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Research Article

Frequency Control of Islanded Microgrids Using a Hybrid Grey Wolf and Cuckoo Search Optimized Tilt Integral Derivative Controller

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ABSTRACT

This research presents a novel approach for frequency control in an islanded AC Microgrid (MG) system, which integrates multiple renewable energy sources such as solar and wind energy. Variations in the output of these renewable sources can cause fluctuations in both frequency and power within the microgrid. To address these disturbances, a suitable controller is necessary. In this study, a Tilt Integral Derivative (TID) controller is designed for the microgrid, with its parameters optimized and tuned using a novel hybrid Grey Wolf and Cuckoo Search (HGW-CS) algorithm to mitigate these fluctuations. The proposed microgrid consists of various distributed generation (DG) sources, including a Diesel Engine Generator (DEG), Flywheel Energy Storage System (FESS), Battery Energy Storage System (BESS), Micro Turbine (MT), Fuel Cell (FC), and Aqua-electrolyze (AE), all working together to meet the load demand. The performance of the novel HGW-CS-based TID controller is evaluated under different scenarios, demonstrating its robustness and superior performance even in adverse conditions. All simulations were conducted in MATLAB, and the results indicate that the proposed controller outperforms conventional controllers in terms of stability and response to disturbances.

Keywords: Tilt Integral Derivative TID, Cuckoo search, Grey Wolf Optimization (GWO), Islanded MG, PID control

INTRODUCTION

The conventional power system typically comprises generation, transmission, and distribution, relying on energy sources such as coal, water, nuclear, and diesel generators. In contrast, non-conventional generating systems include solar, wind, tidal, and geothermal energy for electrical conversion. Frequency is a key indicator in a power system, reflecting the balance between generation and demand. A drop in frequency signifies an imbalance, indicating the need for frequency control between generators and load demands.

Automatic generation control (AGC) or load frequency control (LFC) are mechanisms used to maintain the scheduled frequency and power interchange. These systems, governed by individual turbine and generator systems, monitor changes in network-wide frequency and adjust the mechanical power input to generators to restore the target frequency. Various controllers, including conventional and non-conventional types, have been proposed, utilizing classical control methods [2-4], modern optimal control [5], and intelligent control techniques [6, 7]. These controllers aim to improve the dynamic response of the system and increase stability by reducing steady-state errors.

However, classical control techniques often fail to provide the desired performance due to increased system complexities and nonlinearities [8, 9]. While modern optimal control can design controllers with performance criteria in mind, the algorithms used to identify model parameters are often complicated and uncertain [10]. These challenges are particularly evident in conventional power generation systems. In remote areas, where conventional power systems are impractical, traditional generation and control methods are often unsuitable for regulating frequency and voltage.

A Microgrid (MG) is a decentralized network of electricity sources and loads that operates autonomously or in conjunction with the larger grid. It is often used in island mode or connected to the traditional grid, with local energy sources serving areas where long-distance transmission from a centralized source is expensive or unfeasible,such as remote or hilly regions [11]. Although Microgrids offer significant advantages for powering off-grid areas, they face challenges due to their nonlinear structure, dynamic complexity, and instability. These issues can energy sources serving areas where long-distance transmission from a centralized source is expensive or unfeasible, such as remote or hilly regions [11]. Although Microgrids offer significant advantages for powering off-grid areas, they face challenges due to their nonlinear structure, dynamic complexity, and instability. These issues can cause mismatches between load and generation, leading to frequency and voltage deviations, which may result in system blackouts. Therefore, optimization controllers with intelligent systems are crucial to ensure the stability of the system under varying loads and environmental conditions [12].

Abbreviations		K_{DEG}	: DEG gain
		T_{DEG}	: DEG time constant
AGC	: Automatic Generation Control	ΔP_{WTG}	: WTG power output
LFC	: Load frequency Control	ΔP_W	: WTG power input
MG	: Microgrid	K_{AE}	: AE gain
WTG	: Wind Turbine Generator	T_{AE}	: AE time constant
STPG	: Solar Thermal Power Generator	ΔP_{AE}	: AE power output
TF	: Transfer Function	Δu	: Control action signal
TID	: Tilt Integral Derivative Controller	K_{FESS}	: FESS gain
PID	: Proportional Integral Derivative	T_{FESS}	: FESS time constant
PI	: Proportional Integral	ΔP_{FESS}	: FESS power output
I	: Integral	K_{BESS}	: BESS gain
PSO	: Particle Swarm Optimization	T_{BESS}	: BESS time constant
ISE	: Integral of Squared Error	ΔP_{BESS}	: BESS power output
Nomenclature		K_{MT}	: MT gain
		T_{MT}	: MT time constant
ΔP_{DEG}	: DEG power output	ΔP_{MT}	: MT power output
K_{FC}	: FC gain	M_s	: Inertia constant (=0.4)
T_{FC}	: FC time constant	D	: Damping constant (=0.03)
ΔP_{FC_k}	: FC power output	U	: Input Control Signal
K_s	: Solar part STPG gain	ΔP_W	: Disturbance Signal of Wind
T_s	: Solar part STPG time constant	ΔP_{sol}	: Disturbance Signal of Solar
K_T	: Thermal part STPG gain	ΔP_L	: Disturbance Signal of Load
T_T	: Thermal part STPG time constant	T^{max}	: Simulation Time Range
ΔP_{STPG}	: STPG power output	Δf	: Change in frequency
ΔP_{sol}	: STPG power input	$\vec{A}, \vec{C}$	: Grew Wolf Vectors of Coefficient
K_{WTG}	: WTG gain	$\vec{X}$	: Grew Wolf Position Vector
T_{WTG}	: WTG time constant	t	: Current Iteration

The Distributed Energy Resources (DERs) such as Diesel Engine Generator (DEG), Wind Turbine Generator (WTG), Battery Energy Storage System (BES), Photovoltaic (PV) systems, Fuel Cells (FC), and Flywheel Energy Storage (FES) are essential components of the Microgrid (MG) structure. In islanded mode, the MG operates with these DERs, where the primary challenges stem from environmental and economic constraints. Power generation from WTG and PV is highly dependent on climate conditions, making them unreliable for secondary frequency control [13]. Meanwhile, Micro Turbines (MT) and Diesel Engine Generators (DEG) can provide electrical energy to meet demand, compensating for energy shortfalls. However, they come with limitations such as slow response

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times, inability to effectively manage MG system dynamics, and nonlinearities that complicate controller design, particularly during sudden load or power demand changes. As a result, integrating MT or DEG with energy storage elements becomes crucial to rapidly address these disadvantages and enhance system stability [14].

This paper focuses on designing a robust frequency control system for MGs in islanding mode, specifically targeting the secondary regulation loop. The primary objective is to adjust setpoints to maintain frequency stability [15]. There are two main control structures for secondary regulation in MGs: centralized and decentralized. In the centralized structure, a single Microgrid controller oversees the system, while the decentralized approach allows independent operation of various units within the MG [16, 17]. For islanded MGs, a centralized control structure is preferred, which is the focus of this study. In contrast, decentralized control is more suitable for grid-connected MGs [16].

The integration of various energy resources, including offshore wind, PV, FC, DEG, and energy storage elements like FES and BES, has been explored in the literature [18] to minimize frequency deviations. This integration is often done using a Unit Commitment (UC) strategy, with a Proportional-Integral (PI) controller applied to optimize performance. The popularity of PID controllers in both academic and industry sectors can be attributed to their simplicity, ease of design, robustness, wide applicability, and near-optimal performance [19-23]. However, achieving the desired control performance with PID controllers can be challenging in the presence of unknown nonlinearities, time delays, and model uncertainties.

Recent research has proposed decentralized control strategies [17], μ-based controllers using the D-K iteration method [24], and robust μ-synthesis controllers [25] to regulate frequency in MGs. While these robust control methods offer solutions, they are often complex and difficult to implement due to the need for accurate model parameter identification. As a result, intelligent control strategies have emerged, offering a flexible and efficient approach to managing complex systems and improving performance under varying conditions.

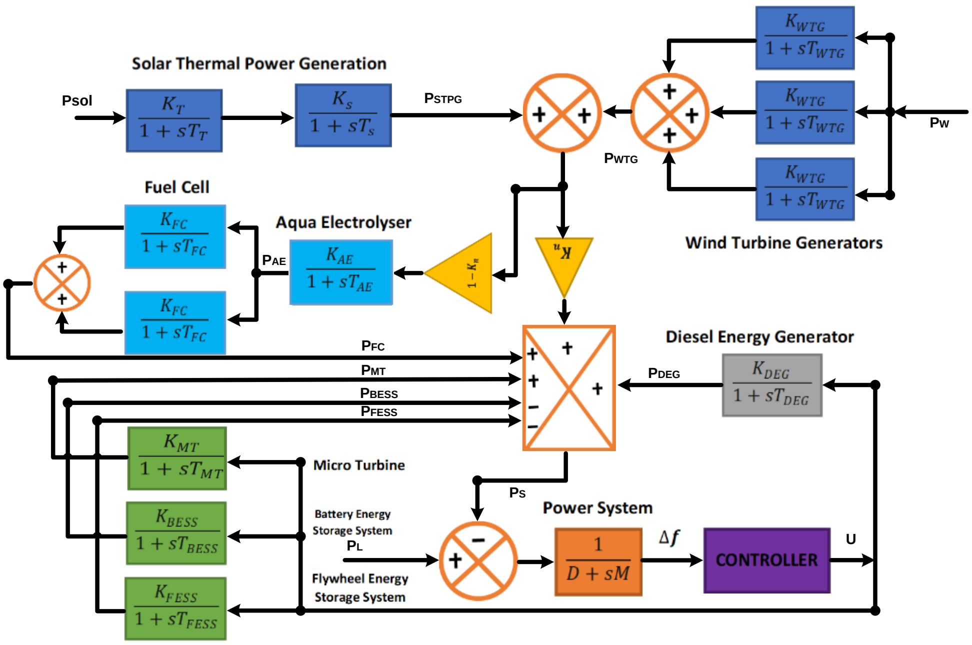

Figure 1. Block Diagram of proposed Islanded Micro Grid System

The fundamental concept behind the fuzzy logic technique is to create a model that mimics the decision-making process of a human operator when designing a controller. Fuzzy logic, based on the concept of fuzzy sets, was first introduced by Professor Zadeh [26]. This work was later expanded by the introduction of linguistic variables, which are variables defined as fuzzy sets [27-29]. One of the most popular applications of fuzzy logic is in control

