Journal of Mechatronics, Electrical Power, and Vehicular Technology 14 (2023) 166-176

Journal of Mechatronics, Electrical Power, and Vehicular Technology

CrossMark

e-ISSN: 2088-6985
p-ISSN: 2087-3379

mev.brin.go.id

Optimization of load frequency control using grey wolf optimizer in micro hydro power plants

Irvandy Ilza Novendra [a], I Made Wirawan [a], Arya Kusumawardana [b, *], Aung Ko Latt [c]

[a] Department of Electrical and Informatics Engineering, Universitas Negeri Malang
Semarang Street no. 5, Malang, 65145, Indonesia

[b] Faculty of Applied Science and Technology, Universitas Negeri Malang
Semarang Street no. 5, Malang, 65145, Indonesia

[c] Executive Engineer (EE), Electric Power Generation Enterprise (EPGE), Ministry of Electric Power (MOEP), Building No. 27, Nay Pyi Taw, 15011, Myanmar

Received 13 October 2023; 1st revision 13 November 2023; 2nd revision 30 November 2023;
Accepted 3 December 2023; Published online 29 December 2023

Abstract

Micro hydro power plants (MHPP) is one of the renewable energy that can be utilized as a distributed generation with controllable power output. One common issue in MHPP systems is the non-constant rotation of the generator caused by load fluctuations. This instability leads to variable frequencies, which can potentially harm electrical equipment. To address this problem, the volume of water entering through the governor can be adjusted to synchronize the turbine and generator rotation with the load. This approach helps dampen frequency oscillations and ensures that the system operates within desired limits. Therefore, there is a need for technology that can enhance the performance of micro hydro power plant units, specifically load frequency control (LFC). This research proposes the application of the grey wolf optimizer (GWO) algorithm to optimize the PID controller parameters for MHPP LFC. MHPP has been modeled in both isolated and grid-connected modes using Simulink MATLAB R2020a. The best cost function value for an isolated mode system was obtained with ISE_{im}, yielding a value of 0.067653, while for a grid-connected mode system, it was achieved with ISE_{gm}, with a value of 0.015861. The results of the frequency deviation response performance of the LFC using GWO indicate that the fastest settling time was achieved with the cost function $ITAE_{im}$ in isolated mode, and with IAE_{gm} in grid-connected mode. The cost function that produces the smallest peak overshoot and peak undershoot parameter values varied depending on changes in the system load.

Keywords: load frequency control; grey wolf optimizer; micro hydro power plant.

I. Introduction

The limited availability of fossil fuels has led to the increased use of renewable energy as an alternative. Some of the alternative sources of energy include wind, solar, and water. Indonesia is an archipelagic country with abundant natural resources, particularly water. Therefore, Indonesia has a great potential to develop large-scale and small-scale hydropower plants to utilize these resources as environmentally friendly alternative energy. Small-scale hydropower plants that are widely developed are micro hydro power plants (MHPP). MHPP has technical and economic advantages. This is because micro hydro does not require a large water storage installation and is environmentally friendly [1].

Despite having a number of advantages, MHPP is also facing a number of challenges, including maintaining the stability of frequency and voltage [2][3]. A common problem in the MHPP system is the non-constant rotation of the generator due to load changes. This results in unstable frequency that can potentially damage electrical equipment [4]. To address this problem, the volume of water entering through the governor has been adjusted to enable the turbine and generator's rotation to adapt to the load. This adjustment dampens the frequency oscillation and maintains the system performance within the desired limits [5]. Consequently, technology was needed to enhance the micro hydro

* Corresponding Author. Tel: +62 857 4916 6444
E-mail address: arya.kusumawardana.ft@um.ac.id

doi: https://dx.doi.org/10.14203/j.mev.2023.v14.166-176
2088-6985 / 2087-3379 ©2023 National Research and Innovation Agency

How to Cite: I.I. Novendra, I.M. Wirawan, A. Kusumawardana, A.K. Latt, "Optimization of load frequency control using grey wolf optimizer in micro hydro power plants," *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, vol. 14, no. 2, pp. 166-176, Dec. 2023.

power unit's performance, namely load frequency control (LFC). LFC incorporates a PID-based controller that requires optimization to achieve the desired performance [6]. The PID controller comprises three parameters: proportional gain, integral gain, and derivative gain, all of which influence the system's output response [7]. K_p governs the extent to which the controller's output changes in response to error fluctuations, K_i governs the response to cumulative error, and K_d regulates the response to error rate fluctuations [8]. An optimal control system can maintain the frequency stability of an MHPP even in the face of load variations [9].

Several studies have been conducted to improve the performance of LFC. In the study [10][11], a PID-based controller design approach with manual tuning was implemented in hydropower plants, it was found that the system takes a long time to reach stability. Then from the study [12][13], fuzzy logic-based LFC controller tuning was developed that was applied to several power system areas. The results of a better and faster frequency response were obtained compared to only using manual tuning methods, but there is no specific mathematical formulation to select the appropriate fuzzy parameters (such as input, scalability factor, membership function, rule base, and so on). Usually, these parameters are selected using certain empirical rules so they may not be optimal parameters. The selection of an incorrect input-output scale factor can significantly affect the performance of LFC [14].

Therefore, to address the issues mentioned in previous studies, the latest research employs stochastic algorithms, commonly known as metaheuristic algorithms, to determine the optimal values of PID controller parameters [15]. One of the most widely adopted algorithms is the grey wolf optimizer (GWO), introduced in 2014. GWO represents a population-based swarm intelligence algorithm that simulates the hunting behavior of a wolf pack [16]. GWO finds extensive application in solving optimization problems across various domains due to its simplicity and minimal control parameter requirements [17]. In a study conducted [18], an automatic generation control (AGC) investigation was conducted on two-area systems using three optimization algorithms: GWO, genetic algorithm (GA), and particle swarm optimization (PSO). The comparative analysis revealed that the system employing the controller tuned using GWO demonstrated superior dynamic response compared to GA and PSO. Consequently, this study proposes the application of the grey wolf optimizer algorithm to optimize the PID controller parameters in the load frequency control (LFC) of MHPP. MHPP has been modeled in both isolated and grid-connected modes. The next section discusses in more detail about this research method.

II. Materials and Methods

This section discusses research related to the modeling of the MHPP system in both isolated and grid-connected modes, along with the utilization of the GWO algorithm for optimization. The software employed in this research was Simulink MATLAB R2020a.

