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Improving DC Voltage Regulation using Optimal PID Controller Based on Particle Swarm Optimization Algorithm

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***Abstract*—Regulated direct current (DC) is essential for numerous applications like renewable energy systems, electronics, and transportation. Achieving accurate, stable, and responsive DC regulation presents a significant challenge. This paper investigates the implementation of a Proportional-Integral-Derivative (PID) controller and explores its parameter tuning using the Particle Swarm Optimization (PSO), and Gray wolf optimization GWO methods. The dynamic response characteristics of PID based on controller is compared against both a conventional PID controller tuned by Ziegler-Nichols tuned method and gray wolf optimization (GWO) algorithm. The dynamic response characteristics of PID based on controller is compared against both a conventional PID controller tuned by Ziegler-Nichols tuned method and gray wolf optimization (GWO) algorithm through simulations in MATLAB 2020. Simulation results demonstrate that the PSO-tuned PID controller achieves superior performance with significant improvements in key metrics. The rise time is drastically reduced from 5.4978e-^{04} seconds to 4.6743e^{-10} seconds, the settling time drops from 0.0075 seconds to 8.323e^{-10} seconds, and the overshoot is effectively eliminated, approaching near zero. This work highlights the advantages of PSO-based PID tuning for achieving precise and efficient DC regulation.**

***Index Terms*—DC Regulation, PID Controller, Particle Swarm Optimization (PSO), Dynamic Response, Rise Time, Settling Time, Overshoot, MATLAB.**

I. INTRODUCTION

1.1. *Background and Significance of DC Voltage Regulation*

The development for improving DC voltage regulation using advanced control techniques should focus on several key areas. This includes exploring the application of metaheuristic optimization methods for fine-tuning controller parameters in grid-connected fuel cell systems, as well as evaluating the effectiveness of these controllers compared to traditional ones. Additionally, it is crucial to investigate optimal tuning of PID controller parameters for enhancing dynamic response in islanded AC microgrids using artificial intelligence methods. A hybrid optimization approach that combines different techniques has shown promise in improving voltage profiles and microgrid performance. Also, innovative methods such as sliding mode control and other nonlinear control approaches are considered when external

disturbances and model uncertainty are involved. In robotic systems control process a high precision in trajectory tracking, so the disturbance observers can be involved for improvement [1], [2], [3], [4]

1.2. *PID Controller with Particle Swarm Optimization Method*

Improving the performance of the buck converter follows the manipulation of the switch duty cycle which finally can effect on the DC voltage control. Many control approaches can fulfill this demand, one of these approaches is the PID controller. This controller has many advantages such as simplicity, adaptability, high accuracy, from the other side it has many drawbacks such, dealing with linear systems, tuning complexity, sensitivity to Noise. These drawbacks and especially the nonlinear problem can be treated using different methods of tuning procedure of the coefficients of the PID controller. One of the most efficient methods is the particle swarm optimization (PSO) methods, this method comes into play when nonlinearity and external disturbances are in scene. Using PSO to optimize PI controller parameters has proven to be an effective method for real-time operation with reduced complexity [1] [1].
Implementing this method for tuning PID controller can improve the dynamic response characteristics such as percentage overshoot, rising time settling time, and steady state error which enhance Dc voltage regulation and provide improvement to stability and power quality performance [5].

1.3. *Research Objectives*

The paper goal is to o optimize the PID controller parameters for regulating DC voltage in a buck converter using Particle Swarm Optimization (PSO). This refers to the specific technical benefits of the research improving the performance of a buck converter by finding the best possible settings for the PID controller using PSO[5], [6].

II. LITERATURE REVIEW

Regulating DC voltage using buck converter that use PID controller is a challenging space that many researchers have examined to enhance power quality and enhance the dynamic response and stability. Literature review in this paper highlights several key areas of focus such as:

2.1. Improved Dynamic Response and Stability:

[7]: Focuses on enhancing the dynamic response of a buck-boost converter using a PID controller in continuous conduction mode. The Ziegler-Nichols tuning method is used and simulations demonstrate improved performance under various input voltage and load variations.

[9]: Explores using a PID controller optimized by the Grey Wolf Optimization (GWO) algorithm to improve the performance of a boost converter. The study compares different scenarios, showing that GWO tuning leads to faster response, better robustness, and more effective voltage regulation.

