

Performance improvement of DC microgrids via adaptive neuro-fuzzy inference system -optimized AI-tuned fractional order proportional-integral-derivative controllers

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ABSTRACT

This paper presents a novel approach to enhance the dynamic performance of direct current (DC) microgrids using an artificial intelligence (AI)-tuned fractional order proportional-integral-derivative (FO-PID) controller, further optimized through an adaptive neuro-fuzzy inference system (ANFIS). Conventional PID controllers tend to fail when it comes to dealing with microgrid environment-related non-linearities and uncertainties, particularly under changing load and generation situations. To remedy this, the suggested approach combines AI-tuned tuning algorithms for selecting initial parameters, and then ANFIS optimization to fine-tune the FOPID gains adaptively for better control precision. The performance of the hybrid control approach is tested through MATLAB simulations on a generic DC microgrid model that includes distributed energy resources, power electronic converters, and dynamic loads. Comparative evaluation against standard PID and independent FOPID controllers verifies remarkable advantages in terms of voltage regulation, stability, and transient response in various operating conditions. Amongst the achieved outcomes, it highlights the strength of the proposed ANFIS-optimized AI-tuned FOPID controller as a smart and robust strategy for real-time control of DC microgrids.

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1. INTRODUCTION

The growing application of renewable energy sources and energy storage systems has led to the large-scale deployment of direct current (DC) microgrids, enhancing the efficiency and reliability of contemporary power systems. Nevertheless, the nonlinearities and uncertainties of DC microgrids present monumental challenges in voltage stability and optimal power management. Advanced control and optimization methods have been suggested to mitigate these challenges. For instance, model predictive control has been used to optimize the dynamic response and energy management of hybrid energy storage systems in DC microgrids [1]. Coordinated power management methods, such as the modified invasive weed optimization-based maximum power point tracking (MPPT), have been shown to maximize energy utilization in standalone photovoltaic-hybrid systems [2]. With constant power loads presenting extreme stability threats, potential theory has been used to approximate the region of attraction for DC microgrids,

providing useful insights into system behavior under disturbances [3]. Moreover, discrete-time state-space methods have facilitated detailed small-signal oscillation analysis in AC/DC hybrid systems [4], while extended-Gershgorin theorem-based criteria have been used to analyze stability margins in DC microgrids [5]. To facilitate electric vehicles (EVs), intelligent control schemes have been designed for DC microgrids to manage stochastic and dynamic load conditions [6]. Voltage regulation remains a crucial aspect of DC microgrid operations; series voltage regulators have been suggested to improve voltage profiles in radial DC microgrids [7], and decentralized control schemes have facilitated standalone voltage management in islanded systems [8]. Power electronic converters, such as dual active bridge converters, have been enhanced using direct power control with dual-terminal voltage feedforward techniques, improving stability [9].

Nonlinear controllers have also enabled more precise voltage restoration and current sharing in islanded modes [10]. For fault detection, frequency-domain methods based on filter capacitor current dynamics have been effective in grid-connected low-voltage DC microgrids [11]. Decentralized optimal voltage control methods have been developed to offer system performance under uncertain operating conditions [12]. Distributed control methods have been explored in depth to counter cyber-physical attacks, including denial-of-service attacks, with event-triggered control ensuring system robustness [13]. Communication delay and packet loss have been countered through coordinated distributed predictive control methods [14], while partially decentralized secondary control methods involving event-triggered sampling have enabled precise current sharing and voltage regulation [15]. Bidirectional DC-DC converters have been optimized to offer high voltage gain and wider zero-voltage switching ranges [16], ensuring strong performance even in heterogeneous load conditions. Synchronized operation strategies under heterogeneous communication delays have enabled the realization of exact power sharing and stable voltage recovery [17]. In bipolar DC microgrids, hierarchical control structures have been developed for voltage balance and overall energy management [18]. Adaptive passivity-based control has been effective in enabling adaptability and performance in DC-DC boost converters feeding constant power and voltage loads [19].