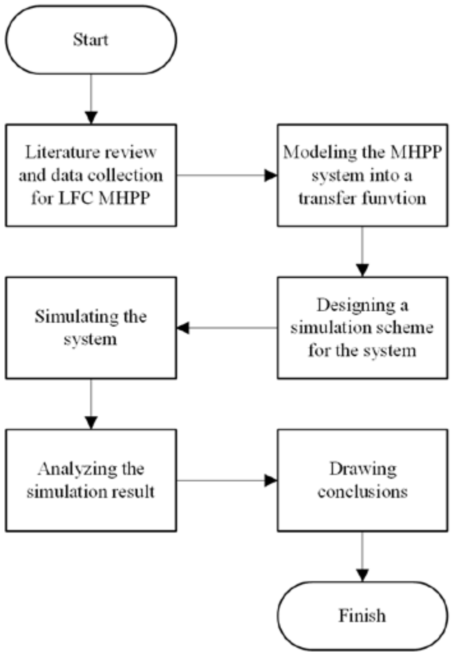

Figure 1. Flowchart diagram to obtain the impact of proposed algorithm

A. Methods

Figure 1 depicts the flow diagram of this research. The research proceeded in stages, commencing with a literature review and the collection of data pertaining to the Load frequency control (LFC) of MHPP. Subsequently, after acquiring the necessary data, the MHPP system was modeled as a transfer function. Following this, the design of the LFC system simulation for MHPP was undertaken. The simulation was then executed based on the established system scheme. Subsequent to this, each scheme was compared in terms of performance. Ultimately, the results of the comparison were analyzed, leading to the formulation of conclusions.

B. System modelling

System modeling was carried out after the transfer function of the MHPP parts was obtained. From the transfer function, the LFC system simulation scheme on MHPP was then designed, consisting of two schemes, namely the MHPP scheme without grid connection or isolated mode and the MHPP connected to the grid or grid-connected mode. Each scheme has been integrated with a PID controller without GWO and a PID controller with GWO. Following this, the GWO program was created and applied as a controller optimization algorithm for the MHPP system. The output of the controller parameters and the value of the cost function were then displayed. Subsequently, an analysis was conducted based on the frequency deviation response of each cost function. Finally, the responses were compared, and conclusions were drawn.

An explanation of the system flow diagram can be found in Figure 2. In the subsequent chapter, the LFC system modeling of the MHPP and the GWO algorithm employed in this research are elucidated. The data utilized for this study were sourced from previous research [19]. These data were chosen due to the previous research's modeling of LFC into a linear model, which simplifies analysis. Moreover, the previous study also employed different methods, namely Sliding Mode Control and Model Order Reduction. Thus, this study aims to explore an alternative approach to optimizing LFC in MHPP.

C. Micro hydro power plant

Figure 3 and Figure 4 depicted the micro hydro power plant system, which had been integrated into the Simulink MATLAB program. The block diagram above illustrates the parameters signifying each component of the micro hydro power plant. Water flowing through the penstock initiated the rotation of the turbine, as modeled in the Turbine and Penstock block, incorporating the nominal water start-up time parameter in the penstock (T_w). The conversion of water energy into mechanical power (ΔP_G) constituted one of the generator's input variables. The Generator block generated frequency deviation (ΔF), which was subsequently fed back into the controller block. The controller's output (ΔP_C) served as the input for the Servo and Governor block, encompassing the mechanical time constant parameter (T_m) and (T_e) electric time constant. The Servo and Governor block's output (ΔX) was looped back as input and computed in conjunction with the controller block, ultimately becoming the input for the Turbine and Penstock block. Additionally, the Generator block received an input from the step and ramp signal, representing Load Disturbance (ΔP_L) or load change. This signal determined the functioning of the LFC system and could vary in magnitude based on the electrical power load's fluctuations.

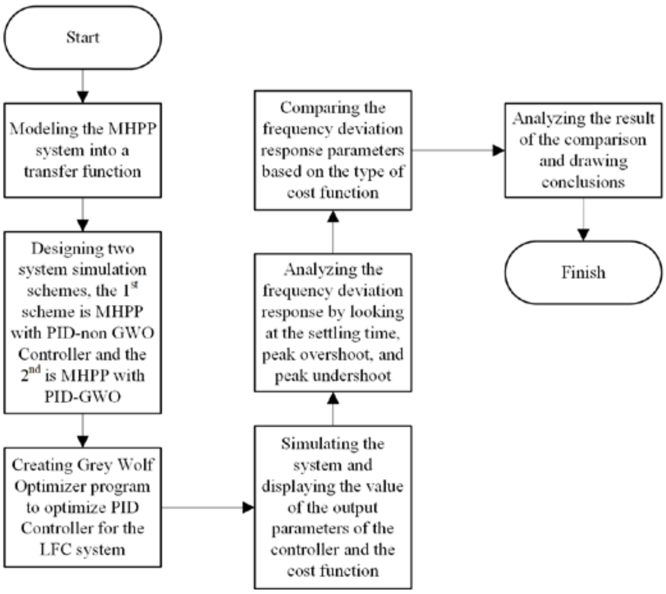

Figure 2. Flowchart for modelling and verification of system under test

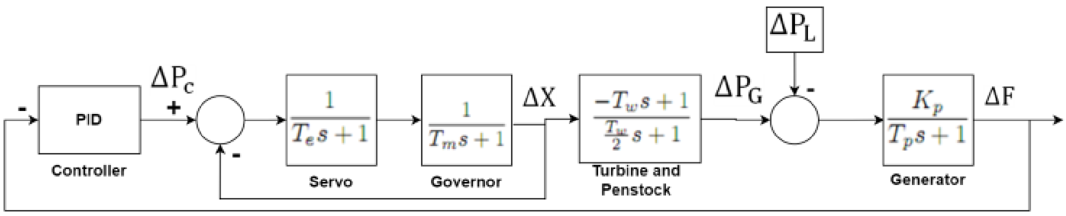

Figure 3. Isolated mode MHPP system block diagram

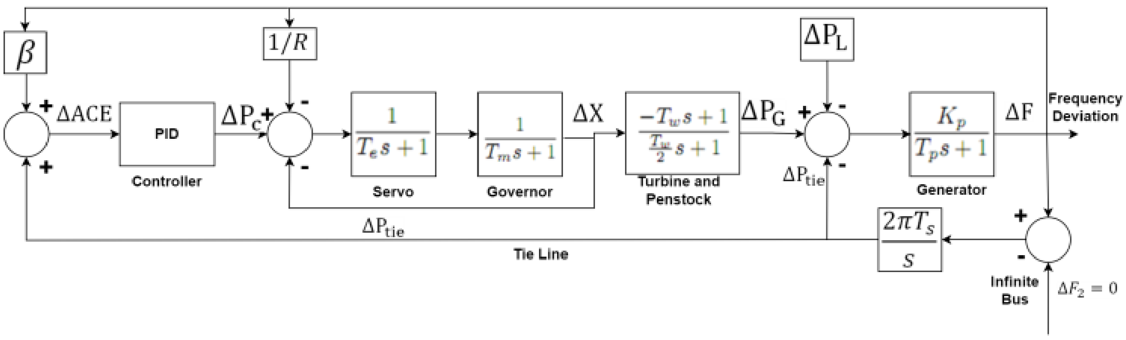

Figure 4. Grid-connected mode MHPP system block diagram

Table 1.
MHPP parameters value

Parameter	Value	Description
T_w	4	Nominal start time of water in penstock (s)
T_m	0.001	Governor mechanical time constant (s)
T_e	0.01	Servo electric time constant (s)
K_p	50	Generator gain constant (Hz/(pu•kW))
T_p	64.64	Generator time constant (s)
R	10	Governor speed regulation (Hz/(pu·kW))
ΔP_L	0.03	Step function of load disturbance (pu·kW)
β	0.2083	Frequency bias factor ((pu·kW)/Hz)
T_s	0.0866	Synchronizing power coefficient of tie line (s)
P_s	50	Generator power rating (kW)