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engineering, which has garnered attention from both scientists and industrial researchers. Mamdani and Assilian [30-33] presented the first successful application of fuzzy logic for controlling a laboratory-scale plant. Additionally, Holmblad and Ostergaard [34] applied fuzzy logic to control cement kilns in an industrial setting. Fuzzy logic has also been employed to develop linguistic controller rules, which simplify the controller to a conventional nonlinear controller, allowing for the application of nonlinear control theory techniques [35]. Various types of fuzzy logic controllers have been proposed in several studies [36-38], including self-tuning fuzzy controllers [39], stable adaptive fuzzy controllers [40], and single-input fuzzy logic controllers [41], among others.

In a related application, Guerrero et al. [14] presented the use of a Hopfield fuzzy neural network algorithm combined with Particle Swarm Optimization (PSO) and fuzzy logic methods for regulating frequency deviations. A Proportional-Integral-Derivative (PID) controller was utilized [42] to enhance frequency control performance, particularly in the presence of system instabilities, and PSO-based mixed H2/H∞ optimization was proposed for tuning the controller parameters. Additionally, a fuzzy-based PID controller for ensuring the stability of an MG system, which includes components such as Micro Turbines (MT), Fuel Cells (FC), and Energy Storage Systems (ES), was described in [43]. While linear control methods have been effective in certain cases, they often exhibit physical limitations and uncertainties. These methods provide successful control for dynamic systems but often propose complex controllers with the same order for both the controller and the system [44]. To address these challenges, several researchers have explored fractional-order controllers, including robust optimization [45], self-tuned fractional-order fuzzy PID controllers using the Cuckoo Search algorithm [46], and Tilt Integral Derivative (TID) controllers using hybrid Dragonfly and Pattern Search algorithms [47].

However, in the existing literature, there is limited research on tuning the TID controller with novel hybrid optimization techniques for frequency control in Microgrids. While many studies have investigated TID controllers with single optimization techniques [42-43], this paper fills the gap by investigating a Microgrid system with a TID controller tuned using the novel hybrid Grey Wolf and Cuckoo Search (HGW-CS) optimization algorithm to address frequency control issues.

The TID controller consists of a tilted component, represented by the transfer function
s
−
1
n
s
−
n
1
combined with integral and derivative components. This controller is essentially an enhancement of the traditional PID controller, improving system stability and enhancing controller response speed. The parameters of the TID controller are estimated by minimizing the performance index ISE (Integral Squared Error). This paper also compares the dynamic response of TID, PID, and PI controllers, optimizing the performance and parameters of each controller using the same HGW-CS optimization technique. The results demonstrate that, in terms of stability and system response, the TID controller outperforms both the PID and PI controllers.

The structure of this paper is as follows: Section II presents the mathematical modeling of the Microgrid, while Section III focuses on the mathematical modeling of the power system. Section IV contains the state-space dynamic model. The design of the TID controller is discussed in Section V, and Section VI explains the novel HGW-CS algorithm. Section VII presents the simulation results and discussions, followed by the conclusion in Section VIII.

MICROGRID MATHEMATICAL MODELLING

The block diagram of islanded Microgrid system is shown in Fig.1. The mathematical modelling of different components used in Microgrid [46, 47] is given below. The DEG consists of a generator and diesel engine and different components (CBs, starters, Control Systems) and its model is given in (1)

$$G_{DEG}(s) = \frac{K_{DEG}}{1+sT_{DEG}} = \frac{\Delta P_{DEG}}{\Delta u} \qquad (1)$$

FC consists of two electrodes of anode and cathode is used for generation of electric energy taking hydrogen (H_2) as the fuel input to it. Numbers of FC stacks are used for the required amount of electricity and its model is given in (2).

$$G_{FC_k}(s) = \frac{K_{FC}}{1+sT_{FC}} = \frac{\Delta P_{FC_k}}{\Delta P_{AE}}, k = 1,2 \qquad (2)$$

STPG is used solar irradiation for generation purposes. The irradiation is used for producing steam on heating the fluid and this steam is used for generation of electricity. The STPG model is given in (3).

$$G_{STPG}(s) = \frac{K_s}{1+sT_s} \cdot \frac{K_T}{1+sT_T} = \frac{\Delta P_{STPG}}{\Delta P_{sol}} \qquad (3)$$

WTG uses wind power to rotate the blades and these blades are coupled with the generator and produce the electricity. The WTG model is given in (4).

$$G_{WTG}(s) = \frac{K_{WTG}}{1+sT_{WTG}} = \frac{\Delta P_{WTG}}{\Delta P_W} \qquad (4)$$

AE converts the water into H_2 and oxygen and hen, this H_2 is used as the fuel of FC. The $(1 - K_n)$ amount of power of WTG and STPG is used by the AE for production of H_2 The AE model is given in (5).

$$G_{AE}(s) = \frac{K_{AE}}{1+sT_{AE}} = \frac{\Delta P_{AE}}{(\Delta P_{WTG}+\Delta P_{STPG}).(1-K_n)} \qquad (5)$$

$$K_n = \frac{P_t}{(P_{WTG}+P_{STPG})} \qquad (6)$$

MT is the small gas turbine which used for generation of electricity and its model is given in (7).

$$G_{MT}(s) = \frac{K_{MT}}{1+sT_{MT}} = \frac{\Delta P_{MT}}{\Delta u} \qquad (7)$$

Table 1: Gain & Time constant of various components as per [46, 47]

Components	Gain(K)	Time Constant(T)
DEG	0.003	2
FC	0.01	4
STPG	1.8, 1	1.8, 0.3
WTG	1	1.5
AE	0.002	0.5
MT	1	2
FESS	- 0.01	0.1
BESS	-0.003	0.1

FESS stores the kinetic energy by rotating the rotor continuously and stored kinetic energy is proportional to square of the rotational speed. The FESS model is given in (8).

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$$G_{FESS}(s) = \frac{K_{FESS}}{1+sT_{FESS}} = \frac{\Delta P_{FESS}}{\Delta u} \qquad (8)$$

BESS stores the energy and supplies the required energy at the time of the requirement. The BESS model is given in (9).

$$G_{BESS}(s) = \frac{K_{BESS}}{1+sT_{BESS}} = \frac{\Delta P_{BESS}}{\Delta u} \quad (9)$$

POWER SYSTEM MATHEMATICAL MODELLING

Power system TF in MG as per the Fig.1 is given in (10).

$$G_{PS}(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{D+M_s} \qquad (10)$$

STATE SPACE DYNAMIC MODEL

The State-Space model of MG system according to [46, 47] is given in (11 – 15)

$$\dot{x} = Ax + B_1 w + B_2 u \qquad (11)$$

$$Y = C\dot{x} \qquad (12)$$

Where

$$x^T = \begin{bmatrix} \Delta P_{WTG} \ \Delta P_{STPG} \ \Delta P_{DEG} \ \Delta P_{FC} \\ \Delta P_{AE} \ \Delta P_{MT} \ \Delta P_{FESS} \ \Delta P_{BESS} \ \Delta f \end{bmatrix} \qquad (13)$$

$$w^T = [\Delta P_w \ \Delta P_{sol} \ \Delta P_L] \qquad (14)$$

$$y = \Delta f \qquad (15)$$

TID CONTROLLER DESIGN

The TID Controller is similar to PID Controller having three control parameters K_T,K_I,K_D with tuning parameter n. In TID controller proportional action is replaced by tilted proportional action with the transfer function $S^{\frac{-1}{n}}$. This TF is known as Tilt compensator [47]. Hence the controller is known as TID Controller. It maintains the response of the system stable under different parameter variations. TID controller provides better disturbance rejection ratio as well as simpler tuning. The mathematical derivation of TID is given in (16).

$$TF_{TID} = \frac{K_T}{S^{\frac{1}{n}}} + \frac{K_I}{S} + K_D \qquad (16)$$

Where $n \neq 0$.

For the design of nature inspired optimization techniques with controller, objective function is necessary. So, it is designed based on the desired constraints and specifications. In this work, integral of squared error (ISE) is considered, where ISE suggested the square of the error over the time period. So, the large errors are improved. ISE based objective function for the islanded MG can be defined as

$$J = ISE = \int_0^{T_{max}} (\Delta f)^2 \, dt \qquad (17)$$

Where $T^{max} = 250\,s$. The controller parameters such as K_T, K_I, K_D ,n are known as constraints. So, the optimization problem can be written as

Minimum J

$$K_{T_{min}} \leq K_T \leq K_{T_{max}}$$

$$K_{I_{min}} \leq K_I \leq K_{I_{max}}$$

$$K_{D_{min}} \leq K_D \leq K_{D_{max}}$$

$$n_{min} \leq n \leq n_{max}$$

Subjected to

Where J, $K_{X_{min}}$ and $K_{X_{max}}$ are objective function, minimum value and maximum value respectively.

