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Optimal parameter identification of fractional-order proportional integral controller to improve DC voltage stability of photovoltaic/battery system

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ABSTRACT

This study addresses the critical challenges of voltage stabilization in DC microgrids, where the inherent variability of renewable energy sources significantly complicates reliable operation. The focus is on optimizing the fractional-order proportional-integral (FO-PI) controller using four advanced techniques a whale optimization algorithm (WOA), grey wolf optimizer (GWO), genetic algorithm (GA), and sine cosine algorithm (SCA). Voltage instability poses substantial risks to the reliability and efficiency of DC microgrids, making the optimization of the FO-PI controller an essential task. Through comparative analysis, the study demonstrates that WOA outperforms the other methods, achieving superior voltage stability, resilience, and overall system performance. Notably, WOA achieves the lowest average cost function at 0.0004, compared to 0.892 for GWO, 0.659 for GA, and 0.096 for SCA, showcasing its effectiveness in fine-tuning the controller's parameters. These findings highlight WOA robustness as a powerful tool for enhancing microgrid performance, especially in voltage regulation. The study underscores WOA potential in ensuring the reliable and efficient integration of renewable energy systems into DC microgrids and lays the groundwork for further research into its application in more complex and dynamic grid scenarios. By optimizing the FO-PI controller, WOA significantly contributes to the long-term stability and efficiency of DC microgrids.

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1. INTRODUCTION

In the modern energy landscape, there is a significant shift away from conventional energy sources like oil, coal, and natural gas toward greener alternatives. This transition is driven by the urgent need to reduce greenhouse gas emissions and lessen reliance on finite natural resources [1], [2]. As the world increasingly adopts renewable energy sources such as hydroelectric, solar, fuel cells, and wind power, it encounters new challenges, particularly in energy conversion and management due to the intermittent and variable nature of these sources [3]. To effectively address these challenges, advanced technologies like DC converters and maximum power point (MPP) Tracking systems are crucial. DC converters are essential for harnessing renewable energy, as they convert the variable electrical output from these sources into a stable form suitable for storage and use. However, MPP tracking systems enhance efficiency by continuously adjusting the electrical load to ensure renewable energy sources operate at their maximum power output [4]. Additionally, maximum power point tracking (MPPT) systems ensure that renewable energy sources operate at peak efficiency by continuously adjusting the electrical load.

This advanced technique is used to optimize the power output of renewable energy systems, including fuel cells, photovoltaic (PV) solar panels, and wind turbines. MPPT systems continuously adapt the load connected to the renewable energy source to maintain optimal power output, even as sunlight intensity or wind speed varies. The necessity of MPPT stems from the nonlinear characteristics of renewable energy sources, where power output is highly dependent on environmental conditions. By optimizing power extraction, MPPT systems significantly enhance the efficiency and output of renewable energy installations [5], [6]. Various MPPT algorithms have been developed to meet different system requirements and complexities. The perturb and observe (P&O) and incremental conductance (Inc-Con) methods are widely used for their simplicity and effectiveness in many situations. More advanced algorithms, such as neural networks, fuzzy logic controllers, and the adaptive neuro-fuzzy inference system (ANFIS), offer adaptive capabilities that efficiently handle variable conditions, making them ideal for more complex or large-scale applications [7]. These advanced MPPT techniques are crucial for maintaining high efficiency in the DC voltage link of hybrid systems, ensuring that renewable energy sources are used to their fullest potential.

As renewable energy usage expands, microgrids have emerged as a versatile solution for localized energy distribution. Microgrids are decentralized networks that can operate independently from the traditional grid [8], offering enhanced reliability, resilience, and the potential for a reduced environmental footprint. However, the stability of these microgrids, particularly in terms of voltage regulation, is paramount to their effectiveness and protection.

Achieving optimal stability in the DC voltage link is pivotal for the efficient operation of hybrid renewable energy systems. Instabilities can lead to inefficient power transfer, potential safety risks, and reduced system longevity [9]. Therefore, serval study was conducted to develop a stable controller for maintaining stable DC voltage. Proportional integrator (PI) has been established as the standard and widely used controller in various applications [10] while focusing on adopting the sliding mode controller (SMC) as a robust control strategy was developed in [11]. Additionally, highlights the development of the super twisting sliding mode control (STSMC) controller to maintain higher performance standards provided in [12].

