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Research Article

Robust DC Voltage Regulation Under Load Variations in Renewable Microgrids: A Hybrid GWOPSO and ALO Algorithm Comparative Study

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ARTICLE INFO	ABSTRACT

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The energy management system is essential to ensure the balance of the electrical network, in particular in the face of fluctuations in the production of renewable energy and electricity demand. This paper proposes an optimized PID controller based on hybrid metaheuristic GWOPSO. The microgrid associates renewable energies, and battery. The main objective of the optimization using the GWOPSO is to improve the DC voltage, which is compared to the battery current for building the modulator of the buck boost converter. The proposed control strategy optimally coordinates power source transitions between the PV array and battery storage, while favoring wind turbine generation as the primary supply. MATLAB simulations validate the approach's effectiveness in maintaining stable microgrid operation across diverse load and generation scenarios.The results obtained show the response of PSOGWO is faster than ALO response implemented with two objective functions with a rise time equal to 0.0590 s against 0.0658 s and 0.0619 s.

Keywords: PV, Wind, Metaheuristic, Hybrid Metaheuristic, Rise time, Overshoot.

INTRODUCTION

Algeria is concerned by the increase in the consumption of electrical energy and the reduction of CO_2 emissions. In recent years, it has adopted a green based on renewable energies (REs) for the protection of the environment and compliance with climate standards. As part of its national energy transition strategy, Algeria is positioning itself as a key renewable energy producer through diversified power generation. The country's comprehensive development plan incorporates solar PV, wind, biomass, combined heat and power systems, geothermal resources, and potential concentrated solar power projects. Official projections indicate that renewable sources will account for nearly 40% of the nation's total power generation capacity and over one-quarter of its domestic electricity supply by the end of this decade [1]. The adoption of a solar PV-wind-battery hybrid system standalone sector will reduce pressure on the main grid power since residential loads are the most demanding load types during winter and summer periods [2]. The adoption of a renewable energy-based micro-grid is more useful in terms of energy-saving. Several studies have been done in terms of increasing the efficiency of the microgrid system [3].

DC bus regulation is crucial in modern power systems as it ensures stable voltage levels in the DC link, which directly impacts the efficiency and reliability of power electronic converters. A well-regulated DC bus enhances system performance by minimizing voltage fluctuations ensures smooth operation of connected inverters and converters, prevents overvoltage or undervoltage conditions that could damage sensitive components, facilitates efficient power transfer between AC and DC systems, essential for renewable energy integration, and ensures proper charging/discharging of batteries and supercapacitors in hybrid systems. By maintaining a stable DC bus voltage, the overall Energy Management System (EMS) can achieve better control, higher efficiency, and improved resilience in microgrids, renewable energy systems, and industrial applications.

The incorporation of renewable energy sources into microgrids has become a key focus in modern power systems, driven by the need for eco-friendly and reliable electricity networks. Solar arrays and wind generators offer substantial ecological benefits, including lower carbon output and minimized dependence on conventional fuel sources [4]. Nevertheless, their variable generation patterns and inherent unpredictability create operational complexities when deploying these technologies in isolated or grid-connected microgrid setups [5].

To make these microgrids more efficient, it is necessary to have a more efficient, fast and robust energy management system. As the classical control methods have shown their limits, the new methods of artificial intelligence (AI) have confirmed their superiorities in optimizing the control parameters and increasing the performance of microgrids. This has been demonstrated through several articles in the literature.

Recent research by Zhao et al. [6] presents an innovative fuzzy-logic enhanced control framework for hybrid DC microgrid systems comprising dual energy clusters. Their hierarchical power management approach demonstrates enhanced operational reliability and resource utilization efficiency while effectively regulating DC bus voltage and optimizing power distribution. Simulation results validate the system's performance. The study highlights artificial intelligence's growing role in complex power management applications. Current literature [7-10] suggests AI-based control will increasingly dominate not just microgrid operations but broader smart grid management, particularly in renewable energy and distributed resource integration.

