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Optimizing Load Frequency Control in Power Systems: A Comparative Study of BWOA and PSO-Tuned PID Controllers

Devendra Patel*, Sandeep Bhongade*‡, Ankit Singh*, R S Mandloi**

*Department of Electrical Engineering, Research Scholar, Shri G.S.Institute of Technology & Science, Indore-03 M.P-INDIA

**Department of Electrical Engineering, Faculty, Shri G. S. Institute of Technology & Science, Indore-03 M.P-INDIA

(bhongadesandeep@gmail.com, devpatel30926@gmail.com, connect2ankitsign@gmail.com, ravindrasmandloi@yahoo.com)

‡ Corresponding Author; Sandeep Bhongade, Department of Electrical Engineering, Faculty, Shri G.S.Institute of Technology & Science, Indore-03 M.P-INDIA, Tel: +91 07312541569,

Fax: +91 07312432540, Email ID: bhongadesandeep@gmail.com

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Abstract- This paper investigates the application of advanced optimization algorithms, namely the Particle Swarm Optimization (PSO) and Black Widow Optimization Algorithm (BWOA), for tuning Proportional-Integral-Derivative (PID) controllers in load frequency control (LFC) systems. The study explores the performance of controllers under various tuning strategies, including the conventional Ziegler-Nichols method, PSO, and BWOA, focusing on power generation, power deviation, and frequency deviation. The BWOA, inspired by black widow spiders' hunting and survival strategies, emerges as a promising optimization method, showcasing superior performance compared to traditional and contemporary approaches. The results demonstrate that BWOA-tuned controllers exhibit enhanced dynamic response, stability, and efficiency in load frequency control systems.

Keywords: Black Widow Optimization Algorithm Load Frequency Control, Particle Swarm Optimization, Proportional-Integral-Derivative, Ziegler–Nichols.

1. Introduction

Ensuring the stable and reliable operation of a power system is of utmost importance for efficient electricity delivery. A crucial component in achieving this is Load Frequency Control (LFC), which holds a pivotal role in balancing power generation with load demand. LFC is implemented to guarantee the effective operation and control of power systems, playing a vital role in supplying consumers with continuous, high-quality, and reliable electrical energy.

In case of sudden changes in consumer demands in power systems; Undesirable consequences may occur, such as the system frequency deviating from its nominal value and eventually the system becoming unstable [1].

It is seen that the counter frequency changes if there is a difference between the power outputs of the synchronous generators in the system and the instantaneous load changes. In other words, if a balance cannot be established between the amount of power produced and the amount requested, the frequency increases or decreases. If the amount of power produced is greater than the demand, the operating speed of the generators will increase and, as a result, the frequency will increase. In the opposite case, that is, if the amount of power demanded in the system is greater than the production value, the frequency will decrease [2].

A well-tuned LFC system ensures that the system frequency remains within acceptable limits, avoiding deviations that could lead to disruptions and instability. In the pursuit of enhancing the performance of LFC systems, advanced control strategies have been sought, with optimization techniques proving instrumental in achieving optimal tuning of controllers [3].

This research embarks on a comprehensive exploration, delving into the application of the PSO and BWOA. Both algorithms play a crucial role in the fine-tuning of PID controllers, specifically within the intricate domain of load frequency control. The initial tuning of PID controllers is accomplished using the Ziegler–Nichols method. Subsequently, optimization with PSO and BWOA aims to pinpoint optimal PID parameters that minimize predefined cost or error functions associated with the LFC system. This integration of multiple optimization algorithms is designed to address the challenges posed by the diverse and evolving operating conditions present in modern power systems.

Motivated by the nuanced dynamics of modern power systems and the imperative for adaptability in controller tuning, this research presents a distinctive and innovative approach. Conventional tuning methods may prove inadequate in optimizing the performance of LFC systems, prompting the utilization of BWOA and PSO. These optimization algorithms offer adaptive and efficient approaches inspired by natural behaviors. The selection of these algorithms is grounded in their adaptability, simplicity, and efficiency, making them ideal candidates for enhancing the tuning process of PID controllers within the intricate realm of load frequency control.

The selection of the Black Widow Optimization Algorithm is driven by its distinctive features, notably its strategic hunting approach that effectively navigates the solution space and a reproductive strategy that broadens the quest for optimal solutions. This algorithm's adaptability to diverse optimization problems, coupled with its simplicity and efficiency, positions it as an appealing choice for refining the tuning process of PID controllers.

In contrast, conventional PSO serves as a standard method for optimizing the parameters of Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) controllers. PSO involves a population-based optimization technique where potential solutions, represented as particles, iteratively adjust their positions in the solution space based on their individual and collective experiences. While PSO is a widely recognized and utilized optimization method, the choice to integrate the more advanced Black Widow Optimization Algorithm (BWOA) arises from the latter's demonstrated superiority in terms of adaptability, exploration efficiency, and solution diversity. The unique characteristics of BWOA make it a more advanced and promising method for optimizing the parameters of P, PI, and PID controllers, offering a sophisticated alternative to conventional optimization approaches.