Metaheuristic algorithms are known for their ability to find optimal solutions in regions where optimization is too complex, allowing us to find promising approaches to improve control strategies in hybrid systems [13]. In order to develop a robust control mechanism that maintains the robustness and flexibility of the DC voltage link, serval strategies such as colony-based optimization (CBO), particle swarm optimization (PSO), and genetic algorithms (GA) have been proposed to develop robust control mechanisms that ensure the stability and efficiency of the DC voltage link under various operating conditions [14]. To address these challenges, this study has opted for the whale optimizer algorithm (WOA) for its straightforwardness [15], minimal parameter requirements, rapid convergence, robustness, and wide applicability across different wide applications including engineering, clustering, classification, robot path planning, image processing, network optimization [16].

This study explores the application of the whale optimizer algorithm (WOA) to fine-tune a fractional-order PID (FO-PID) controller, with the goal of improving voltage stability in DC microgrids. By comparing WOA with other optimization algorithms, such as grey wolf optimizer (GWO), genetic algorithm (GA), and sine cosine algorithm (SCA), the research aims to identify a robust approach for ensuring reliable and stable microgrid operation. The proposed strategy leverages these advanced algorithms to effectively manage the inherent fluctuations in renewable energy outputs, ensuring a consistent and reliable power supply. The effectiveness of these optimization techniques will be assessed based on several metrics, including mean optimization results, standard deviation of outcomes, convergence analysis, and sensitivity analysis for determining optimal parameters such as Ki, KP, and lambda (λ) through a series of simulation tests. This analysis demonstrates the potential of these methods in enhancing the adaptability and efficiency of renewable energy systems. Through this approach, the paper contributes to the broader discourse on renewable energy adoption, offering insights into advanced control strategies that can facilitate a smoother transformation to a sustainable energy future.

The paper outcome is structured across five key sections. The first section introduces the research topic, outlining its background, objectives, and significance within the field. system modeling follows with a comprehensive overview of the structural and functional components of the system. While, the control strategy and optimization techniques section detail the methodologies, models, and approaches used to optimize system performance. The results and discussion section then presents the findings, showcasing data, analyses, and key insights that support the study's hypotheses. Finally, the conclusion summarizes the research outcomes and their implications.

2. SYSTEM MODELING

The study hybrid system architecture integrates various components to optimize energy generation, storage, and distribution while enhancing power quality. At the core of this setup is an 8 kW photovoltaic (PV) array that harnesses solar energy. Complementing the PV array is a 6 kW lithium-ion battery system, which provides storage to balance supply and demand fluctuations by charging during periods of surplus power and discharging when there is a power deficit. To maximize the efficiency of the PV array, a DC-to-DC converter with maximum power point tracking (MPPT) is employed, ensuring the PV system consistently works at peak power output. Additionally, a bidirectional DC-DC converter is crucial in maintaining the DC load for isolated areas, ensuring seamless power distribution, utilization, and enhanced power quality. This comprehensive architecture efficiently manages renewable energy resources, storage, and distribution, contributing to sustainable power solutions for both on-grid and off-grid applications. Figure 1 illustrates the global structure of the studied system.

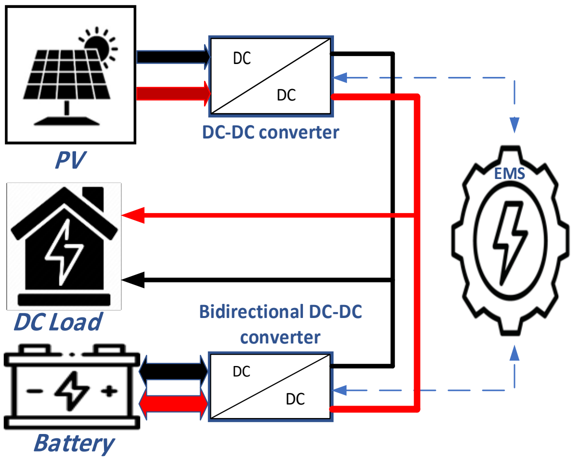

Figure 1. Structure diagram of the studied system

2.1. Photovoltaic array

The PV array in our system is constructed utilizing the single-diode model, which is one of the most common techniques for depicting the electrical characteristics of PV cells [17]. This model incorporates a single diode to simulate the nonlinear relationship between the voltage and current of the cell and includes multiple parameters, the photocurrent (Iph), which represents the current generated by the incident light the diode saturation current (Io), which increases with temperature, the series resistance (Rs), which accounts for losses due to the resistance of the material in the cell, the shunt resistance (Rsh), representing leakage currents via the cell and the ideality coefficient of the diode, which indicates the cell's deviation from ideal behavior. By accurately reflecting the performance under different irradiance and temperature conditions, this model serves as a critical tool for predicting the energy output and efficiency of the PV array. Figure 2 represents the PV array of a single-diode model.

