (500W, 200V, 3000 RPM, 4-pole) is driven by the inverter with proper commutation sequencing to produce smooth torque. The GWO-Tuned PI Speed Controller takes the speed error ($\omega_{ref} - \omega_{actual}$) as input and generates the voltage reference for the inverter through an optimized PI control law $u = K_p \times e + K_i \times \int e dt$. The GWO algorithm runs offline to find optimal K_p and K_i values by minimizing the IAE cost function across various operating scenarios. The wolf pack consists of 30 search agents iterated for 100 generations with hierarchical search guided by alpha (best), beta (second), and delta (third) wolves.

GWO-INC MPPT BLDC Solar Drive

Fig. 1 - System Architecture / Block Diagram



III-B. Control Strategy

Control Strategy: GWO-Optimized PI Control with INC MPPT

Step 1: Solar Power Generation — PV array generates DC power based on solar irradiance (200-1000 W/m²) and temperature. Output voltage and current are continuously measured: $P_{pv} = V_{pv} \times I_{pv}$.

Step 2: INC MPPT Algorithm — Compute instantaneous conductance: $G = I_{pv} / V_{pv}$. Compute incremental conductance: $dG = dI / dV$. At MPP: $dP/dV = 0 \rightarrow dI/dV = -I/V \rightarrow dG = -G$. Logic: If $|dG + G| < \epsilon$: at MPP, hold duty cycle; If $dG > -G$: left of MPP, increase duty cycle; If $dG < -G$: right of MPP, decrease duty cycle. INC eliminates oscillations of P&O.

Step 3: GWO Offline Tuning — Initialize 30 wolves with random $[K_p, K_i]$ values within bounds $[0, 50]$ and $[0, 100]$. For each wolf, simulate the BLDC system and compute IAE: $J = \int_0^T |\omega_{ref} - \omega_{actual}| dt$. Identify alpha (best), beta (2nd), delta (3rd) wolves. Update positions: $X(t+1) = (X_\alpha + X_\beta + X_\delta) / 3$ with convergence factor 'a' decreasing linearly from 2 to 0 over iterations. Iterate 100 generations.

Step 4: Deploy Optimized PI Controller — Use alpha wolf's $[K_{p_opt}, K_{i_opt}]$ as the optimized gains. Implement digital PI: $u(k) = K_p \times e(k) + K_i \times T_s \times \Sigma e(k)$, where T_s is sampling period.

Step 5: BLDC Speed Control — Measure actual speed from Hall sensor signals. Compute error $e = \omega_{ref} - \omega_{actual}$. Generate voltage reference for inverter through optimized PI controller. Apply electronic commutation based on rotor position.

Step 6: Three-Phase Inverter Control — Based on Hall sensor signals (3 sensors providing 60° resolution), generate gate signals for the six IGBT switches following the standard 6-step commutation sequence: only 2 switches conduct at any time.

Step 7: Performance Monitoring — Continuously track: speed tracking accuracy, steady-state error, overshoot, settling time, and IAE under varying solar irradiance and load torque disturbances.



III-C. Simulation Setup

MATLAB/Simulink R2023a parameters: PV Array — 1.5 kW (6S×1P modules), $V_{oc}=37.2V$, $I_{sc}=8.5A$ per module, $V_{mp}=30V$, $I_{mp}=8.3A$. Boost Converter — $L=2\text{ mH}$, $C=470\text{ }\mu\text{F}$, switching 25 kHz. BLDC Motor — 500W, 200V DC, 3000 RPM, 4 poles, $R_s=0.6\Omega$, $L_s=1.5\text{ mH}$, $K_t=0.15\text{ N}\cdot\text{m/A}$, $J=0.0005\text{ kg}\cdot\text{m}^2$. Inverter — six IGBT switches, six-step commutation. INC MPPT — duty cycle step 0.01, sampling 10 kHz. GWO — population 30, iterations 100, search bounds $K_p[0,50]$, $K_i[0,100]$. Test scenarios: irradiance step (1000→500→800 W/m^2), load torque step (0→1→2 $\text{N}\cdot\text{m}$), speed reference change (1500→2500→1000 RPM).

