An ALO-Tuned 2DOF-PID Controller for Enhanced Frequency Regulation in Hybrid PV–Thermal Power Systems

Sitthisak Audomsi
Faculty of Engineering, Mahasarakham University, Maha Sarakham, 44150, Thailand
sitthisak.seagame@gmail.com

Chatmongkol Areeyat
Faculty of Engineering, Mahasarakham University, Maha Sarakham, 44150, Thailand
67010353011@msu.ac.th

Jagraphon Obma
Department of Computer Engineering, Rajamangala University of Technology ISAN, Khonkaen Campus, Khonkaen, Thailand
jagraphon.ob@rmuti.ac.th

Xiaoqing Yang
Shanxi Vocational University of Engineering Science and Technology, Shanxi, China
yangxqmty0907@163.com

Worawat Sa-ngiamvibool
Faculty of Engineering, Mahasarakham University, Maha Sarakham, 44150, Thailand | Electrical and Computer Engineering Research Unit, Mahasarakham University, Maha Sarakham 44150, Thailand
wor.nui@gmail.com (corresponding author)

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ABSTRACT

This study investigates the optimization of a two-degree-of-freedom PID (2DOF-PID) controller using the Ant Lion Optimizer (ALO) for enhanced frequency regulation in a hybrid Photovoltaic (PV)–Reheat Thermal Power System under sudden load disturbances. To benchmark performance, conventional PID and PI controllers were also tested to assess their ability to minimize the frequency fluctuations and manage the inter-area power exchanges. Simulations were carried out in MATLAB/Simulink using a dual-area dynamic model, and the performance was evaluated based on standard control metrics, including the settling time, overshoot/undershoot, and the Integral of Absolute Error (IAE). The results indicate that the ALO-optimized 2DOF-PID controller reduced the average settling time by nearly 40% and IAE by 12.6%, compared to the best-performing PID controller in the benchmark group. These findings highlight the advantages of combining the 2DOF-PID architecture with an evolutionary optimization strategy, offering improved dynamic and nonlinear control performance. The proposed approach shows strong potential for application in next-generation renewable energy systems and smart grids.

Keywords- Ant Lion Optimization (ALO); 2DOF-PID controller; hybrid power system; load frequency control; PV-Reheat Thermal Power System

I. INTRODUCTION

The increasing need for energy and for the reduction of greenhouse gas emissions has driven the energy sector to widely adopt renewable energy sources, particularly solar power. Solar-reheat thermal power systems or PV-Reheat Thermal Power Systems have received great attention for their capacity to harness the solar energy in both electrical and thermal modalities, improving the overall efficiency of the energy system [1, 2]. The PV-Reheat Thermal Power System has nonlinear dynamics and considerable variability resulting from external factors, such as variations in light intensity, temperature, and load, which complicate the regulation of the temperature and power stability. Conventional controllers, such as PI or PID, despite their extensive use, are insufficient in effectively adapting to variations [3].

Numerous efforts have been made to enhance the effectiveness of PID controllers using optimization techniques, such as Particle Swarm Optimization (PSO) [4], Genetic Algorithm (GA) [5], and Grey Wolf Optimizer (GWO) [6]. However, these approaches often exhibit limitations in escaping the local optima and adapting to complex, nonlinear systems. Moreover, the integration of 2DOF-PID controllers with recent metaheuristic algorithms, such as the ALO in the context of thermal power systems remains underexplored [7, 8].

This study presents the design of a 2DOF-PID controller for a PV–Reheat Thermal Power System in which the ALO algorithm is employed to determine the optimal control parameters. The performance of the proposed controller is assessed in comparison with conventional PI and PID controllers using the IAE as the evaluation criterion.

This study centers on the simulation of the PV–Reheat Thermal Power System using a dynamic model that captures both steady-state and transient behaviors. The results highlight the effectiveness of the ALO-tuned 2DOF-PID controller in enhancing the system stability and minimizing the dynamic error, thereby affirming its suitability for modern hybrid energy applications.