HYBRID GREY WOLF AND CUCK SEARCH ALGORITHM

Grey Wolf Optimization (GWO)

The Grey Wolf Optimization (GWO) algorithm, as described by Mirjalili et al. [48], is inspired by the hunting mechanism of grey wolves. Grey wolves live in groups, and within these groups, there are four distinct hierarchies. The first hierarchy is the Alpha (α) wolves, who are the leaders responsible for making decisions regarding hunting, sleeping, and other activities. The second group is the Beta (β) wolves, who assist the Alpha wolves in decision-making and other tasks, essentially acting as subordinates. The third group is the Omega (ω) wolves, which are the lowest-ranked and submit to the authority of the other wolves. Any wolf that does not belong to the Alpha, Beta, or Omega groups is classified as a Delta (δ) wolf. Delta wolves obey the Alpha and Beta wolves but have authority over the Omega wolves. The GWO algorithm mimics the hunting behavior of these wolves in three main stages:

Tracking and Chasing the Prey: In the first stage, wolves track and chase the prey. Encircling and Harassing the Prey: During the second stage, the wolves encircle and harass the prey to weaken it.

Attacking the Prey: Finally, in the third stage, the wolves launch an attack on the prey.
The mathematical model of GWO is derived based on the encircling behavior, where the wolves position themselves around the prey. This process is fundamental to the optimization algorithm, as it simulates how wolves use their coordinated movements to successfully capture their prey.

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$$\vec{D} = \left|\vec{C}.\vec{X}_P(t) - \vec{X}(t)\right| \quad (18)$$

$$\vec{X}(t+1) = \vec{X}_P(t) - \vec{A}.\vec{D} \quad (19)$$

$\vec{A}$ and $\vec{C}$ can be determined as

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \quad (20)$$

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$$\vec{C} = 2.\vec{r}_2 \qquad (21)$$

Where the value of a ⃗decreased from 2 to 0 linearly at the iteration time $\vec{r}_1$and $\vec{r}_2$values lies between 0 to 1 randomly.

The (18) and (19) show grew wolf improved its position according to the movement of the prey. $\vec{r}_1$and $\vec{r}_2$vector helps grew wolf to achieve any positions. Hence grew wolf improved its position at any random point around the prey.

Hunting: - Prey location can be found out by the grew wolf and encircling the prey. Alpha guided the other wolfs for hunting. There are enough

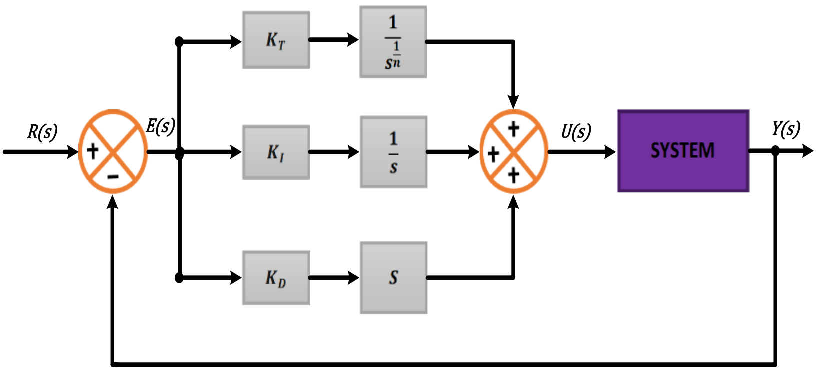

Figure 2. Block Diagram of TID Controller

knowledge of beta and delta on the location of prey. So, position is updated by wolfs according to the search agent position. So, mathematical equation is derive given below.

$$\begin{cases} \vec{D}_\alpha = |\vec{C}_1.\vec{X}_\alpha - \vec{X}| \\ \vec{D}_\beta = |\vec{C}_2.\vec{X}_\beta - \vec{X}| \\ \vec{D}_\delta = |\vec{C}_3.\vec{X}_\delta - \vec{X}| \end{cases} \qquad (22)$$

$$\begin{cases} \vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.(\vec{D}_\alpha) \\ \vec{X}_2 = \vec{X}_\beta - \vec{A}_1.(\vec{D}_\beta) \\ \vec{X}_3 = \vec{X}_\delta - \vec{A}_1.(\vec{D}_\delta) \end{cases} \qquad (23)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1+\vec{X}_2+\vec{X}_3}{3} \qquad (24)$$

The position of prey is calculated by Alpha, beta and delta. So, other wolfs improved their position around the prey.

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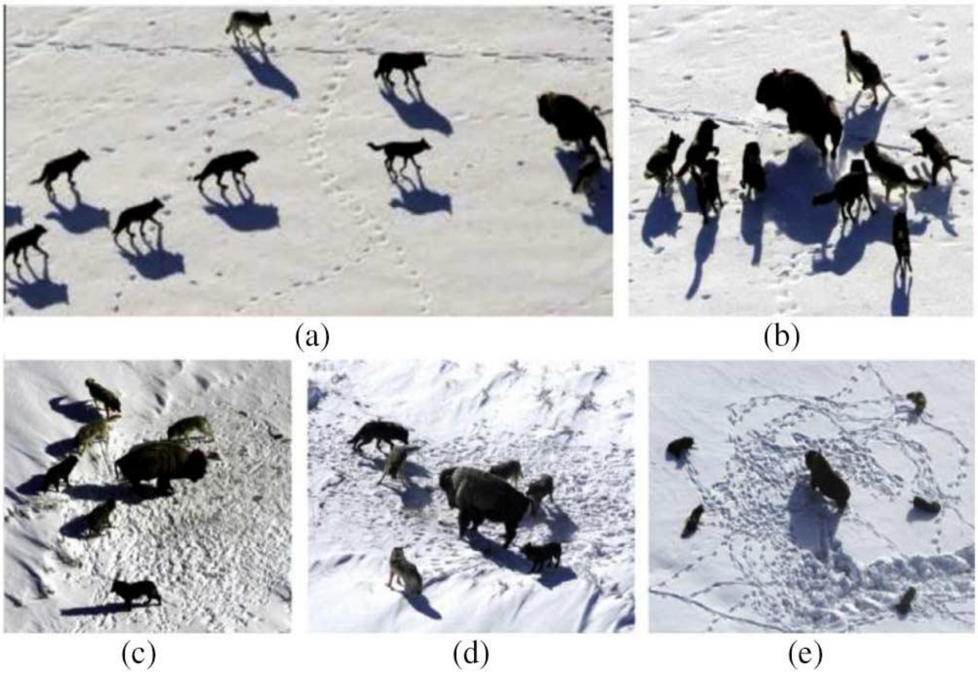

Figure 3. Hunting behaviour of grey wolves: (a) Tracking the prey, (b) to (d) Harassing and encircling the prey, and (e) Attacking the prey.

Attacking: The hunting process concludes when the wolves attack the prey, or in other words, when the prey stops moving. Mathematically, if the value of a decreases, the range of the vector A also decreases. This allows the search agent's position to update progressively between its current position and the prey's location. The search agents adjust their positions based on the locations of the Alpha, Beta, and Delta wolves in the GWO algorithm, eventually attacking the prey.

Searching:
The search begins from the positions of the Alpha, Beta, and Delta wolves. As seen in Eq. 20, the vector A forces the search agents to move towards the prey. In other words, the GWO algorithm performs a global search to find the fittest solution. The vector C contains random values, which assign random weights to the prey. In GWO, the vector C provides these random values both during the initial iterations and the final iterations, ensuring variability in the search process throughout the algorithm.

Cuckoo Search (CS)

The Cuckoos are pretty birds with amazing sounds. The reproduction strategy of Cuckoo is strange. Three rules are followed for describing the CS [49].

I. One no. of egg is laid by each cuckoo at a time. Nest is chosen randomly for dumping the egg.
II. The finest nest with very better-quality eggs will proceed for next generation.
III. The host nests availability is fixed. The host bird found out the cuckoo's egg with probability $p_a \in [0,1]$. Hence, the host bird throws away that egg or leave the nest and build a new nest

The new solution $x^{(t+1)}$with cuckoo i and a Lèvy fight happened

$$x_i^{(t+1)} = x_i^{(t)} + \alpha \oplus L\grave{e}vy(\lambda) \quad (25)$$

Where, α is step size and its value is 1. $\oplus$ known as entry wise multiplications.

A random walk is produced by Lèvy fight when random step size is withdrawn from Lèvy distribution.

$$\textbf{Lèvy} \sim \boldsymbol{u} = \boldsymbol{t}^{-\lambda}, \quad (\mathbf{1} < \boldsymbol{\lambda} \leq \mathbf{3}) \quad (26)$$

New solutions are obtained from Lèvy walk.Best solution is found out from these solutions, which speed up the local search

SIMULATION RESULTS AND DISCUSSION

In this section, the frequency response simulation results are obtained from MG system considering various disturbances such as $\Delta P_W, \Delta P_{sol}$ *and* ΔP_L. The proposed hGW-CS algorithm with TID controller is verified. This proposed methodology is used in comparison of PI, PID and TID controllers. The controller parameters $((K_P, K_I, K_D, K_T))$ are achieved by using this hGW-CS algorithm. Hence, the frequency response of islanded MG system is verified.

The parameters of PID and TID controllers are obtained by using the (17) as an objective function to minimize the fitness values and maximum iteration size 50 is taken in hGW-CS algorithm for iteration purposes.

Case-I: Fluctuation of Solar Power (ΔP_{sol})

In this case fluctuation of solar power is considered which is shown in Fig. 4 and Fig. 5 shows constant wind and load power with disturbances. Fig. 6 represents the controller's frequency response curve of islanded MG system. Table 2 shows comparison of different optimization techniques at (ΔP_{sol}).