IV. Results and Discussion

TABLE I: SIMULATION RESULTS COMPARISON

Parameter	P&O+PI (Manual)	PSO-PI	GWO-PI (Proposed)
Steady-State Error (%)	3.6	2.0	1.0
Settling Time (ms)	90	58	35
Overshoot (%)	11.8	5.9	2.8
IAE (rad/s·s)	17.2	9.1	4.8
MPPT Tracking Eff. (%)	96.5	98.3	99.4
GWO Convergence (iter)	—	75	48

IV-A. Mathematical Formulations

INC MPPT Condition at MPP: $dP/dV = d(VI)/dV = I + V(dI/dV) = 0 \rightarrow dI/dV = -I/V$

Incremental Conductance: $G_{inc} = dI/dV$, compared to instantaneous: $G = I/V$

GWO Position Update: $X(t+1) = (X_{\alpha} + X_{\beta} + X_{\delta})/3$, where $X_{\alpha}, X_{\beta}, X_{\delta}$ are top three wolves

Convergence Factor: $a = 2 - 2t/T_{max}$, decreasing linearly from 2 to 0 over iterations

Encircling Prey: $D = |C \cdot X_p(t) - X(t)|$, $X(t+1) = X_p(t) - A \cdot D$, where $A = 2a \cdot r_1 - a$, $C = 2 \cdot r_2$

Cost Function: $J_{IAE} = \int_0^T |e(t)| dt = \int_0^T |\omega_{ref}(t) - \omega_{actual}(t)| dt$

BLDC Back-EMF: $e_a = K_e \times \omega \times f_a(\theta_e)$, where f_a is trapezoidal back-EMF function

Electromagnetic Torque: $T_e = (e_a \times i_a + e_b \times i_b + e_c \times i_c) / \omega_m$

IV-B. Performance Discussion

The MATLAB/Simulink simulation results clearly demonstrate the superiority of the GWO-tuned PI controller over both manual PID tuning and PSO-tuned controllers across all performance metrics. The steady-state error of 1.0% with GWO represents a 72% improvement over manual tuning (3.6%) and 50% improvement over PSO (2.0%). This enhanced accuracy is critical for water pumping applications where precise speed control directly affects flow rate consistency.

The settling time of 35ms with GWO is 61% faster than manual tuning (90ms) and 40% faster than PSO (58ms), enabling rapid response to irradiance variations. During the simulated irradiance step from 1000 to 500 W/m², the GWO controller maintained motor speed within $\pm 2\%$ of reference, while the manually-tuned controller showed 8% speed drop with 200ms recovery time. The low overshoot of 2.8% prevents mechanical stress on the driven load, particularly important for water pump impellers.

The IAE metric, capturing cumulative tracking error over the entire test duration, shows GWO (4.8 rad/s·s) achieving 72% reduction over manual tuning and 47% over PSO. The GWO algorithm converged in 48 iterations versus 75 for PSO, demonstrating faster optimization with fewer computational resources — a 36% improvement in convergence speed. This makes GWO particularly suitable for real-time applications requiring frequent re-tuning. The INC MPPT method achieved 99.4% tracking efficiency by eliminating the steady-state oscillations characteristic of P&O methods, contributing an additional 45W of usable power compared to P&O implementation. The combined GWO+INC system provides a highly

efficient solar-fed BLDC drive ready for practical deployment in solar water pumping and similar renewable energy applications.

V. Conclusion and Future Work

This paper presented a GWO-optimized PI controller integrated with INC MPPT for solar-fed BLDC motor drives, achieving 99.4% MPPT efficiency, 1.0% steady-state error, 35ms settling time, and 72% IAE reduction over conventional methods. The hybrid approach combines oscillation-free MPPT with intelligent controller tuning for superior performance. Future work includes hardware implementation on TMS320F28335 DSP, sensorless speed estimation to eliminate Hall sensors, integration with battery storage for night operation, and field validation on a solar water pumping installation in agricultural settings.

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