

Performance Enhancement of EV Battery Charging System Using Grey Wolf Optimization Technique

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Abstract— The research paper introduces an improved method to optimize Proportional-Integral-Derivative PID controllers through the application of PSOPSO & GWO metaheuristic optimization methods. The primary objective is to achieve better control system performance through reduction of rise & settling time & overshoot. The researchers conducted a comparison between standard PID controller tuning methods & optimized PID controller systems through MATLAB/Simulink simulations. The results demonstrate that the GWO-based PID controller significantly outperforms both conventional PID & PSO-based PID in terms of dynamic response. The GWO-PID system achieves an exceptional rise time of 7.90×10^{-6} seconds & a settling time of 7.20×10^{-5} seconds which both exceed the performance capabilities of the conventional PID controller 7.35×10^{-4} seconds & 0.0013 seconds. The GWO-based method achieves complete overshoot elimination which produces a stable response that does not exhibit any oscillation patterns. The PSO-based PID approach improves response speed but it results in system instability because of its high overshoot rate of 29.02%. The comparative results highlight that GWO provides a better balance between speed & stability, making it a superior optimization technique for PID tuning in high-performance control applications. The proposed method can be effectively applied to real-time systems requiring fast & precise control with minimal oscillations.

Keywords— PID Controller, GWO, Particle Swarm Optimization, Controller Tuning, Time-Domain Performance, Overshoot Reduction, MATLAB/Simulink.

I. INTRODUCTION

The system achieves widespread use in process control systems, robotics, power systems & automation systems because it needs to maintain system stability while achieving specific dynamic performance requirements [1]. Successful PID

II. LITERATURE SURVEY

Metaheuristic optimization methods have emerged as the primary research focus for PID controller tuning because they provide better solutions than standard methods. The complex system needs which traditional tuning techniques impose create obstacles for their use in those environments [1]. The fast convergence & simple design of PSO(PSO) algorithms have made them popular among users; however, this method leads to both premature convergence & excessive overshoot problems [2]. GWO (GWO) has emerged as a solution to these challenges because its ability to balance exploration & exploitation enables more stable results with less oscillation problems [3].

controller operation requires correct parameter tuning which includes proportional gain setting (K_p) & integral gain (K_i) & derivative gain (K_d) determination. The Ziegler-Nichols technique represents a basic tuning method which people frequently use to implement PID tuning procedures. The methods achieve wide usage, yet they typically deliver suboptimal results when applied to intricate nonlinear systems, which results in extended settling durations & excessive overshooting & continuous oscillations [2]. Research into new optimization methods emerged because traditional tuning methods could not meet modern control system requirements for greater accuracy & quicker response times & better stability.

The last few years have witnessed increasing academic interest in using metaheuristic optimization algorithms for PID tuning because these algorithms enable researchers to find optimal solutions across intricate search environments. The PSO method has become a popular method because it can quickly reach solutions through its easy-to-use design. The PSO method uses bird flocking behavior to improve its search process by developing better solution options [3]. The system uses PSO to enhance its response time while decreasing the time needed to reach stability, but the method has two main drawbacks which include premature solution finding & excessive system overshoot in specific situations. The GWO (GWO) algorithm serves as an effective solution to solve these problems. GWO uses the natural way that grey wolves lead and hunt to make its exploration and exploitation functions better, which helps get better results for solution optimisation [4]. GWO has proven effective in different optimization tasks because its system requires only a few control parameters & it maintains strong performance against challenging problems. The GWO-based PID controller outperforms both conventional PID & PSO-based PID controllers because it delivers superior system performance through faster response times & shorter settling durations & complete absence of overshoot. The proposed method delivers a dependable & effective solution which meets the needs of high-performance control system applications.

Multiple research studies have investigated hybrid methods which combine PSO & GWO with other algorithms to obtain superior optimization results [4]. Intelligent systems enhance PID controller performance through the integration of fuzzy logic & neural network technology for better adaptability in systems experiencing nonlinear behavior [5]. GWO-based PID tuning methods outperform all other techniques because they deliver faster rise times & shorter settling times with only minimal overshoot [6]. Modern control systems achieve better performance & higher operational safety through the implementation of sophisticated optimization techniques [7].