2.2 Tuning Methods for PID Controllers:

[10]: Examines various tuning methods for PID controllers, including traditional approaches (Ziegler-Nichols, Cohen Coon, Astrom- Hagglund, Chien-Hrones Reswick) and fractional order PID controllers (FOPID). The analysis emphasizes the benefits of FOPID controllers for improving stability and step response characteristics.

2.3 Applications in Different Systems:

[8]: Applies PID controllers with Evolutionary Programming (EP) and Genetic Algorithm (GA) optimization to a DC servo motor. The study shows the effectiveness of Fuzzy Logic Controllers (FLC) and compares the performance of FLC+EP and FLC+GA-based control schemes.

[11]: Focuses on the use of PID controllers in robotic applications. This study analyzes the dynamic response of a multi-fingered robot hand (MFRH) using both traditional and modern controllers, highlighting the improved performance of the Particle Swarm Optimization (PSO)-tuned PID controller.

[12]: Investigates a multi-operating point fuzzy PID control strategy for a series diesel-electric hybrid tractor (SDEHT) to improve fuel efficiency. Adaptive particle swarm optimization (APSO) is used to optimize the fuzzy PID controller parameters.

III. METHODOLOGY

3.1 Design of Step/down Converter

The buck converter circuit is illustrated in Figure 1:

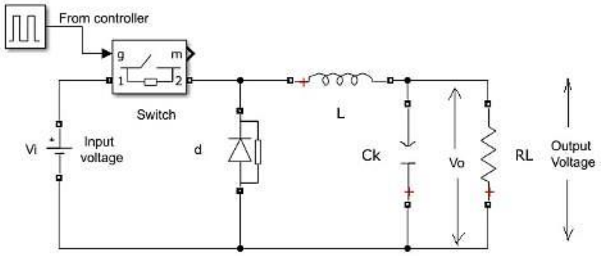

Fig. 1. Non-isolated buck converter circuit [13].

A step-down converter, and sometimes is called buck converter, represents a specific kind of DC/DC converter that effectively transforms a higher input voltage into a reduced output voltage. The stepping down converter is a famous device implemented in sustainable energy systems, battery charging systems, a electric vehicles, power electronics, and telecommunication systems and various voltage regulation mechanisms.

The function of the buck converter is adopted through turning the switch (typically MOSFET) on and off respectively. In On state the energy accumulate in the inductor, while in Off state of the switch the accumulated power in the inductor is released and transmitted to the load via diode as in Fig.1.

Manipulating the switch is achieved by changing the duty cycle through control circuit which oversees the output voltage and modifies the duty cycle as needed.

Developing a step-down converter working in continuous conduction mode (CCM) necessitates the utilization of the following mathematical formulas with the following parameters:

a) Input voltage = 48V, b) Load resistance = 10Ω, c) output voltage = 18V, d) switching frequency = 40000Hz, voltage ripple r =0.005.

1) Calculating duty cycle (D):

$$D=\frac{V_{out}}{V_{in}}=\frac{18}{48}=0.375 \tag{1}$$

2) Calculating minimum value of inductor:

$$L_{\min}=\frac{(1-D)*R_L}{2*f_{(sw)}}=\frac{(1-0.375)*10}{2*4e10}=78\mu H \tag{2}$$

1) Calculating minimum value of inductor:

$$C_{\min}=\frac{(1-D)}{8*L*f_{(sw)}^{2}*r}=\frac{(1-0.375)}{8*(78e-6)(4e10)*(0.005)}=100\mu F \tag{3}$$

Where:

V_{out} – Output Voltage, V_{in} – Input Voltage, L- inductance, C- capacitance, D- duty cycle, $f_{(sw)}$ – Switching frequency, R- Load resistance.

The research methodology involves developing a simulation model of the conventional buck converter system and implementing PID controller using Z-N tunning method and PID controller using GWO and compare the results with the proposing method. The performance of the controllers is evaluated under various operating conditions, including load changes and input voltage disturbances.

Key performance metrics such as settling time, overshoot, and steady-state error are analyzed to compare the effectiveness of the two controllers.