II. SYSTEM MODELING

A. *PV-Reheat Thermal Power Model*

Figure 1 illustrates the block diagram of a hybrid power generation system comprising two interconnected subsystems: Area 1, representing a reheat thermal power generation unit, and Area 2, corresponding to a grid-connected PV system. This configuration is widely adopted as a benchmark model for analyzing the LFC performance in hybrid renewable-thermal networks.

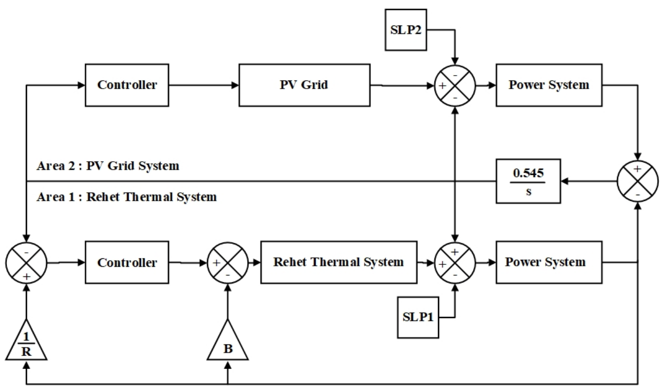

Fig. 1. Block diagram of the PV-Reheat Thermal Power System (self-developed).

In Area 1, the thermal energy is converted into electrical output through a series of dynamic components, namely the governor, turbine, and reheater, with each modeled using first-order transfer functions. The reheater stage introduces an additional time delay to reflect the intermediate reheating of steam. The frequency deviation in this area (Δf_1) is regulated through a local controller, while a feedback gain of 0.8 and a participation factor of 0.4 are incorporated into modeling the inter-area dynamics and control allocation.

Area 2 encapsulates the dynamics of a PV-based power generation system, which is approximated by a second-order transfer function given by:

$$G_{PV}(s) = \frac{-18s + 900}{s^2 + 100s + 50} \quad (1)$$

This function captures the relatively fast and inertia-less response of solar generation units, particularly under conditions involving rapid changes in solar irradiance or maximum power point tracking. An independent controller is also deployed in Area 2 to regulate the frequency deviation denoted by (Δf_2).

The two areas are interconnected through a tie-line, enabling the power exchange between the subsystems, represented by the variable ΔP_{12}. The dynamic effect of this power exchange on frequency is modeled using the transfer function $\frac{0.545}{s}$, while the power system dynamics in Area 1 are represented by $\frac{120}{20s+1}$.

The external disturbances are introduced via two step changes in load, Load Change 1 and Load Change 2, applied individually to each area. These disturbances serve as test inputs to assess the robustness and adaptability of the proposed control strategies under dynamic and nonlinear operating conditions [9]. Collectively, this model serves as a comprehensive simulation framework for evaluating advanced controller designs, such as the ALO-tuned 2DOF-PID, within hybrid energy systems that demand both rapid responsiveness and high stability across multiple generation technologies.

B. *2DOF-PID Structure*

Figure 2 displays the block diagram of a 2DOF-PID, which is commonly applied to enhance the performance in both the setpoint tracking and disturbance rejection [10]. The inclusion of two weighting coefficients, one proportional (PW) and one derivative (DW), allows the controller to adjust its response more effectively in the face of rapid system fluctuations, contributing to a better overall performance under varying operating conditions [11, 12].

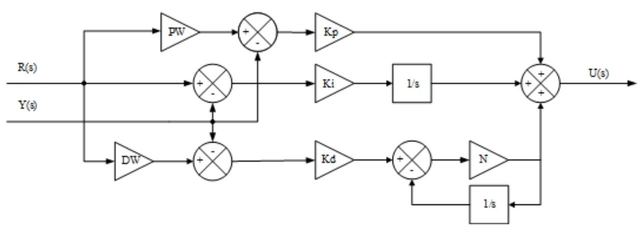

Fig. 2. Block diagram two-degree-of-freedom PID controller (self-developed).