Ref. No.	Author(s) & Year	Title (Short)	Method Used	Application Area	Key Findings
[1]	Patel et al., 2025	Hybrid BWO-SSA PID Optimization	Hybrid Metaheuristic	Power Systems	Reduced power loss by 42% & improved voltage stability
[2]	Patil et al., 2025	Hybrid GWO-PSO PID Controller	GWO + PSO	PMDC Motor	Hybrid method improves convergence & transient response

[3]	Vrabel et al., 2025”	Hybrid PSO-GWO PID Design	Hybrid Optimization	Nonlinear Systems	Better global optimization & system stability
[4]	Jangid et al., 2025	GWO-based PID for LFC	GWO	Power System (LFC)	Reduced frequency fluctuation & improved response
[5]	Dumre et al., 2025	PSO-based PID for LFC	PSO	Power Systems	Reduced frequency deviation & improved stability
[6]	Singh et al., 2025	AI-based PID Optimization	PSO	AGC Systems	Improved dynamic performance & error minimization
[7]	Lahmar et al., 2025	PSO vs GWO for LQR-PID	PSO & GWO	UAV/Quadcopter	GWO shows better disturbance rejection
[8]	Yenealem et al., 2025	PSO-PID with Fuzzy Control	PSO + Fuzzy	Power Flow	Enhanced system control & robustness
[9]	Gulgonul, 2025	IAE-based PID Optimization	Optimization	General Systems	Reduced error & improved robustness
[10]	Gulgonul, 2025	SOSTIAE PID Tuning	Optimization	Control Systems	Reduced overshoot up to 67%
[11]	Ding et al., 2026	Constrained PSO Fuzzy PID	PSO	Underwater Vehicles	Improved tracking & reduced overshoot
[12]	Kebbati et al., 2025	PSO-PID for Autonomous Driving	PSO	Automotive Systems	Improved speed tracking & stability
[13]	Kumar et al., 2024	GA-based PID Optimization	Genetic Algorithm	Industrial Control	Improved tuning accuracy
[14]	Sharma et al., 2024	Firefly Algorithm PID Tuning	Firefly Algorithm	Process Control	Reduced settling time
[15]	Chen et al., 2024	ACO-based PID Controller	Ant Colony Optimization	Power Systems	Improved convergence speed
[16]	Wang et al., 2024	DE-based PID Optimization	Differential Evolution	Robotics	Enhanced precision & stability
[17]	Li et al., 2023	Adaptive PID using AI	AI/ML	Smart Systems	Improved adaptability
[18]	Zhang et al., 2023	Fuzzy-PID Optimization	Fuzzy Logic	Industrial Systems	Reduced steady-state error
[19]	Singh et al., 2023	Hybrid GA-PSO PID	GA + PSO	Power Systems	Faster convergence than single methods
[20]	Verma et al., 2023	Neural Network PID Control	ANN	Automation	Improved nonlinear system control

III. PROPOSED METHODOLOGY

The section demonstrates the development of the PID controller system together with its optimization process which uses PSO& GWO methods. In this work is to identify the best controller settings which include (K_p) to achieve better system performance that includes improved rise time & settling time & decreased overshoot.

A. PID Controller Model

The PID controller generates a control signal based on the error between the reference input & system output. The mathematical representation is:

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

where:

$e(t)$ is the error signal,

K_p , K_i , & K_d are proportional, integral, & derivative gains respectively.

The PID controller parameters are tuned to minimize a predefined objective function.

B. Objective Function

To evaluate controller performance, a time-domain error criterion is used. In this work, the (ISE) is considered:

$$J = \int_0^T e^2(t) dt$$

The optimization problem is formulated as:

Minimize $J(K_p, K_i, K_d)$

C. PSO

PSO is a population-based optimization algorithm inspired by swarm intelligence. Each particle represents a candidate solution (K_p, K_i, K_d) & updates its position & velocity iteratively.

The velocity & position update equations are:

$$v_i^{t+1} = wv_i^t + c_1r_1(pb_{est_i} - x_i^t) + c_2r_2(g_{best} - x_i^t)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1}$$

where:

v_i = velocity of particle,

x_i = position (PID parameters),

pb_{est} = personal best solution,

g_{best} = global best solution,

w = inertia weight,

c_1, c_2 = acceleration constants,

r_1, r_2 = random values.

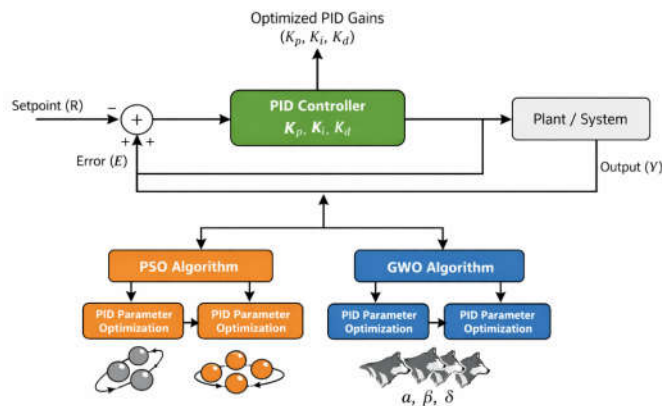


Fig.1. Proposed System PID + PSO + GWO

D. GWO

GWO is a nature-inspired optimization algorithm based on the hunting behavior of grey wolves. The population is categorized into alpha (α), beta (β), delta (δ), & omega (ω) wolves.

