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Optimizing Frequency Stability in Micro Grid-Connected Hybrid Power Systems Using a Novel PSO-GWO Hybrid Approach

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ABSTRACT : This research paper explores the intricacies of managing frequency in a hybrid power system connected to a microgrid. The system combines solar Photovoltaic (PV), wind, and diesel-engine generator (DEG) sources, along with a Superconducting Magnetic Energy Storage system (SMES). The focus is on overcoming challenges arising from sudden shifts in load demand and power fluctuations from renewable sources that lead to variations in frequency. To address these issues, the hybrid system strategically incorporates energy storage devices, with a specific emphasis on the SMES unit. The study delves into the operations of the SMES, conducting detailed analyses of both steady-state and dynamic performance using a PI controller. Significantly, the controller parameters undergo optimization through a unique hybrid strategy, combining Particle Swarm Optimization-Grey Wolf Optimization (PSO-GWO). The investigation incorporates refined constraints on inductor current to tackle discontinuous conduction and storage limitations. Implemented within the MATLAB Simulink environment, the study highlights the pivotal role of the SMES system in enhancing frequency stability during scenarios with variable power generation and unpredictable load demands. Remarkable for its innovative approach, this paper presents a pioneering contribution, building upon previous research and introducing a hybrid optimization methodology that surpasses standalone GWO and PSO methods in effectively addressing frequency regulation challenges within microgrid-connected Hybrid Power Systems.

KEYWORDS: Diesel-Engine Generator, Grey Wolf Optimization, Particle Swarm Optimization Photovoltaic Superconducting Magnetic Energy Storage.

I. INTRODUCTION

The drive towards sustainable energy solutions has spurred the incorporation of renewable sources into power systems, resulting in the emergence of micro-grid-connected hybrid power systems. These systems, which integrate solar Photovoltaic (PV), wind, and Diesel-Engine Generators (DEG), show potential to meet the growing demand for dependable electricity while addressing environmental concerns. Nevertheless, the inherent variability of renewable sources and the unpredictable nature of load demands present substantial challenges to the stability of these hybrid systems [1].

The challenge at hand revolves around the frequency fluctuations caused by sudden shifts in load demand and the intermittent power output from renewable sources. This unpredictability poses a risk to the consistent operation of micro-grid-connected hybrid power systems, underscoring the importance of innovative solutions to improve frequency stability. Tackling this issue is vital not only for the efficient functioning of existing systems but also for shaping the future landscape of sustainable energy infrastructure.

Driven by the urgent need for robust frequency regulation mechanisms, this research concentrates on the role of Superconducting Magnetic Energy Storage (SMES) units in alleviating the adverse effects of load demand fluctuations and power variations from renewable sources within micro-grid connected hybrid power systems [2]. The motivation behind this focus lies in the understanding that the integration of renewable energy, while essential for environmental sustainability, demands advanced technologies to guarantee the stability and reliability of power systems. SMES, with its swift response and minimal energy losses during charge and discharge cycles, emerges as a promising solution to confront the frequency stability challenges posed by the inherent variability of renewable sources.

The investigation unfolds through two carefully crafted simulation phases, aiming to offer a thorough understanding of the SMES unit's impact on frequency stability across diverse operational conditions. In the initial phase, a steady-state examination utilizing a Proportional-Integral (PI) controller with a step load change response sheds light on the system's behavior under stable conditions and its reaction to abrupt load variations. Subsequently, the second phase

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extends the analysis to dynamic performance over a typical day, capturing the system's adaptability to arbitrary changes in load demands. This dual-phase simulation approach ensures a comprehensive exploration of the SMES unit's effectiveness in maintaining frequency stability. In the pursuit of optimized performance, a hybrid optimization approach, specifically integrating Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO), is employed to fine-tune controller parameters [3]. The choice of this hybrid optimization technique is motivated by the aim to leverage the strengths of both algorithms, synergistically combining PSO's global exploration capabilities with GWO's local exploitation efficiency. This strategic fusion aims to overcome the limitations of individual optimization methods, offering a more robust and effective solution for controller parameter optimization in the context of micro-grid-connected hybrid power systems [3]. Moreover, the investigation takes practical limitations into account by addressing constraints on inductor (coil) current, recognizing the potential for discontinuous conduction in the face of substantial disturbances and constrained storage capacity, understanding the intricate dynamics involved in frequency regulation within micro-grid-connected hybrid power systems. By emphasizing the crucial role played by SMES units in strengthening stability amidst fluctuating power generation and erratic demand loads, the discoveries of this investigation have the potential to profoundly influence the design and functionality of upcoming energy infrastructures. The research stands as a testament to collective efforts directed towards creating resilient and sustainable energy systems, addressing contemporary challenges posed by the dynamic interplay of renewable sources and evolving energy demands. The research commences with a thorough review of existing literature in Section II, providing insights into relevant studies within the domain. Section III elucidates the intricacies of the proposed methodologies. Following this, Section IV presents the outcomes obtained from simulations conducted in MATLAB, accompanied by a thorough analysis. The paper concludes in Section V, where the findings are summarized, and concluding remarks are provided.