Within the Grid-Connected Mode system, an additional block parameter, referred to as the regulation coefficient $(1/R)$, is incorporated. This coefficient is multiplied by ΔF and calculated in conjunction with the output of the controller (ΔP_C) and (ΔX). The controller's input is derived from △ACE, which represents the discrepancy between the set point frequency of the electrical system and the actual frequency of the electrical system. The formula for △ACE encompasses the product of ΔF with the frequency bias factor (β), along with the value of ΔP_{tie}. At the input of the Generator block, aside from the incremental power (torque) output of the turbine (ΔP_G) and Load Disturbance (ΔP_L), the ΔP_{tie} parameter is also taken into account. The values of the MHPP parameter are outlined in Table 1.

D. Grey wolf optimizer model

Figure 5 illustrates the flowchart of the GWO algorithm utilized in this study to optimize PID parameters. In the optimization of PID parameter values, a Performance Index serves as the cost function or objective function to calculate fitness values for obtaining optimal PID parameter values. The study employed four objective functions, namely, the Integral of absolute error (IAE), integral of squared error (ISE), integral of time absolute error (ITAE), and integral of time multiplied squared error (ITSE). The equations of the four cost functions for the Isolated Mode MHPP system can be seen in equations (1) to (4) which is indicated by the subscript *im* and for the grid-connected mode MHPP system in equations (5) to (8) which is indicated by the subscript *gm*.

Table 2.
GWO parameters value

GWO Parameter	Value
Max iterations	50
Wolf population	30
Dimension	3
Upper limit of PID parameters	2
Lower limit of PID parameters	-2

$$IAE_{im} = \int_0^{t_{sim}} |\Delta F| dt \quad (1)$$

$$ISE_{im} = \int_0^{t_{sim}} (\Delta F)^2 dt \quad (2)$$

$$ITAE_{im} = \int_0^{t_{sim}} t.|\Delta F| dt \quad (3)$$

$$ITSE_{im} = \int_0^{t_{sim}} t.[(\Delta F)^2] dt \quad (4)$$

$$IAE_{gm} = \int_0^{t_{sim}} |\Delta ACE| dt \quad (5)$$

$$ISE_{gm} = \int_0^{t_{sim}} (\Delta ACE)^2 dt \quad (6)$$

$$ITAE_{gm} = \int_0^{t_{sim}} t.|\Delta ACE| dt \quad (7)$$

$$ITSE_{gm} = \int_0^{t_{sim}} t.[(\Delta ACE)^2] dt \quad (8)$$

The parameters for GWO utilized in this study were derived from experiments tailored to the optimization problem, which pertains to LFC, and the computational time required. The specific GWO parameter values are detailed in Table 2.

III. Results and Discussions

Simulation data analysis was carried out to assess the performance difference in LFC between scenarios with and without GWO optimization. This evaluation encompassed both the isolated mode and grid-connected mode MHPP systems. The LFC performance analysis was based on the frequency deviation response of the MHPP, utilizing controller

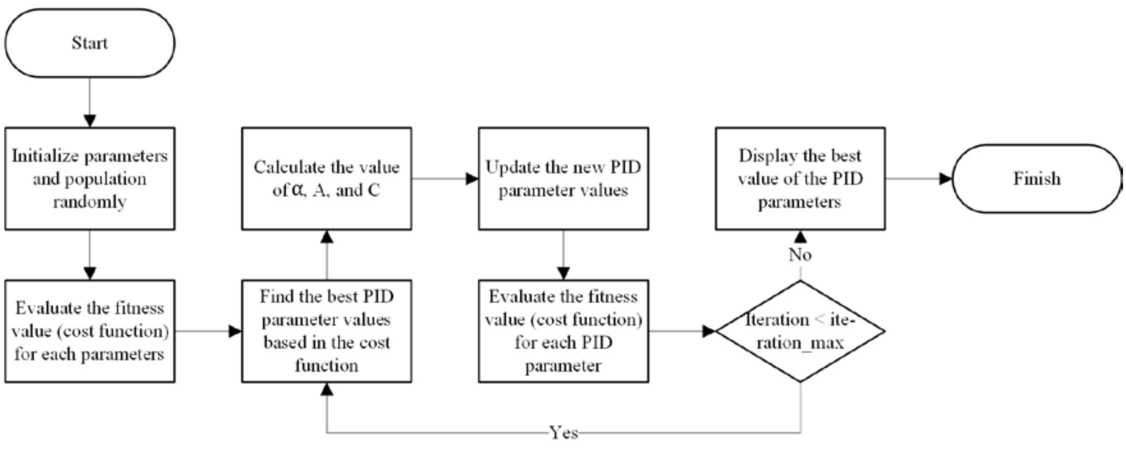

Figure 5. GWO algorithm flowchart in optimizing PID

parameter values derived from each cost function. The parameters examined consist of settling time, and peak overshoot as in work [20]. However, this work adds the peak undershoot parameter [21].

A. Load disturbance

The load disturbance, ΔP, value used in this simulation is 0.03 pu, and dynamic. Load disturbance is modeled as a unit step function on the load with a value of 0.03 pu. While on, the dynamic load is modeled by using a combination of unit step and ramp. The shape of the load disturbance can be seen in Figure 6 and Figure 7.

B. Frequency deviation response in non-GWO MHPP

It can be observed that when the PID controller parameters are not optimized using GWO, the frequency deviation response tends to be unstable. This can be observed from Figure 8 and Figure 9, where the frequency deviation response in the isolated mode MHPP without the use of the GWO algorithm shows a slow nature and does not reach a stable value (steady state).

In addition, a similar thing also happens in the grid-connected mode non-GWO MHPP, the frequency deviation response shows instability and oscillation. This means that the frequency deviation is unable to reach a stable state and experiences fluctuations or unwanted changes. The PID parameters used for both systems are taken from the study [19] which can be seen in Table 3.

C. Convergence results versus iterations on isolated mode MHPP with GWO

Based on the GWO parameters in Table 2, the results are in accordance with Table 4 (using cost functions such as work [22]) and Figure 10, where the lowest cost function value is achieved by the integral square error (ISE_{im}) cost function with a value of 0.067653. Meanwhile, the highest cost function value is achieved by the integral time absolute error ($ITAE_{im}$) cost function with a value of 0.53078.