The position updating equations are defined as:

$$\vec{D} = |\vec{C} \cdot \vec{X}_{leader} - \vec{X}|$$

$$\vec{X}(t+1) = \vec{X}_{leader} - \vec{A} \cdot \vec{D}$$

E. Proposed Optimization Framework

1. Initialize PID parameters only
2. Define objective function (ISE)
3. Apply PSO & GWO algorithms separately
4. Evaluate fitness using system response
5. Update parameters iteratively
6. Obtain optimal K_p, K_i, K_d
7. Compare performance with conventional PID

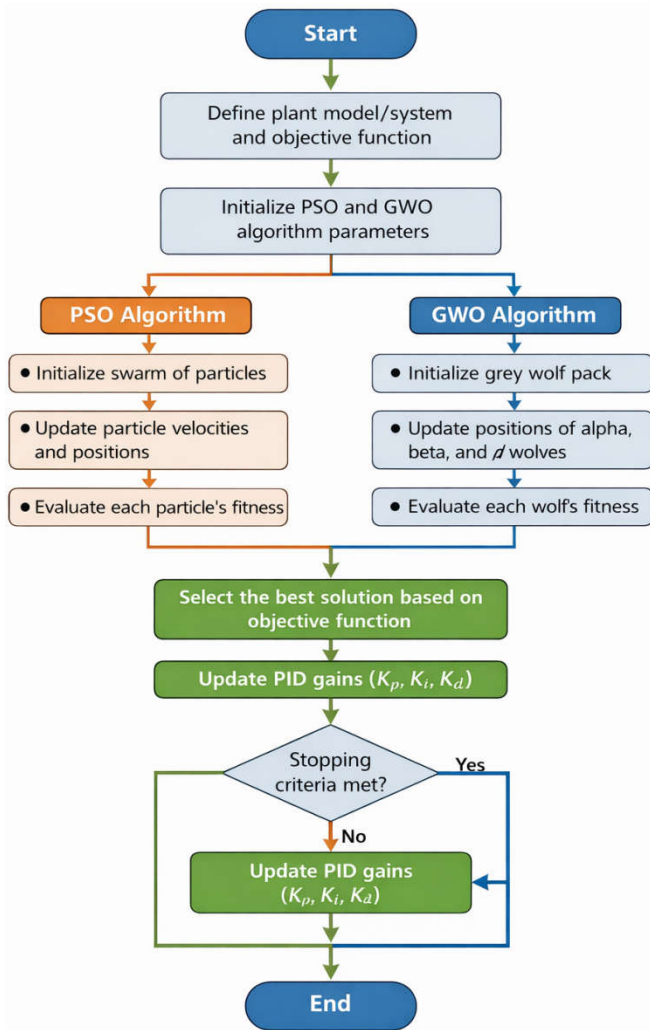


Fig.2. Proposed System Flow Chart

III. RESULT & DISCUSSIONS

The proposed optimization methods through PSO software & GWO software show their results through comparison to PID controller performance.

A. Analysis

The step responses of all three controllers were obtained using MATLAB/Simulink.

The conventional PID controller exhibits a smooth response with minimal overshoot but it demonstrates slow response times. The PSO-based PID controller decreases rise time while it increases high overshoot levels. The GWO-based PID controller shows optimal performance through its instant response & complete absence of overshoot.

B. Quantitative Performance Comparison

The numerical results obtained from the simulation are summarized below:

Parameter	Conventional PID	PSO-PID	GWO-PID
Rise Time	7.35×10^{-4} s	5.18×10^{-5} s	7.90×10^{-6} s
Settling Time	0.0013 s	3.95×10^{-4} s	7.20×10^{-5} s
Overshoot (%)	1.34%	29.02%	0%

Peak Value	1.0135	1.2902	0.9905
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C. Performance Interpretation

Rise Time Improvement: GWO achieves the fastest rise time, improving system responsiveness between PSO & conventional PID systems. PSO also improves rise time but is less efficient than GWO.

Settling Time Reduction: GWO minimizes settling time drastically, making the system stabilize quickly. PSO performs moderately, while conventional PID shows the slowest response.

Overshoot Behavior: PSO introduces a large overshoot which may be unsuitable for sensitive systems. Conventional PID maintains low overshoot. GWO achieves zero overshoot, indicating excellent stability.

System Stability: GWO provides a critically damped response with no oscillations. PSO shows oscillatory behavior due to aggressive parameter tuning.