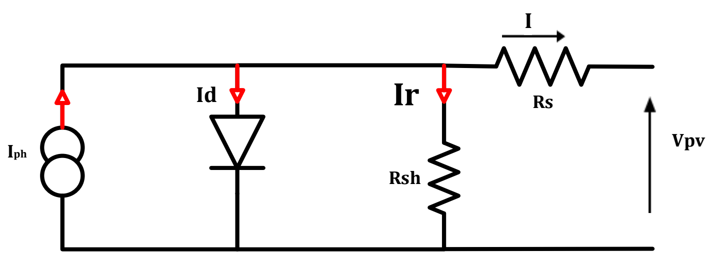

Figure 2. PV cell of SDM model

The connection between the output current and voltage is represented by the (1).

$$I = I_{pv} - I_d - \frac{V + R_s I}{R_{sh}} \tag{1}$$

The current generated by the PV array, denoted as Ipv, results from the generation of electron-hole pairs within a solar cell. Meanwhile, the current flowing across the Shockley diode, referred to as Id, is defined by (2). In this equation, $Isat$ represents the reverse saturation current, which assesses the leakage or recombination of minority carriers through the $p-n$ junction when under reverse bias, as detailed in (3). According to the single-diode (SDM) model, the Shockley current follows a single exponential dependence, which is impacted by the diode ideality coefficient, a. The bandgap energy ($Egap$) of the semiconductor material plays a vital role in this conduct for crystalline silicon at 25 °C, $Egap$ is 1.12 eV.

$$i_d = I_{sat}\left(exp^{\frac{qv}{akt}} - 1\right) \quad (2)$$

$$I_{sat} = CT^3 \exp^{\left(-\frac{Egap}{kt}\right)} \quad (3)$$

PV generators, in practice, comprise numerous cells arranged in series and parallel rather than as single units. Each cell operates at a voltage of a few hundred millivolts, while at high irradiance, it can generate current in the range of several amperes. The (4) is expanded using (1) and (2):

$$I = I_{pv} - I_{sat}\left(exp^{\frac{v}{aNsV_t}} - 1\right) - \frac{V+R_S I}{R_{sh}} \quad (4)$$

Vt is defined as the thermal voltage of the cell in (5):

$$V_t = \frac{K\,T}{q} \quad (5)$$

2.2. Boost converter

In hybrid renewable energy systems featuring both PV arrays and wind turbines, the boost converter is essential for enhancing system efficiency [18]. It steps up the low voltage from the PV array to higher levels required for storage charging or direct use. The converter operates by saving energy in an inductor during the on-mode phase and releasing it at a higher voltage in the Off-mode phase, maintaining that power transfer is maximized while maintaining voltage stability. This converter is connected with a P&O maximum power point (MPP) tracking controller as depicted in Figure 3, which is crucial for managing the switching operations. The P&O MPPT controller optimizes the duty cycle of the boost converter's switch based on real-time data, ensuring the system continually operates near its maximum power point. This dynamic adjustment is vital for accommodating the variable power output from solar and wind sources, ultimately ensuring consistent, reliable, and efficient power provided to meet demand and ensure system stability [19].

