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Comparative Analysis of Fuzzy Logic, PID, and FOPID Controllers in DC Microgrid Voltage Regulation for Power Plants: Integrating Renewable Energy Sources

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ABSTRACT

The worldwide direction moving towards sustainable energy solutions requires more advanced control mechanisms within power systems, especially in DC microgrids that combine renewable energy sources like solar panels and wind turbines with conventional power setups. This paper addresses the necessary challenge of maintaining steady and efficient DC voltage control—important for the dependability and performance of power plants. Specifically, it looks at the efficiency of four different control strategies: classic PID (Proportional-Integral-Derivative) controllers, Fuzzy Logic Controllers (FLC), Fractional Order PID (FOPID) controllers, and a new mixed system that merges Fuzzy Logic with PID controllers in a Fuzzy-PI layout. Our approach utilizes a strict comparative analysis using MATLAB Simulink simulations, assessing each controller's capacity to manage dynamic load shifts, adjust to the unpredictability of renewable energy inputs, and preserve strong voltage stability under various operational cases. The simulations are crafted to single out the most effective control strategy to boost efficiency and toughness in microgrid operations. This study adds substantially to the progress of control strategies in hybrid energy systems, offering important insights into the creation of more complex and reliable power management solutions. By evaluating the performance of these varied controllers, we aim to underline potential upgrades in control systems that could support better energy management in intricate grid setups, thereby encouraging the wider inclusion of renewable energy technologies into power grids.

1. Introduction

Lately, a movement going in direction of energy systems being more decentralized has brought forward the very important significance of Direct Current (DC) microgrids within the changing scene of power being distributed. DC microgrids, they are, like, playing a key part in bringing in renewable energy sources, making energy efficiency better, plus making the grid more resilient. Among, you know, the many challenges tied to DC microgrids, voltage regulation really leaps out as a core problem that hits system stability and, uh, efficiency hard. Voltage regulation is super important in

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DC microgrids for keeping a stable and dependable power supply, mainly because renewable energy sources like the sun and wind are so variable. The changing inputs from these renewables, along with different and always changing load demands, create unique hurdles in keeping the best voltage levels [1], which until now, has been managed using the conventional voltage regulation methods such as Proportional-Integral-Derivative (PID) controllers. However, the complex and non-linear behaviors often seen in most of the DC micro-grids today due to the presence of renewable energy in such grids, cannot be managed by these conventional voltage regulation methods [2]. Hence, new control algorithms such as fuzzy logic controllers, neuro-fuzzy systems, and fractional-order controllers are developed for these systems as they are considered smart techniques with better adaptability and performance. Fuzzy logic controllers, for instance, can excellently handle unclear inputs compared to the old methods because it can tweak control decisions based on heuristic rules, as earlier reported. The better performance of these methods is due to their reliance on machine learning (ML), artificial intelligence (AI), and advanced mathematical principles to handle the non-linear dynamics and natural uncertainties of DC micro-grids adaptively [3-5].

Voltage control techniques have seriously advanced but there are still significant gaps in knowledge regarding the comparative analysis of some of the existing voltage control algorithms under varying operation conditions within DC micro-grids; such analysis is crucial not only in understanding the strengths and weaknesses of each control strategy, but also to guide the integration of these technologies into a cohesive system capable of managing the complexities of modern power grids [4,6]. Relevant studies to highlight the need for such analyses include [7,8] which discuss challenges of integration and opportunities in DC microgrid configurations. That article aims to fill this gap in research by a detailed comparative analysis of various control algorithms, to assess their efficacy in robust voltage regulation within DC microgrids. Through this examination, article seeks identifying optimal strategies and propose potentially hybrid approach combining multiple control mechanisms to capitalize on their respective advantages [9]. Key references guiding this analysis includes [10,11], which be providing insights into the latest developments in fuzzy and fractional PID control within complex grid environments. Findings expected to contribute significantly to both theoretical and practical aspects of DC microgrid management, providing insights valuable for researchers and practitioners alike in design and operation of systems critical [12-14].