III. ANT LION OPTIMIZER

The ALO is a nature-inspired metaheuristic algorithm designed to address complex optimization problems, including the tuning of control parameters in advanced control systems. The algorithm draws inspiration from the predatory behavior of antlions, members of the Myrmeleontidae family, particularly during their larval stage [13]. In nature, antlions construct conical pits in sandy terrain to trap the passing prey, usually ants, by inducing them to slide toward the center through rotational sand displacement. This behavior has served as the conceptual foundation for modeling the search and trap dynamics in optimization.

Translating this behavior into a computational framework, the ALO simulates the interaction between the antlions (elite solutions) and ants (candidate solutions) to guide the search process. As ants move randomly within bounded search spaces, they are gradually attracted toward elite antlions, resulting in convergence to global optima over successive iterations [14]. This mechanism has proven effective in maintaining a balance between exploration and exploitation in high-dimensional, nonlinear problem domains [15].

In the context of this study, the ALO algorithm is applied to optimize three essential parameters of the PID (2DOF-PID) controller: proportional gain, integral gain, and derivative gain. The objective is to minimize the control error, as evaluated through a selected performance index. The hunting process in ALO is abstracted into five primary stages, each corresponding to distinct phases of the antlion behavior, which together ensure adaptive search dynamics that reflect the unpredictable nature of real-world systems [16].

1. Stochastic process
2. Trap formation
3. Seizing
4. Capturing prey
5. Reconstruction

The observations of antlion behavior in natural settings have revealed a notable correlation between their underground activity and external factors, such as the hunger and lunar phases. Studies have shown that when subjected to hunger or full moon conditions, antlions tend to construct deeper and wider pits as a means of improving their chances of capturing prey. This instinctive hunting strategy has been abstracted into the ALO algorithm, where it serves as the foundation for balancing exploration and exploitation throughout the optimization process [17]. In the present work, the ALO algorithm was applied to fine-tune the control parameters of the PID (2DOF-PID) controller. This method provides multiple benefits, including enhanced global search capability, improved convergence speed, and an increased ability to escape the local optima features, particularly useful when optimizing in complex, nonlinear environments [18].

The algorithm was developed using MATLAB R2024a through a custom .m file, while the power system under evaluation, a PV-Reheat Thermal Power System, was modeled in SIMULINK. This integrated framework incorporates the 2DOF-PID controller for Load Frequency Control (LFC) and serves as the basis for evaluating the control performance, as illustrated in Figure 1.

IV. SIMULATION SETUP

To evaluate the performance of the ALO in tuning the parameters of the PID (2DOF-PID) controller, a series of simulations was carried out using the PV–Reheat Thermal Power System model introduced in Section 2. The main control objective was to reduce the frequency deviations caused by the load disturbances under dynamic and nonlinear operating conditions.

The 2DOF-PID controller comprises five tunable parameters: the proportional gain KP, the integral gain KI , the derivative gain KD, the initial feedback gain in the proportional domain (PW), and the initial feedback gain in the derivative domain (DW). To maintain the stability of the solution search and adhere to physical constraints, all five parameters are confined to the similar range of -2 to 2 [19]. The objective function used for parameter optimization is the Integral of Time-weighted Absolute Error (ITAE), which emphasizes the long-term performance by assigning greater weight to errors that occur later in the system response. This makes it particularly effective for reducing sustained deviations. ITAE is defined by:

$$\mathrm{ITAE}=\int_0^T |\Delta f(t)|\ dt \qquad (2)$$

where $\Delta f(t)$ denotes the frequency deviation at time t , and T represents the overall duration of the simulation.

The ALO algorithm was implemented as a custom .m file in MATLAB R2024a and integrated with the PV–Reheat Thermal Power System model in SIMULINK. The population consisted of 30 individuals, including both ants and antlions, and the maximum number of iterations was set to 50 to ensure adequate convergence. The simulation duration was selected to capture both the transient and steady-state system behavior. To evaluate the controller's performance, two gradual step load disturbances were introduced, one in Area 1 (reheat thermal unit) and one in Area 2. This scenario was chosen to reflect realistic operating conditions and assess the controller's effectiveness under nonlinear and time-varying dynamics.