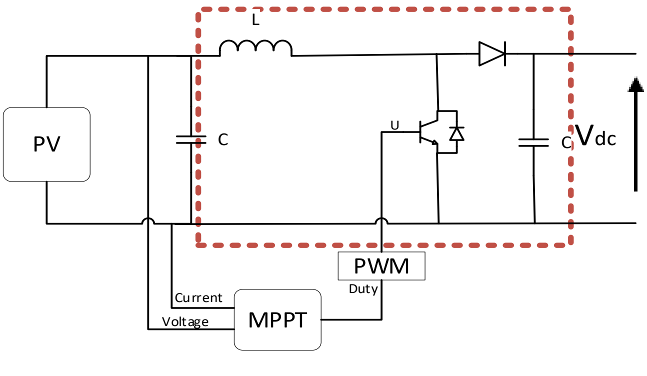

Figure 3. DC-DC boost converter

The P&O approach is a commonly utilized algorithm for MPPT in photovoltaic (PV) systems. As depicted in Figure 4 The method involves periodically perturbing the operating voltage or current of the PV array and observing the resulting changes in power output. If a perturbation increases the power output, subsequent adjustments are made in the same direction. Conversely, if the perturbation reduces the power output, the direction is reversed. This iterative process continues until the system stabilizes near the maximum power point, ensuring efficient energy harvesting. Despite being simple and easy to implement.

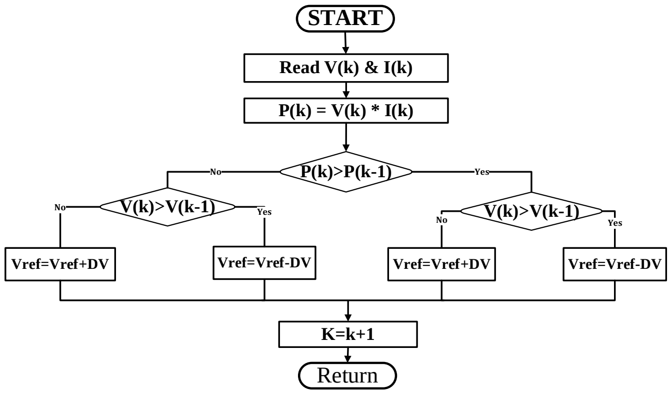

Figure 4. P&O flowchart

2.3. Bidirectional DC-to-DC converter

The bidirectional DC-to-DC converter is crucial in hybrid renewable energy systems, particularly for its role in managing energy flows between the battery and the microgrid. This converter can switch the direction of power flow to either charge the battery with surplus energy from sources like wind, or to discharge the battery when the grid requires additional power. This flexibility is vital for stabilizing the intermittent output of renewable energy sources and enhancing microgrid resilience and efficiency. Figure 5 represents the bidirectional DC-DC converter diagram. Operationally, the converter utilizes two switches, S1 and S2, which are essential for its dual functionality in both boost and buck modes. In boost mode, activated by switch S1, the converter steps up a lower voltage from renewable sources to a higher voltage for storage or direct grid usage. In buck mode, activated by switch S2, it steps down the voltage to meet the energy demand of the grid. This dynamic ability to adjust energy flow ensures a continuous and efficient power supply, balancing generation, storage, and consumption within the microgrid [20].

2.4. Lithium battery

The lithium battery is chosen for its superior characteristics in terms of faster charging capabilities, high energy density and longer life cycles compared to other battery technologies [21]. In the context of a microgrid, the lithium battery acts as an energy reservoir to stabilize the power supply by smoothing out the fluctuations in energy production from renewable sources. It provides a reliable backup power source during periods of high demand or low solar irradiance, thus maintaining consistent availability of electricity. The modeling of the lithium battery as depicted in Figure 6 includes the charge and discharge cycles, efficiency losses, and the impact of temperature and aging on its performance [22].

These detailed descriptions provide a foundational understanding of each component's role and functionality within the system, pivotal for analyzing the overall efficiency and stability of the microgrid [22]. In the discharging phase, the formula used to calculate the battery voltage is provided as in (6).

$$V_{Bat} = E0 - K \cdot \frac{Q}{Q-it} \cdot i^{*} - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot exp(-B \cdot it) \quad (6)$$

In the charging phase, the equation for the battery voltage is given as in (7).

$$V_{Bat} = E0 - K \cdot \frac{Q}{it+0.1 \cdot Q} \cdot i^{*} - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot exp(-B \cdot it) \quad (7)$$

In the studied model, A represents the amplitude related to the exponential zone, while B serves as the reciprocal of the time constant within this zone. E_Bat denotes the voltage of the when it is disconnected from any load, and $E0$ is provided as the battery's steady voltage. The term Ibatt refers to the current involved in the charging or discharging processes. K is utilized to indicate the voltage that is associated with the polarization. Additionally, Q describes the battery’s utilized capacity, specifying the total capacity that has been used. Finally, V_Bat is the voltage noticed at the electrical contact points of the batteries.