These studies collectively underscore the growing relevance of hybrid optimization methods in enhancing microgrid control systems. They provide strong evidence for the applicability of algorithms like GWOPSO and ALO in achieving fast, robust, and reliable DC voltage regulation, particularly when performance is evaluated using comprehensive dynamic metrics. However, while many of the aforementioned studies have shown improvements in general voltage regulation performance, relatively few have explicitly focused on optimizing key dynamic time-domain parameters such as rise time, settling time, and peak time. These parameters are critical for ensuring both stability and responsiveness of the DC bus, particularly under sudden load changes. This observation underscores the need for more targeted control strategies that simultaneously address both robustness and dynamic responsiveness—an area where hybrid metaheuristic algorithms like GWOPSO and ALO may hold significant promise.

In this study, we will present the results of three smart controllers whose parameters were optimized by the metaheuristic ALO with two different objective functions and the hybrid metaheuristic PSOGWO. The paper includes an introduction that defines the problem and presents the state of the art in the field and three other sections. Section 2 presents the microgrid modeling, while Section 3 presents the methodology PID optimization controller adopted in this study. The last section presents the results obtained as well as the performance of the responses of the three smart controllers. Finally, the paper ends with a conclusion that summarizes the contributions of the three smart controllers.

METHODS

Microgrid is composed of dispersed energy sources. It is operating in parallel or independently as is depicted in figure 01.Its primary objective is to guarantee local, unfailing, and available power continuity and safety for consumers [11-18].

Microgrids are reduced topologies of the traditional electricity grid. They include renewable energy generation, distribution, and control. However, they differ from traditional electricity grids in that they are more closely aligned between electricity generation and consumption, resulting in significant efficiency and high reliability, as well as reductions in transmission costs. Another advantage is that microgrids are greens.

The system enables real-time regulation of power generation assets, facilitating independent operation with self-healing capabilities. Whether under standard load conditions, peak demand scenarios, or during utility grid outages,

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the microgrid maintains uninterrupted operation and can even provide excess power to the primary network when required [1].

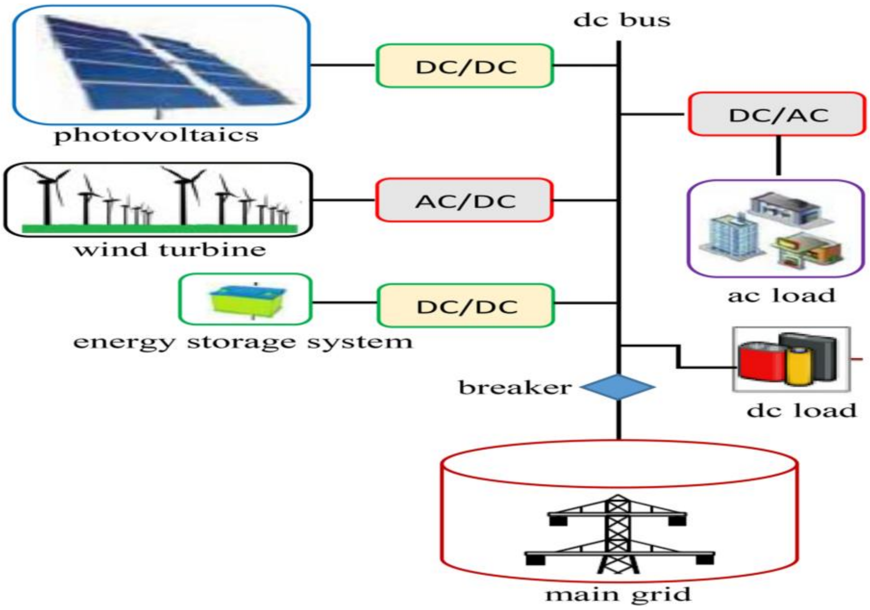

Figure 1. Microgrid topology

3.1. Metaheuristic Ant Lion Optimizer (ALO)

It is a metaheuristic inspired by the hunting behavior of antlions in nature. It is introduced by Seydali Mirjalili [20] to solve constrained engineering optimization problems. It is used to optimize the parameters of the smart controllers in this study. Ants can easily detect the location of food using stochastic movement. This behavior is expressed mathematically by the following equations:

$$X(t) = [0, cumsum(2r(t_1) - 1, \dots \dots \dots., cumsum(2r(t_n) - 1] \quad (1)$$

Where X(t) is the ant random walk, n is the max_iterations, t is the random walk step size, and r(t) is a function defined as follows:

$$r(t) = \begin{cases} 1 \; if \; rand > 0.5 \\ 0 \; \; if \; rand < 0.5 \end{cases} \quad (2)$$

Where rand is a randomly generated number uniformly distributed in the range [0,1].