The ideal parameter values obtained through ALO-based tuning were applied to replicate the dynamic behavior of the system under various load conditions. These results were then compared against those achieved by conventional control strategies, specifically PI and PID controllers, by employing widely accepted performance metrics, such as overshoot, settling time, and steady-state error, as displayed in Figure 3.

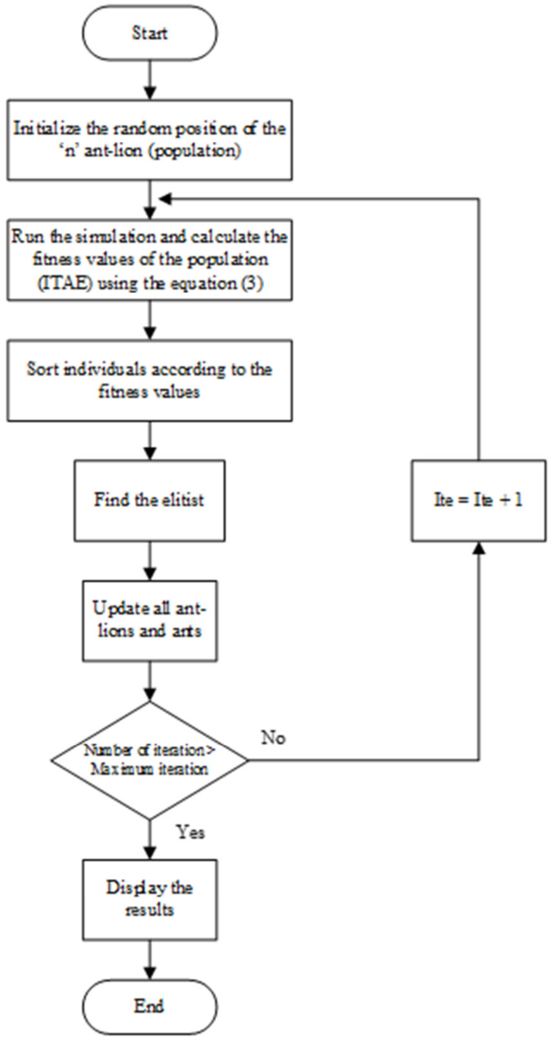

Fig. 3. Flowchart of the ALO (self-developed).

V. RESULTS AND DISCUSSION

This section delineates the simulation outcomes and performance evaluation of a 2DOF-PID controller, parameterized by the ALO algorithm. The primary aim of the tests is to assess the controller's ability to manage a PV-Reheat Thermal Power System under step load variations. The SLP is 10%, and it compares the control performance with the commonly utilized classic PID and PI controllers. The parameter values are presented in Table I.

This research review examines the primary performance metrics, including the settling time, maximum overshoot, minimum undershoot, signal smoothness, and long-term stability. Graphical and quantitative assessments are conducted to determine which control technique optimally maintains the system stability under complicated dynamic behavior, as seen in Table II.

Figure 4 portrays the frequency deviation response in Area 1 after a step load alteration. The comparison of the performance of 2DOF-PID, PID, and PI controllers reveals that the 2DOF-PID controller yields superior results, exhibiting the lowest undershoot, the smoothest response, and the shortest settling time, in contrast to the PID and PI controllers, which demonstrate oscillatory behavior and prolonged time to attain a steady state.

Figure 5 illustrates the frequency deviation response in Area 2 after a step load alteration. The simulation results indicate that, when comparing the performance of 2DOF-PID, PID, and PI controllers, the 2DOF-PID controller exhibits a greater initial overshoot; however, it effectively diminishes the system oscillations and achieves a steady state more rapidly than the PID and PI controllers, which continue to experience multiple oscillations during the mid-response phase.