This paper not only investigates but also compares the effectiveness of the Black Widow Optimization Algorithm and Particle Swarm Optimization in optimizing PID controller parameters within diesel, wind, and solar generation systems, all within the context of load frequency control. The research objectives encompass an in-depth exploration of the adaptability and efficiency of these optimization algorithms, an assessment of their impact on system performance metrics, and the provision of valuable insights into the optimization of PID controllers in the context of dynamic and interconnected power systems.

2. Literature Review

In the contemporary era, amidst the swift evolution of energy needs and technological advancements, there has been a progressive rise in the adoption of renewable energy sources (RES). This trend is observed alongside conventional electricity generation systems like gas and thermal power plants. The landscape of modern electrical power systems has gained complexity by incorporating RES, including wind, solar, hydro, biomass, geothermal, wave, and tidal energy, in conjunction with conventional power generation units. However, the amalgamation of diverse electricity generation units to meet escalating energy demands, coupled with resultant imbalances between energy production and consumption, contributes to frequency and voltage distortions within interconnected power systems.

In recent times, challenges termed as stability issues in power systems have emerged as prominent subjects under investigation by research groups in the field of power systems. Load Frequency Control (LFC), also known as Automatic Generation Control (AGC), stands out as a crucial mechanism to address these challenges. Its primary goal is to ensure the synchronous and harmonious operation of modern electrical power systems, comprising diverse electricity generation units, within interconnected systems, thereby delivering high-quality energy to consumers. In essence, LFC can be articulated as the maintenance of frequency changes and connected power flows within predefined limits. This involves the delicate balance between load demand on the production and consumer sides, despite the continual fluctuations within the power system. Moreover, effective LFC necessitates the adept design and deployment of the most suitable controller structure to monitor alterations and minimize Field Control Error (FCE) for the efficient control and operation of modern electrical power systems [1-7].

In recent times, researchers in the field of power systems addressing the Load Frequency Control (LFC) issue, recognized as one of the pivotal stability challenges in modern power systems, have sought to enhance system performance. They have explored a plethora of controller structures and optimization algorithms to mitigate stability problems. The existing body of literature encompasses various investigations aiming to mitigate the fluctuations or oscillations in frequency and power flow within connection lines that arise with changing operational conditions in power systems. Two primary focal points emerge within these studies: the optimization algorithms employed for refining controller design and the optimization of controller parameters. Optimization algorithms stand out as highly influential parameters for enhancing performance in tackling the LFC problem. Furthermore, the controller structures devised for addressing this problem exhibit distinct advantages and disadvantages in comparison to one another.

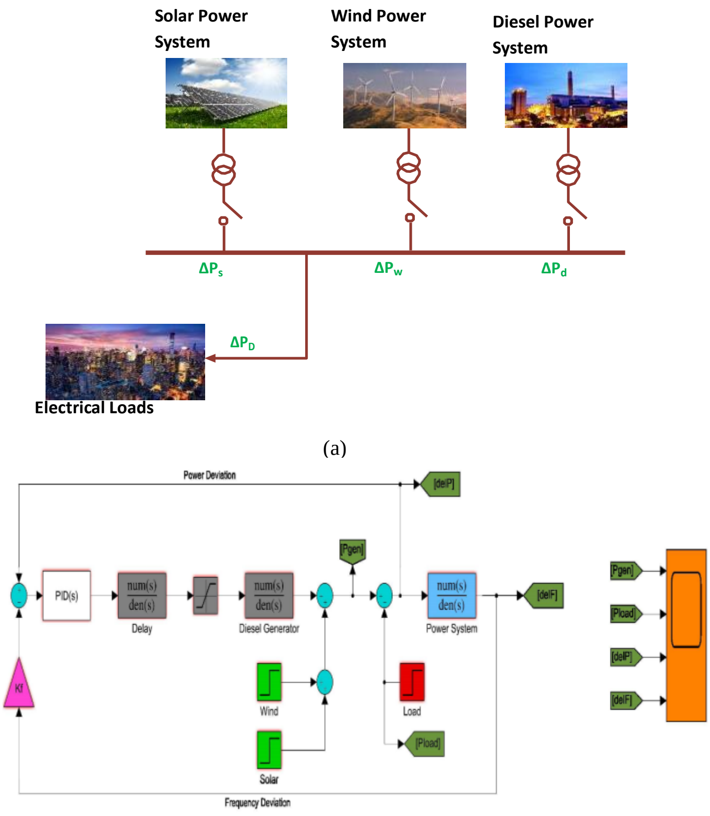
After conducting an extensive literature review, it becomes evident that owing to their adaptability, conventional PID and PI controllers have been commonly employed in LFC designs [8]. Various optimization algorithms, such as Gravitational Search Algorithm (GSA) [9], Enhanced Stochastic Fractal Search (ESFS) [10], Teaching–Learning-Based Optimization (TLBO) [11], Imperialist Competitive Algorithm (ICA) [12], Bacterial Foraging Optimization Algorithm (BFOA) [13] [14], Ant Colony Optimization (ACO) [15], Genetic Algorithm (GA) [16], Flower Pollination Algorithm (FPA) [17], and Whale Optimization Algorithm (WOA) [18], have been utilized to optimize PID controller parameters. The literature asserts that a PID controller with optimized parameters outperforms many other controller structures in enhancing system performance under specific operating conditions across diverse power systems. Moreover, a study introduces PI, PID, and Proportional-Integral-Derivative-Plus-Second-Order-Derivative controllers as separate secondary controllers. In [19], the controller parameters are tailored using Ant Lion Optimization (ALO), demonstrating the superior performance of the PID + DD controller concerning shorter settling times, reduced overshoot, and minimized oscillations. In the study by authors referenced in [20], they delved into the fine-tuning process of a sigmoid PID controller designed for an autonomous voltage regulator, employing a nonlinear sine-cosine algorithm. Additionally, as outlined in the work of researchers cited in [21], a detailed elucidation was provided regarding the optimization of a fractional order PID controller tailored for an automatic voltage regulator (AVR) system, aiming to achieve its optimal operational settings. In a similar vein, the utilization of a PSO-PID controller for LFC within a standalone multi-source power system was explored by the scholars documented in [22]. Furthermore, computational scrutiny concerning PID and PSO-PID optimization techniques for Multi-Input Multi-Output (MIMO) process control systems was conducted by the authors mentioned in [23]. The authors referenced in [24] conducted a comparative study on load frequency regulation in a deregulated electricity system across multiple areas, employing soft computing techniques. The research contrasts the performance of auto-tuned PID, genetic algorithm (GA), and particle swarm optimization (PSO) controllers under unregulated conditions, specifically focusing on load frequency regulation in two-area power systems. Furthermore, in [25], authors introduced a linked power system featuring thermal and hydroelectric plants with reheat in each location. To enhance system realism, Governor Dead Band (GDB) was implemented in each plant, with controllers including fuzzy PID, fractional-order PID (FOPID), and proportional–integral–derivative (PID). The study employed robust heuristic algorithms, utilizing teaching learning-based optimization (TLBO) and Differential evolution (DE) to determine optimal controller gains, with DE-optimized controllers yielding superior performance compared to TLBO-tuned counterparts. Additionally, in [26], a heuristic intelligent optimization algorithm was proposed to optimize controller parameters for interconnected power systems in two regions. This method utilized regional control deviation as the objective function and applied PID controllers with an improved whale optimization algorithm to minimize load frequency fluctuations within specified ranges.