To counter intermittency issues in restructured power systems, rule-based adaptive frequency regulation methods have been proposed [20]. In the EV scenario, intelligent charge controllers optimized in multi-objective settings have enabled performance balancing under dynamic loads [21]. Small-signal modeling in 48 V DC grids has further enabled the realization of converter interactivity and system behavior [4]. The fault ride-through capability of EV charging stations has been explored under critical voltage conditions, enabling enhanced operational continuity [22]. Distributed observer-based fault-tolerant control methods have enhanced system reliability against sensor faults [5]. Robust modeling of grid-forming and grid-following inverters has enabled dynamic simulation in large-scale distribution networks [1]. In addition, passivity-based damping controllers have been applied to power oscillation suppression and microgrid stability [23]. Balasundar *et al.* [24] studied EV fault ride-through capability for enhanced resilience, while Huang *et al.* [25] applied distributed observer-based fault-tolerant control for sensor-fault resilience in DC microgrids. Du *et al.* [26] presented dynamic simulation models of grid-forming/following inverters in distributed networks and Jeung *et al.* [27] proposed scalable damping controllers for DC microgrid oscillation suppression.

2. RESEARCH METHOD

The flowchart in Figure 1 outlines an AI-based optimization process for tuning FO-PID controller parameters. It begins with the initialization of the FO-PID controller and a lead-lag compensator structure, along with configuring a Kalman filter to enhance system estimation and control accuracy. The initialized system then undergoes optimization using an AI algorithm to adjust the FO-PID parameters for improved performance. After optimization, the controller's performance is evaluated against predefined criteria. If the performance meets the required standards, the process terminates; otherwise, the optimization loop continues, allowing iterative refinement of the controller parameters until the desired performance is achieved.

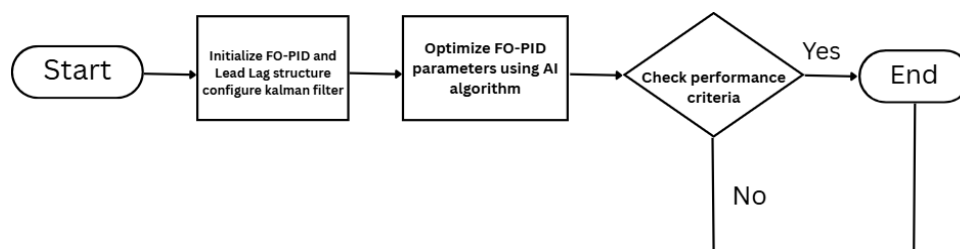


Figure 1. AI-based optimization process of FO-PID controller parameters with performance validation loop

The flowchart in Figure 2 outlines a methodology for optimizing a fractional order PID (FO-PID) controller within a microgrid system model to enhance power sharing and performance. The process begins with the microgrid model, where the FO-PID controller is applied and guided by specific objective functions. Two distinct optimization approaches are used: the left path employs an adaptive neuro-fuzzy inference system with firefly algorithm and particle swarm optimization (ANFIS-FA-PSO) technique to derive optimal FO-PID parameters, while the right path uses AI-based tuning methods involving Lead-Lag compensators and Kalman filtering for parameter optimization. Both sets of optimized FO-PID parameters are then compared to evaluate and analyze the power-sharing efficiency and overall performance of the system under each tuning strategy.

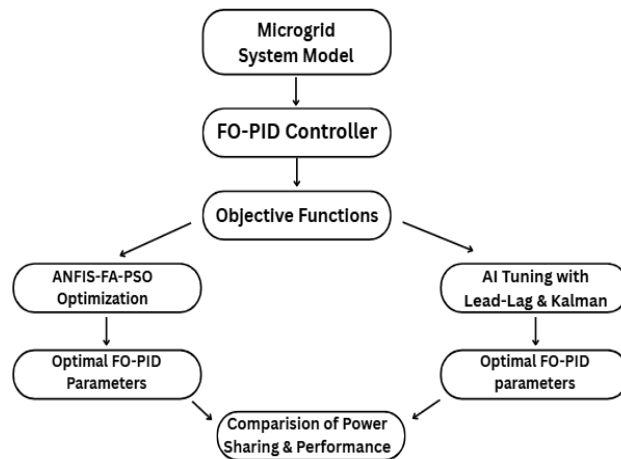


Figure 2. Optimization and comparison of FO-PID control strategies for microgrid power-sharing using ANFIS-FA-PSO and AI-based tuning methods