Thanks to the act of switching, we have the ability to establish a state -state model for such converter[13] :

$$\dot{\mathbf{x}}(t) = \mathbf{A}*\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \mathbf{B}*u(t) = \begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{1}{R_{load}C} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{LC} \end{bmatrix} V_{source} * u(t) \tag{4}$$

$$\mathrm{y} = \mathrm{C}*\mathrm{x(t)} = \begin{bmatrix} 1 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Transfer function for step/down converter can be calculated using equations [13]:

$$T_{buck} = \mathbf{C}*[s\mathbf{I}-\mathbf{A}]^{-1}*\mathbf{B}$$

$$T_{buck}(s) = \frac{V_{ouput}(s)}{D(s)} = \frac{V_{source}/L*C}{s^2 + \frac{1}{R*C}s + \frac{1}{L*C}} \tag{5}$$

Developing an advanced control system for a step/down converter entails the selection of an appropriate control methodology and the optimization of controller parameters.

3.2 Design of Classical PID Controller

A schematic diagram of PID controller illustrated in **Fig.2:**

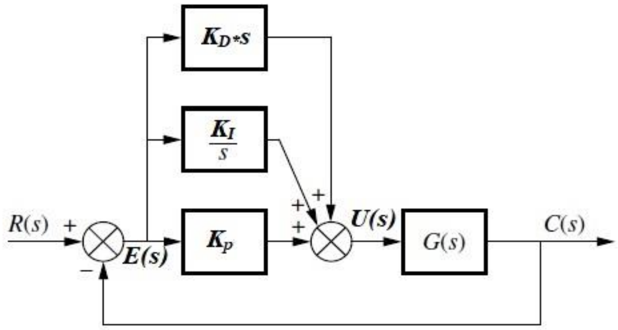

Fig. 2 PID controller.

The transfer function of the PID controller can be evaluated using equation [14]:

$$\frac{U(s)}{E(s)} = K_p + \frac{K_I}{s} + K_D*s = \frac{K_p*s + K_I + K_{D*}*s^2}{s} \tag{6}$$

Where:

U(s) – controlled signal, *E(s)*- Error signal, K_p -proportional gain, K_I – integral gain, K_D – derivative gain.

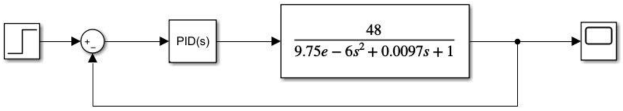

Fig. 3. Step/down converter with PID controller

Using equation (7) to calculate K_{cr} , P_{cr} and Table 1, we can establish the values of K_p, K_I, K_D .

TABLE 1

Controller	K_p	T_i	T_d
PID	0.6*Kcr*	0,6*Pcr*	0.125*Pcr*

$$G_c(s) = Kp\left(1 + \frac{1}{T_i*s} + T_d*s\right) = 0.6Kcr\left(1 + \frac{1}{0.5P_{cr}s} + 0.125P_{cr}s\right) \tag{7}$$

3.3 *Design of PID Controller Tuned by PSO Method*

PSO is a computational technique inspired by the collective movement of natural swarms, like birds, fish. PSO is a powerful and versatile optimization technique used in various fields, including Machine learning, Robotics, Engineering design. It's used to find optimal solutions (max. or min.) to problems by iteratively improving candidate solutions. Each particle in this system is considered as a point in a multi-dimensional space, and its movement is influenced by its past experiences as well as the experiences of other particles. The position with the best fitness for each particle is referred to as its p_{best}, while the overall best position among all particles is referred to as g_{best}. Initially, the positions of p_{best} and g_{best} are distinct. However, by adjusting their movements based on the p_{best} and g_{best} directions, the particles gradually converge towards the global optimum [15], [16].

The particle position and velocity are updated according to equation:

$$\begin{aligned} v_i(t) &= w*v_i(t-1) + c_1*r_1\left(p_{best} - x_i(t-1)\right) + c_2*r_2\left(g_{best} - x_i(t-1)\right); \\ x_i(t) &= x_i\left(t-1\right) + v_i\left(t\right). \end{aligned} \tag{8}$$

Where:

w-Inertia weight factor, *vi*- velocity of particle, c_1,c_2 - Cognitive and social acceleration factor, r_1,r_2 - Random numbers uniformly distributed (0,1), p_{bes} *t*- position corresponding to best fitness, g_{best}- position overall best out of all the particles.

Fig.4 shows the steps of a program that uses particle swarm optimization (PSO) to calculate the value of each particle. The first step is to start the process, the second step is to define the initial values for the parameters used in the PSO algorithm. These parameters might include the number of particles, the search space, and the fitness function. In the third step a population of particles is generated, and each particle is assigned a random position within the search space.