2. Literature survey

The ensuring that the voltage is controlled effectively is crucial for maintaining stability and efficiency within DC microgrids, especially when integrating renewable energy sources. This examination delves into the latest progressions in control algorithms, placing particular emphasis on their comparative analysis specifically for DC microgrids. Each referenced study adds to an intricate comprehension of the ways in which different control strategies are able to improve the performance of power systems in various contexts. Proposals have been made for the hybridization of the Internet of Things (IoT) with smart grids and neuro-fuzzy systems to achieve a robust approach to the regulation and monitoring of energy systems; for instance, [15] proposed an integrative system that involved the use of the Adaptive Neuro-Fuzzy Inference System (ANFIS) moderators for the improvement of the function of solar/wind power stations. An attested efficacy standing at 99.74% is indicative of the proficiencies of IoT in amplifying grid reactivity and steadfastness via contemporaneous data scrutiny and pliant regulatory apparatuses. Concentrating on the docket of electric vehicle (EV) recharging, [5] investigates the application of fuzzy logic arbiters in the orchestration of energy dispensation betwixt photovoltaic (PV) assemblies and accumulative energy reserves. Such schema not alone certifies voltage equilibrium but also maximizes the renewable energy exploitation. The dispersed control archetype sustains grid equilibrium amidst fluctuating load scenarios, epitomizing the flexible nature of fuzzy controllers within fluid milieus. Fractional-order PID (FOPID) controllers provided more accuracy in the handling of the performative aspects of voltage-lift converters, which are essential elements in the increasing-up voltage metrics within DC architectures.

As explicated in reference [16], herewith controllers permit finetuning of the transient alongside the steady-state responses, thereby enlarging the robustness and also the effectiveness of the cumulative system. The flexibility of the voltage control systems could be improved by the integration of fractional calculus to a level that may not be possibly achieved by the traditional PID controllers. The ability of fuzzy PI controllers to mitigate voltage oscillations alongside dynamically fortifying performance, particularly amidst instance's abrupt fault emergence or, exceedingly, load shifts dynamically was determined by [17] in the AC-DC micro-grid hybrids. Significant enhancement in systemic stability and performance has been reported using the Mode Fractional-order Proportional-Integral-Differential controllers [18] in the interconnection power architectures with both static and renewable energy sources. The combination of many complex computational techniques such as FL, neuro-fuzzy systems, and fractional calculus for the control of DC micro-grids has been widely recommended in the literature; this is in consideration of the specific advantages and limitations of each technique within the grid. It is believed that a hybridized system could exploit all the benefits of the individual systems to counter the related challenges associated with the use of each one; thereby providing solution to most of the complex power control systems that may not be addressed using the individual techniques.

Until now, studies are yet to be reported on the comparative analysis of the existing power control techniques using different performance metrics under authentic grid states; hence, there may be a need to methodically analyse this control method with the intent of arriving at a power control method that will combine the positives of the existing system while addressing their individual drawbacks. DC micro-grid control algorithms have progressed significantly but currently requires the development of adaptable, robust and effective solutions that will handle the complex demands associated with the integration of renewable energy systems into micro-grids. This has been considerably discussed in this article, with each discussion providing new solutions aimed at improving stability and efficiency of power control systems.

3. Methodology

3.1 Overview

In this section, the method used to compare different control algorithms in a DC microgrid is examined. The MATLAB Simulink software is used for simulations with a variety of controllers such as pre-defined Fractional Order Proportional-Integral (FoPI) controller, classical Proportional-Integral-Derivative (PID) controller, Fuzzy Logic Controller (FLC), and augmented PI controller guided by Fuzzy Logic (Fuzzy-PI). Test for all these controllers are conducted under simulated conditions representing real oscillations of environmental input together with grid loads, whereby their efficiency and suitability for practical DC microgrid applications are determined rigorously. The key terms used in the discussion on power control systems in this study are presented and described in Table 1.