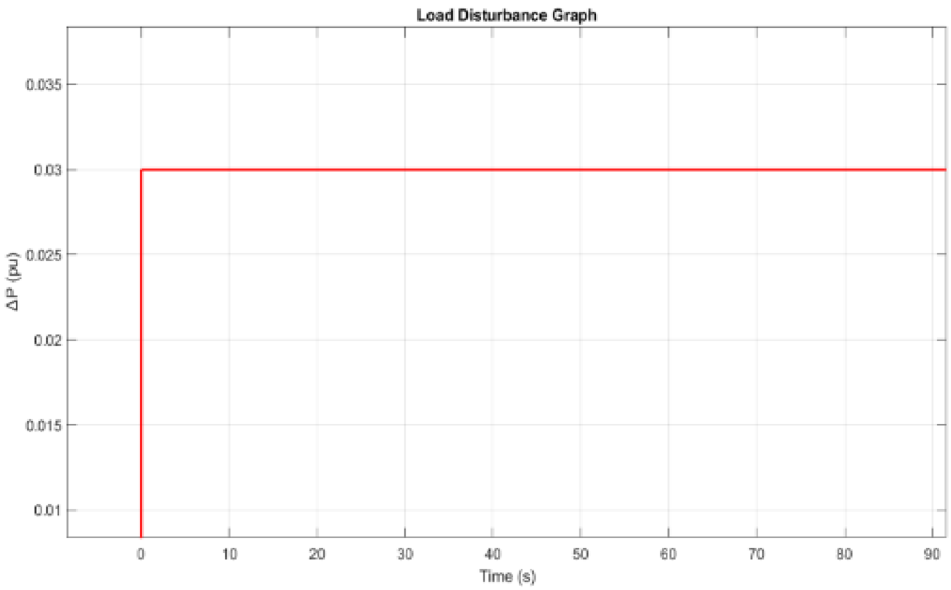

Figure 6. Load disturbance with a value of 0.03 pu

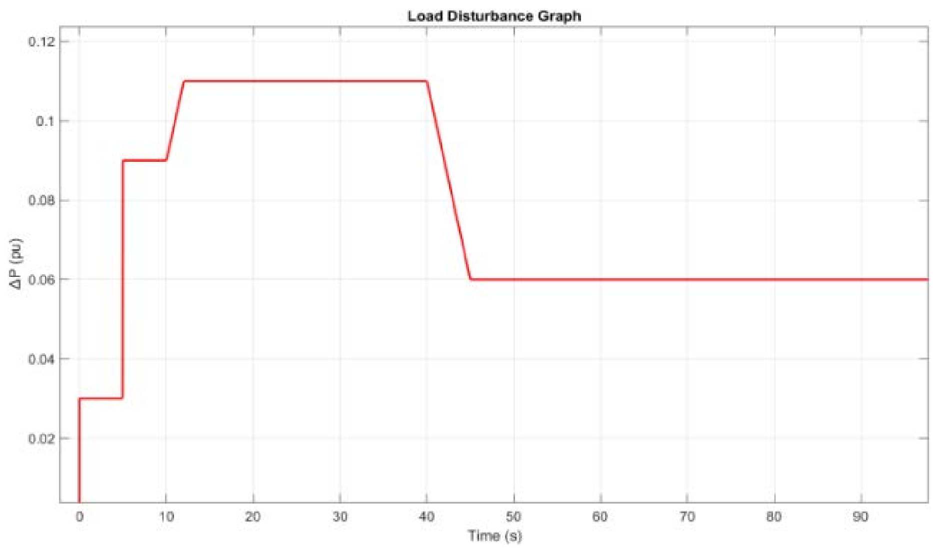

Figure 7. Load disturbance graph with dynamic values

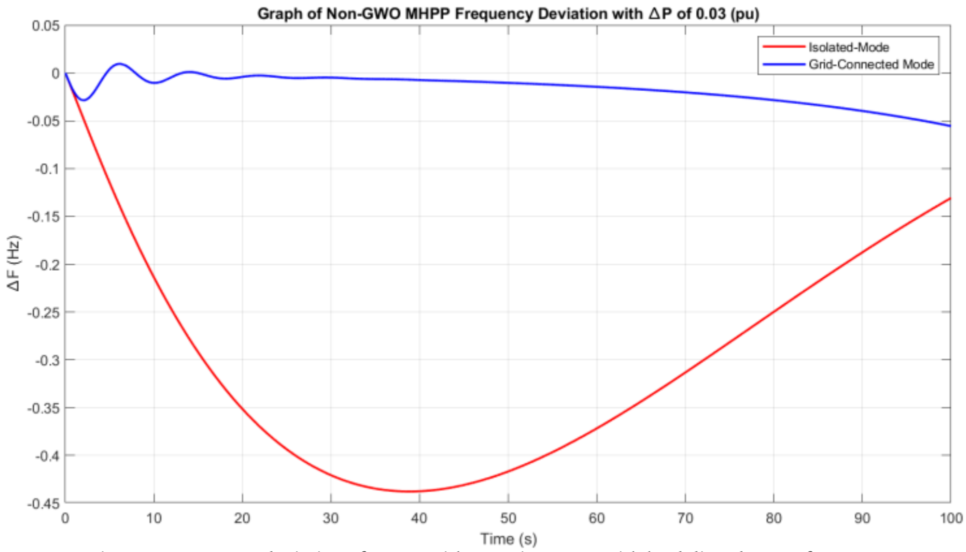

Figure 8. Frequency deviation of MHPP without using GWO with load disturbance of 0.03 pu

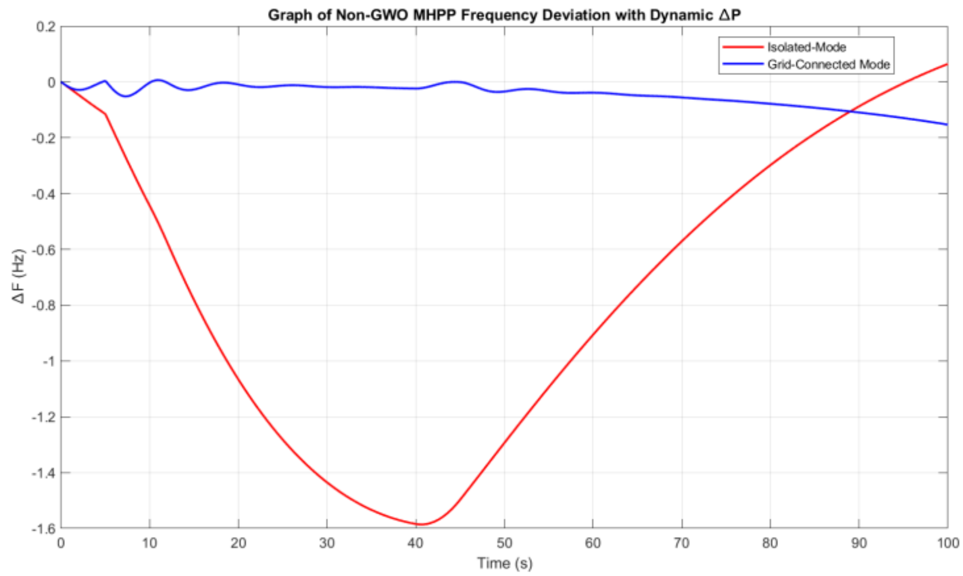

Figure 9. Graph of MHPP frequency deviation without using GWO with dynamic load disturbance