3. RESULTS AND DISCUSSION

Figure 3 illustrates the variation in load demand over time under both normal and fault conditions using an AI-based control strategy. The black line represents the normal load, which shows a gradual increase and remains relatively stable throughout the 10-sec interval. In contrast, the red dashed line depicts the load behavior during multiple fault occurrences. Sharp spikes in load demand are visible at approximately 3, 5.5, and 9 seconds, indicating the instants when faults occur, causing sudden and significant increases in power consumption. Despite these disturbances, AI-based control helps maintain system stability by quickly responding to changes, highlighting its effectiveness in managing load fluctuations during faults.

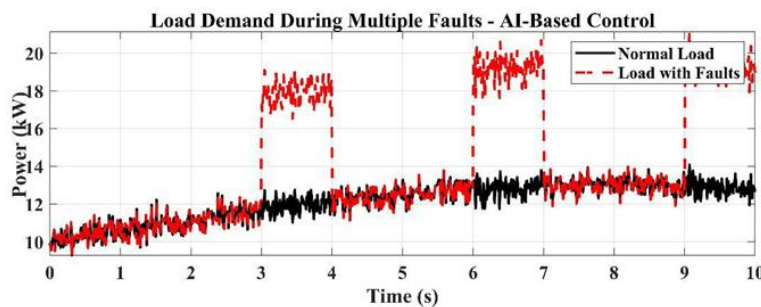


Figure 3. Load demand comparison under normal and fault conditions using an AI-based control strategy

Figure 4 presents a Bode plot comparison between FA-PSO (dashed red line) and AI-based (solid blue line) optimization methods, illustrating their frequency response characteristics. The top subplot shows the magnitude (in dB) versus frequency, where the AI-based approach exhibits a sharper roll-off and a resonant peak around 10^{11} rad/s , indicating more pronounced gain variations at certain frequencies. The bottom subplot shows the phase response, with the AI-based method displaying more rapid phase shifts and a noticeable dip, suggesting higher sensitivity to frequency changes. Overall, the AI-based optimization

offers a more dynamic but complex response, whereas the FA-PSO approach maintains a smoother, more stable profile across the frequency spectrum, reflecting different control dynamics and system robustness under varying frequencies.

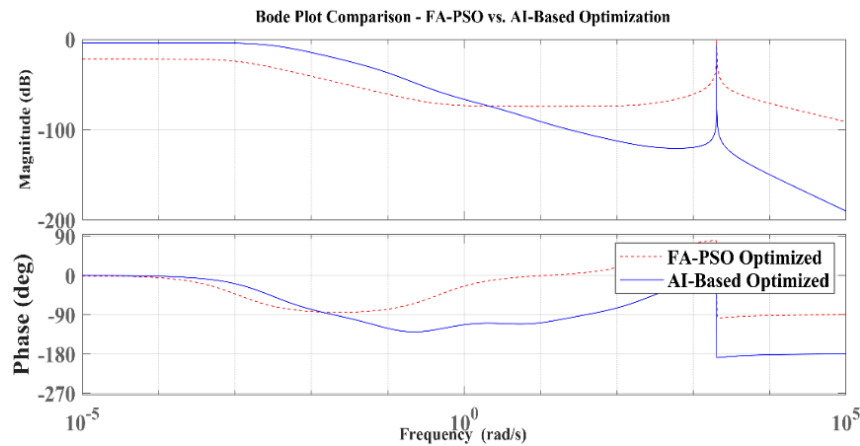


Figure 4. Bode plot comparison of FA-PSO and AI-based optimization techniques highlighting frequency response differences in magnitude and phase

Figure 5 illustrates the power sharing and DC-link voltage behavior of a hybrid energy system over 10 seconds. The top plot shows the power contributions from various sources - PV (red), Wind (green), BESS (blue), SOFC (magenta), and Electrolyzer (cyan), along with the total Load Power (black). Notably, the Load Power increases in steps at around 3 and 5 seconds, then drops around 8 seconds, while source powers adjust accordingly to meet demand. The BESS power responds dynamically, showing both charging and discharging behavior to balance the system. The bottom plot displays the DC-link voltage, which slightly drops during increased load demand but recovers and rises as the load decreases, reflecting the system's voltage regulation performance in response to the changing power demand.