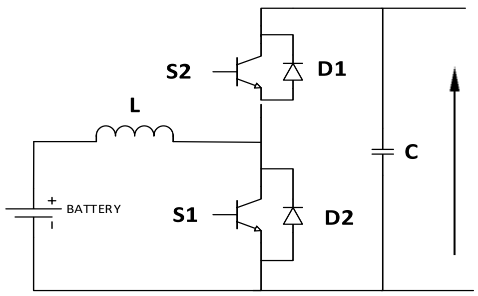

Figure 5. Bidirectional DC-DC converter

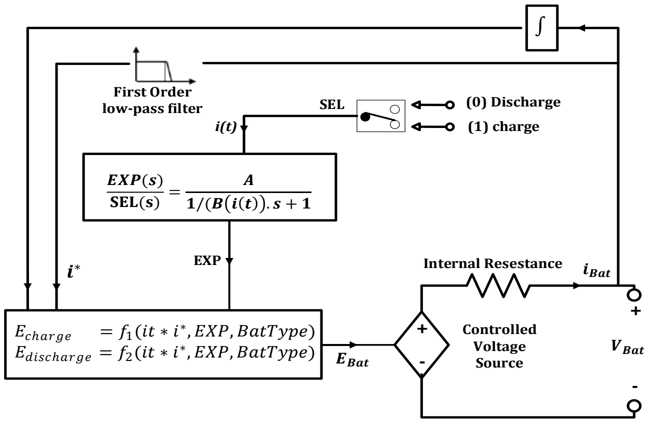

Figure 6. Lithium batteries equivalent circuit

3. CONTROLLER AND OPTIMIZATION STRATEGY

A fractional order PI controller serves as a pivotal component in ensuring voltage stability within electrical systems [23]. By evaluating the reference voltage (V_ref) with the measured voltage (V_dc), the PI controller effectively regulates the output current to maintain desired voltage levels. Acting as the interface between these inputs, the controller continuously adjusts the system's parameters to minimize the deviation between the reference and measured voltages. Figure 7 illustrates the schematic bloc of his controller. This proactive control mechanism ensures that the system remains within acceptable voltage limits, thereby enhancing stability and reliability.

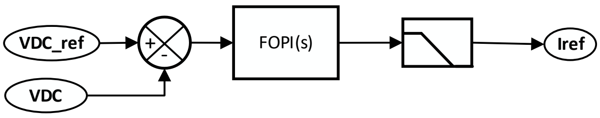

Figure 7. FOPI bloc of voltage control structure

The (8) and (9) indicates the transfer function of the FO-PI controller.

$$C(S) = \frac{U(S)}{\mathrm{E(S)}} = K_p + K_i S^{-\lambda} \tag{8}$$

$$G_c(s) = \frac{U(s)}{E(s)} = K_p + K_i \frac{1}{s}, (\lambda > 0) \tag{9}$$

The (10) is expanded from (7) and (8) respectively.

$$U(t) = K_p. e(t) + K_i D^{-\lambda}\, e(t) \tag{10}$$

Within a fractional order-PI, λ denotes a positive real number, indicating the FO-PI control term. Correspondingly, Kp and Ki, represent proportional and integral gain respectively. In this work, various optimization algorithms including genetic algorithm (GA), sine cosine algorithm (SCA), grey wolf optimizer (GWO) and whale optimization algorithm (WOA) were explored. Each of these algorithms has been used to optimize a common objective function which is the integral absolute error over time that is defined as in (11):

$$J = \int_0^t |\Delta V_{DC}| dt \ = |\, V_{DC}^{*} - V_{DC}\,| dt \tag{11}$$

where the goal is to find the minimum cost of J.

3.1. Genetic algorithm

GA emulates the procedure of natural selection where the fittest individuals are appointed for reproduction in order to produce offspring of the next generation [24]. It starts by initializing a population of potential solutions and evolves these solutions over several generations. Across operations like selection, crossover, and mutation, GA iteratively improves the solutions to find the optimum value.

3.2. Sine cosine algorithm

SCA uses a mathematical model that oscillates between sine and cosine functions to navigate the search space. This algorithm explores potential solutions by adjusting the amplitude of oscillations, which effectively directs the search toward global and local minima based on the sine and cosine rules. It dynamically balances the exploration and exploitation phases to enhance the optimization process [25].