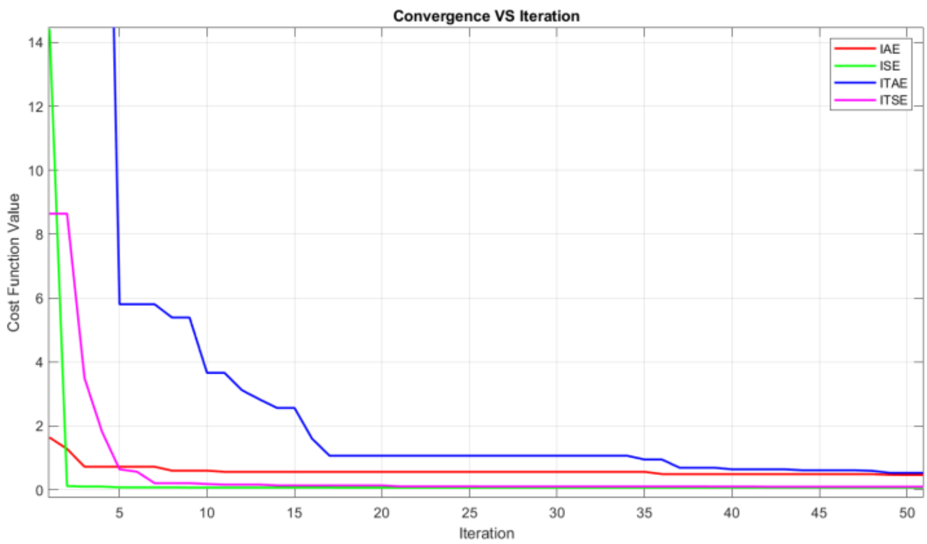

Figure 10. Value of cost function to iteration on MHPP isolated mode with GWO

Table 3.
Non-GWO MHPP PID parameters

MHPP System	K_p	K_i	K_d
Isolated mode	0.056	0.002	0.0001
Grid-connected mode	0.660	0.060	0.0010

Table 4.
Results of the best PID parameter values and cost function of MHPP isolated mode with GWO

Cost Function	K_p	K_i	K_d	Cost Function Value
IAE_{im}	0.89394	0.130140	1.2644	0.462730
ISE_{im}	0.78009	0.081098	1.2598	0.067653
$ITAE_{im}$	0.89423	0.130710	1.2658	0.530780
$ITSE_{im}$	0.86092	0.111540	1.2701	0.096459

D. Frequency deviation response on MHPP isolated mode using GWO with load disturbance of 0.03 pu

In Figure 11, with the use of GWO, the ΔF response can stabilize and reach the steady-state value. The fastest settling time of 4.3198 s is achieved by the cost function IAE_{im}. Meanwhile, the longest settling time is achieved by ISE_{im} with a value of 15.0398. The ΔF response with the lowest peak undershoot is obtained by the cost function ISE_{im} with a value of -0.1909 Hz. The lower result in terms of peak undershoot shows that the system is closer to the desired reference value.

In the ISE_{im} and $ITSE_{im}$ cost functions, the peak overshoot response is 0 Hz, which means that the system using these cost functions does not experience overshoot. Based on the Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia (PERMEN ESDM) Number 20 of 2020, the increase and decrease in the frequency of the four types of cost functions are still within the tolerance limits. The results of the MHPP isolated mode performance with GWO can be seen within Table 5.

E. Frequency deviation response on MHPP isolated mode using GWO with dynamic load disturbance

In Figure 12, when ΔP becomes dynamic, the ΔF response on the four cost functions used fluctuates at the first second and then the system tries to stabilize, where only IAE_{im} and $ITAE_{im}$ can reach a steady state. After that, at the 5th second, ΔF on the four cost functions decreases due to load changes to 0.09 pu. After that, the system tries to stabilize again and only IAE_{im} and $ITAE_{im}$ succeed in reaching their steady-state values. At the 10th second, the load increases so that ΔF decreases, but then all four cost functions succeed in reaching their steady state. Then at the 40th second, the load decreases so that ΔF increases, and the system of all four succeeds in stabilizing again.

Cost function $ITAE_{im}$ reaches the fastest settling time at 46.7902 s, while ISE_{im} reaches the longest settling time at 56.8203 s. Cost function ISE_{im} produces the ΔF response with the lowest peak undershoot, which is -0.4254 Hz. The lower value at the peak undershoot shows that the system is closer to the desired reference value.

Based on the Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia (PERMEN ESDM) Number 20 of 2020, only the ISE_{im} cost function has a frequency increase and decrease that is within the tolerance limit, while the other three types exceed the tolerance limit. The performance values of MHPP isolated mode with GWO can be found in Table 6.

Table 5.
Performance results of frequency deviation response of MHPP isolated mode using GWO with load disturbance of 0.03 pu

Cost Function	Settling Time (s)	Peak Overshoot (Hz)	Peak Undershoot (Hz)
IAE_{im}	04.3198	2.915e-03	-3.617e-01
ISE_{im}	15.0398	0.000e-03	-1.909e-01
$ITAE_{im}$	04.2222	1.642e-03	-3.679e-01
$ITSE_{im}$	07.4456	0.000e-03	-3.083e-01

Table 6.
Performance results of frequency deviation response of MHPP isolated mode using GWO with dynamic load disturbance

Cost Function	Settling Time (s)	Peak Overshoot (Hz)	Peak Undershoot (Hz)
IAE_{im}	46.8134	1.530e-01	-6.968e-01
ISE_{im}	56.8203	1.749e-01	-4.254e-01
$ITAE_{im}$	46.7902	1.529e-01	-7.037e-01
$ITSE_{im}$	50.1630	1.656e-01	-5.925e-01

Table 7.
Results of the best PID parameter values and cost function of MHPP grid-connected mode with GWO

Cost Function	K_p	K_i	K_d	Cost Function Value
IAE_{gm}	0.25303	-0.17698	0.2328000	0.418460
ISE_{gm}	0.32472	-0.17716	-0.3715700	0.015861
$ITAE_{gm}$	0.28253	-0.16100	0.4727200	2.933400
$ITSE_{gm}$	0.24747	-0.17606	0.0034052	0.087138

F. Convergence results versus iterations on grid-connected mode MHPP with GWO

Based on Figure 13 and Table 7, the results show that the lowest cost function value is achieved by the integral square error (ISE_{gm}) cost function with a value of 0.015861. The highest cost function value is 2.9334, which is achieved by the integral time absolute error $ITAE_{gm}$ cost function.