Table. 2: Comparison between various optimization techniques at ΔP_{sol} as per [46, 47]

Parameters	PSO: PID	GWO: PID	HGW-CS: PID
K_P	2.8562	1.5454	2.6783
K_I	2.1869	0.3263	0.6348
K_D	1.0380	1.5454	1.0637
ISE	1.442	1.406	0.9985

The process the work has been done as:

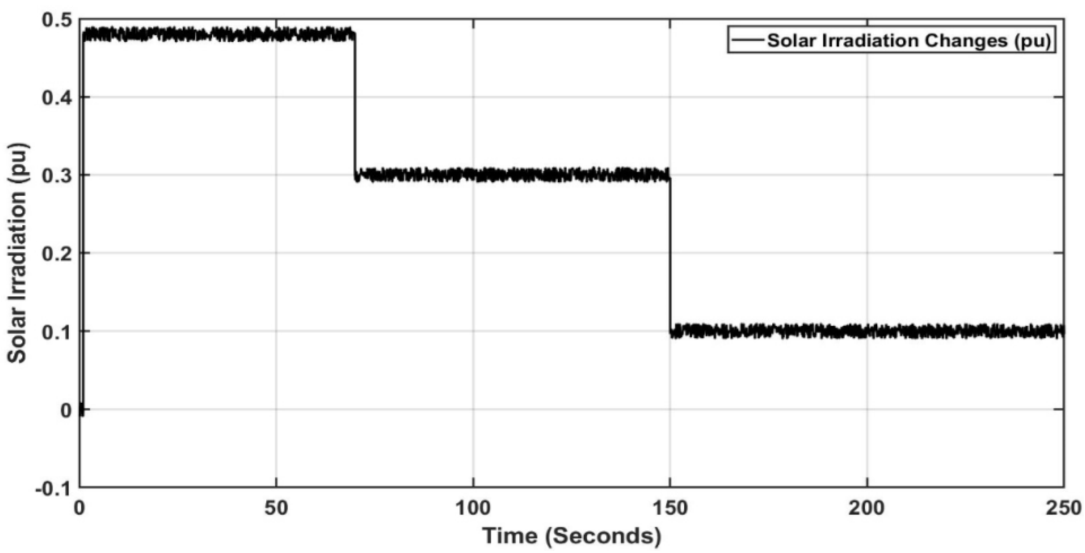

Figure 4. Fluctuation of solar power (ΔP_{sol})

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- The response of the islanded MG having PI controller with HGW-CS algorithm is written in legend as "HGW-CS Based PI controller".
- The response of the islanded MG having PID controller with HGW-CS algorithm is written in legend as "HGW-CS Based PID controller".
- The response of the islanded MG having TID controller with proposed HGW-CS algorithm is written in legend as "Proposed HGW-CS Based TID controller".

The HGW-CS optimization technique is compared with convectional optimization techniques of PSO, GWO using common PID controller. The tuned parameters of controllers optimized with the help of HGW-CS algorithm are given in Table.3 and Fig. 6 shows the performance analysis of proposed TID controller with other controllers. From the Table. 3, it can be seen that HGW-CS based TID controller is most efficient and stable and this controller improves the MG system performances with less oscillation in comparison with other controllers as shown in Fig.6.

Table 3. Parameters of different controllers based HGW-CS technique at ΔP_{sol}

Parameters	HGW-CS: PI	HGW-CS: PID	HGW-CS: TID
K_T	----	----	3.0000
K_P	2.8044	2.6783	----
K_I	0.1240	0.6348	0.9041
K_D	----	1.0637	2.0000
n	----	----	0.1282
ISE	2.32	0.9985	0.4198

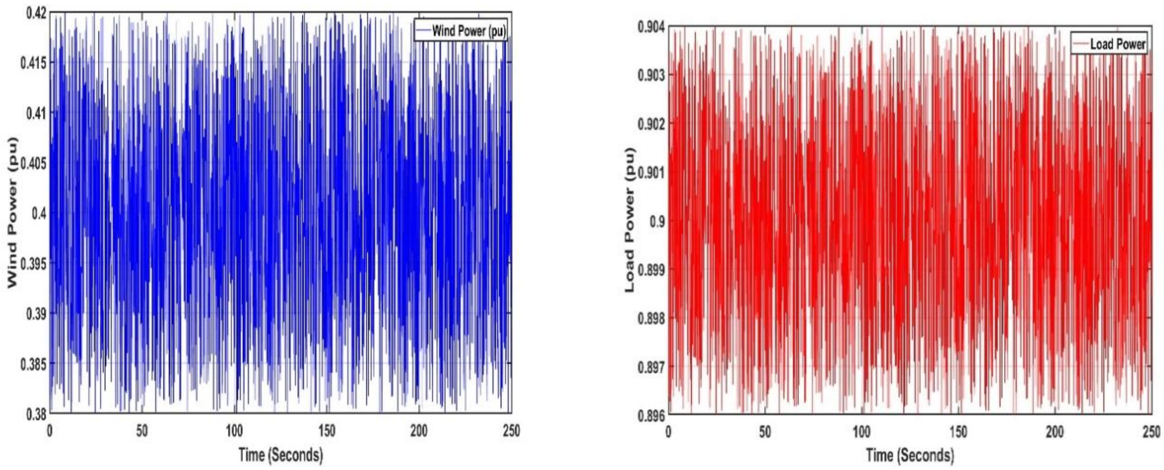

Figure 5. Wind and load power

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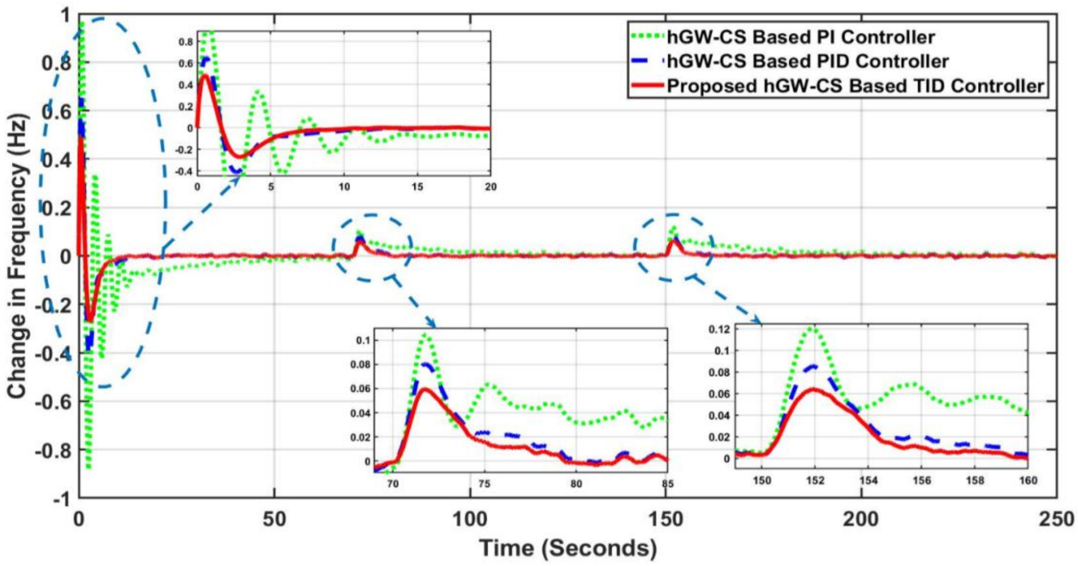

Figure 6. Frequency response curve of Case-I

Case-II: Fluctuation of wind power ΔP_W

In this case wind power fluctuation is considered as shown in Fig. 7 and Fig. 8 represents constant solar and load power with disturbances. The frequency response curve of controllers of islanded MG system is shown in Fig. 9. Table 4 shows the comparison of different optimization techniques at (ΔP_W) . The hGW-CS optimization technique is verified with PSO, GWO techniques using the PID controller and the tuned parameters of PID controller is given in Table 4.The pproposed TID controller performance analysis with other controllers is shown in Table 5 and it shows the controller gives better stability response than other controllers and also at the same time the controller gives lesser oscillation of the system than other controllers as depicted in Fig.9.

Table 4. Comparison between various optimization techniques at ΔP_W

Parameters	PSO: PID	GWO: PID	hGW-CS: PID
K_P	4.7071	1.9569	2.8050
K_I	0.8750	0.5029	1.2966
K_D	0.3711	1.2937	2.0000
ISE	1.444	1.385	0.8888

Table 5. Parameters of different controllers based hGW-CS technique at ΔP_W

Parameters	hGW-CS: PI	hGW-CS: PID	hGW-CS: TID
K_T	----	----	2.9985
K_P	3.0000	2.8050	----
K_I	0.2347	1.2966	0.1618
K_D	----	2.0000	0.8373
n	----	----	0.4490
ISE	3.118	0.8888	0.5881