3.3. Grey wolf optimizer

GWO simulates the leadership hierarchy and hunting strategy of grey wolves. It identifies different wolves with the role's alpha, beta, and delta that guide the pack. During optimization, wolves encircle their prey, adjust their positions, and finally pounce when the opportunity is ripe. This hierarchical strategy and guided exploration help in efficiently converging toward the best solution [26].

3.4. Whale optimization algorithm

WOA mimics the bubble-net-chasing technique of humpback whales. This algorithm includes encircling prey, creating bubble nets for trapping, and then finally attacking the prey. The algorithm's ability to switch between encircling behavior and the spiral-shaped path toward the prey makes it robust in handling different kinds of optimization issues [27], [28]. Figure 8 depicts a flowchart illustrating the functioning of the WOA algorithm. It outlines the step-by-step process.

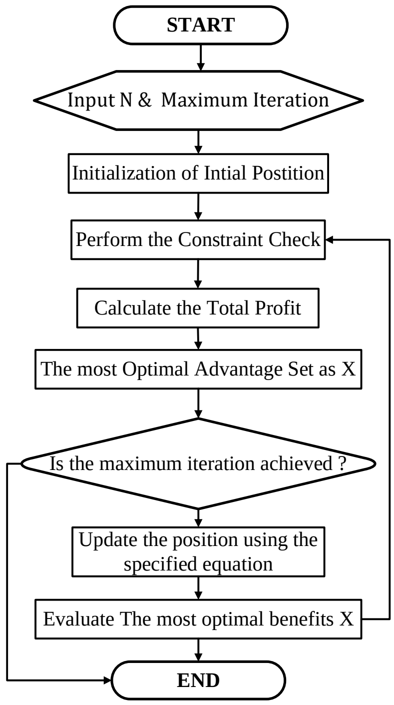

Figure 8. WOA flowchart

4. RESULTS AND DISCUSSION

In the results section, this study presents the findings and performance metrics obtained from a comparative analysis of four techniques, GWO, WOA, GA, and SCA. The simulations were conducted and evaluated within the MATLAB environment, the simulation was tested under 15 iterations and 3 runs for each algorithm. Table 1 provides a comprehensive overview.

As illustrated in Table 1, the results for the four optimizer techniques GWO, WOA, GA, and SCA, show their average values across three runs as 1.332, 0.148, 1.072, and 0.317 respectively. The GWO optimizer excels in the first run but performs poorly in the second and third runs. In contrast. The GA optimizer starts strong but struggles in subsequent runs. The SCA optimizer produces consistent results in two out of three runs. Notably, GWO achieves the best single iteration value of 1.3279, while WOA demonstrates robustness throughout all simulations, the WOA optimizer is robust, consistently delivering similar values across all three runs and achieving the best standard deviation score with 0.0004 compared with GWO, GA, and SCA with 0.892, 0.659, and 0.096 respectively. Figure 9 depicts the convergence curves of the four algorithms. In conclusion, WOA displays superior performance by effectively combining characteristics such as standard deviation, mean, and best overall score across the tests.

Figure 10 shows the voltage response for the quad algorithms. The graph gives a clear vision of their performance, in the face of disturbance rejection and flexibility, this figure offers a comparative analysis between the quad algorithms. The curve demonstrates the superiority of the proposed algorithm compared to other algorithms with a very short response time compared to the other algorithms, excellent tracking and very good precision which is of the order of 0.01 V. These observations collectively suggest that WOA emerges as the most effective and superior algorithm overall.

Table 1. The performance of the four optimizer techniques

Iter	GWO	WOA	GA	SCA
1	0.1279	0.1475	0.1497	0.2427
2	2.2588	0.1475	1.4122	0.2544
3	1.6102	0.1483	1.6533	0.4529
Best	0.1279	0.1475	0.1497	0.2427
Worst	2.2588	0.1483	1.6533	0.4529
Mean	1.332	0.148	1.072	0.317
STD	0.892	0.0004	0.659	0.096