In this research paper, conventional P, PI, and PID controller structures are devised to mitigate oscillations in frequency and network power variations within a multi-source single-domain modern electric power system featuring renewable energy sources. These controller structures undergo testing to enhance system performance under varying operating conditions. Despite the positive impact observed, instances occur where controller parameters, derived from either user experience or mathematical methods, may fall short in effectively improving system performance. To enhance the study's robustness and effectiveness, the controller parameters undergo meticulous fine-tuning using the PSO algorithm [27] before the implementation of the advanced BWOA optimization [28]. This multi-step optimization approach is systematically employed to elevate the performance of P, PI, and PID controllers, thereby contributing to a more resilient and optimized control strategy tailored to the dynamic nature of the electric power system.

3. Proposed Methodology

3.1. Modeling of A Multi-Source Single-Zone Power System

Within this segment, we present a dynamic test system characterized by multiple sources within a single zone, encompassing renewable energy resources. The focal point of examination revolves around the Load Frequency Control (LFC) problem, deemed crucial in addressing stability issues within contemporary power systems. The power system's transfer function model is meticulously crafted using the MATLAB/Simulink environment, aligning with LFC requirements. The proposed schematic diagram for the test system is delineated in Figure 1(a), while Figure 1(b) portrays the commonly utilized transfer function model for LFC design and analysis. This composite system encompasses three distinct units: diesel, wind, and solar.



(a)

(b)

Fig. 1. "(a) Comprehensive schematic diagram and (b) Transfer function model of the test system"

3.2. Modeling of Controllers

Within the power system framework, the controller output ΔP_{ref} signifies the inputs pertaining to the load disturbance ΔP_D control field. The generator frequency error Δf, along with the field control error (FCE), serves as the outputs emanating from the control field. The mathematical expression delineating the FCE specific to diesel, wind, and solar power systems is encapsulated in Equation (1).

$$FCE = -B\Delta f \tag{1}$$

Here, B defines the frequency bias parameter. The mathematical expression of the speed governor for diesel, wind, and solar power systems is shown in Equation (2).

$$G_g(s) = \frac{\Delta P_g}{\Delta P_v} = \frac{1}{sT_g+1} \tag{2}$$

In this context, ΔP_v represents the input directed towards the speed regulator, and the determination of this quantity is articulated by Equation (3). The parameter R assumes the role of defining the speed regulation parameter within the speed regulator, while ΔP_{ref} embodies the command dispatched to the system, specifying the reference power value to be generated.

$$\Delta P_v = \Delta P_{ref} - \frac{1}{R}\Delta f \tag{3}$$

The system comprises the representation of the generator pair and load, characterized by the K_{ps} gain and T_{ps} time constant. The mathematical articulation of the frequency error at each field output is elucidated through the following equations.

$$G_p(s) = \frac{K_{ps}}{sT_{ps}+1} \tag{4}$$

$$\Delta f(s) = G_p(s)[\Delta P_t(s) - \Delta P_D(s)] \tag{5}$$

Equation (5) represents the mathematical expression for the frequency error (Δf) at each field output in the power system, considering diesel, wind, and solar power systems.