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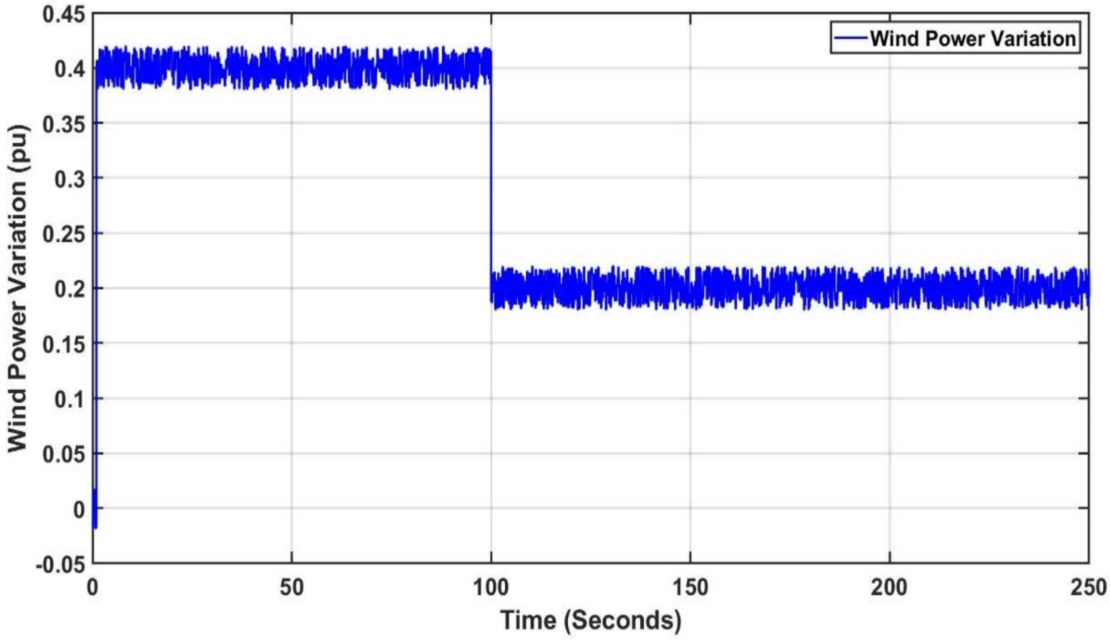
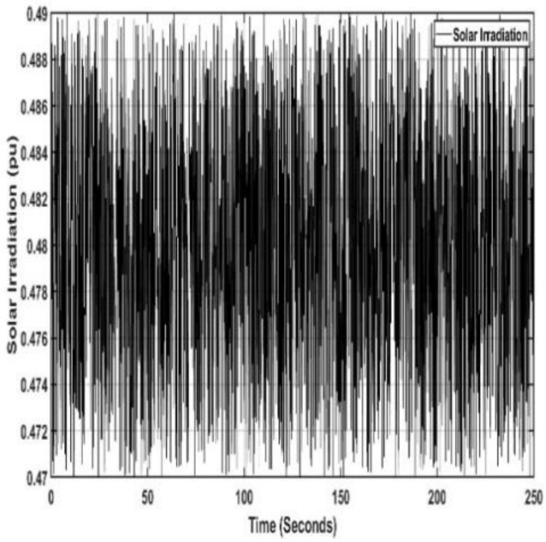


Figure 7: Fluctuation of wind power ΔP_W



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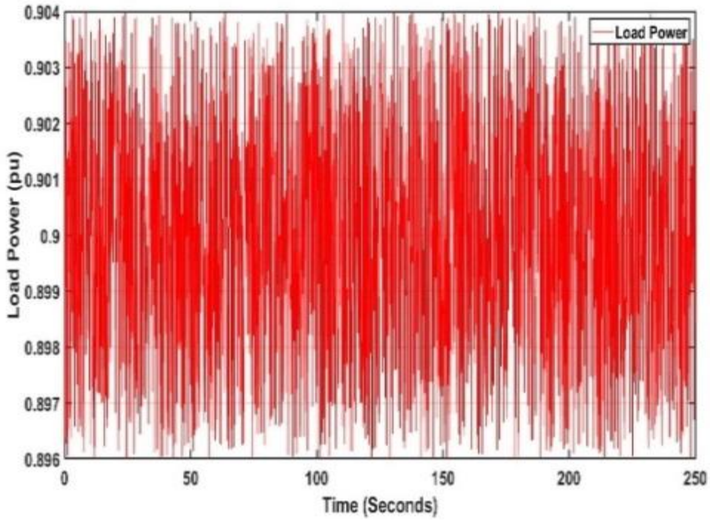

Figure 8. Solar and load power

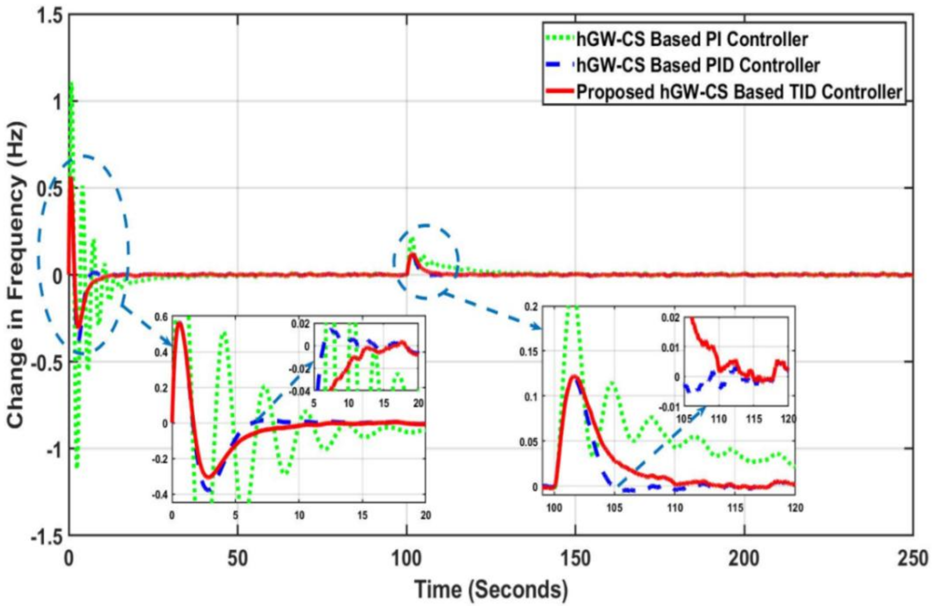

Figure 9. Frequency response curve of Case-II

Case-III: Load power variation ΔP_W

In this case, the fluctuation of load power is considered, as shown in Fig. 10, while Fig. 11 illustrates the constant solar and wind power with disturbances. The frequency response curve of different controllers used in the Microgrid (MG) system is shown in Fig. 12. From Table 6, it is evident that the hGW-CS based PID controller outperforms both the PSO-based PID and GWO-based PID controllers. The Integral Square Error (ISE) for the hGW-CS based PID is lower than that for the other optimization-based PID techniques. From the Table 6, it can be seen that the hGW-CS based PID is compared with PSO based PID and GWO based PID and the ISE of the hGW-CS based PID is less than other optimization technique based PID. Also, Table. 6 represents the tuned values of $K_P, K_I, K_D$and Table.7 gives the detailed optimized values of different controllers used in MG system. The TID controller used in hGW-CS algorithm provides better performance and more stable as compared to other controllers.

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Table. 6: Comparison between various optimization techniques at ΔP_W

Parameters	PSO: PID	GWO: PID	hGW-CS: PID
K_P	1.5161	2.1774	2.7578
K_I	1.0740	1.5170	0.7622
K_D	1.0851	0.8881	0.6967
ISE	1.434	1.11	0.9813

Table 7. Parameters of different controllers based hGW-CS technique at ΔP_W

Parameters	hGW-CS: PI	hGW-CS: PID	hGW-CS: TID
K_T	----	----	2.9988
K_P	3.0000	2.7578	----
K_I	0.5394	0.7622	1.9901
K_D	----	0.6967	1.9448
n	----	----	0.0395
ISE	2.0000	0.9813	0.5455