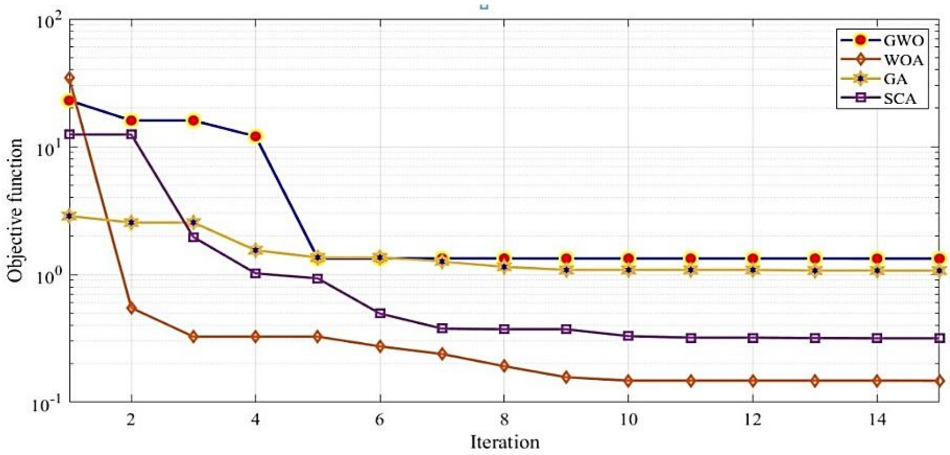

Figure 9. Convergence curves of the four techniques

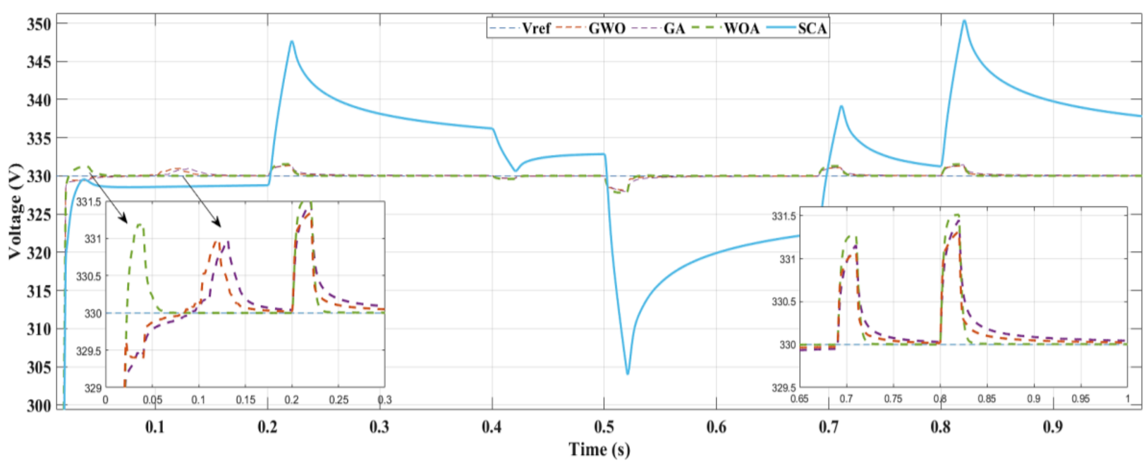

Figure 10. Voltage dynamique response of four techniques

This powerful technique is demonstrated by its ability to achieve stable energy management between the battery and PV system across the stable controller. As illustrated in Figure 11, the energy management system exhibits a seamless operation depicted by smooth and stable power curves throughout the simulation. From 0 to 0.2 sec the power demand exceeds that generated by the photovoltaic (PV) system, and the battery seamlessly steps in, to supply the additional load requirement, ensuring uninterrupted power supply. This feature is particularly crucial during periods of low irradiation when the PV output is diminished. The battery system adeptly manages the power deficit, thereby maintaining continuous energy provision. Conversely, during 0.2 to 0.5 sec where the power demand falls below the capacity of the PV array, surplus energy is diverted to charge the battery, optimizing energy storage for future use. As displayed in Figure 12 the battery's state of charge (SOC) shows the charging and discharging behaviors across different scenarios This dynamic interplay between PV generation, battery storage, and load management ensures efficient utilization of renewable energy resources while guaranteeing a reliable and sustainable power supply.