The following step is to evaluate fitness of each particle using a fitness function. The fitness function determines how good a particular solution is, after that the fitness of each particle is evaluated using a fitness function. The position and velocity of each particle are updated based on its own best position (pbest) and the best position found by the entire swarm (gbest). Next step checks if a particle has improved its fitness compared to its previous best position (pbest).

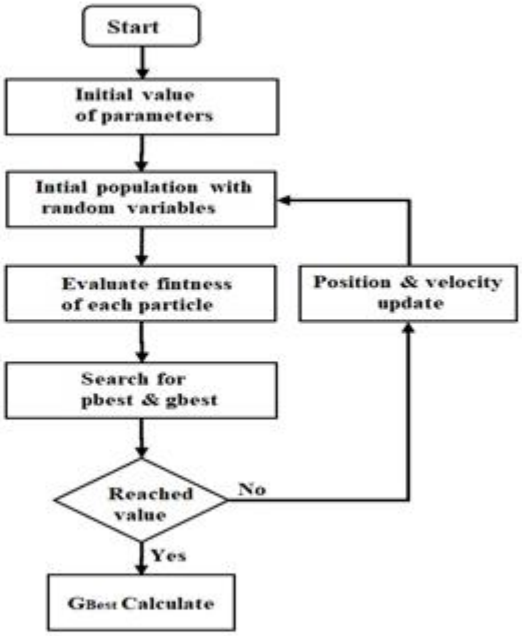

Fig. 4. PSO flow chart [11]

If so, the particle's current position becomes its new pbest. The gbest (global best) is also identified as the particle with the best fitness value among the entire swarm. If the stopping criterion (maximum number of iterations or finding a sufficiently good solution) has been met the process moves to gbest Calculation. If the stopping criterion hasn't been met, the process loops back to initial population.

IV. SIMULATION SETUP

The dynamic response characteristics of PID based on controller is compared against both a conventional PID controller tuned by Ziegler-Nichols tuned method and gray wolf optimization (GWO) algorithm with respect to PSO algorithm through in MATLAB 2020. To demonstrate the efficacy of the proposed techniques, the closed loop response dynamic of the converter without controller is driven in Fig.5.

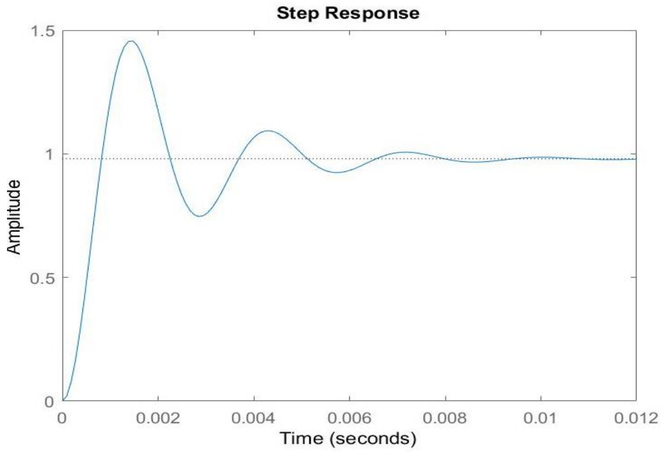

Fig. 5. Response of close loop of step/down converter without controller.

Where the percentage overshoot %PO is equal to 48.6 % at 1.47 msec, the rising time is 5.4978e-04 sec and settling time is 0.0075 sec, percentage overshoot is 48.6346.

A PID controller is added to the converter in order to improve the dynamic response, the tuning method is Ziegler-Nichols method as in **Fig.6** [8].

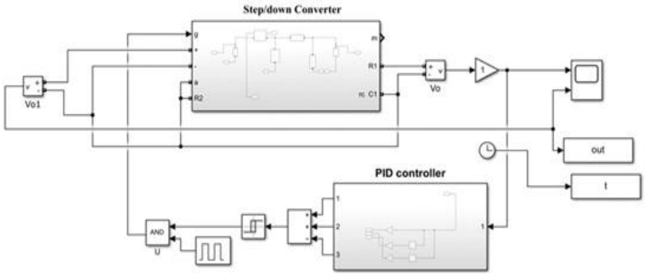

Fig. 6. PID using Z-N.

The dynamic response of the step/down converter Using PID controller with Ziegler-Nichols tuning method can be seen in **Fig. 7**. The rising time now is 0.0075 sec, while settling time now is 0.00748 sec, percentage overshoot is 7.08.