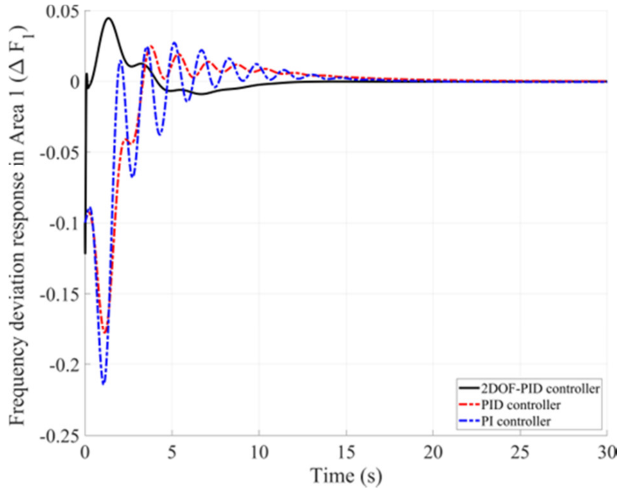

Fig. 4. Frequency deviation response in Area 1 under a step load disturbance, comparing 2DOF-PID, PID, and PI controllers.

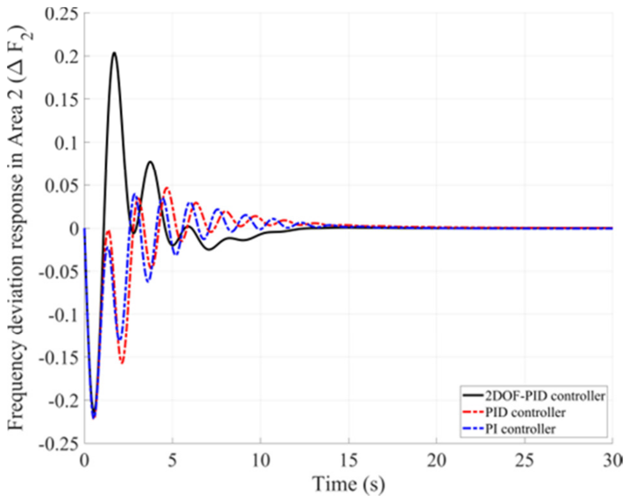

Fig. 5. Frequency deviation response in Area 2 under a step load disturbance, comparing 2DOF-PID, PID and PI controllers.

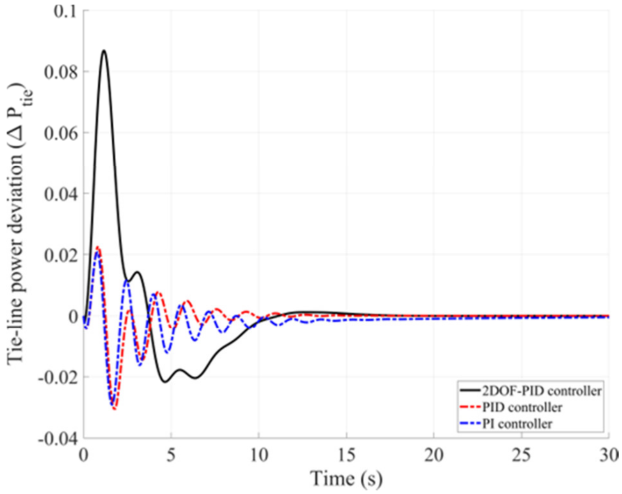

Fig. 6. Tie-line power deviation ΔP_{tie} response in Area under a step load disturbance, comparing 2DOF-PID, PID, and PI controllers.

Figure 6 depicts the power deviation response along the ΔP_{tie} transmission line in a two-area system following a step load shift, comparing the efficacy of 2DOF-PID, PID, and PI controllers. The 2DOF-PID controller, although exhibiting a higher initial peak value than its counterparts, may attenuate system vibrations more rapidly and attain a steady state more swiftly, whereas the PID and PI controllers demonstrate lower peak values but experience more oscillations before achieving a steady state.