Here,

- $\Delta f(s)$ is the Laplace transform of the frequency error.
- $G_p(s)$ is the transfer function representing the generator pair and the load in the system, with KpsKps gain and TpsTps time constant.
- $\Delta P_t(s)$ is the Laplace transform of the total power generated by all sources.
- $\Delta P_D(s)$ is the Laplace transform of the load disturbance.

This equation captures the relationship between the frequency error and the difference between the total generated power and the load disturbance in the power system, incorporating the dynamics of the generator pair and load.

The overall power generated (P_{gen}) in the power system, considering diesel (P_d), wind (P_w), and solar (P_s) power systems, can be expressed as the sum of their individual contributions:

$$P_{gen} = P_d + P_w + P_s \tag{6}$$

Here,

- P_d is the power generated by the diesel power system.
- P_w is the power generated by the wind power system.
- P_s is the power generated by the solar power system.

This formula provides a comprehensive representation of the overall power generation in the multi-source single-zone power system, taking into account the contributions from diesel, wind, and solar power systems.

The above-mentioned equations represent the modeling of a multi-source single-zone power system specifically including diesel, wind, and solar power systems.

3.3. Ziegler–Nichols Method for Tuning of Controllers

1) Proportional (P) Controller

The Proportional (P) controller serves as a foundational feedback controller, modifying the control input proportionally to the error signal. This error signal represents the disparity between the desired setpoint and the current system output.

Mathematical Formulation: The output of the P controller $(u(t))$ is given by:

$$u(t) = K_p \cdot e(t) \tag{7}$$

Where:

K_p is the proportional gain.

$e(t)$ is the error signal at time t.

2) Proportional-Integral (PI) Controller

The PI controller incorporates an integral term, in addition to the proportional term, to eliminate steady-state error and improve system stability.

Mathematical Formulation: The output of the PI controller $(u(t))$ is expressed as:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau)\,d\tau \tag{8}$$

Where:

K_p is the proportional gain.

K_i is the integral gain.

$e(t)$ is the error signal at time t.

3) Proportional-Integral-Derivative (PID) Controller

The PID controller builds upon the PI controller by introducing a derivative term that considers the anticipated future behavior derived from the rate of change in the error signal.

Mathematical Formulation: The output of the PID controller $(u(t))$ is given by:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau)\,d\tau + K_d \cdot \frac{de(t)}{dt} \tag{9}$$

Where:

K_p is the proportional gain.

K_i is the integral gain.

K_d is the derivative gain.

$e(t)$ is the error signal at time t.

These controllers have a pivotal function in governing the system dynamics of the electric power system, with the objective of reducing deviations from the desired setpoint and improving the overall system performance. In the subsequent sections, the parameters K_p, K_i, and K_d undergo initial tuning through the Ziegler–Nichols method and are subsequently optimized using advanced optimization algorithms. This includes the utilization of PSO followed by the application of the BWOA, with the aim of systematically amplifying the effectiveness of the control strategy within the dynamic framework of the power system.

3.4. Ziegler–Nichols Method for Tuning of Controllers

The Ziegler–Nichols method stands as a frequently employed heuristic strategy for fine-tuning PID controllers. This approach entails the recognition of the critical gain and oscillation period within the system under specific conditions, subsequently utilizing these values to ascertain the appropriate controller gains. The ensuing section provides an intricate delineation of the Ziegler–Nichols method tailored for each category of controller:

4) Ziegler–Nichols Method for Proportional (P) Controller

Determine Ultimate Gain (K_u)*:*

- Gradually increase the proportional gain (K_p)until sustained oscillations are observed.
- The critical gain at the onset of sustained oscillations is denoted as K_u.

Calculate Proportional Gain (K_p)*:*

- Set K_p to be approximately 0.6 times K_u:

$$K_p = 0.6 \cdot K_u \tag{10}$$

5) Ziegler–Nichols Method for Proportional-Integral (PI) Controller

The

Determine Ultimate Gain (K_u) *and Oscillation Period* (P_u)*:*

- Follow the same procedure as for the P controller.
- Measure the oscillation period (P_u).

Calculate Proportional Gain (K_p) *and Integral Gain* (K_i)*:*

- Set K_p to be approximately 0.45 times K_u:

$$K_p = 0.45 \cdot K_u \tag{11}$$

- Set K_i to be $\frac{K_p}{P_u}$:

$$K_i = \frac{K_p}{P_u} \tag{12}$$

6) Ziegler–Nichols Method for Proportional-Integral-Derivative (PID) Controller

Determine Ultimate Gain (K_u) *and Oscillation Period* (P_u)*:*

- Follow the same procedure as for the P controller.
- Measure the oscillation period (P_u).