Table 1
Description of some of the key terms used in this study

Abbreviation	Full name	Definition
FoPI	Fractional Order PI	A type of proportional-integral controller that incorporates fractional calculus to refine system response to dynamic changes.
PID	Proportional-Integral-Derivative Controller	A control loop feedback mechanism widely used in industrial control systems that calculates an error value and applies corrections based on proportional, integral, and derivative terms.
FLC	Fuzzy Logic Controller	This controller uses FL to apply a set of linguistic rules that are related to variable states within the system, managing the degrees of truth rather than Boolean logic.
Fuzzy-PI	Fuzzy Logic Enhanced PI Controller	A controller that merges FL with standard PI control structure for better system adaptability and responsiveness to rapid operational changes.
DC	Direct Current	An electric current flowing in one direction only, typically used in low-voltage applications and easy to transform into other forms of energy like mechanical and heat.
SA	Simulated Annealing	A probabilistic technique for approximating the global optimum of a function, used as a meta-heuristic to approximate global optimization in a large search space.
ITAE	Integral of Time-multiplied Absolute Error	A performance criterion for control systems that factors in the error over time, weighing errors that occur later in the response more heavily.

A very difficult process was designed for comparing different control schemes in a DC microgrid, and Figure 1, flowchart shows this. The first system setup is the beginning of the procedure aimed at establishing basic components and structure for subsequent simulation of the DC microgrid. This configuration forms the basis of the entire comparative study. The methodology commences by setting up the system which then proceeds to configure four types of controllers namely: Fuzzy Logic Controller (FLC), Classic PID controller, Fractional Order PI (FoPI) controller, and Fuzzy-PI controller. Each controller deals with specific dynamics that occur in a DC microgrid. Grid fluctuations are optimized with FoPI controller using meta-heuristic techniques. The parameters of the classic PID controller are linked to those of a FoPI controller, albeit excluding its fractional part, so that they can be used as measuring benchmarks.

Fuzzy Logic Controller uses a series of predefined rules to handle the non-linearities inherent in microgrid while Fuzzy-PI controller combines the robustness of PI control with fuzzy logic adaptiveness to enhance system stability and response. The controllers configured in this manner are then integrated into detailed Simulink models. These models mimic how controllers interact with the microgrid under different test scenarios that are essential in appraising their efficiency. Among these scenarios are uniform test conditions for assessing standard performance; dynamic test conditions that introduce complex environmental changes; and fixed scenario tests that consider the steady state behavior of these controllers. The testing period is followed by performance evaluation which measures effectiveness using metrics like settling time, peak overshoot and rise time for each controller.

These tests help in the comparison of each controller’s ability to stabilize and optimize the microgrid performance, using both visuals and quantitative methods. The process ends with a concluding section that provides a summary and also offers some insight into future microgrid control strategies or possible recommendations. Besides highlighting the abilities and limitations respectively inherent within every control strategy, this permits continued enhancements of microgrid management.