TABLE I. PARAMETER VALUES FOR EACH CONTROLLER TYPE

Controller	**Area 1**				
	K_P	K_I	K_D	P_W	D_W
2DOF-PID	2.0000	2.0000	1.0530	0.2876	1.9949
PID	-2.0000	-0.7223	0.4487	-	-
PI	-1.9950	-0.7289	-	-	-
Controller	**Area 2**				
	K_P	K_I	K_D	P_W	D_W
2DOF-PID	-1.1592	-0.3102	1.9792	2.0000	1.9703
PID	-0.6531	-0.4091	-1.1076	-	-
PI	-1.3946	-0.1007	-	-	-

Table I presents the parameter values for each controller type utilized in the regulation of the PV-Reheat Thermal Power System, categorized into two regions: Area 1 and Area 2. Each region possesses distinct dynamic characteristics; hence, the parameter tuning must be adequately examined in relation to the system's environment.

Table II presents the performance indices for each controller type, 2DOF-PID, PID, and PI, employed to regulate the PV-Reheat Thermal Power System during a step load change, considering the frequency signal behavior in Area 1, Area 2, and the power deviation across the transmission line. The assessment criteria include the Settling Time: the duration required for the system to attain a steady state within ±5%. Overshoot: the signal value that surpasses the intended value following the disturbance. Undershoot: the lowest value of the signal during the first period, IAE: the cumulative total of absolute errors throughout time.

TABLE II. PERFORMANCE INDICES FOR EACH CONTROLLER TYPE

Performance	**2DOF-PID**		
	ΔF_1	ΔF_2	ΔP_{tie}
Settling time	11.336	12.153	14.158
Overshoot	0.0445	0.2035	0.0867
Undershoot	-0.1215	-0.2142	-0.0217
IAE	0.83128		
Performance	**PID**		
	ΔF_1	ΔF_2	ΔP_{tie}
Settling time	19.672	19.672	9.4728
Overshoot	0.0247	0.0465	0.0225
Undershoot	-0.1776	-0.2217	-0.0305
IAE	0.95149		
Performance	**PI**		
	ΔF_1	ΔF_2	ΔP_{tie}
Settling time	16.942	16.275	18.880
Overshoot	0.0272	0.0393	0.0208
Undershoot	-0.2139	-0.2208	-0.0291
IAE	0.93999		

The comparative analysis indicates that the 2DOF-PID controller outperforms all metrics, yielding markedly reduced settling times compared to the PID and PI across all domains, particularly in Δf_1 and Δf_2 , which decrease from 16–19 s to roughly 11–12 s. It possesses the most effective capability to minimize the overshoot and undershoot, evidenced by the lowest values of ΔP_{tie} at –0.0217 and overshoot at 0.0867, signifying a steady and secure reaction to overcontrol. The IAE value, indicative of the controller's overall efficiency in minimizing the error over time, revealed that the 2DOF-PID yielded the lowest IAE at 0.83128, whereas the PID and PI configurations produced values of 0.95149 and 0.93999, respectively.

In conclusion, the 2DOF-PID controller outperforms both categories of conventional controllers regarding the recovery speed, signal smoothness, and overall error minimization, rendering it highly appropriate for managing multi-area power generating systems amid unknown load disturbances.

VI. CONCLUSION

This study aims to design and evaluate the effectiveness of a 2DOF-PID controller, utilizing parameter optimization via the Ant Lion Optimizer (ALO), for frequency regulation in a Photovoltaic (PV)-Reheat Thermal Power System under sudden load fluctuations.

The simulation results and comparisons with the PID and PI controllers demonstrate that the proposed controller significantly reduces the frequency deviations, minimizes the overshoot and undershoot, and achieves a shorter settling time. Furthermore, it yields the lowest Integral of Absolute Error (IAE) value, indicating superior control efficiency over conventional methods. The originality of this work lies in the novel application of ALO to tune a 2DOF-PID controller within a PV-Reheat Thermal Power System, an integration not previously reported in the literature.

The primary contribution is the demonstration that such an integration markedly enhances the frequency stability and system robustness under nonlinear and dynamic load conditions, thus offering a promising control strategy for future hybrid energy systems.

Future research can extend this work by testing the ALO-tuned controller under stochastic load conditions or in multi-area systems incorporating renewable energy sources, such as wind and biofuels. Additionally, its performance could be benchmarked against other metaheuristic algorithms, including Grey Wolf Optimizer (GWO), WOA, or hybrid variants, to further validate its effectiveness.

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