A Gray wolf optimization method is considered to tune PID controller [10] as in **Fig. 8**.

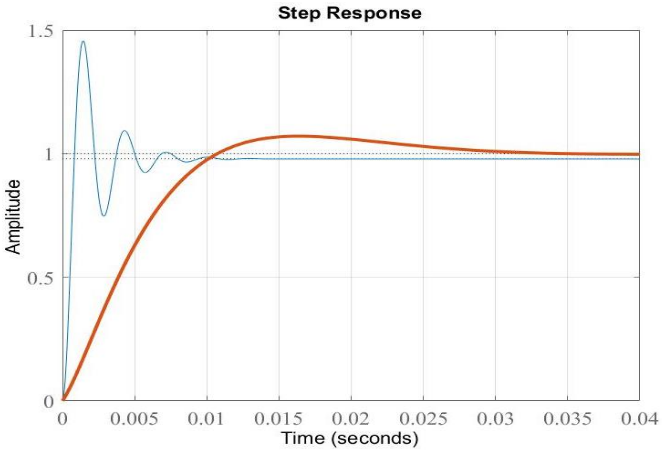

Fig. 7. Response of PID controller using Z-N

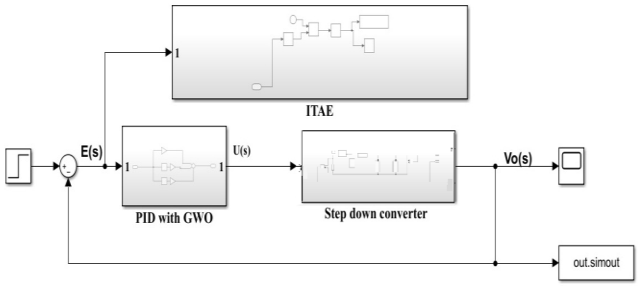

Fig. 8. PID controller using GWO

The dynamic response of the step/down converter Using PID controller with GWO can be seen in **Fig. 9**:

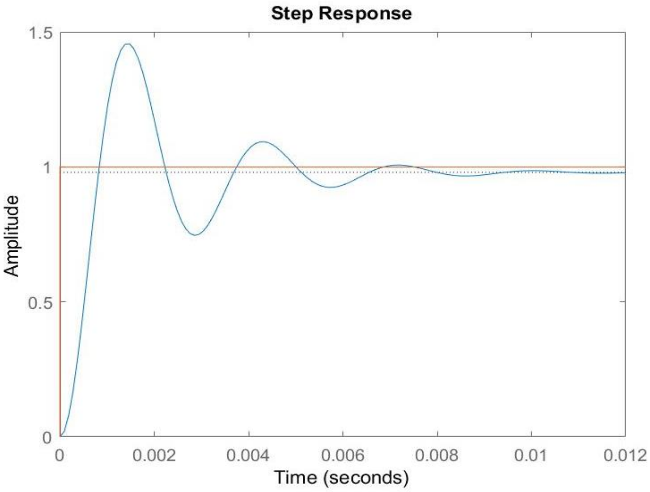

Fig. 9. Response of PID controller using GWO.

Finally, the proposed tuning method (PSO) is tested and the simulation results shows a superior outcomes in system overshoot, settling time, and rise time. The rising time is 1.29e-9 sec, the settling time is 2.3e-09 sec, see **Fig.** 10, **Fig.** 11.

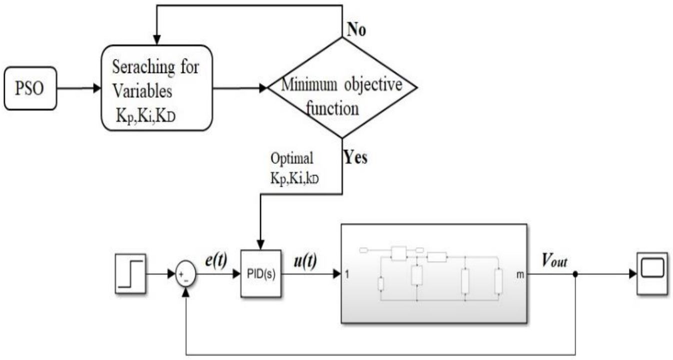

Fig. 10. Flow process of the Proposed PID controller using PSO.