3.1.1. Random walk of ants

Ants perform boundary-normalized random walks during optimization to maintain feasible search space positions.

$$X_i^t = \frac{(X_i^t - a_i)(d_i^t - c_i^t}{b_i - a_i} \quad (3)$$

For each i-th variable, ai and bi define the random walk's lower/upper limits, whereas cit and dit specify its time-dependent bounds during the t-th iteration.

3.1.2. Trapping in antlions traps

The equations below model how antlion traps influence the random movement of ants

$$c_i^t = \text{Antlion}_j^t + c^t \quad (4)$$

$$d_i^t = \text{Antlion}_j^t + d^t \quad (5)$$

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3.1.3. Building traps

The ALO algorithm employs a probabilistic selection mechanism during the optimization process, favoring higher-fitness antlions through a weighted random choice approach. This methodology enhances the likelihood of successful prey capture by preferentially selecting superior trap builders.

3.1.4. Sliding ants against toward antlion

The algorithm's biological inspiration dictates that higher-fitness antlions build larger trapping pits, while prey agents (ants) exhibit centralized movement patterns. Upon successful capture, the antlion employs a sand-flinging behavior to prevent escape. This interaction is quantitatively represented by the equations below, where parameter I governs the power of this mechanism:

$$c^t = \frac{c^t}{I} \tag{6}$$

$$d^t = \frac{d^t}{I} \tag{7}$$

3.1.5. Catching preys and rebuilding the traps

The predator-prey interaction dynamics, involving prey capture and subsequent trap reconstruction for future hunting success, are mathematically represented by the following system of equations:

$$\mathrm{Antlion}_j^t = \mathrm{Ant}_i^t, if\ f(\mathrm{Ant}_i^t) > f(\mathrm{Antlion}_j^t) \tag{8}$$

[27] the position of the selected ant at iteration t.

3.1.6. Elitism

The preservation of superior solutions constitutes a fundamental feature of evolutionary computation techniques. Within the Ant Lion Optimizer framework, each iteration maintains an elite solution representing the highest-performing antlion. This dominant solution directs the search behavior of all other candidate solutions throughout the optimization process. The mathematical formulation of this elitist preservation strategy is presented below.

$$\mathbf{Antlion}_j^t = \frac{\mathrm{R}_A^t + \mathrm{R}_E^t}{2} \tag{9}$$

R_A^t represents the random walk centered on the selected antlion, while R_E^t denotes the random walk around the elite antlion at each iteration. The variable Ant_j^t indicates the position of the j-th ant at iteration t.

3.2. Hybrid Metaheuristic PSOGWO

The hybrid metaheuristic PSOGWO combines the advantages of PSO and GWO to enhance optimization performance.

3.2.1. Metaheuristic PSO

PSO is inspired by the social behavior of birds. Each particle changes with a velocity and position updated based on its personal best position (pbest) and the global best position (gbest). The update equations are:

$$v_i(t+1) = \omega v_i(t) + c_1 r_1 (pbest_i - x_i(t)) + c_2 r_2 (gbest_i - x_i(t)) \tag{10}$$

$$x_i(t+1) = x_i(t) + v_i(t+1)$$

vi denotes the velocity of the particle, while xi represents its position. The parameter w is the inertia weight, and c1, c2 are the cognitive and social acceleration coefficients, respectively. The terms r1 and r2 are uniformly distributed random numbers in the interval [0,1].

3.2.2. Metaheuristic GWO

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GWO is inspired by the social hierarchy and hunting strategy of grey wolves. Wolves are ranked into three categories: alpha (best solution), beta (second-best solution), and delta (third-best solution). The other wolves (omega) update their positions based on the positions of alpha, beta, and delta. The update equations are:

$$D_\alpha = |C_1 X_\alpha - X| \quad (11)$$

$$D_\beta = |C_2 X_\beta - X| \quad (12)$$

$$D_\delta = |C_3 X_\delta - X| \quad (13)$$

$$X(t+1) = \frac{X_\alpha - A_1 D_\alpha + X_\beta - A_2 D_\beta + X_\delta - A_3 D_\delta}{3} \quad (14)$$

Where A and C are variable coefficients.