II. LITERATURE REVIEW

The increasing impact of greenhouse gases on the Earth's atmosphere and the diminishing reserves of fossil fuels have sparked a growing interest in clean and sustainable energy sources. In current discussions, hydro energy, solar energy, wind energy, and biogas emerge as the leading contenders for providing a cleaner and more sustainable alternative [4] [5]. The influence of wind and solar power in global electricity generation has seen a substantial rise, with a growing emphasis on their use in distributed generations and microgrids (MGs) [6]. Solar power systems find primary application in supplying electricity to off-grid areas where grid extension is impractical, while wind power integration is more commonly associated with grid-based operations. Solar Photovoltaic (PV) arrays offer enhanced installation flexibility, enabling easy mounting on domestic locations [7]. The widespread deployment of wind and solar PV power plants for distributed generations and microgrids leverages the variable power generated from these sources to meet local load demands or inject excess power into local grids [8]. However, the intermittent and uncertain nature inherent in renewable technologies introduces a spectrum of technical, economic, and social barriers [9]. The integration of these renewables into existing grids and microgrids poses additional technical challenges, particularly concerning frequency and voltage regulations. Operational issues arise in distributed systems due to the variable penetrations of distributed renewable sources, demanding urgent attention from researchers and regulatory authorities to formulate optimal solutions [10].

Addressing the frequency regulation challenges associated with micro-grid connected Hybrid Power Systems (HPS), energy storage technologies emerge as crucial components. Contemporary storage technologies, capable of performing multifaceted functions like backup power supply, active/reactive power injection, or absorption from/to the grid, have been proposed in existing literature [11] [12] [13]. While conventional storage options such as Battery Energy Storage Systems [14] and Hydro Pump Storage [15] are prevalent, they grapple with issues such as high response times, limited lifecycle, storage capacity constraints, large unit volumes, and environmental hazards [16] [17]. In response to these challenges, this paper proposes the utilization of Superconducting Magnetic Energy Storage (SMES) technology to ensure the stable operation of hybrid power systems. SMES offers inherent advantages, including swift response times, significant storage efficiency, and the capability to inject or absorb real/reactive power, making it a viable solution Prior studies have examined the impact of SMES during transient disturbance conditions in grid-connected power systems [11], as well as its application in on-grid and off-grid modes [19]. Additionally, the literature covers topics such as neural network-based frequency control , power flow control and management schemes ,that incorporate energy storage devices, and concepts of power flow control based on knowledge domains .Expanding on previous research endeavors [14] this paper introduces innovative aspects, including a small stability analysis of a solar-based hybrid system with step load response, the implementation of a Proportional-Integral (PI) controller for system frequency response control, and the tuning of controller parameters using a Particle Swarm Optimization-Grey Wolf Optimization (PSO-GWO) hybrid algorithm-based optimization approach. Furthermore, the paper explores an additional hybrid

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power system solely based on renewable power generation, analyzing the effects of SMES during both steady-state and dynamic state operations. In addressing critical gaps in existing literature, these additions contribute valuable insights to the discourse on micro-grid connected Hybrid Power Systems and their sustainable operation.

III. PROPOSED METHODOLOGY

A. Modeling of Hybrid Power Systems (HPS)

A Hybrid Power System (HPS) combines various energy sources, including solar, wind, and traditional generators, alongside energy storage, to establish a dependable and sustainable power supply. This comprehensive overview encompasses the components and mathematical formulations that delineate the behavior of an HPS.

1. Solar Photovoltaic (PV) Model

The PV model represents the electrical output generated by solar panels. The power (P_{PV}) is given by:

$$P_{PV} = A \cdot \eta \cdot G \cdot PR \tag{1}$$

In this context:

- A represents the surface area of the PV array,
- η stands for the efficiency of PV cells,
- G denotes the solar irradiance,
- PR is the performance ratio, taking into consideration various losses.