Calculate Proportional Gain (K_p)*, Integral Gain* (K_i)*, and Derivative Gain* (K_d)*:*

- Set K_p to be approximately 0.6 times K_u:

$$K_p = 0.6 \cdot K_u \tag{13}$$

- Set K_i to be $\frac{2K_p}{P_u}$:

$$K_i = \frac{2K_p}{P_u} \tag{14}$$

- Set K_d to be $\frac{K_p \cdot P_u}{8}$:

$$K_d = \frac{K_p \cdot P_u}{8} \tag{15}$$

The Ziegler–Nichols method provides initial tuning parameters for P, PI, and PID controllers based on system characteristics observed during experiments. These initial parameters can then be further fine-tuned using advanced optimization algorithms like PSO and the BWOA to enhance the controllers' performance in the dynamic context of the electric power system.

3.5. Particle Swarm Optimization for Optimizing PID Parameters

The PSO methodology emerges as a heuristic optimization approach inspired by the collective behavior observed in birds and fish. In the present research, the application of PSO is instrumental in the systematic fine-tuning of parameters associated with P, PI, and PID controllers. The subsequent section offers an elaborate exposition of the PSO optimization method tailored to each category of controller:

7) PSO Optimization for Proportional (P) Controller

1. Initialize Particles: Commence by setting the initial conditions for particles, assigning random positions and velocities within the parameter space that symbolizes the proportional gain (K_p).
2. Objective Function: Define an objective function J that evaluates the performance of the P controller:

$$J = Objective(K_p) \tag{16}$$

   This objective function quantifies the controller's performance, considering criteria such as minimizing steady-state error or reducing overshoot.

3. Update Particle Positions and Velocities: Iterate the adjustment of particle positions and velocities according to the PSO equations.:

$$v_i(k+1) = w \cdot v_i(k) + c_1 \cdot r_1 \cdot \big(p_i(k) - x_i(k)\big) + c_2 \cdot r_2 \cdot \big(g(k) - x_i \tag{17}$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \tag{18}$$

4. Update Personal and Global Best Positions: Revise the personal best positions $p_i(k+1)$ and the global best position $g(k+1)$ in accordance with the objective function
5. Repeat: Repeat steps 3 and 4 until a convergence criterion is met.
6. Extract Tuned Parameters: The tuned parameter for the P controller (K_p) is obtained from the particle with the best fitness, which minimizes the objective function J.

8) PSO Optimization for Proportional-Integral (PI) Controller

Extend the process to accommodate two parameters (proportional gain K_p and integral gain K_i).

9) PSO Optimization for Proportional-Integral-Derivative (PID) Controller

Similarly, extend the process to include three parameters (proportional gain K_p, integral gain K_i, and derivative gain K_d).

In each case, the objective function is crucial for assessing the controller's performance, and the PSO optimization method systematically searches for parameter values that minimize this objective function.

3.6. Black Widow Spider Optimization Algorithm (BWOA) for Tuning P, PI, and PID Controllers

BWOA is a meta-heuristic optimization algorithm developed to capture spiders' prey and optimize resources. This algorithm was designed inspired by the hunting and survival strategies of spiders in nature. Spiders' hunting behavior is generally fast, effective and strategic. This algorithm mimics the ability of Black Widow Spiders to capture their prey and use resources more effectively [29]. Below is a detailed description of the BWOA optimization for tuning P, PI, and PID controllers.

1. Initialization:
    - Create an initial population of candidate solutions, representing potential values for the controller parameters of P, PI, and PID controllers.
2. Movement Strategy:
    - The spider's movement within the optimization space is defined by two different strategies: linear and spiral.
    - Linear Movement for P Controller:

$$K_p(t+1) = \begin{cases} K_p^*(t) - m \cdot K_{p_{r_1}}(t), & if\ rand(\cdot) \le 0.3 \\ K_p^*(t) - \cos(2\pi\beta)\, K_p(t) & Otherwise \end{cases} \tag{19}$$

Here,

- ○ $K_p(t+1)$: New proportional gain of the P controller.
- ○ $K_p^*(t)$: Best proportional gain found in the previous iteration.
- ○ m, r_1, β: Randomly generated parameters.

- Spiral Movement for PI Controller:

$$K_i(t+1) = K_i^*(t) - \cos(2\pi\beta)\, K_i(t) \tag{20}$$

- ○ Here, similar to P controller with $K_i(t+1)$ and $K_i^*(t)$ representing integral gain.

- Spiral Movement for PID Controller:

$$K_d(t+1) = K_d^*(t) - \cos(2\pi\beta)\, K_d(t) \tag{21}$$

- ○ Similar to P and PI controllers with $K_d(t+1)$ and $K_d^*(t)$ representing derivative gain.