3.2.3. **Hybrid Metaheuristic PSOGWO**

The combination of PSO and GWO leverages the strengths of both methods: the fast convergence of PSO and the robustness of GWO. The hybridization is low-level because we combine the features of metaheuristics. It is co-evolutionary because we do not use the two variants one after the other. They operate in parallel. It is mixed because there are two distinct variants involved in generating the final solutions to the problems. In PSOGWO, the position of the first three agents is updated using the equations (19-21). Instead of using usual mathematical equations, we control the exploration and exploitation of the gray wolf in the search space by inertia constant. The modified set of governing equations is

$$D_\alpha = |C_1 X_\alpha - \omega * X| \quad (15)$$

$$D_\beta = |C_2 X_\beta - \omega * X| \quad (16)$$

$$D_\delta = |C_3 X_\delta - \omega * X| \quad (17)$$

The speed is updated as follows:

$$v_i(t+1) = \omega * (v_i(t) + c_1 r_1 (X_1 - X_i(t)) + c_2 r_2 ((X_2 - X_i(t)) + c_3 r_3 ((X_3 - X_i(t)) \quad (18)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (19)$$

Where ω is the inertia. In this study, PSOGWO is used to optimize the parameters of the smart controllers with enhanced precision.

3.3. **Objective function**

It is defined to evaluate the performance of the smart controllers and guide the optimization process using ALO and PSOGWO.

The primary objective function is defined as:

$$f = \min\,(\min(a) + \min(b) + \min(c) + \min(d)) \quad (20)$$

Where a, b, c, and d represent specific performance criteria respectively, rise time, settling time, overshoot, and undershoot.

Another objective function used is the Integral of Time multiplied by Squared Error (ITSE):

$$f = \int te^2 dt \quad (21)$$

Where e is the error and t is the time. This function penalizes persistent errors and promotes a fast and stable response.

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RESULTS

In this study, DC voltage regulation was improved using two metaheuristic algorithms: ALO and PSOGWO. The ALO's algorithm was tested with two distinct objective functions to evaluate its performance under different criteria. The responses of the DC voltage in the microgrid were compared for each scenario. The investigated microgrid is shown in Figure 1.