G. Frequency deviation response on grid-connected mode MHPP using GWO with load disturbance of 0.03 pu

Figure 14 shows the variation of ΔF response between different types of cost function, where using GWO, the ΔF response can be stable and reach the steady-state value. In terms of settling time, the cost function IAE_{gm} reaches the fastest settling time of 27.9660 s, while the cost function ISE_{gm} has the longest settling time of 47.0490 s. Furthermore, the

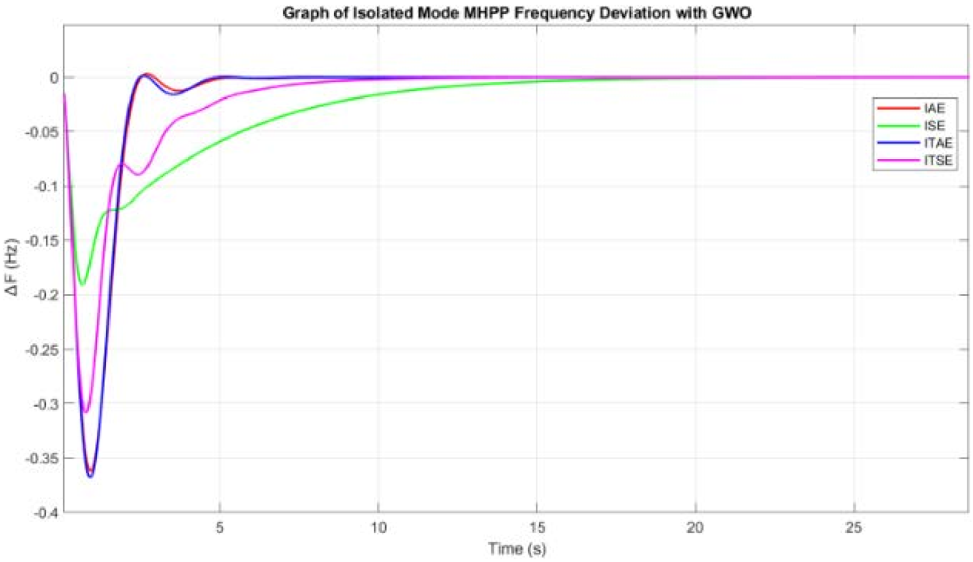

Figure 11. Graph of isolated mode MHPP frequency deviation using GWO with load disturbance of 0.03 pu

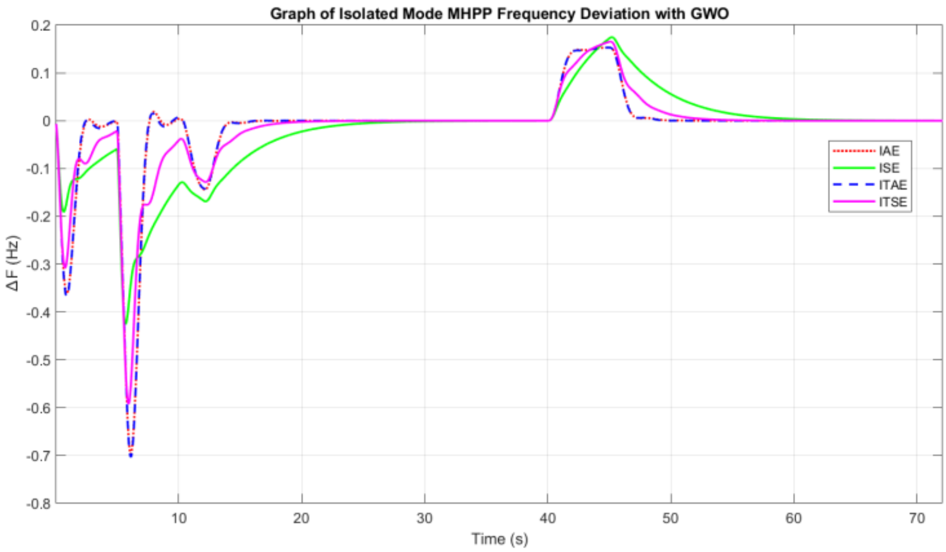

Figure 12. Graph of isolated mode MHPP frequency deviation using GWO with dynamic load disturbance

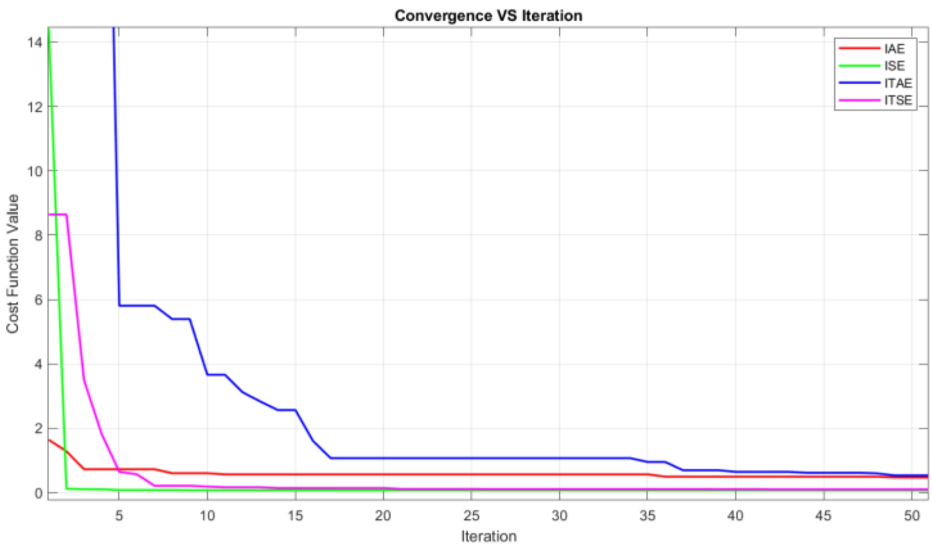

Figure 13. Value of cost function to iteration on MHPP grid-connected mode with GWO