3. Pheromones:
    - Pheromones are utilized to guide the search process and represent the quality of potential controller solutions.
    - Pheromone ratio for each controller parameter:

$$pheromone\ (i) = \frac{fitness_{max} - fitness(i)}{fitness_{max} - fitness_{min}} \tag{22}$$

- Replacement Strategy for P Controller:

$$K_p(t) = K_p^*(t) + \frac{1}{2}\left[K_{p_{r_1}}(t) - (-1)^{\sigma} K_{p_{r_2}}(t)\right] \tag{23}$$

- Replacement Strategy for PI Controller:

$$K_i(t) = K_i^*(t) + \frac{1}{2}\left[K_{i_{r_1}}(t) - (-1)^{\sigma} K_{i_{r_2}}(t)\right] \tag{24}$$

- Replacement Strategy for PID Controller:

$$K_d(t) = K_d^*(t) + \frac{1}{2}\left[K_{d_{r_1}}(t) - (-1)^{\sigma} K_{d_{r_2}}(t)\right] \tag{25}$$

- ○ Where, σ is a binary number randomly generated.

4. Time Complexity:
    - The time complexity of BWOA is related to the maximum number of iterations (T_{max}), the population size (S_{pn}), and the computational time complexity of evaluating the function value of the optimization problem $(O(f))$.Mathematically expressed as:

$$O(T_{max} \cdot S_{pn} \cdot f) \quad (26)$$

The BWOA method provides an adaptive and efficient approach for tuning the parameters of P, PI, and PID controllers. By emulating the hunting and reproductive strategies of black widow spiders, the algorithm balances exploitation and exploration, aiming to converge towards optimal controller parameters. This application of BWOA in the context of load frequency control systems holds promise for improving the performance and adaptability of controllers in dynamic power systems.

4. Simulation Results and Discussion

The simulation results illustrate a comprehensive comparative analysis of power generation, power deviation, and frequency deviation with P, PI, and PID controllers under different tuning methodologies. Figures 2-7 depict the performance of controllers tuned by the conventional Ziegler-Nichols method, highlighting their limitations. However, the breakthrough emerges in Figures 8 and 9, where a comparative analysis of power and frequency deviation reveals the superior performance of controllers tuned by two advanced optimization methods, PSO and BWOA.

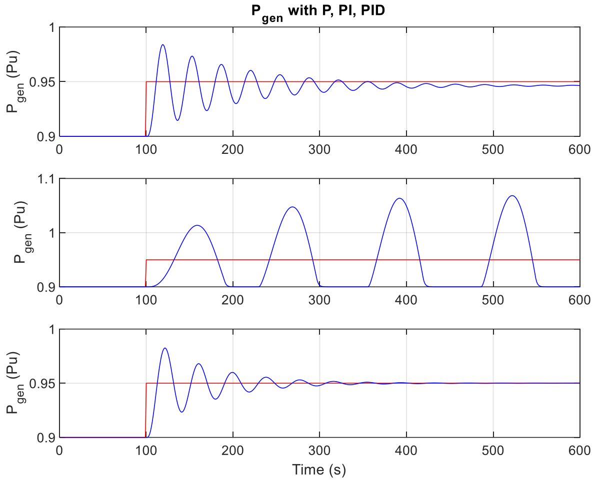


Fig. 2. Power generation with P, PI, and PID controllers

Figure 2 displays the power generation results achieved using three distinct controllers: proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID). Each controller has been fine-tuned to achieve optimal performance in regulating power generation. The graph provides a clear depiction of how these optimized controllers effectively maintain steady power output over time, showcasing their superior performance compared to untuned counterparts.

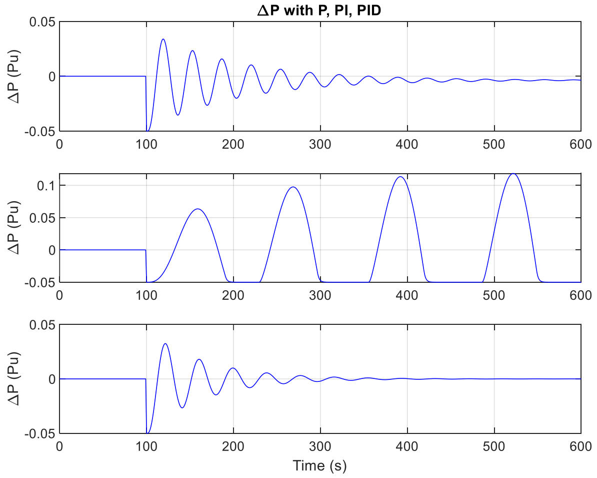


Fig. 3. Power deviation with P, PI, and PID controllers

Figure 3 illustrates the minimal power deviation achieved by systems employing proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers. Through meticulous tuning, these controllers have demonstrated remarkable effectiveness in minimizing deviations from the desired setpoint, ensuring stable power output throughout the operation.