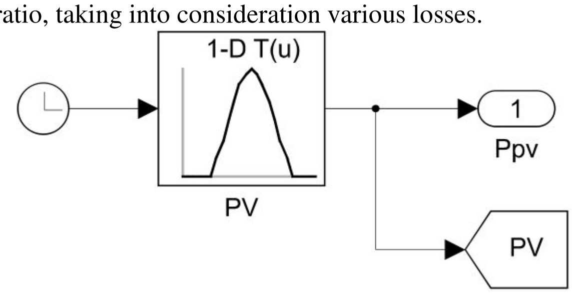

Figure 1: Modeling of Solar Photovoltaic (PV) Model

2. Wind Speed to Power Conversion Model

The wind power model calculates the electrical output from wind turbines. The power (P_W) is determined by:

$$P_W = \frac{1}{2} \cdot \rho \cdot A \cdot V_r^3 \cdot C_p \tag{2}$$

Where:0

- ρ is air density,
- A is the swept area of the wind turbine blades,
- V_r is the resultant wind velocity,
- C_p is the power coefficient.

The resultant wind velocity (V_r) can be calculated using the formula:

$$V_r = \sqrt{V_{air}^2 - V_{wind}^2} \tag{3}$$

Where:

- V_{air} is the ambient wind speed,
- V_{wind} is the wind speed due to the turbine's rotation.

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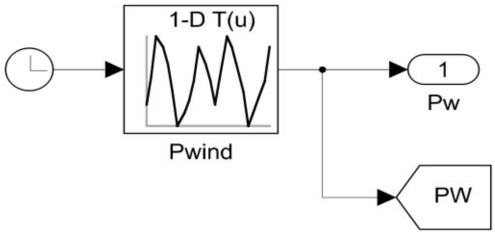

Figure 2: The modeling process for converting wind speed into power

3. **Diesel Engine Generator (DEG) Model**

The DEG model simulates the performance of a diesel generator. The electrical power output (P_{DEG}) is given by:

$$P_{DEG} = \eta_{GEN} \cdot \eta_{MECH} \cdot Q_{FUEL} \tag{4}$$

Where:

- η_{GEN} is the generator efficiency,
- η_{MECH} is the mechanical efficiency,
- Q_{FUEL} is the heat energy from fuel combustion.

The power generation equation incorporating dynamic responses is [23]:

$$\Delta P_d = -\left(\frac{1}{R} + \frac{K_I}{s}\right)\left(\frac{1}{T_{sg} \cdot s + 1}\right)\left(\frac{K_{DEG}}{T_{DEG} \cdot s + 1}\right)\Delta f_e \tag{5}$$

Where:

- ΔP_d is the change in power,
- R is the resistance,
- K_I is the integral gain,
- s is the Laplace operator,
- T_{sg} is the time constant for the speed governor,
- K_{DEG} is the gain for the diesel engine,
- T_{DEG} is the time constant for the diesel engine,
- Δf_e is the change in frequency.

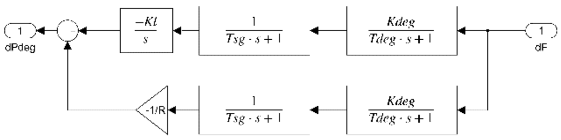

Figure 3: Modeling of Diesel Engine Generator Model

4. **Superconducting Magnetic Energy Storage (SMES) Model**

The SMES model outlines the characteristics of the superconducting coil. The stored energy (E_{SMES}) is defined as:

$$E_{SMES} = \frac{1}{2} \cdot L \cdot I^2 \tag{6}$$

Where:

- E_{SMES} is the stored energy,
- L is the inductance of the superconducting coil,

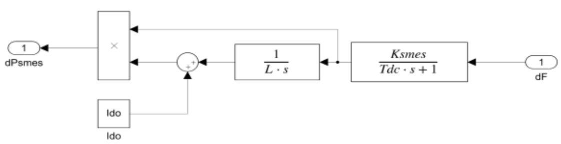

Figure 4: Modeling of Superconducting Magnetic Energy Storage Model

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5. **Hybrid Power System Integration**

Within the integration of the Hybrid Power System, the control strategy relies on the controlling error ($\Delta P_{control}$), defined as the disparity between the alteration in load demand (ΔP_{load}) and the shift in net power production (ΔP_{HPS}). The expression for the controlling error is as follows:

$$\Delta P_{control} = \Delta P_{load} - \Delta P_{HPS} \tag{7}$$

Here:

- $\Delta P_{control}$ represents the controlling error,
- ΔP_{load} signifies the alteration in load demand,
- ΔP_{HPS} denotes the shift in net power production.
-

$$G_{HPS}(s) = \frac{\Delta P_{HPS}(s)}{\Delta f_{HPS}(s)} = \frac{1}{2\pi \cdot M_{HPS} \cdot s} \tag{8}$$

This transfer function represents the dynamic relationship between frequency variation and power deviation in the Hybrid Power System, guiding the system's response to changes in load demand and ensuring stable operation.