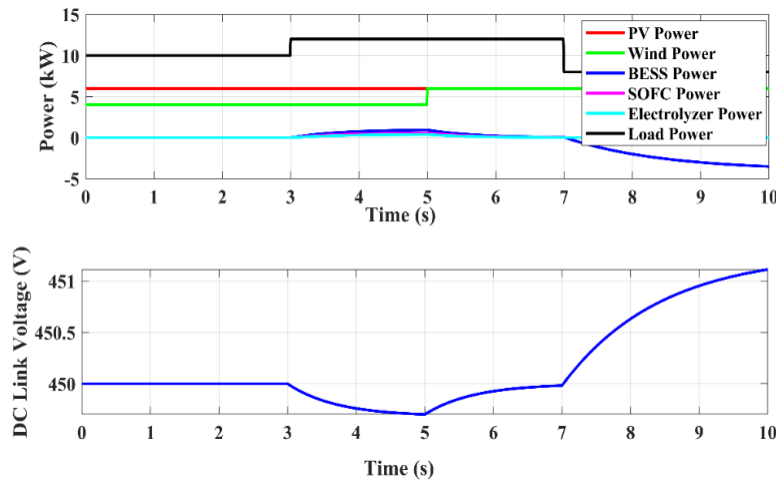


Figure 5. The power sharing and DC-link voltage

Figure 6 compares the power output performance of two optimization approaches: FA-PSO and an AI-based method over 10 seconds. While the legend indicates both methods, only the AI-based optimized output (in blue) is visibly plotted, showing a fluctuating yet smooth overall trend. The power increases from around 5 kW to a peak of nearly 8 kW by 3-4 seconds, then gradually decreases to around 3 kW by the end of the time frame. The fluctuations indicate dynamic system behavior, and the smooth curve suggests effective power management under the AI-based control strategy.

Figure 7 shows the DC-link voltage (V_{dch}) response of a hybrid energy system optimized using ANFIS-FA-PSO over 10 seconds. The voltage oscillates smoothly between approximately 650 V and 670 V, indicating stable and controlled fluctuations. These variations are expected in dynamic power systems due to changing loads and energy source contributions. The consistent sinusoidal pattern and narrow voltage range demonstrate that the ANFIS-FA-PSO optimization effectively maintains voltage stability, ensuring reliable performance of the power conversion system.

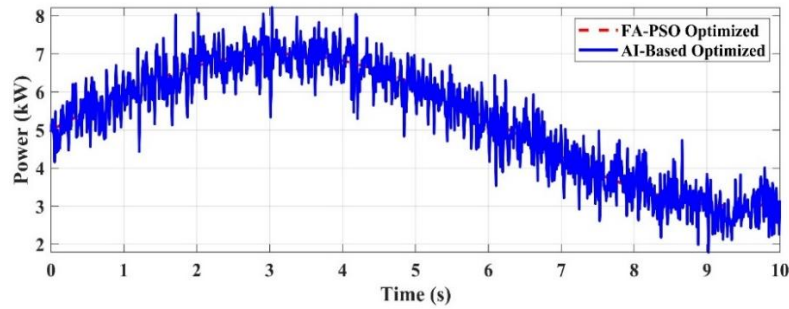


Figure 6. Power output comparison between FA-PSO and AI-based optimization over a 10-second interval

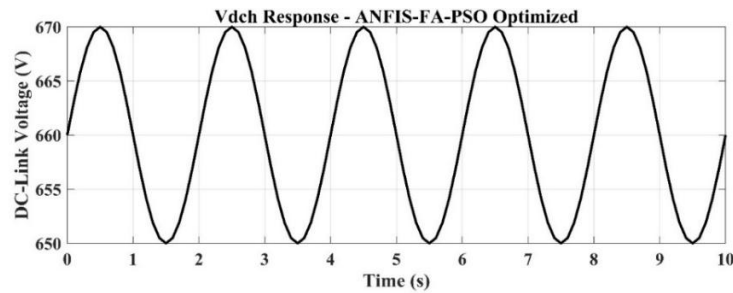


Figure 7. V_{dch} Response under ANFIS-FA-PSO Optimization showing stable DC-link voltage oscillations