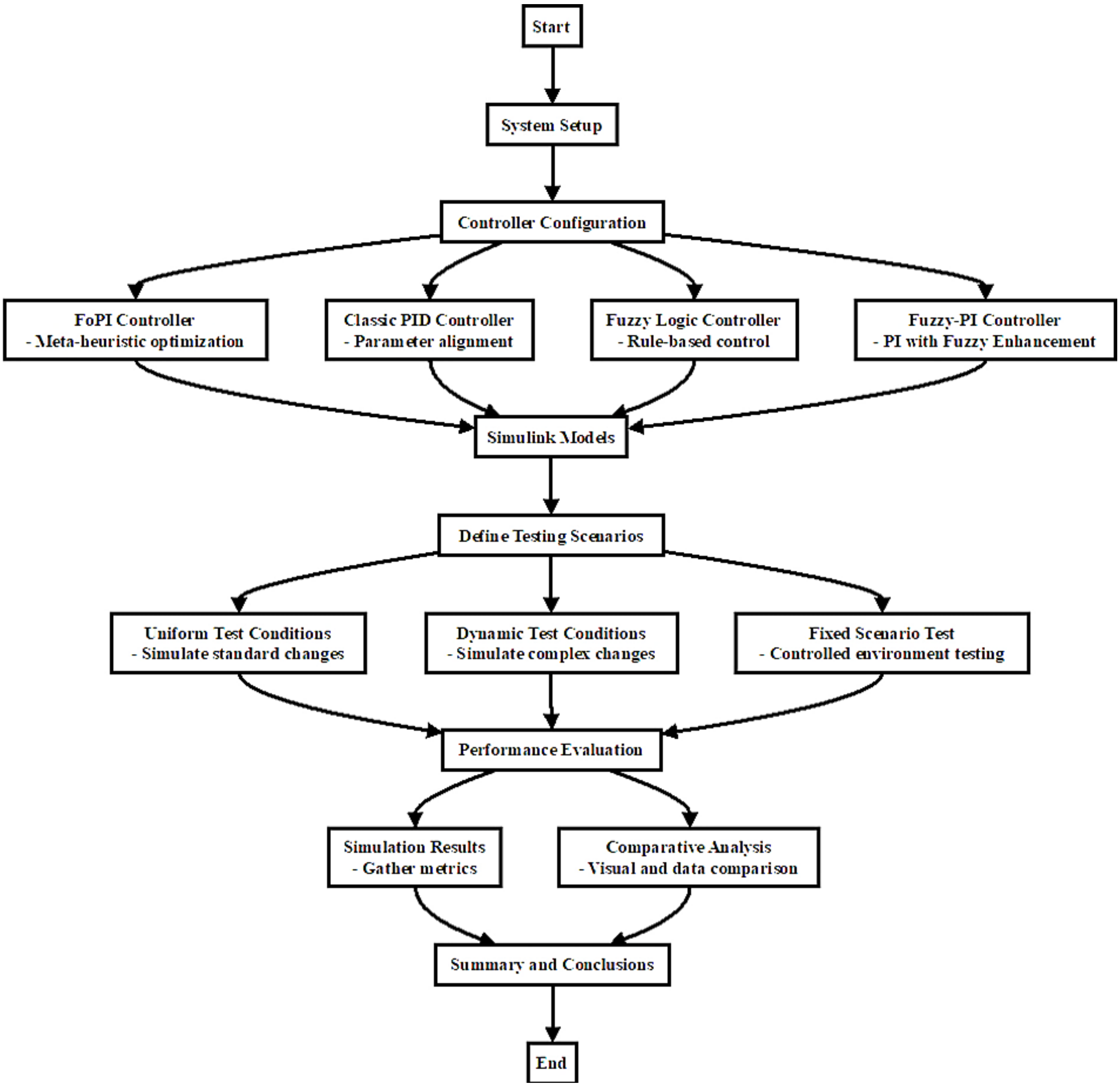

Fig. 1. Flowchart depicting the methodology for comparing control algorithms in a DC microgrid, highlighting controller configuration, simulation setup, testing scenarios, and performance evaluation

3.2 System Description

The DC Microgrid configuration used for this study is composed of critical components necessary to mimic actual power distribution networks. It involves photovoltaic arrays, wind turbines, battery storage systems as well as different consumer loads linked by means of a network made up of converters and control systems. Each element is designed with features representative of complex behaviours happening in the grid.

A very graphic representation of Figure 2 is given, which gives an overall description of the architecture of a DC microgrid system, indicating how various elements and control mechanisms are integrated. The considered structure in this work is aimed at ensuring optimum performance of the control system for micro-grid operation as it is developed based on the use of primary energy sources like Wind Turbine and Solar Panels Models which are all connected individually using boost converters. The role of these transformers in the DC micro-grid is to ensure sufficient generation of power from the solar cells or wind turbines and to ensure the optimal usage of the generated power in the system; the Boost Converter is needed for the solar panels to improve the generation of the needed voltage to meet grid standards. The output of the wind turbine is improved for smooth integration into power grids using the Wind Turbine Converter as it uses battery storage via a Battery Management System (BMS); the BMS also requires a Bi-directional Buck-Boost Converter for optimum power flow between these storage components and the DC bus; it also ensures efficient management of the charge-discharge cycle to ensure that the system responds well to changes in power demand or supply. The operation of these devices is governed by control systems to ensure optimum performance.