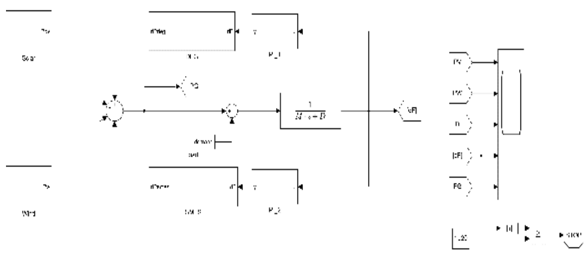

Figure 5: Modeling of Micro-Grid Connected Hybrid Power System

The hybrid power system is an integrated amalgamation of various energy sources and storage systems. Providing a thorough elucidation of mathematical formulations for each component facilitates dynamic simulations and analyses, allowing the design and optimization of HPS for optimal performance and sustainability. The control strategy amplifies the adaptability of the system to fluctuating load demands, ensuring efficient and stable operation.

6. **PI Controller Design**

The PI controller is defined by two parameters: the proportional gain (K_p) and the integral gain (K_i). These parameters have a direct impact on how the controller reacts to deviations from the desired system frequency. The transfer function of a PI controller is articulated as:

$$G_c(s) = K_p + \frac{K_i}{s} \tag{9}$$

Where:

- $G_c(s)$ is the transfer function of the PI controller,
- K_p is the proportional gain,
- K_i is the integral gain,
- s is the Laplace operator.

The proportional gain governs the instant reaction to the present frequency error, while the integral gain deals with the cumulative historical frequency error, proficiently eradicating steady-state errors. Figure 6 provides an illustration of the PI controller modeling.

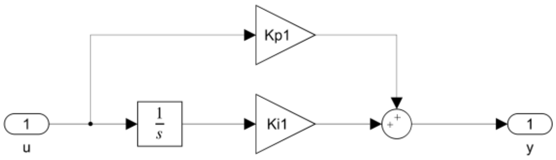

Figure 6: Modeling of PI controller

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Objective Function for PI Controller Design: The objective function for the optimal design of the PI controller encompasses the performance criteria that require optimization using the frequency error integral time square error (FEITSE) method. The objective function $F(X)$ is articulated as:

$$F(X) = \int_0^{\infty} f_e^2(t)dt \tag{10}$$

Where:

- $F(X)$ is the objective function.
- $f_e(t)$ is the frequency error signal, representing the difference between the desired and actual system frequencies.

The integral term signifies the cumulative square of the frequency error over time, underscoring the necessity to minimize frequency deviations and guarantee a sturdy and responsive controller.

B. Optimal Design of PI Controller using PSO-GWO Hybrid Optimization

Within the realm of Hybrid Power Systems (HPS), attaining an optimal design for the Proportional-Integral (PI) controller is crucial to ensuring stable and efficient system performance. This section delivers an in-depth account of the optimal design process, utilizing the PSO-GWO hybrid algorithm. The approach amalgamates the merits of both PSO and GWO to adeptly traverse the parameter space and identify the optimal PI controller parameters.

1. Particle Swarm Optimization (PSO)

PSO, an optimization algorithm, draws inspiration from the collective behavior observed in bird flocks or fish schools. In this approach, a population of potential solutions, referred to as particles, explores the search space to uncover the optimal solution. Each particle adjusts its position based on its individual experience and the experiences of the best-performing particle within the population. The equation governing the position update for each particle in PSO is expressed as:

$$X_i^{(t+1)} = X_i^{(t)} + V_i^{(t+1)} \tag{11}$$

Here:

- $X_i^{(t+1)}$ denotes the updated position of particle i in the $(t + 1)$ iteration,
- $V_i^{(t+1)}$ represents the velocity of particle i in the $(t + 1)$ iteration.

The velocity undergoes an update by considering both personal best (P_{best}) and global best (G_{best}) information.

2. Grey Wolf Optimization (GWO)

GWO draws inspiration from the hunting behavior of grey wolves and is categorized as a metaheuristic optimization algorithm. In GWO, there are three distinct types of wolves (alpha, beta, and delta) assumed to lead the pack, with other wolves adjusting their positions based on the locations of these leaders.
The equation governing the position update for each wolf in GWO is provided as:

$$X_i^{(t+1)} = X_\alpha^{(t)} - A \cdot D_i^{(t)} \tag{12}$$

Here:

- $X_i^{(t+1)}$ signifies the updated position of the wolf i in the $(t + 1)$ iteration,
- $X_\alpha^{(t)}$ represents the position of the alpha wolf in the t iteration,
- A is a coefficient,
- $D_i^{(t)}$ is a random vector

3. PSO-GWO Hybrid Optimization

The hybrid optimization approach harnesses the strengths of both the PSO and GWO algorithms. In each iteration, the PSO algorithm steers the population toward promising regions within the search space, and subsequently, the GWO algorithm is employed to exploit these regions more effectively.
The hybrid optimization process encompasses the following steps:

- Initialization: Start the population of particles with random positions and velocities.
- Fitness Evaluation: Assess the fitness of each particle using the objective function, which, in the context of PI controller design, aligns with the FEITSE method.