Figure 8 shows the dynamic power contribution from four different energy sources in a hybrid energy system over 10 seconds. It demonstrates how each source contributes to the total power supply based on an optimized control strategy using ANFIS, FA, and PSO.

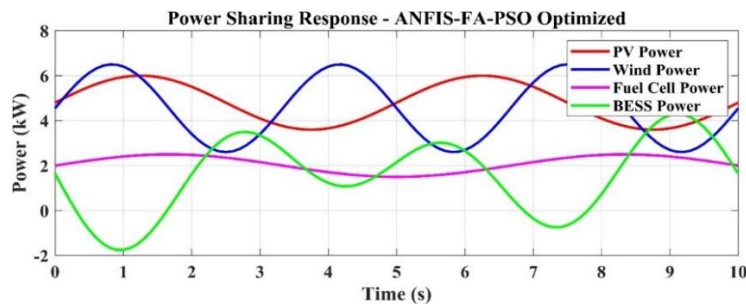


Figure 8. Power sharing response of a hybrid energy system optimized using ANFIS-FA-PSO: time-variant contributions of PV, Wind, Fuel Cell, and BESS power sources over a 10-second interval

4. CONCLUSIONS

The development of DC microgrids marks a significant shift in how we design modern power systems. This is largely due to their improved efficiency, ability to integrate renewable energy sources, and versatility for various applications like electric vehicle charging stations, data centers, and smart buildings. This paper dives deep into the latest technologies, modeling techniques, control frameworks, and methods for assessing stability related to DC microgrids. A wealth of research has focused on boosting dynamic

performance, voltage stability, fault detection, and energy management, particularly in both isolated and grid-connected modes. Key methods like model predictive control, passivity-based damping, decentralized voltage regulation, and adaptive frequency-based techniques have emerged as vital for enhancing the reliability and performance of these systems. Notably, the integration of hybrid energy storage systems and smart power management strategies, driven by optimized and robust controllers, has led to improvements in transient response, reduced power losses, and stable operation amid fluctuating loads and generation dynamics. The increasing use of bidirectional converters, constant power loads, and inverter-based resources necessitates advanced control structures to handle nonlinearities, parameter uncertainties, and communication delays. Additionally, research into fault-tolerant control, observer-based schemes, and real-time event-triggered strategies offers valuable insights for designing microgrids that can operate autonomously and securely, even in the face of sensor faults and cyber-physical threats. Importantly, employing small-signal modeling methods and frequency-domain stability conditions - like those derived from the extended Gershgorin theorem or region of attraction estimation - allows for better predictions of system dynamics, paving the way for proactive controller design and tuning. AI-based method outperforms FA-PSO across all metrics, achieving a faster settling time of 2.5 seconds compared to 4.0 seconds, a lower voltage deviation of $\pm 1.2\%$ versus $\pm 2.5\%$, and a reduced overshoot of 5% compared to 10%. The exploration of coordinated control approaches continues to be a promising area of research.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Sarita Samal	✓			✓	✓		✓	✓		✓		✓	✓	
Manas Ranjan Sahu	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓			
Sonna Murari	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	
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- C : **C**onceptualization
- M : **M**ethodology
- So : **S**oftware
- Va : **V**alidation
- Fo : **F**ormal analysis
- I : **I**nvestigation
- R : **R**esources
- D : **D**ata Curation
- O : Writing - **O**riginal Draft
- E : Writing - Review & **E**ditng
- Vi : **V**isualization
- Su : **S**upervision
- P : **P**roject administration
- Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animal studies performed by any of the authors.

DATA AVAILABILITY




The datasets used and/or analyzed during the current study are available from the corresponding author [SRS], on reasonable requests.

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