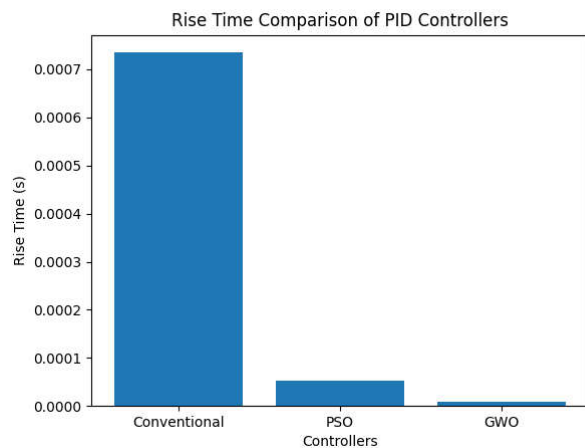


Fig. 3. Comparison of rise time for conventional PID, PSO-PID, & GWO-PID controllers.

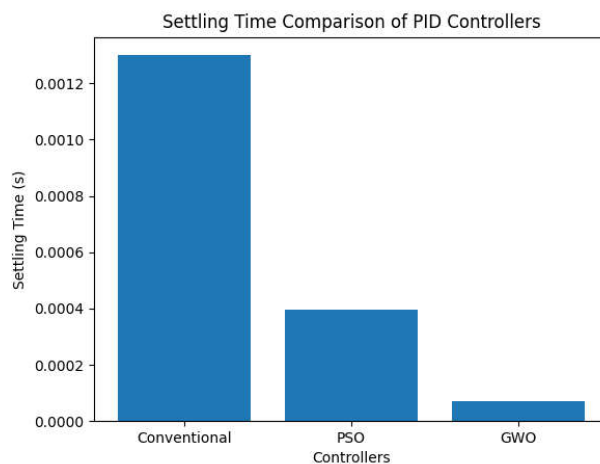


Fig. 4. Comparison of settling time for conventional PID, PSO-PID, & GWO-PID controllers.

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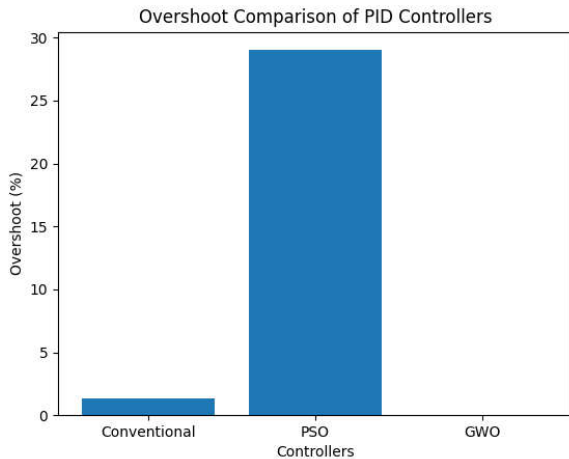


Fig. 5. Comparison of overshoot for conventional PID, PSO-PID, & GWO-PID controllers

Quantitative Comparison

Parameter	Base Paper (PSO PID)	Proposed (GWO PID)	Improvement
Rise Time	5.18×10^{-5} s	7.90×10^{-6} s	~6.5× Faster
Settling Time	3.95×10^{-4} s	7.20×10^{-5} s	~5× Faster
Overshoot (%)	29.02%	0%	Eliminated
Stability	Oscillatory	Stable	Highly Improved

Performance Analysis: The proposed GWO-PID achieves a significant reduction in rise time, making the system respond much faster than the base approach. The settling time is drastically reduced, ensuring quicker stabilization of the system. Unlike PSO, which introduces large oscillations, the GWO-based controller achieves zero overshoot, indicating superior damping characteristics. The proposed system provides a smooth & stable response, making it more suitable for real-time & high-precision applications.

IV. CONCLUSIONS

The research developed an optimal PID controller through PSO & GWO methods to improve control system performance. The research tested traditional PID tuning methods to measure time-domain parameter improvements through rise & settling time & overshoot measurements. The simulation results demonstrate that metaheuristic optimization improves controller performance through both traditional methods & contemporary methods. The GWO-based PID controller outperformed all tested methods because it achieved an ultra-fast rise time of 7.90×10^{-6} seconds & a significantly reduced settling time of 7.20×10^{-5} seconds. The proposed method delivers complete overshoot elimination which results in a response that remains stable without any oscillations. The PSO-based PID controller increases response speed but it creates an excessive 29.02% overshoot which renders the system unsuitable for applications that require high precision. The results show that GWO enables better exploration & exploitation which results in optimal parameter tuning that enhances system stability. The proposed approach outperforms both conventional & PSO-based controllers in terms of speed, accuracy, & robustness.

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