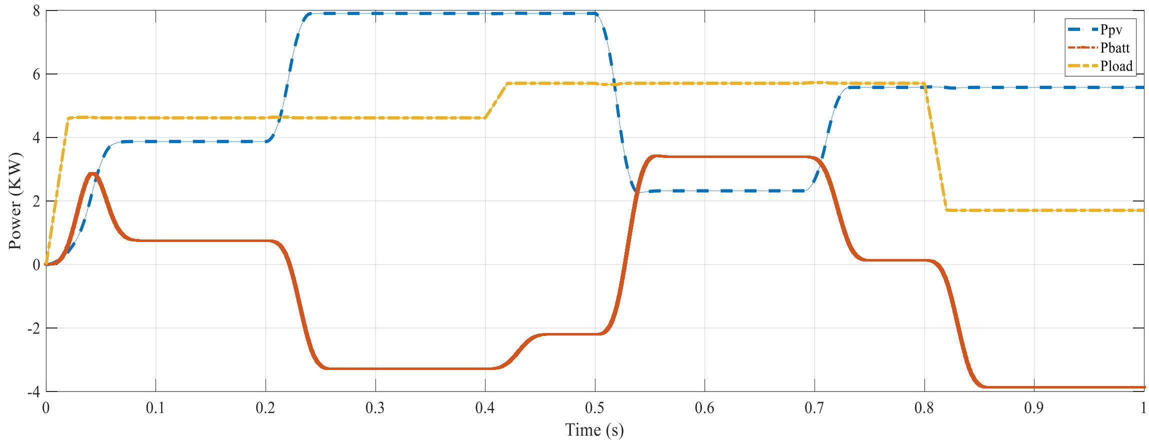

Figure 11. The power balance profile PV, battery, and DC load

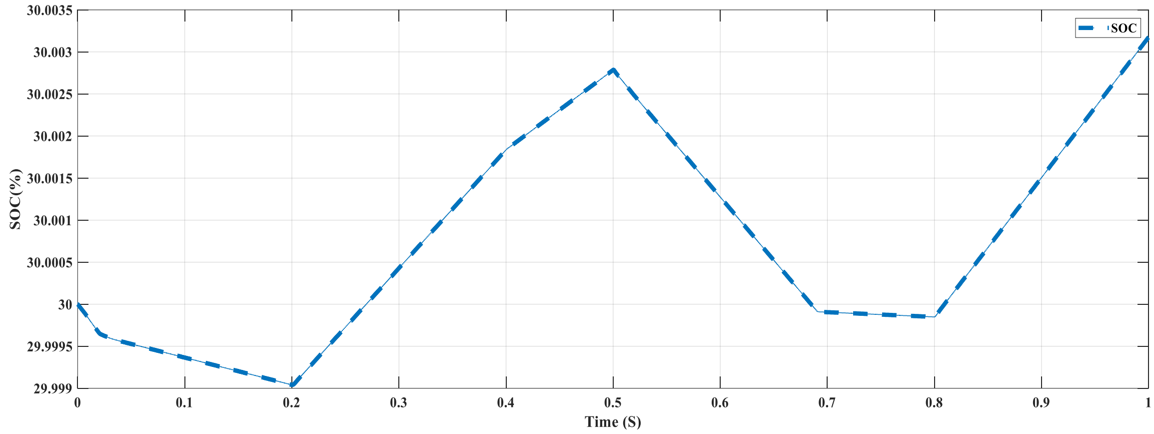

Figure 12. Battery SOC state of charge under variable scenarios

5. CONCLUSION

In conclusion, this paper investigated the optimization of a fractional order proportional integrator (FOPI) controller for stabilizing DC voltage in hybrid and DC microgrid applications using four algorithms a sine cosine algorithm, genetic algorithm, grey wolf optimizer, and whale optimization algorithm (WOA). The development and validation of the controller's performance were carried out using MATLAB software, and the performance was evaluated under variable climatic conditions After a thorough analysis of robustness, response time, and accuracy, WOA proved to be the most efficient and efficient among the algorithms studied. The lowest average cost function of 0.148 is achieved by WOA followed by SCA (0.317). In addition, the best standard deviation score with 0.0004 (WOA) compared to GWO, GA, and SCA with 0.892, 0.659, and 0.096 respectively.

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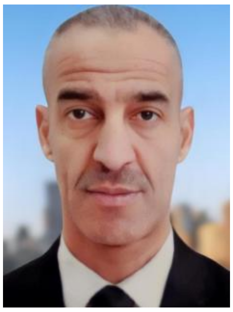

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