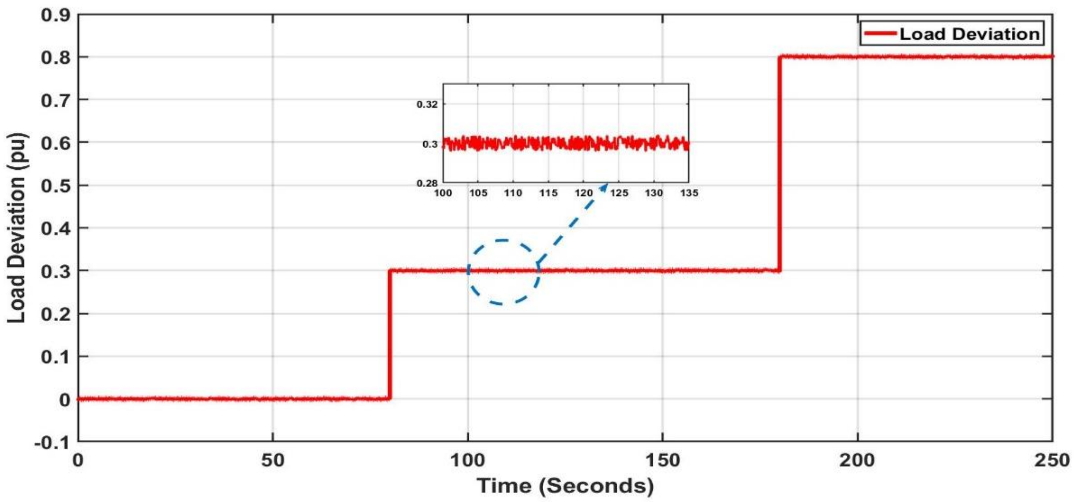

Figure 10. Load power deviation ΔP_L

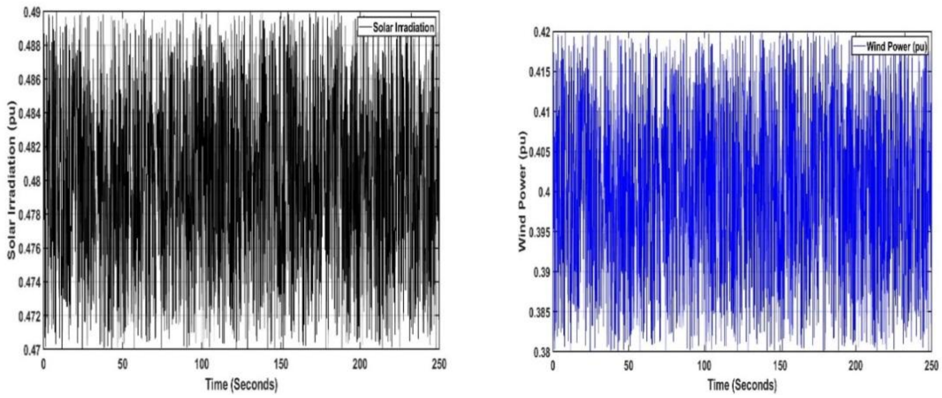

Figure 11. Solar and Wind power

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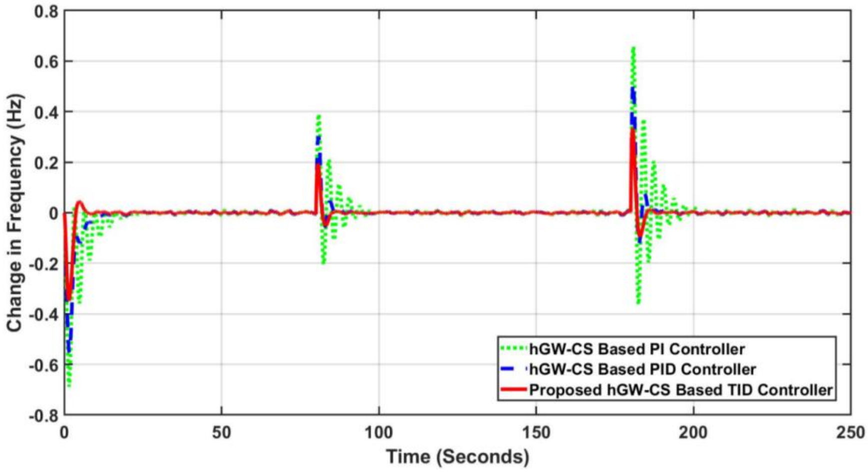

Figure 12. Frequency response curve of Case-III

Case-IV: Changes in ΔP_{sol},ΔP_W and ΔP_L

The changes in ΔP_{sol}, ΔP_W and ΔP_L are shown in Fig. 13. The frequency response curve of the different controller using hGW-CS algorithm in MG is shown in Fig. 14. The comparison between different optimization techniques at case-IV condition is given in Table.8 and the ISE is less in hGW-CS based PID controller in comparison with other optimization techniques as shown in Table.9.The hGW-CS based TID controller used in MG provides lesser oscillation and the stability of the system is more as shown in Fig.14.

Table 8. Comparison between various optimization techniques at ΔP_W

Parameters	PSO: PID	GWO: PID	hGW-CS: PID
K_P	1.3468	2.9587	2.9930
K_I	1.8728	1.0180	0.6687
K_D	3.9345	1.4293	1.6671
ISE	1.333	1.133	0.9429

Table 9. Parameters of different controllers based hGW-CS technique at

Parameters	hGW-CS: PI	hGW-CS: PID	hGW-CS: TID
K_T	----	----	3.0000
K_P	2.3851	2.9930	----
K_I	0.1629	0.6687	0.7708
K_D	----	1.6671	2.0000
n	----	----	0.2431
ISE	3.565	0.9429	0.6471

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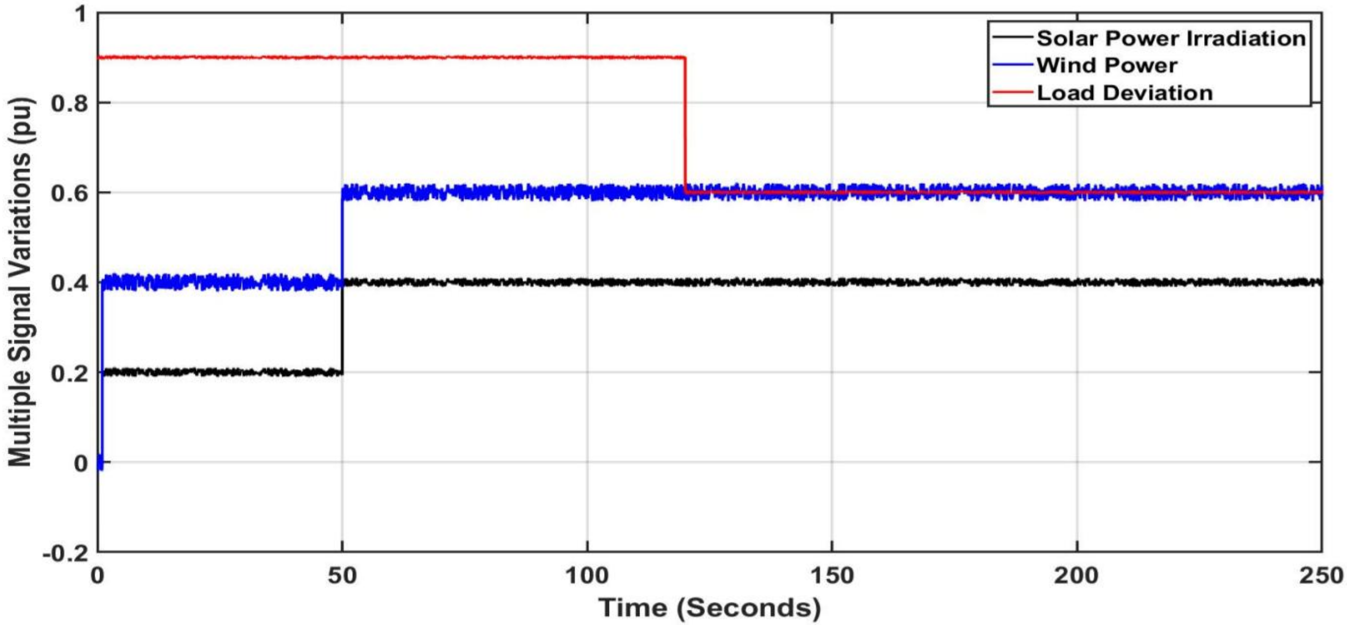

Figure 13: Load power deviation of Case-IV

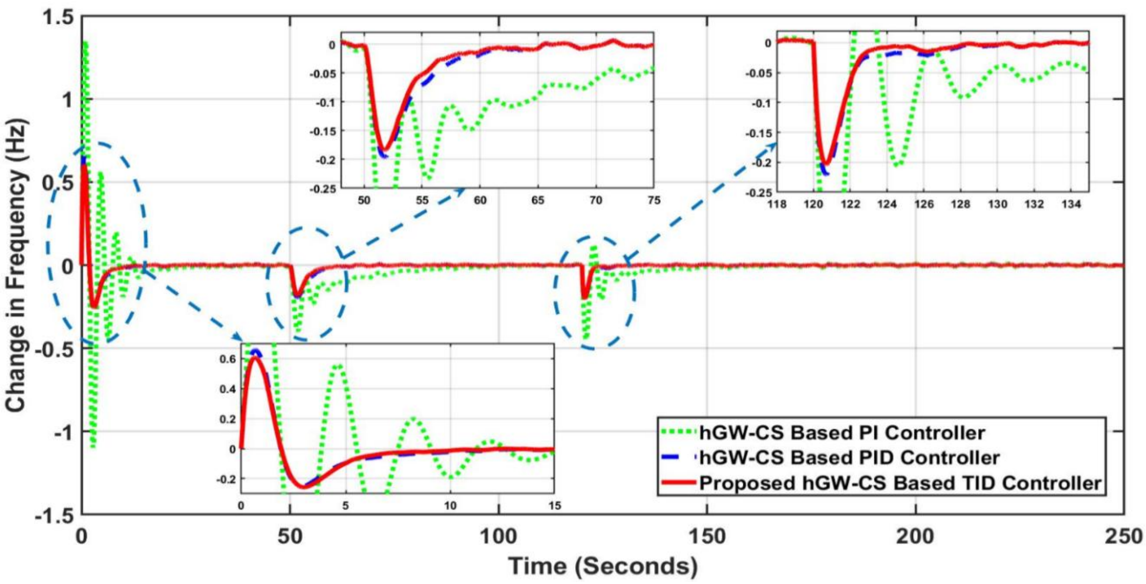

Figure 14. Frequency response curve of Case-I

VALIDATION OF PROPOSED CONTROLLER IN OPAL-RT HIL PLATFORM

OPAL-RT is a Canadian based company that specializes in real-time simulation technology for power systems, power electronics, and electric drives. The company provides software and hardware solutions to help engineers and researchers design, test, and validate their systems in a virtual environment before implementing them in the real world. OPAL-RT's real-time simulators can replicate complex power systems and control algorithms in real-time, enabling engineers to perform hardware-in-the-loop (HIL) testing of their systems. This allows them to identify potential issues and optimize their designs before deploying them in the field. OPAL-RT's simulators can also be used for research and development purposes, allowing researchers to study the behaviour of power systems under various conditions and scenarios. OPAL-RT offers a range of products and services, including hardware-in-the-loop simulators, software tools for model development and simulation, and consulting and training services. The company serves customers in various industries, including automotive, aerospace, defence, renewable energy, and power electronics. The digital simulator compiles the discrete time model with a fixed step size. The proposed model is validated on OPAL-RT 4510 RCP/HIL Kintex 7 FPGA based real time simulator. The Simulink Model is developed on

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RT LAB version 2021.3.4.320 to form three subsystems, i.e. master, slave and console subsystems. The master subsystem is the main subsystem and is prefixed as "SM_". The console subsystem is created which contains all the scopes blocks and other necessary components that can be modified during the compiling period .For large and complex model slave subsystem is integrated with main model for faster computation. The model is then executed on the top simulator (OP4510) and the results are captured on a mixed signal oscilloscope YOKOGAWADLM 3024, 2.5 GS/s, 200 MHz is used. The whole laboratory set up of the OPAL-RT system is structured in the Micro-grid research Lab of Department of Electrical Engineering, SOA deemed to be University, Odisha, India. The Figure 15 shows the entire framework of the system and table 10 gives a description of the configuration of each component which is part of the system.