Boost Converters in solar panels are managed using FoPI Controllers for optimum efficiency; these converters are governed by meta-heuristics to ensure excellent performance. For the wind turbines, they are controlled using Classic PID Controller; their operational dynamics are more precisely controlled using BMS with FLC. The role of the Fuzzy-PI Controller is to ensure voltage stability on the DC bus level; it is needed for optimum power reliability within the distribution system through electrical loads. Finally, the User Interface permits system performance monitoring by an operator who is also capable of making adjustments to ensure optimum operation and maintenance of the microgrid. This interactive component is crucial for real-time control and troubleshooting which makes DC microgrid more flexible and user friendly.

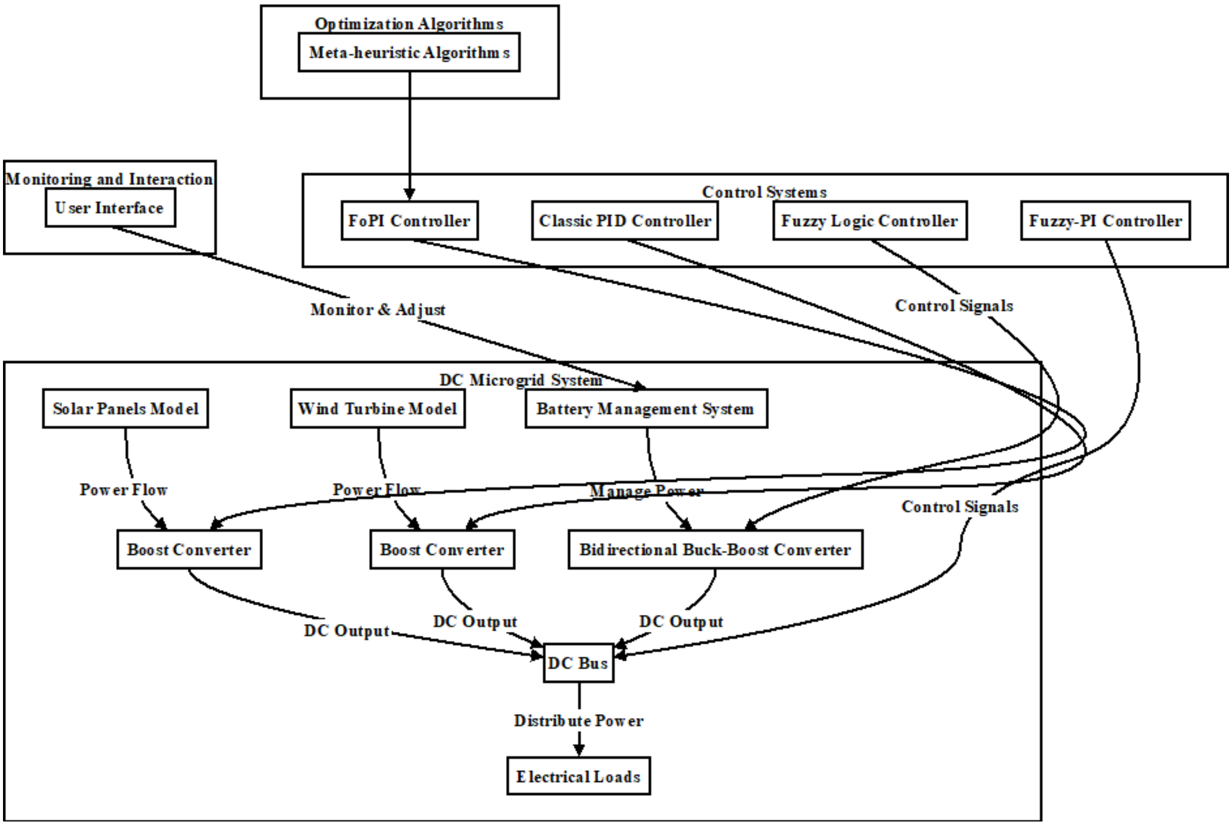

Fig. 2. Illustration of the interconnected DC micro-grid system in terms of the component relationships and the adopted control methods for efficient performance