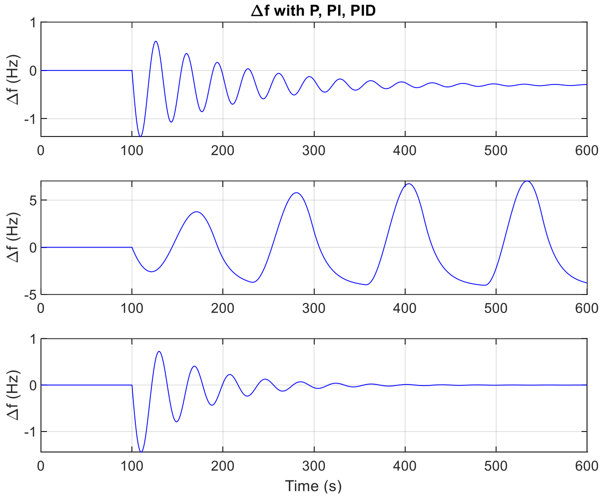


Fig. 4. Frequency deviation with P, PI, and PID controllers

In Figure 4, the frequency deviation of a power system controlled by proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers is showcased. Through rigorous optimization, these controllers have significantly enhanced frequency stability, as evidenced by the minimal deviations observed over time. This underscores their ability to maintain system stability even under varying operating conditions.

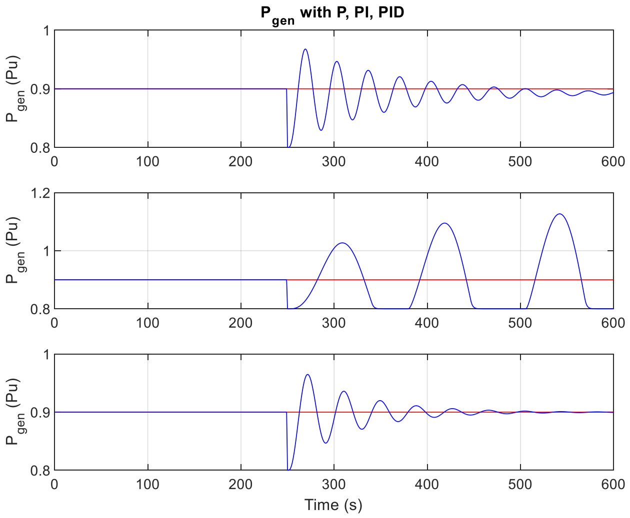


Fig. 5. Power generation with P, PI, and PID controllers tuned by Ziegler-Nichols method

Figure 5 highlights the optimized power generation achieved by systems utilizing proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers tuned using the Ziegler-Nichols method. Through precise parameter tuning, these controllers have attained peak performance, ensuring efficient and stable power generation operations.

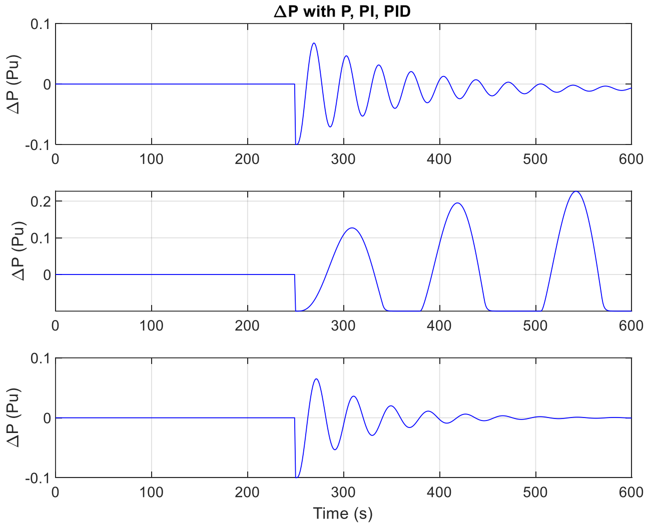


Fig. 6. Power deviation with P, PI, and PID controllers tuned by Ziegler-Nichols method

Figure 6 illustrates the minimized power deviation achieved by systems employing proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers tuned using the Ziegler-Nichols method. Through meticulous tuning based on this method, these controllers have effectively reduced power deviations to negligible levels, ensuring precise control and stability in power generation.

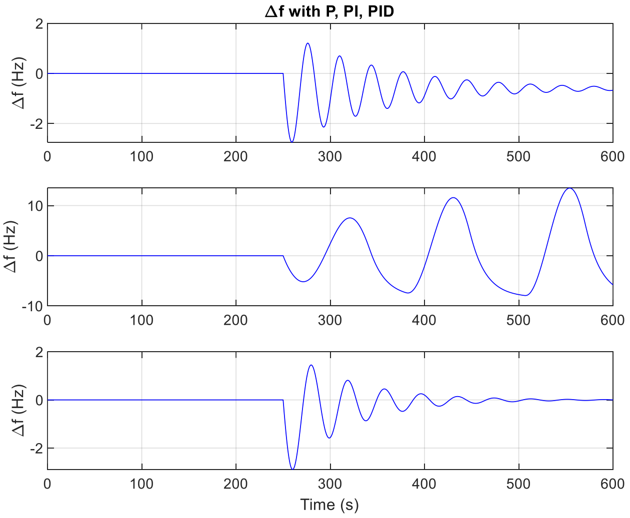


Fig. 7. Frequency deviation with P, PI, and PID controllers tuned by Ziegler-Nichols method

Figure 7 showcases the enhanced frequency stability achieved by systems controlled by proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers tuned using the Ziegler-Nichols method. Through optimized parameter tuning, these controllers have significantly minimized frequency deviations, ensuring consistent and stable operation of the power system.