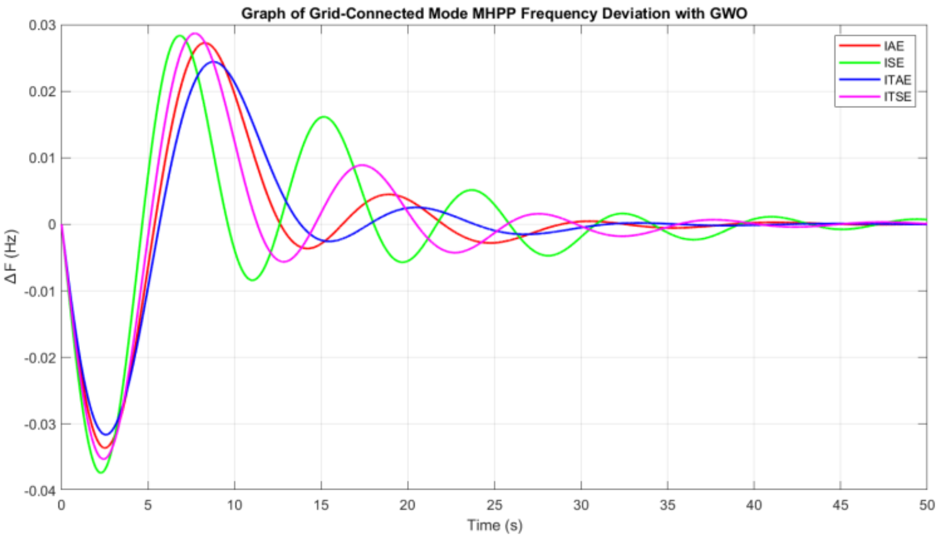

Figure 14. Graph of Grid-connected mode MHPP frequency deviation using GWO with load disturbance of 0.03 pu

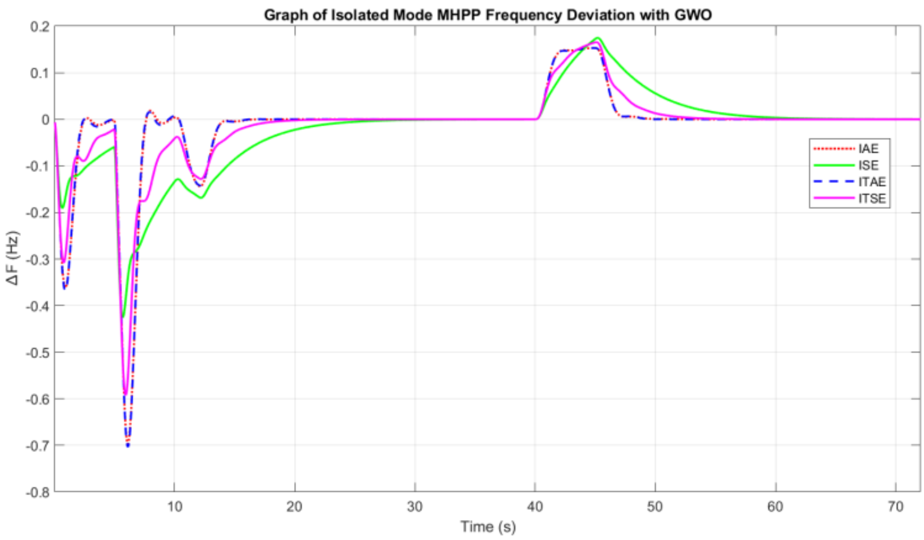

Figure 15. Graph of grid-connected mode MHPP frequency deviation using GWO with dynamic load disturbance

comparison of peak undershoot shows that the cost function $ITAE_{gm}$ has the lowest value of -0.03162 Hz, indicating that the system is closer to the desired reference value.

Based on the Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia (PERMEN ESDM) Number 20 of 2020, the increase and decrease in frequency of the four types of cost functions are still within the tolerance limits. The results of the MHPP grid-connected mode performance parameter values with GWO can be seen in Table 8.

H. Frequency deviation response on grid-connected mode MHPP using GWO with dynamic load disturbance

Figure 15 shows the variation of ΔF response from different types of cost function when $\triangle$P becomes dynamic. The ΔF response on the four cost functions used experiences a decrease and oscillation. At the first second, the ΔF on the fourth cost function system drops to more than 0.03 Hz and then rises back to 0.04 Hz at the fifth second. Then the system manages to approach the steady-state value at the tenth second. After that, ΔF experiences an increase to more than 0.03 Hz and the system tries to return to its steady-state value accompanied by oscillation until the fortieth second. At the fortieth to the eightieth second, ΔF again experiences an increase and decrease and oscillation due to load changes until it finally can stabilize and reach its steady-state value.

The cost function IAE_{gm} reaches the fastest settling time at 70.9186 s, while ISE_{gm} reaches the longest settling time at 81.4575 s. The cost function $ITSE_{im}$ produces the ΔF response with the lowest peak undershoot, which is -0.4238 Hz. The lower value at the peak undershoot shows that the system is closer to the desired reference value. According to the Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia (PERMEN ESDM) Number 20 of 2020, the increase and decrease in frequency of the four types of cost function are still within the tolerance limits. The performance parameter values of MHPP grid-connected mode with GWO can be found in Table 9.

Table 8.
Results of frequency deviation response performance of MHPP grid-connected mode using GWO with load disturbance of 0.03 Pu

Cost Function	Settling Time (s)	Peak Overshoot (Hz)	Peak Undershoot (Hz)
IAE_{im}	27.9660	2.726e-02	-0.03361
ISE_{im}	47.0490	2.835e-02	-0.03735
$ITAE_{im}$	29.6771	2.442e-02	-0.03162
$ITSE_{im}$	34.7235	2.868e-02	-0.03529

Table 9.
Results of frequency deviation response performance of MHP grid-connected mode using GWO with dynamic load disturbance

Cost Function	Settling Time (s)	Peak Overshoot (Hz)	Peak Undershoot (Hz)
IAE_{im}	70.9186	3.809e-02	-4.280e-02
ISE_{im}	81.4575	3.911e-02	-4.809e-02
$ITAE_{im}$	72.6298	3.705e-02	-4.396e-02
$ITSE_{im}$	77.5711	3.724e-02	-4.238e-02

IV. Conclusion

In this research, GWO algorithm is successfully designed to optimize the PID parameters used as LFC in the MHPP system. MHPP is basically a high-order complex system. Thus, the analytical approach to obtain PID parameters cannot produce optimal parameters. Moreover, system disturbances in the form of load deviations make the system have uncertainty parameters. To test the effectiveness of GWO in generating optimal parameters, this work tests it on two MHPP systems, the first system is an off-grid system and the second system is an on-grid system. Both systems are modeled in the frequency domain and simulated for verification using Matlab/Simulink. There are two scenarios, the first scenario is by giving a constant load deviation and the second scenario is by giving a fluctuating load deviation. Both scenarios apply to both off-grid and on-grid systems. Based on the verification results, the system response with GWO optimization is better than the system without optimization. This is shown from the system response without GWO at t <100s has not reached a steady state and unstable conditions occur in the grid-connected system. While the system with GWO reaches a steady state at t < 50s. Moreover, the test also utilizes several cost functions, namely, IAE, ISE, ITAE, and ITSE. Based on the four cost functions, the system response results in both tests are quite diverse. Interestingly, in the off-grid system, the lowest settling time value is when GWO uses ITAE. While in the on-grid system, the lowest value is when using IAE. This condition is consistent for both scenarios. Although the proposed GWO has been able to produce optimal parameters and a better response compared to the system without GWO, detailed testing related to the selection of cost functions suitable for off-grid and on-grid systems still needs to be researched in the future. In addition, PID controllers are less suitable for higher-order or nonlinear systems. Therefore, it is necessary to conduct further research to produce a controller that is suitable for MHPP and at the same time robust to changes in load deviation.