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- PSO Update: Adjust the position and velocity of each particle using the PSO algorithm.
- GWO Exploitation: Once a predefined number of iterations have passed or certain criteria are met, transition to GWO to further exploit the promising regions identified by PSO.
- Optimal Solution: Determine the optimal solution based on the best-performing solution achieved throughout the entire hybrid optimization process.

4. **Optimal Design Process for PI Controller using PSO-GWO**

The PSO-GWO algorithm is employed to determine the optimal values of K_p and K_i that minimize the objective function. The algorithm iteratively updates a population of potential solutions (particles or wolves) based on their individual and collective fitness, where fitness is determined by evaluating the objective function (Equation (10)).
The updating equations for K_p and K_i for each iteration in the PSO-GWO process, incorporating the method, are defined by:

$$K_p^{(t+1)} = X_{best}^{(t)} + r_1 \cdot A \tag{13}$$

$$K_i^{(t+1)} = X_{best}^{(t)} + r_2 \cdot B \tag{14}$$

Where:
$X_{best}^{(t)}$ is the best solution found in the current iteration,
r_1 and r_2 are random numbers between 0 and 1,
A and B are coefficients controlling the exploration-exploitation balance.
The iterative process continues until convergence is achieved or a predefined stopping criterion is met. The PSO-GWO hybrid algorithm efficiently explores the parameter space, determining the optimal values of K_p and K_i to achieve the desired control response in Hybrid Power Systems. This integrated approach ensures robust and adaptive control strategies for varying system frequencies. Figure 7 provides the flow diagram for proposed PSO-GWO hybrid approach.

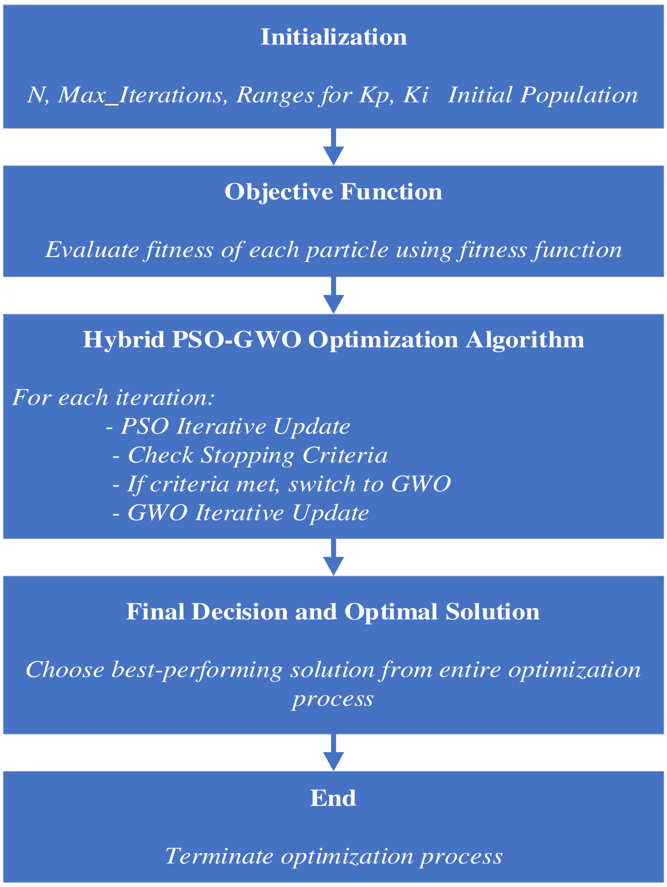

Figure 7: Flow diagram for proposed PSO-GWO hybrid optimization

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IV. Results and Discussion

The results analysis entails a thorough examination of various parameters in the context of a hybrid power system. Figures 8 to 16 provide insights into the changes in PV power, wind power, load demand, generated power, and GWO's alpha fitness over time. respectively. Significantly, Figure 17 illustrates a comparative analysis of frequency deviation, highlighting the superior performance of the PSO-GWO hybrid approach. The hybrid method showcases noteworthy effectiveness in mitigating frequency deviations, surpassing the individual GWO and PSO strategies. This emphasizes the efficacy of the proposed hybrid optimization in improving the stability and regulation of frequency deviations in micro-grid-connected Hybrid Power Systems, thereby asserting its superiority over traditional optimization techniques.