4. Results

Let us first note that the experimental design of comparative analysis of control algorithms in DC microgrid is not just an academic exercise. This incorporates specific parameters for PV and wind turbine modules that are essential towards a meaningful simulation and analysis. These parameters, which are described more fully for each component within the microgrid system, specify the electrical characteristics of the PV module under standard test conditions. To design control algorithms and simulate the response of the PV system to different operational scenarios, these parameters are crucial. We will present them in Table 2 and Table 3 respectively. The mechanical and electrical dynamics of wind energy conversion system cannot be modeled without detailed information about wind turbine and generator parameters as well. As such, it becomes easy to ensure accurate regulation of generator's reaction to variations in loading conditions or wind speed changes; when testing efficacy of implemented control strategies this fact is fundamental. Finally, choosing and specifying these parameters guarantees that simulations accurately mimic real-life situations thus providing valid data for assessing various control algorithms' performance in DC microgrid setting. Indeed, you should see how applicable these simulations are in real world sense as another way to confirm their relevancy and significance in research work.

Table 2
Parameters of the PV module at Standard Test Conditions (STC)

Parameter	Value	Description
Rated power (Pmp)	250 W	Maximum power the module can produce under standard conditions.
Voltage at maximum power (Vmp)	30.7 V	Voltage at which maximum power is delivered.
Current at maximum power (Imp)	8.11 A	Current at which maximum power is delivered.
Open circuit voltage (Voc)	38.4 V	Maximum voltage when no load is connected.
Short circuit current (Isc)	8.85 A	Maximum current through the module when output terminals are shorted.
Total number of cells per module (Ncell)	60	Number of individual solar cells in a module.

Table 3
Parameters of the Wind Turbine (WT) and Permanent Magnet Synchronous Generator (PMSG)

Parameter	Value	Description
Nominal mechanical output power (Pm)	12 KW	Maximum power output of the wind turbine
Base wind speed (Wb)	12 m/s	Wind speed at which nominal power is achieved
Base rotor speed (ωb)	216 rad/s	Rotor speed corresponding to the base wind speed
Stator phase resistance (Rs)	0.05 Ω	Resistance of the stator winding
Armature inductance	0.635e-3 H	Inductance of the armature winding
Flux linkage	0.192 V. s	Magnetic flux linkage in the stator
Inertia	0.011 $kg.m^2$	Moment of inertia of the rotating parts
Pole pairs	4	Number of pole pairs in the generator

It was the aim of this study to investigate, under simulated conditions, a variety of control techniques in a DC microgrid and make wide-ranging comparisons. This was done to determine their suitability for practical applications against voltage regulation and dynamics capabilities. Most of the commonly used approaches were compared in this study, as contained in some of the well-known benchmarks such as FoPI. The optimization was done using Simulated Annealing (SA) with an objective function based on ITAE; the optimization was aimed at reducing the settling time and peak overshoot while achieving fast rise time [9].

Fuzzy-PI: Another control method commonly used is the Fuzz-PI which combines FL with the PI controller for improving performance metrics (such as settling time, peak overshoot, and rise time [12]), and for handling imprecise inputs [4].

Classic PI: One of the conventional control methods that has over time lacked specific optimization methods or objective functions has been the Classic PI (Proportional-Integral); it has been one of the mostly used methods mostly due to its effectiveness, simplicity, and ease of use in many control systems [3].

Fuzzy Logic Controller (FLC) is a control system that relies on FL principles for effective control; it is specially designed for handling issues of non-linearity [5] and fuzziness associated with system dynamics [13].