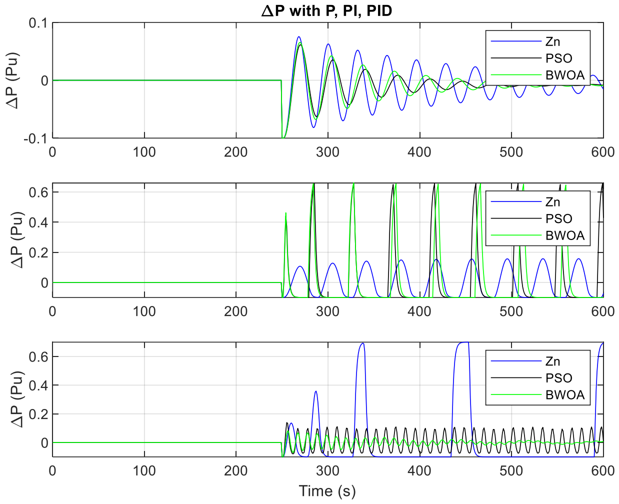


Fig. 8. Comparative analysis of power deviation with P, PI, and PID controllers tuned by Ziegler-Nichols, PSO and BWOA methods

In Figure 8, a comparative analysis of power deviation from the desired setpoint is presented for systems employing proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers tuned using different optimization methods: Ziegler-Nichols, Particle Swarm Optimization (PSO), and Biogeography-Based Optimization Algorithm (BWOA). The results highlight the superior performance of controllers tuned using BWOA, showcasing its effectiveness in achieving minimal power deviations and ensuring stable power generation. Notably, BWOA outperforms both Ziegler-Nichols and PSO methods, underscoring its efficacy in fine-tuning controllers for load frequency control systems.

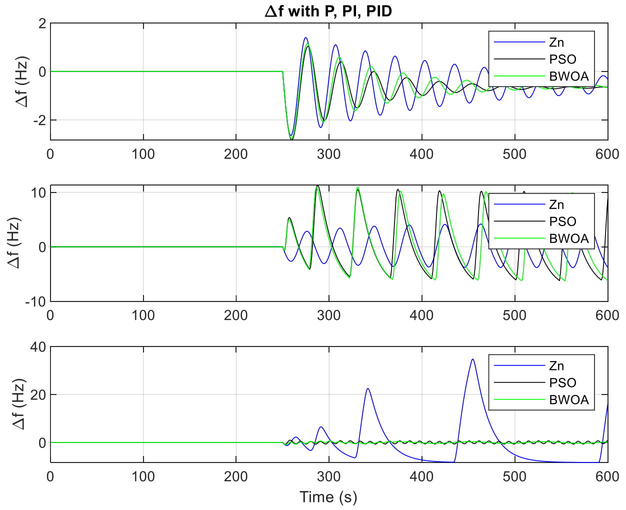


Fig. 9.Comparative analysis of frequency deviation with P, PI, and PID controllers tuned by Ziegler-Nichols, PSO and BWOA methods

Figure 9 presents a comparative analysis of frequency deviation in a power system controlled by proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers tuned using various optimization methods: Ziegler-Nichols, Particle Swarm Optimization (PSO), and Biogeography-Based Optimization Algorithm (BWOA). The results demonstrate the effectiveness of BWOA in enhancing frequency stability compared to traditional tuning methods like Ziegler-Nichols and modern optimization techniques like PSO. The superior performance of BWOA in improving the dynamic response and overall stability of power systems is evident, establishing its efficacy as a robust optimization approach for power system control.

5. Conclusion

In conclusion, the paper underscores the pivotal role of advanced optimization methodologies in fine-tuning PID controllers for load frequency control, particularly in dynamic power system environments. Through a comprehensive comparative analysis, it becomes evident that the Biogeography-Based Optimization Algorithm (BWOA) surpasses both traditional Ziegler-Nichols and contemporary Particle Swarm Optimization (PSO) techniques, showcasing superior adaptability and efficacy in parameter tuning. This study offers valuable insights into the potential of BWOA as a robust tool for optimizing controller performance, thus addressing the intricate dynamics of modern power systems. The findings highlight the distinctive features of BWOA, such as its adaptability and efficiency, positioning it as a promising solution for mitigating the complexities inherent in contemporary power systems. By laying emphasis on BWOA's ability to achieve enhanced dynamic response and stability, this research paves the way for its broader application in power system optimization and control. Future investigations could delve into real-time scenarios, examining BWOA's performance under varying load patterns, integration of renewable energy sources, and response to system disturbances.

Moreover, exploring BWOA's adaptability to diverse control strategies and its potential in addressing specific challenges within power systems represents a promising avenue for further research. By extending the scope to encompass a wider array of control scenarios and system configurations, future studies can provide deeper insights into the efficacy and versatility of BWOA in optimizing power system operations. Ultimately, this research contributes to advancing the understanding and application of advanced optimization techniques in the realm of power system control, laying a solid foundation for continued exploration and innovation in this critical domain.

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