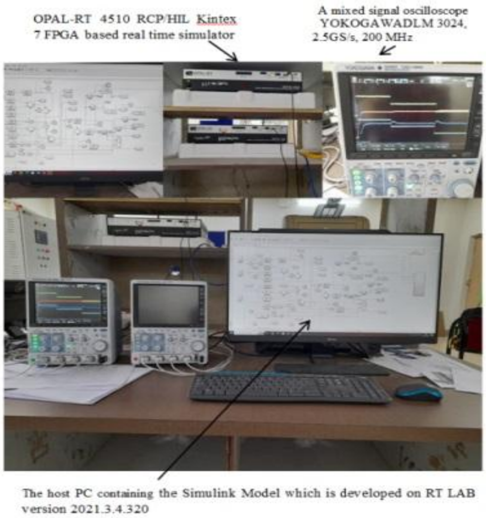

Figure 15. shows the OPAL-RT laboratory set up

Table 10. describes the configuration of each component of the OPAL-RT lab set up.

Parameters	Quantity
Type of Simulation	Real Time
Time step	
Operating System	Redhat v2.6.29.6-opalrt-6.3.0
Simulator	OPAL-RT 4510 RCP/HIL Kintex 7 FPGA
CPU	
Memory	8 GB
FPGA	Kintex 7 FPGA
Software utilized	RT Lab

The RTS is used to authenticate the controller for four different cases simulated in MATLAB 2019a.

Case-I: Fluctuation of Solar Power (ΔP_{sol})

In this case intermittent Solar Power is considered keeping the disturbances owing to load and wind constant. The following results are obtained in real time simulator. Figure 16 shows the fluctuation of solar power. Figure 17 shows change in frequency.

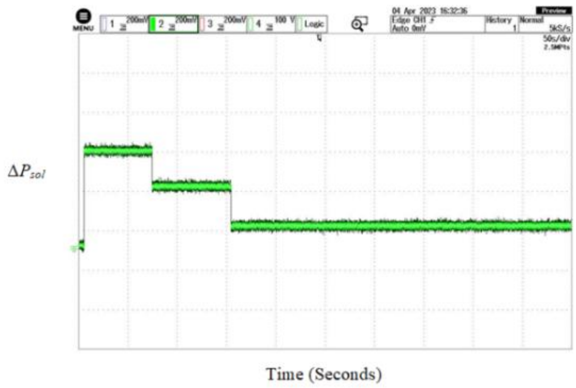

Figure 16. Fluctuation of solar power (ΔP_{sol})

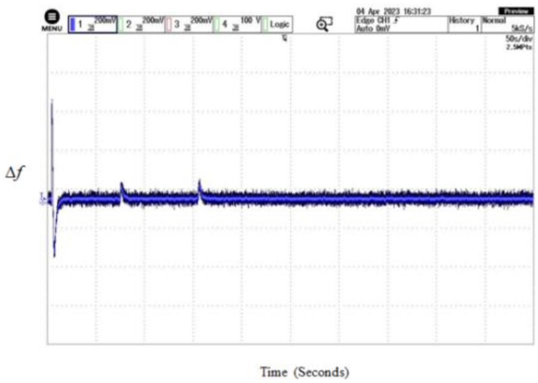

Figure 17. Change in Frequency (Δf)

The x-axis represents the time axis, where each division is 50s.The results obtained in the real time simulator shows the frequency deviation in between time period of 50s-100s and 150s -200s, which is same as the graph shown in Fig 6, the results obtained by simulating the model in Matlab Simulink 2019.

Case-II: Fluctuation of wind power (ΔP_W)

In this case the dynamic nature of wind is considered while keeping the disturbances of load and solar constant. The following results are obtained in OPAL-RT. Figure 18 shows deviation in input wind power. Fig 19 shows the change obtained in frequency curve using OPAL-RT technology, which when compared with the results obtained simulating the Simulink model in matlab to be same.

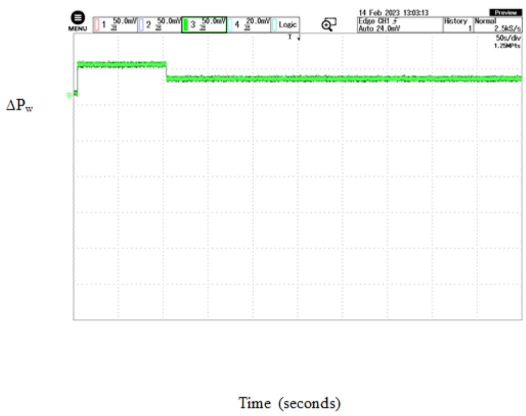

Figure 18. Fluctuation of Wind Power (ΔP_w)

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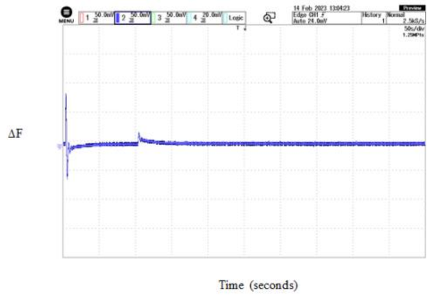

Figure 19. Change in Frequency (Δf)

Case-III: Load power variation (ΔP_L)

In this section the varying load demand are taken into consideration while keeping the disturbances of wind and solar constant. The following results are obtained in OPAL-RT. Figure 20 represents the change in load. Figure 21 indicates the change in frequency due to load deviation. Figure 20 shows the change in frequency obtained in real time which is similar with the signal figure 12 acquired by debugging the model in Matlab Simulink 2019.

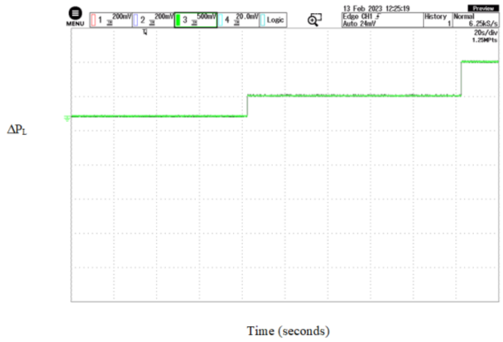

Figure 20. Load power variation (ΔP_L)

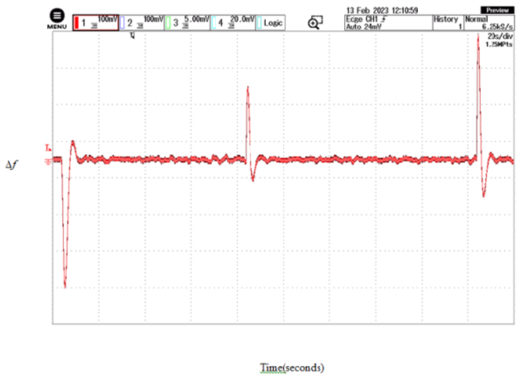

Figure 21. Change in Frequency (Δf)

Case-IV: Changes in $\Delta P_{sol}, \Delta P_W$ and ΔP_L

In this section the non-linear nature of wind and solar is taken into consideration while considering the dynamic behaviour of the load. The following results are obtained in OPAL-RT. Figure 22 shows the total change in power.

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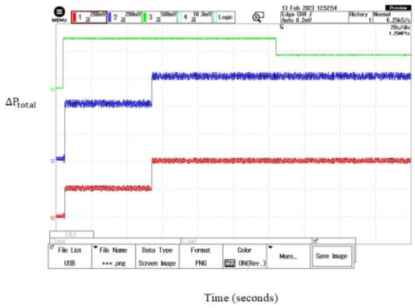

Figure 22. Change in total power of micro grid system

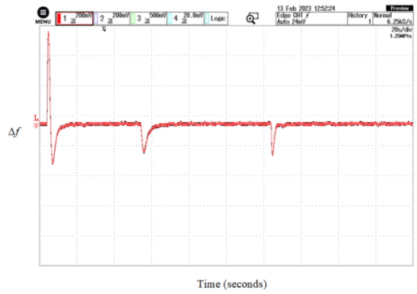

Figure 23. The change in frequency for case 4.

CONCLUSION

The paper gives the detail explanation about the proposed hGW-CS algorithm for TID controller. This proposed technology is implemented in the islanded MG system for the control of frequency deviation. As described above the state space models of various components of islanded MG such as STPG, WTG, electrolyser, FC, FESS, BESS, MT are described. In the first part paper a comparison is done in between hGW-CS algorithm with some other optimization techniques such as PSO and GWO algorithm. The controller parameters such as K_P,K_I,K_D are found by using these algorithms and the proposed hGW-CS algorithm provides better results than other above said algorithms. In the second part, the hGW-CS algorithm based TID controller along with other PID and PI controllers is implemented in islanded MG to reduce the impact of $\Delta P_{sol}, \Delta P_W, \Delta P_L$ From the research work, it can be concluded that hGW-CS based TID gives better performance than hGW-CS based PID and hGW-CS based PI. Hence, disturbances in islanded MG can be overcome by the use of proposed hGW-CS based TID controller.