Declarations

Author contribution

I.I. Novendra: Writing -Original Manuscript, Writing - Review & Editing, Conceptualization, Formal Analysis, Investigation, Visualization. I.M. Wirawan: Formal Analysis, Conceptualization, Investigation, Validation, Supervision. A. Kusumawardana: Writing - Review & Editing, Formal Analytics, Conceptualization, Data Curation, Supervision. A.K. Latt: Review & Editting.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

Reprints and permission: information is available at https://mev.brin.go.id/.

Publisher's Note: National Research and Innovation Agency (BRIN) remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

[1] A. Sugiharto, "PLTMH Sebagai Alternatif Pembangkit Listrik Ramah Lingkungan," *Swara Patra, E-Jurnal PPSDM Migas, Kementerian ESDM RI*, vol. 8 (1), pp. 107–118, 2018.

[2] I. Sami, N. Ullah, S. M. Muyeen, K. Techato, M. S. Chowdhury, and J. S. Ro, "Control Methods for Standalone and Grid Connected Micro-Hydro Power Plants with Synthetic Inertia Frequency Support: A Comprehensive Review," *IEEE Access*, vol. 8, pp. 176313–176329, 2020.

[3] M. R. Djalal, H. Setiadi, and A. Imran, "Frequency stability improvement of micro hydro power system using hybrid SMES and CES based on Cuckoo search algorithm," *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, vol. 8, no. 2, pp. 76–84, Dec. 2017.

[4] Kartiria, S. Amalia, R. Andari, and G. Gumbara, "Pemodelan Sistem Pengontrol Frekuensi pada PLTMH PTPN VI Kayu Aro," *RADIAL: Jurnal Peradaban Sains, Rekayasa dan Teknologi*, vol. 10, no. 2, pp. 265–274, 2022.

[5] Thamilmaran A, Vijayapriya P, Bakkiya Lakshmi S, "Modeling of Micro-Hydro Power Plant and Its Control Based On Neural Network," *International Research Journal of Engineering and Technology*, pp. 677–680, 2015.

[6] B. Dhanasekaran, J. Kaliannan, A. Baskaran, N. Dey, and J. M. R. S. Tavares, "Load Frequency Control Assessment of a PSO-PID Controller for a Standalone Multi-Source Power System," *Technologies (Basel)*, vol. 11, no. 1, p. 22, 2023.

[7] E. W. Suseno, A. Ma'Arif, and R. D. Puriyanto, "Tuning Parameter Pengendali PID dengan Metode Algoritma Genetik pada Motor DC," *Jurnal Telekomunikasi, Elektronika, Komputasi, dan Kontrol*, vol. 8, no. 1, pp. 1–13, 2022.

[8] R. Arindya, "Penalaan Kendali PID untuk Pengendali Proses," *Seminar Nasional Cendekiawan*, pp. 30-37, 2015.

[9] I. Salhi, S. Doubabi, N. Essounbouli, and A. Hamzaoui, "*Frequency* Regulation for Large Load Variations on Micro-hydro Power Plants with Real-time Implementation," *International Journal of Electrical Power and Energy Systems*, vol. 60, 2014.

[10] A. T. Hammid, M. Hojabri, M. H. Bin Sulaiman, A. N. Abdalla, and A. A. Kadhim, "Load Frequency Control for Hydropower Plants using PID Controller," *Journal of Telecommunication,*

Electronic and Computer Engineering, vol. 8, no. 10, pp. 47–51, 2016.

[11] R. R. Bajya and M. R. Taparia, "Modeling of a Nonlinear Hydro Power Plant and Analysis with PID Controllers," *ICCCCM 2016 - 2nd IEEE International Conference on Control Computing Communication and Materials*, no. Iccccm, pp. 16–18, 2016.

[12] H. A. Yousef, K. AL-Kharusi, M. H. Albadi, and N. Hosseinzadeh, "Load Frequency Control of a Multi-Area Power System: An Adaptive Fuzzy Logic Approach," *IEEE Transactions on Power Systems*, vol. 29, no. 4, pp. 1822-1830, 2014.

[13] M. D. Noviantara, I. N. Suweden, and I. M. Mataram, "Analisis Stabilitas Sistem Tenaga Listrik Dengan Automatic Generation Control (AGC) Dua Area Menggunakan Fuzzy Logic Controller," *Majalah Ilmiah Teknologi Elektro*, vol. 17, no. 2, p. 263, 2018.

[14] P. C. Pradhan, R. K. Sahu, and S. Panda, "Firefly Algorithm Optimized Fuzzy PID Controller for AGC of Multi-Area Multi-Source Power Systems with UPFC and SMES," *Engineering Science and Technology, an International Journal*, vol. 19, no. 1, pp. 338–354, 2015.

[15] S. K. Bhagat, N. R. Babu, L. C. Saikia, T. Chiranjeevi, R. Devarapalli, and F. P. García Márquez, *A Review on Various Secondary Controllers and Optimization Techniques in Automatic Generation Control*, Arch Computat Methods Eng., vol. 30, pp. 3081–3111, 2023.

[16] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey Wolf Optimizer," *Advances in Engineering Software*, vol. 69, pp. 46–61, 2014.

[17] G. Negi, A. Kumar, S. Pant, and M. Ram, "GWO: A Review and Applications," *International Journal of System Assurance Engineering and Management*, vol. 12, no. 1, 2020.

[18] E. Gupta and A. Saxena, "Grey Wolf Optimizer Based Regulator Design for Automatic Generation Control of Interconnected Power System," *Cogent Eng*, vol. 3, no. 1, 2016.

[19] D. Qian, S. Tong, and X. Liu, "Load Frequency Control for Micro Hydro Power Plants by Sliding Mode and Model Order Reduction," *Automatika*, vol. 56, no. 3, pp. 318–330, 2015.

[20] V. N. Ogar, S. Hussain, and K. A. A. Gamage, "Load Frequency Control Using the Particle Swarm Optimisation Algorithm and PID Controller for Effective Monitoring of Transmission Line," *Energies (Basel)*, vol. 16, no. 15, p. 5748, 2023.

[21] D. K. Sambariya and S. Shrangi, "Optimal design of PID controller for load frequency control using harmony search algorithm," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 5, no. 1, pp. 19–32, 2017.

[22] S. D. Hanwate and Y. V. Hote, "Optimal PID design for Load frequency control using QRAWCP approach," in *IFAC-PapersOnLine*, vol. 51(4), pp. 651–656, 2018.