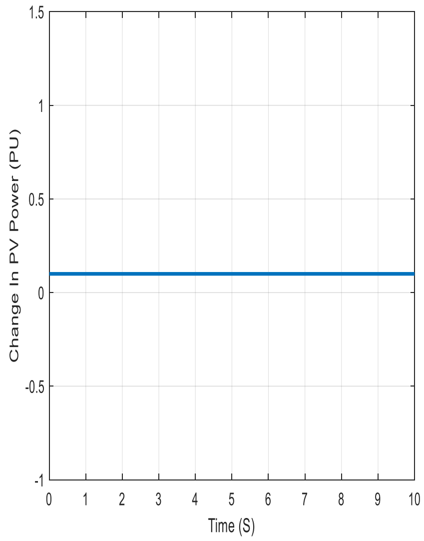

Figure 8: Variation in PV Power Over Time

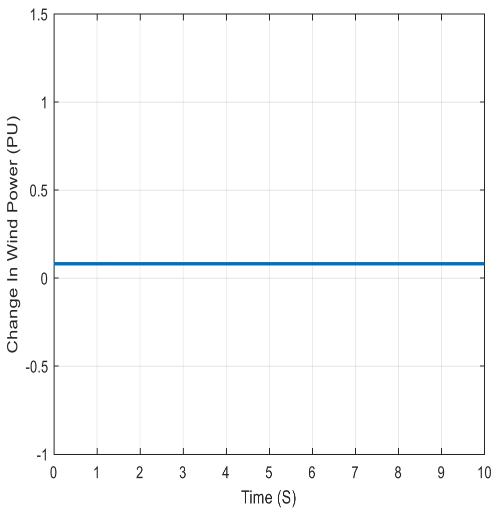

Figure 9: Fluctuations in Wind Power Across Time

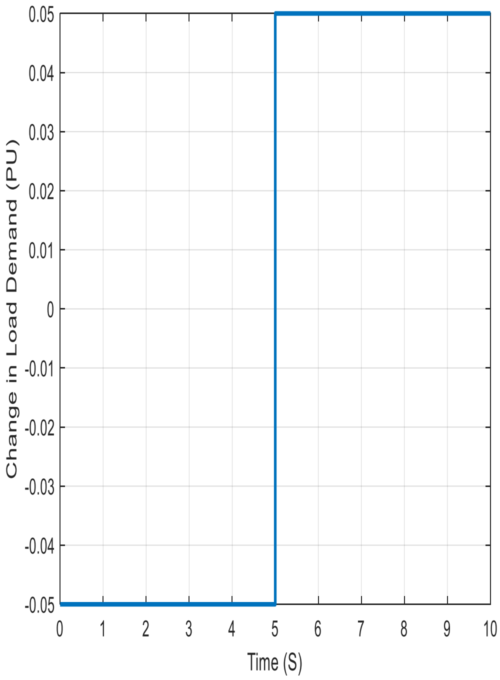

Figure 10: Dynamics of Load Demand Over Time

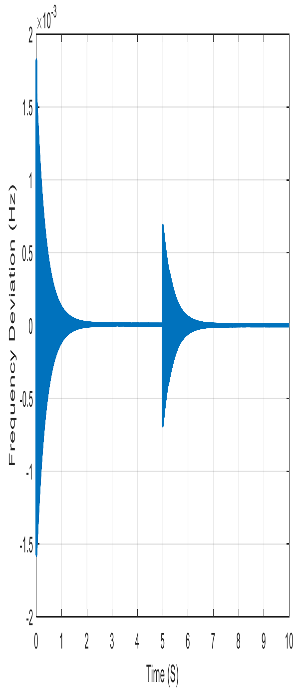

Figure 11: Frequency Deviation over time

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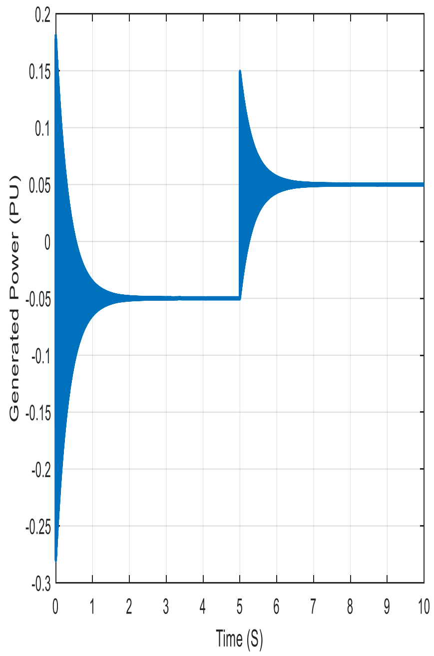