REFERENCE

[1] Alsafran, Ahmed. "Literature review of power sharing control strategies in islanded AC microgrids with nonlinear loads." 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe). IEEE, 2018.
[2] Ranjan, Mrinal, and Ravi Shankar. "A literature survey on load frequency control considering renewable energy integration in power system: Recent trends and future prospects." Journal of Energy Storage 45 (2022): 103717.
[3] Talaat, M., et al. "Artificial intelligence applications for microgrids integration and management of hybrid renewable energy sources." Artificial Intelligence Review (2023): 1-55..
[4] Naderi, Mobin, et al. "Dynamic modeling, stability analysis and control of interconnected microgrids: A review." Applied Energy 334 (2023): 120647.
[5] Khan, Irfan Ahmed, et al. "New trends and future directions in load frequency control and flexible power system: A comprehensive review." Alexandria Engineering Journal 71 (2023): 263-308..
[6] Mbungu, Nsilulu T., et al. "Control and estimation techniques applied to smart microgrids: A review." Renewable and Sustainable Energy Reviews (2023): 113251.
[7] Jasim, Ali M., et al. "Consensus-based intelligent distributed secondary control for multiagent islanded microgrid." International Transactions on Electrical Energy Systems 2023 (2023).

[8] Gulzar, Muhammad Majid, Daud Sibtain, and Muhammad Khalid. "Cascaded Fractional Model Predictive Controller for Load Frequency Control in Multiarea Hybrid Renewable Energy System with Uncertainties." International Journal of Energy Research 2023 (2023).

[9] Seresht, Rezvan Mansoori, et al. "Frequency control scheme of an AC Islanded microgrid based on modified new self-organizing hierarchical PSO with jumping time-varying acceleration coefficients." Cogent Engineering 10.1 (2023): 2157982.

[10] Gouran-Orimi, Sina, and Ali Ghasemi-Marzbali. "Load Frequency Control of multi-area multi-source system with nonlinear structures using modified Grasshopper Optimization Algorithm." Applied Soft Computing 137 (2023): 110135.

[11] Lian, Zhijie, et al. "Decentralized secondary control for frequency restoration and power allocation in islanded AC microgrids." International Journal of Electrical Power & Energy Systems 148 (2023): 108927.

[12] Khaleel, Mohamed Mohamed, Abdussalam Ali Ahmed, and Abdulgader Alsharif. "Energy Management System Strategies in Microgrids: A Review." North African Journal of Scientific Publishing (NAJSP) (2023): 1-8.

[13] Khadanga, Rajendra Kumar, et al. "Modified Sine Cosine-Based Controller for Microgrid Frequency Regulation." Recent Developments in Electrical and Electronics Engineering: Select Proceedings of ICRDEEE 2022. Singapore: Springer Nature Singapore, 2023. 71-84.

[14] Z.Lingwei, S.Liu and X.Xie, "Frequency domain-based configuration and power follow-up control for power sources in a grid-connected Microgrid",Electrical Energy System, vol.10,pp.2499-2514,2015.

[15] Abbasi, Maysam, et al. "Review on the Microgrid Concept, Structures, Components, Communication Systems, and Control Methods." Energies 16.1 (2023): 484.

[16] Rodriguez-Martinez, Omar F., et al. "A Review of Distributed Secondary Control Architectures in Islanded-Inverter-Based Microgrids." Energies 16.2 (2023): 878..

[17] Abbasi, Maysam, et al. "Review on the Microgrid Concept, Structures, Components, Communication Systems, and Control Methods." Energies 16.1 (2023): 484..

[18] Celik, Emre, Nihat Öztürk, and Essam H. Houssein. "Improved load frequency control of interconnected power systems using energy storage devices and a new cost function." Neural Computing and Applications 35.1 (2023): 681-697.

[19] Issa, Mohamed. "Enhanced arithmetic optimization algorithm for parameter estimation of PID controller." Arabian Journal for Science and Engineering 48.2 (2023): 2191-2205.

[20] Dhanasekaran, Boopathi, et al. "Load Frequency Control Assessment of a PSO-PID Controller for a Standalone Multi-Source Power System." Technologies 11.1 (2023): 22.

[21] Khalil, A. Elsawy, et al. "Enhancing the Conventional Controllers for Load Frequency Control of Isolated Microgrids Using Proposed Multi-Objective Formulation via Artificial Rabbits Optimization Algorithm." IEEE Access 11 (2023): 3472-3493.

[22] Boopathi, D., et al. "Investigation of a Microgrid Power System for Frequency Regulation by Implementing Ant Colony Optimization Technique Optimized Secondary Controller." Renewable Energy Optimization, Planning and Control: Proceedings of ICRTE 2022. Singapore: Springer Nature Singapore, 2023. 229-236.

[23] Singh, Balvender, Adam Slowik, and Shree Krishan Bishnoi. "Review on Soft Computing-Based Controllers for Frequency Regulation of Diverse Traditional, Hybrid, and Future Power Systems." Energies 16.4 (2023): 1917.

[24] Y.Han, P.M.Young, A.Jain and D.Zimmerle, " Robust Control for Microgrid frequency deviation reduction with attached storage system", IEEE Transactions Smart Grid vol.6,pp. 557-565,2025.

[25] A.Kahrobaeian and Y.A.I.Mohamed, " Direct single-loop μ-synthesis voltage control for suppression of multiple resonances in Microgrids with power factor correction capacitors",IEEE Transactions Smart Grid vol.4,pp. 1151-1161,2013.

[26] L.A.Zadeh, "Fuzzy sets", Inf Control 8(3),pp. 338–353,1965.

[27] L.A.Zadeh, "The concept of a linguistic variable and its application to approximate reasoning-I", Inf Sci8(3),pp.199–249,1975.

[28] L.A.Zadeh, "The concept of a linguistic variable and its application to approximate reasoning—II", Inf Sci

8(4),pp.301–357,1975.
[29] L.A.Zadeh, "The concept of a linguistic variable and its application to approximate reasoning-III", Inf Sci 9(1),pp.43–80,1975.
[30] E.H.Mamdani, "Application of fuzzy algorithms for control of simple dynamic plant", Proc IEE (Control Sci) 121(12),pp.1585–1588,1974.
[31] E.H.Mamdani and S.Assilian, " An experiment in linguistic synthesis with a fuzzy logic controller", Int J Man Mach Stud 7(1):pp.1–13,11975.
[32] E.H.Mamdani, "Advances in the linguistic synthesis of fuzzy controllers", Int J Man Mach Stud 8(6),pp.669– 678,1976.
[33] E.H.Mamdani and S.Assilian, "An experiment in linguistic synthesis with a fuzzy logic controller", Int J Hum Comput Stud51(2),pp.135–147,1999.
[34] L.P. Holmblad andJ.J. Ostergaard, "Control of a cement kiln by fuzzy logic, In: Gupta MM, Sanchez E (eds) Fuzzy informationand decision processes", Elsevier, North-Holland, pp.389–399,1982.
[35] W.J.Kickert and E.H. Mamdani, "Analysis of a fuzzy logic controller", Fuzzy Sets System 1(1),pp.29–44,1978.
[36] C.C.Lee, " Fuzzy logic in control systems: fuzzy logic controller-I", IEEE Transactions System Management Cybern 20(2),404–418,1990.
[37] C.C.Lee, " Fuzzy logic in control systems: fuzzy logic controller- II", IEEE Transactions System Management Cybern 20(2),pp.419–435,1990.
[38] M.Maeda and S.Murakami, "A design for a fuzzy logic controller", Inf Sci 45(2),pp.315–330,1988.
[39] M.Maeda and S. Murakami, "A self-tuning fuzzy controller", Fuzzy Sets System 51(1), pp.29–40,1992.
[40] L.X.Wang, " Stable adaptive fuzzy control of nonlinear systems", IEEE Transactions Fuzzy System 1(2),pp.146–155,1993.
[41] B.J.Choi, S.W. Kwak and B.K. Kim, "Design of a single-input fuzzy logic controller and its properties", Fuzzy Sets System 106(3),pp.299–308,1999.
[42] H.Bevrani,M.R. Feizi and S. Ataee, " Robust frequency control in an Islanded Microgrid: H∞and μ-synthesis approaches", IEEE Transactions Smart Grid 7, pp. 706–717, 2016.
[43] Y.C.Wu, M.J. Chen, J.Y. Lin, W.S. Chen and W.L. Huang, "Corrective economic dispatch in a Microgrid", International Journal Numerical Model Electron Netw Development Fields 26, pp. 140–150, 2013.
[44] A.G.Tsikalakis,N.D. Hatziargyriou, " Operation of Microgrids with demand side bidding and continuity of supply for critical Loads", Eur. Transactions Electric Power 21, pp. 1238–1254, 2011.
[45] I.Pan and S.Das, "Fractional Order AGC for Distributed Energy Resources Using Robust Optimization", IEEE Transactions on Smart Grid, vol.7, no.5,pp. 2175-2186,2016.
[46] K.Nithilasaravanan, N.Thakwani, P.Mishra, V.Kumar and K.P.S.Rana, "Efficient control of integrated power system using self-tuned fractional-order fuzzy PID control", Neural Computing and Applications, vol.1,pp.1- 18, 2018.
[47] R.K.Khadanga, S.Padhy, S.Panda and A.Kumar, " Design and Analysis of Tilt Integral Derivative Controller for Frequency Control in an Islanded Microgrid: A Novel Hybrid Dragonfly and Pattern Search Algorithm Approach", Arabian Journal for Science and Engineering, vol.1, pp.1-12,2018.
[48] Seyedali Mirjalili, Seyed Mohammad Mirjalili and Andrew Lewis, "Grey Wolf Optimizer",Advances in Engineering Software, Vol. 69, pp. 46-61,2014.
[49] X.-S. Yang and S.Deb, "Engineering Optimisation by Cuckoo Search", International Journal of Mathematical Modelling and Numerical Optimisation, Vol. 1, No. 4, pp. 330–343, 2010.