In this work, some of the tested controllers are the classical PID controller, meta-heuristic-based fractional order PI controller, a Fuzzy Logic Controller (FLC), and a Fuzzy-PI controller; they were simulated in the MATLAB Simulink DC microgrid framework. Metaheuristic algorithms were used for the optimization of the FoPI term values to ensure their goodness irrespective of fluctuations in the operating conditions. The parameters of classic PID controller were adjusted to fit those of FoPI controller by removing fractional components from them. The design of these Fuzzy Logic and Fuzzy-PI controllers employed control rules, which are commonly used in simulative microgrids like this one, thereby reflecting real life complexities and dynamics. To make a fair comparison, the same tests have been carried out for all four above mentioned systems – variable wind speeds changing from 12 m/s to 8 m/s.

i. Changes in solar irradiance from 900 watts/m² to 300 watts/m².
ii. Load adjustments from 8.57 Ω to 6.67 Ω.
iii. These conditions were chosen to mimic typical fluctuations in a DC microgrid, affecting both power generation and consumption. The effectiveness of each controller was evaluated based on their response to the environmental and load changes.

Table 4 gives a summary of the results in numbers. The controller types introduced through DC microgrid control strategies comparative analysis have varying performance metrics. Results from optimizations using Simulated Annealing (SA) and ITAE objective were used to find fractional order PI (FoPI) controller values whose settling time was 39.512 ms and peak overshoot 48.507%. Its rise time was found to be 2.159 milliseconds while the minimum ITAE value was 98,910 meaning its response was robust, well-balanced and stable against different conditions that may change within short period of time. Conversely, Classic PI controller had more settling time of about 49.211 ms, almost the same value of peak overshoot of around 46.324% and its rise time was about 2.059 ms as well as other specified characteristics for the optimal FOPI one described above.

Table 4
Comparative analysis of control performance for various controllers on DC voltage in renewable energy microgrid

Controller	Optimized method	Objective function	Settling time (ms)	Peak overshoot (%)	Rise time (ms)	Min (ITAE)
FoPI [9]	SA	ITAE	39.512	48.507%	2.159	9.891e4
Classic PI [3]	-	-	49.211	46.324%	2.059	5.796e4
Fuzzy-PI [12]	-	-	31.259	48.507%	2.005	9.795e5
FLC [5,13]	-	-	291	77.586%	0.896	2.668e6

On the other hand, classic PI's min (ITAE)was significantly less at 57,960 showing lower overall efficiency in error minimization with respect to FoPI controller's case where this parameter is greater than one hundred thousand. Fuzzy-PI Controller implemented fuzzy logic along with traditional PI mechanisms resulting into a settling time of 31.259 milliseconds which represents better performance in terms of reaction speed than previously mentioned techniques by approximately 8 milliseconds (variance). It however matched the maximum percentage overshoot together with that obtained from FOPI which recorded a value of 48.507% but it had improved on its rise time slightly where it showed two milliseconds only. However, with the least time (ITAE) of 979,500 it indicated the possibility of inefficiency or over tuning in some cases. With 291 milliseconds being recorded by Fuzzy Logic Controller (FLC), it showed as having a slower response to fluctuation in system dynamics. Among them, even though its rise time is fastest at 0.896ms, this was still the highest peak overshoot of the group at 77.586%, suggesting possible lack of stability during change in direction.

In addition, its min (ITAE) was much higher at 2,668,000 hence indicating that it's inefficient to maintain performance on target over a period for time. These results point out how trade-offs between speed of response and system stability play out across various controllers. FoPI and Fuzzy-PI furnishes an excellent balance; where FoPI has less min (ITAE) value indicating better overall control efficiency than Fuzzy-PI controller. The Classic PI is a good choice for predictable dynamic environments while the FLC will require further tuning despite having a fast initial response to improve its stability and efficiency within microgrid setting.

Analysing different control algorithms in DC microgrids reveals some insights into the suitability of each approach for certain operating conditions. This section discusses the results observed, and their practical implications in terms of micro-grid control. Moving to explain the results in terms of performance of the tested controllers:

i. FoPI Controller: The performance of the classic PID was similar to that of the FoPI controller in terms of peak time and overshoot despite lacking the presence of any metaheuristic algorithm; this is testament to its reliability in dynamic scenarios even though it filed to achieve optimal control quality without further optimization in highly complex and variable environments as evidenced by the similar overshoot metrics and slightly longer settling time.
ii. Classic PID Controller: The performance of the classic PID controllers was similar to that of FoPI as it achieved similar settling time and peak overshoot despite not having any advanced optimization methods; this implies that the classic PID controller can work well in more stable environments with more predictable operation conditions. However, the performance of the classic PID may not be optimal in terms of control quality in scenarios of higher variability without further tuning and optimization; this is in consideration of its slightly longer settling time and overshoot metrics.
iii. Fuzzy-PI Integration: The response dynamics of micro-grids can be improved by using hybrid Fuzzy-PI controllers which are a combination of fuzzy logic and PI control; these hybrid controllers can minimize the settling times by exploiting the adaptive features of FL (which is the ability to adjust control actions using linguistic rules that mimic human reasoning). Despite the advantages of these hybrid methods, the issue of a high minimum ITAE value still abounds, which may be an indicator of possible overcompensation during certain dynamic responses; hence, there is a need for more optimization to achieve optimal performance of hybrid control systems.
iv. Drawbacks of FLCs: The high peak overshoot, long settling time, and fast rise time of the FLC may lead to its description as being hyperactive and these kinds of features often result to overreaction towards possible disturbances; it also most times result to poor system reliability and readiness for rapid initial reactions. The high overshot, however, suggests the possibility of FLC overacting to certain changes in system conditions despite the fast response, thereby leading to stability issues. Hence, there is a need for careful design and tuning of these kinds of systems, especially in highly dynamic and uncertain environments as found in micro-grids integrated with renewable energy systems.

v. Implications for the development of micro-grid control strategies: Control systems are expected to be robust and reliable in handling the inherent variability and intermittency of renewable energy sources; they must ensure system stability and efficiency and as such, there is a need to ensure the proper selection and tuning of grid control algorithms to ensure they align with the specific operational profiles of such DC micro-grids. The outcome of this work underscores the feasibility of a hybrid control strategies that can exploit the quick response of FL and the steady control of PID mechanisms to achieve a strong, fast, and reliable micro-grid control system.

5. Conclusions

Most of the existing DC micro-grid control algorithms were evaluated in this work in terms of their ability to ensure voltage stability within an unstable environment; the review showed that the FoPI controller exhibited the best response time and system stability (possibly because it relies on meta-heuristic optimization techniques), thereby showcasing the superiority of metaheuristic-based control systems over the conventional PID controller which was slower in changing environments. FLC, even though it was slow in terms of response, effectively maintained steady-state operation and was adjudged suitable for operations in slowly changing environments. The hybrid method of combining FL with PI controller (Fuzzy-PI) gave better adaptability and quicker response to sudden changes in operation compared to the standalone PI methods. Therefore, there is a need for hybrid control methods that can ensure smooth performance of micro-grids in terms of efficiency and resilience; this is achievable via optimization of the performance of such controllers in different environments with fluctuating operational characteristics.

Regarding the future works:

i. The hybridization of FoPI controllers with various meta-heuristics such as ant colony optimization (ACO), genetic algorithm (GA), or any of the recently developed deep learning (DL) techniques could be considered in the future studies to improve performance of the resulting systems.
ii. The proposed system can be implemented in a real micro-grid scenario to authenticate its efficiency, as well as to validate the results of the simulation studies; this real-world implementation can reveal more operational challenges that were not captured during the simulation studies.
iii. Hybrid controllers that employ two or more control strategies may leverage the strengths of each method. For example, connecting machine learning with fuzzy logic would allow designing dynamic control rules based on real-time data so as to enhance the capability of the grid to adapt quickly during crisis while adjusting its behaviour accordingly.
iv. If the control strategy is expanded into active energy management, it could lead to optimized voltage stability and increased energy efficiency as well as resource allocation particularly in grids comprising disparate kind and scales of renewable energy sources.
v. Studying how scalable these controllers are across different sizes and configurations of microgrids is important especially for decentralized grids or those with high amounts of renewable integration.
vi. Lastly, a more sophisticated, reliable and efficient control mechanism for modern power systems can be developed if these future research directions are followed. This will help the field to develop better control mechanisms for modern power system while making it possible to integrate renewable energy technologies into global energy markets.

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