Figure 12: Visual Representation of Power Generation

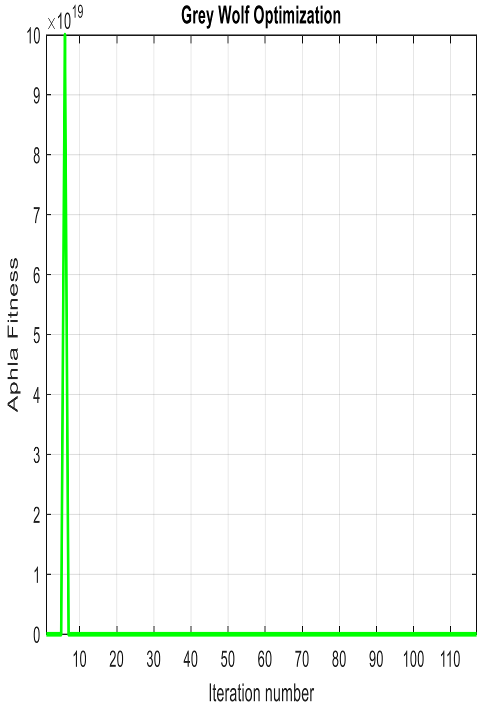

Figure 13: Depiction, GWO's Fitness Across Time

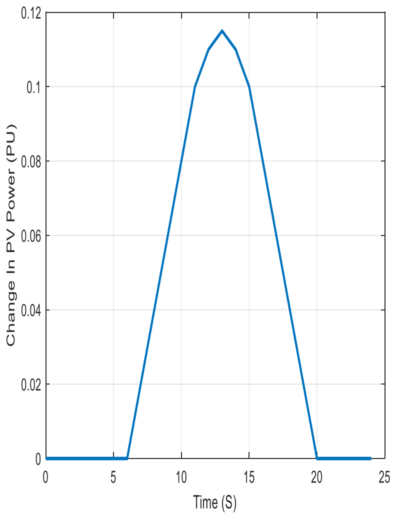

Figure 14: Alterations in PV Power Over Time

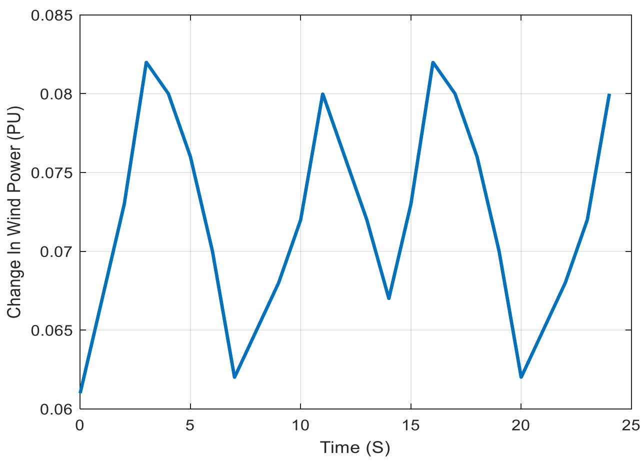

Figure 15: Change in Wind Power Over Time

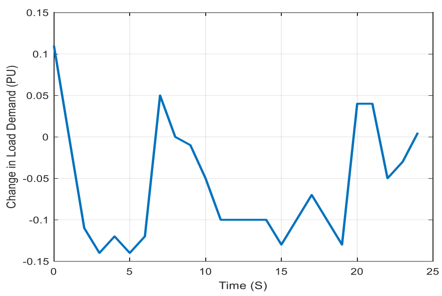

Figure 16: Transformations in Load Demand Over Time

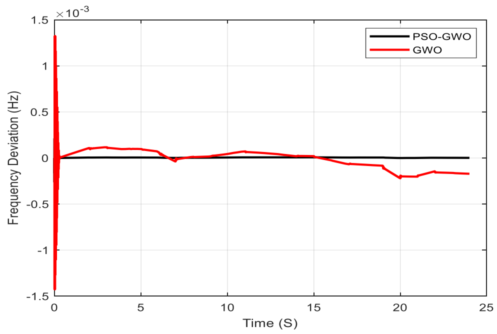

Figure 17: Comparative Analysis of Frequency for GWO and PSO-GWO Methods

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V. CONCLUSIONS

In conclusion, this investigation delves into the intricate challenges of regulating frequency within micro-grid-connected hybrid power systems. By integrating solar PV, wind, and DEG sources with SMES technology, a strategic approach has been adopted to tackle the fluctuations induced by abrupt shifts in load demand and renewable power variations. The inclusion of SMES emerges as a key