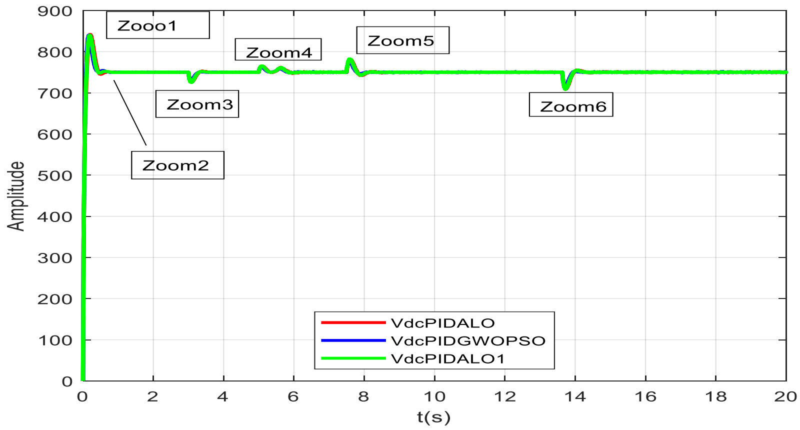

Figure 2. DC voltage for all controllers

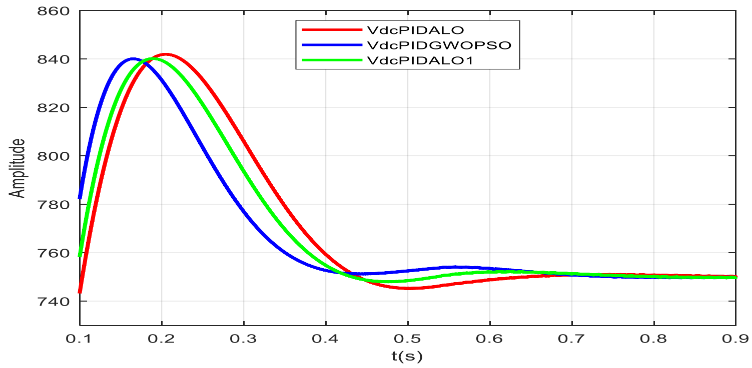

Figure 3. Zoom 1 of DC voltage for all controllers

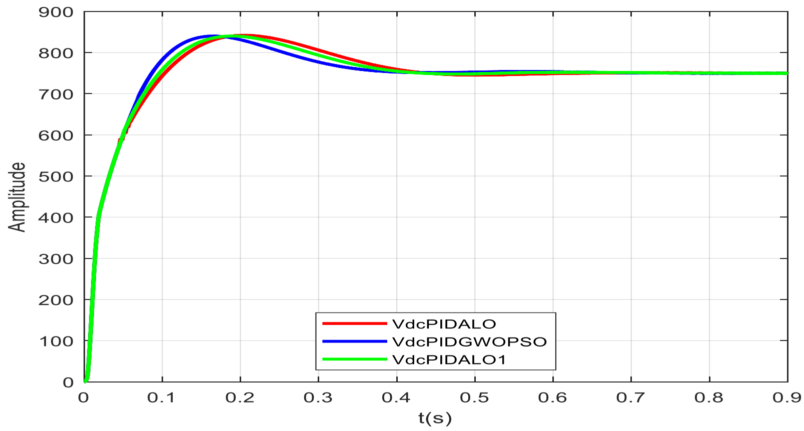

Figure 4. Zoom 2 of DC voltage for all controllers

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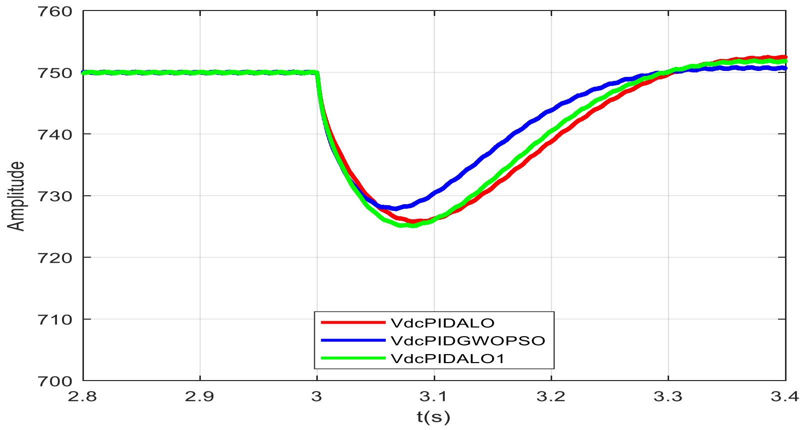