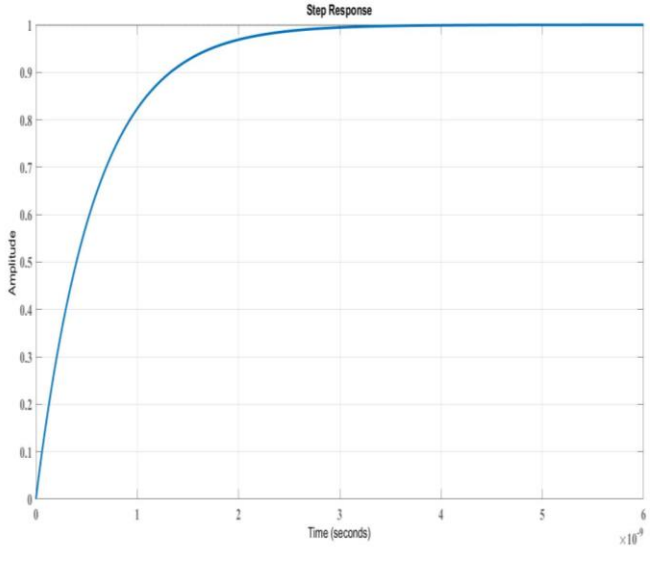

Fig. 10. Response of close loop of PID controller using PSO .

V. RESULTS AND DISCUSSION

The use of Particle Swarm Optimization (PSO) in fine-tuning the Proportional Integral Derivative (PID) controller has shown significant improvements in dynamic response compared to standard PID controllers. This optimization led to reduced overshoot, transient response, and steady-state error, with lower total harmonic distortion percentages for voltage under load variation. The effectiveness of PSO-tuned PID controllers, showing no steady-state error in system frequency with load changes and smoother transients compared to traditional PID designs. These findings demonstrate that PSO-tuned PID controllers offer enhanced performance in terms of DC link fluctuation, voltage stabilization, harmonics reduction. This highlights how advanced control methods such as PSO can substantially improve DC voltage regulation across diverse applications.

The simulation results can be summarized as in Table 2.

TABLE 2
Comparison between different methods of tuning PID

Type of PID controller	Rise time(sec)	Settling Time(sec)	Peak time(sec)	%PO
without controller	5.4978e^{-04}	0.0075	0.00147	48.6346
Using Z-N	0.0075	0.00748	0.0015	7.08
Using GWO	6.829^{-09}	2.035e^{-08}	≈ 0	≈ 0
Using PSO	1.29e^{-9}	2.3e^{-09}	2.99 e^{-09}	≈ 0

VI. CONCLUSION

This paper investigates the application of Particle Swarm Optimization (PSO) for fine-tuning the Proportional Integral Derivative (PID) controller in a DC-DC converter to achieve robust DC voltage regulation. Traditional PID controllers often face challenges in regulating DC voltage under dynamic conditions due to inherent limitations in parameter tuning. This paper aims to demonstrate the effectiveness of PSO in overcoming these limitations, leading to improved dynamic response and enhanced voltage stability.

The performance of the PSO-tuned PID controller was compared with controllers tuned using traditional methods as Ziegler-Nichols (Z-N) and Grey Wolf Optimization (GWO). The analysis focused on key performance indicators such as rise time, settling time, and overshoot.

Simulation results demonstrated the superiority of the PSO-tuned PID controller. The PSO method achieved optimal rise time and settling time values while maintaining near-zero overshoot. This indicates that PSO effectively optimized the PID parameters for improved transient response and reduced system oscillations. Furthermore, the PSO algorithm demonstrated faster convergence and greater adaptability compared to Z-N and GWO methods. In some cases, combining PSO with Z-N for initial parameter estimates further improved the optimization process [5], [17], [18].

Future research can focus on:

1) Hybrid Optimization Approaches: Exploring hybrid optimization techniques that combine the strengths of PSO with other algorithms for cascaded control schemes in microgrids, enhancing overall system efficiency and stability.
2) Variable Structure Control: Developing innovative variable structure control methods to effectively share power between energy storage devices, addressing imbalances between demand and generation and maintaining stable DC bus voltage regulation.
3) Nonlinear Control Algorithms: Investigating the application of nonlinear control algorithms with disturbance observers for controlling complex robotic systems, like continuum robots, to improve trajectory tracking accuracy and robustness in the presence of external disturbances and model uncertainty.

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