element, demonstrating its effectiveness in maintaining frequency stability. The optimization of PI controller parameters, facilitated by the inventive PSO-GWO hybrid method, outshines the performance of standalone GWO and PSO techniques. The imposition of constraints on inductor current further fortifies the system, addressing issues related to discontinuous conduction and storage limitations. The simulation results, conducted in the MATLAB Simulink environment, validate the prowess of the SMES system in ensuring frequency stability across diverse scenarios. Looking ahead, the research envisions extending its scope to real-world implementations, exploring scalability, and tailoring the hybrid optimization approach for other renewable energy systems. This trajectory aims to propel the field toward more practical and dependable micro-grid solutions.

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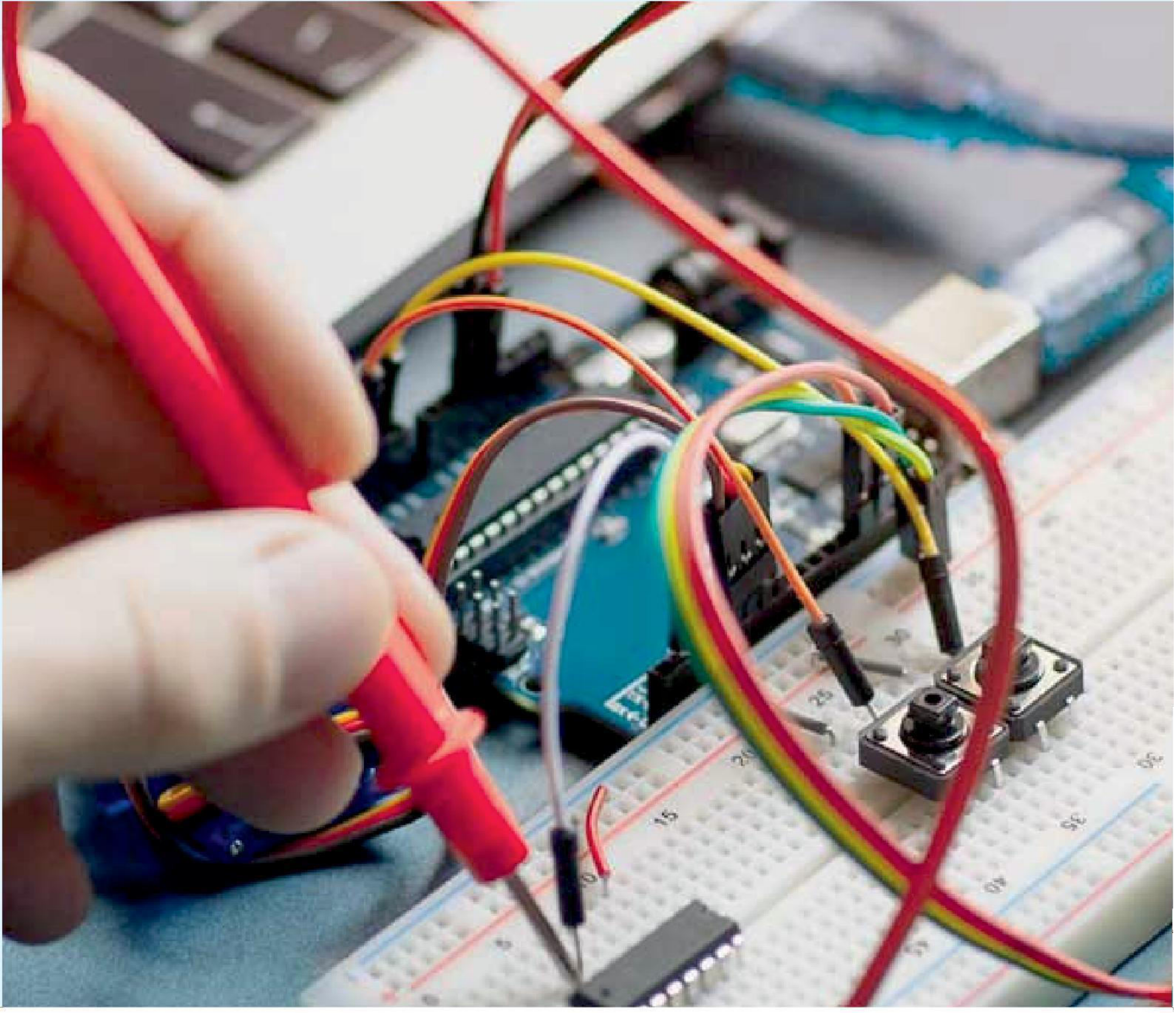

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