Figure 5. Zoom 3 of DC voltage for all controllers

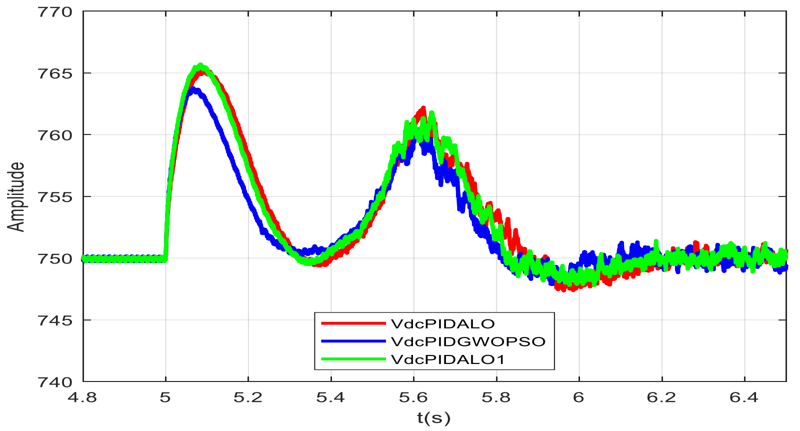

Figure 6. Zoom 4 of DC voltage for all controllers

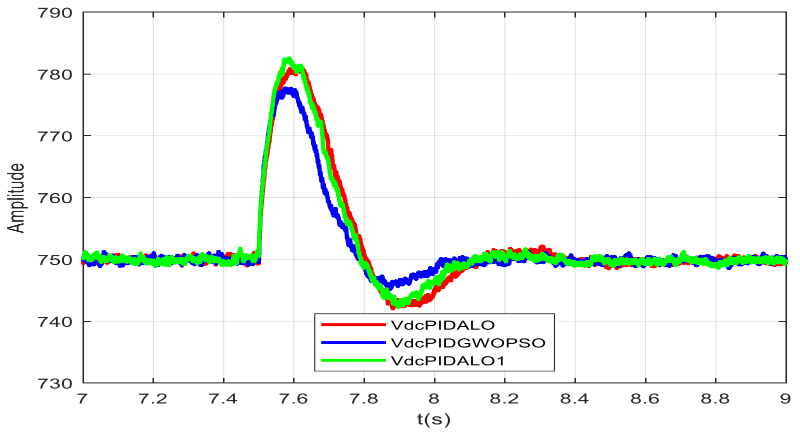

Figure 7. Zoom 5 of DC voltage for all controllers

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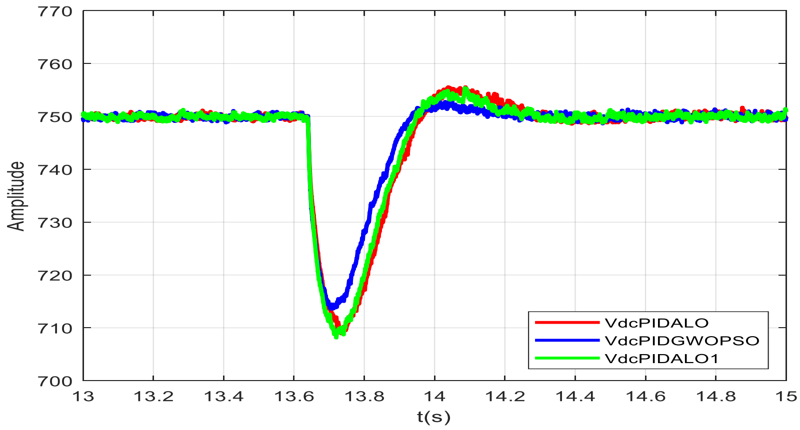

Figure 8. Zoom 6 of DC voltage for all controllers

Table 1. Performances of the three controllers

	PID ALO	PID GWOPSO	PID ALO1
Rise Time	0.0658	0.0590	0.0619
Settling Time	0.3835	0.3322	0.3633
Settling Min	674.9354	674.9523	674.9113
Settling Max	841.9647	840.0882	840.1806
Overshoot	12.2690	12.0216	12.0546
Undershoot	0	0	0
Peak	841.9647	840.0882	840.1806
Peak Time	0.2042	0.1653	0.1892

DISCUSSION

According to results obtained from the ALO using the first objective function, the DC voltage stabilizes at the reference value within 0.3835 seconds, as illustrated in Figures 2 through 8. Nevertheless, an overshoot of 12.2690% is observed (Table 1). In contrast, the ALO algorithm employing the second objective function yields different results: the DC voltage reaches the reference value in 0.3633s (Figs. 2–8) with a reduced overshoot of 12.0546% (Table 1).

According to results obtained from the ALO using different ob-jective functions, we can notice the impact of the objective function on response performances. In another scenario based on the PSOGWO hybrid metaheuristic with the same objective which consists to the control of the DC voltage of the microgrid, the results obtained are different. The DC voltage reaches the reference value in 0.3322 s with an overshoot of 12.0216% (Table 1) as seen in Figs. 2-8. From the performance of both algorithms with three objective functions, it can be concluded that the hybrid metaheuristic PSOGWO outperforms ALO. In addition, the re-sponse of PSOGWO is faster than both scenarios with a rise time (Table 1) equal to 0.0590 s against 0.0658 s and 0.0619 s for ALO with two objective functions. The table 1 presents the DC voltage performances of the three controllers.

CONCLUSION

The comparative analysis of the ALO and the hybrid PSOGWO algorithms for DC voltage control in a microgrid reveals significant differences in performance based on the chosen objective function. The ALO algorithm demonstrates varying response times and overshoot levels depending on the objective function used, with settling

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times of 0.3835 s and 0.3633 s and overshoots of 12.2690% and 12.0546%, respectively. In contrast, the hybrid PSOGWO algorithm achieves superior performance, stabilizing the DC voltage in just 0.3322 s with a slightly lower overshoot of 12.0216%. Additionally, PSOGWO exhibits a faster rise time (0.0590 s) compared to both ALO configurations (0.0658 s and 0.0619 s). These results highlight the efficiency of the hybrid PSOGWO algorithm in optimizing DC voltage regulation, making it a more effective choice for microgrid control applications. Future work could explore further refinements in objective functions or hybrid optimization techniques to enhance system response and stability.

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