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Automatic Load Frequency Control in Isolated Micro-Grid for Remote Area Power Generation

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Abstract

This study focuses on utilising an Automatic Load Frequency Controller (ALFC) within an isolated microgrid to improve the transient response of frequency variations. Addressing the persistent issue of energy shortages requires the expanded deployment of Distributed Generation (DG) systems through the further increased integration of renewable energy sources. A microgrid is a DG that can operate in isolated and grid-connected modes to maximise the benefits of renewable energy. Isolation of the microgrid prevents faults from affecting the microgrid and ensures operational safety. Additionally, intentional islanding is a viable solution for remote area power systems. The extensive integration of renewable energy within microgrids often introduces challenges such as frequency deviations, making frequency stability a critical factor for effective microgrid operation. This research involves modelling an isolated microgrid system that incorporates wind energy, solar energy, a diesel engine generator power generation, a battery energy storage system and biomass energy. The traditional ZN-tuned Proportional-Integral-Derivative (PID) controller is employed to enhance frequency stability. The effectiveness of the ALFC for isolated microgrids is analysed through MATLAB/Simulink simulations under sudden load variations and changes in system inertia. The outcomes of the study are further validated in real-time using an RT simulator, demonstrating the practical application and reliability of the proposed approach.

Keywords: ALFC, Frequency Deviation, Isolated Micro-Grid System, PID Controller, RT Simulator

1. Introduction

Modern electric power systems face significant challenges, including the growing demand for electricity, load constraints during peak periods, power quality issues, transmission and distribution losses, and environmental concerns such as CO_2 emissions. These challenges have paved the way for the adoption of DG systems to address the increasing energy demands. A "Microgrid" (MG) represents a transformative enhancement to traditional power networks, introducing new complexities in integrating renewable and non-renewable Distributed Energy Resources (DERs) into the existing grid infrastructure. A microgrid consists of a network of distributed energy resources and interconnected loads operating within defined electrical boundaries. It can function as a single, controllable entity and seamlessly switch between grid-connected and islanded modes. Expanding the number of autonomous microgrids and interconnecting them has emerged as an effective strategy to enhance the reliability and resilience of power networks. This approach redefines the role of distributed generation by treating isolated microgrids as self-contained power system cells. These cells, for instance, can be managed as single dispatchable loads capable of responding to grid disturbances within seconds. Isolated microgrids are particularly advantageous for remote power generation, where delivering electricity to distant areas poses logistical and financial challenges. The complexities of isolated microgrids are compounded by the integration of renewable energy sources, variability in generation, high transmission costs, environmental changes, and system parameters affecting frequency stability. Ensuring frequency stability is critical for the secure and efficient operation of electric power systems.

To address the issue of frequency deviations in isolated microgrids, ALFC plays a pivotal role. ALFC helps maintain

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the balance between power supply and demand, ensuring frequency variations remain within acceptable limits. To enhance frequency stability, effective and reliable control strategies are essential[1,2]. Over time, researchers have developed numerous conventional control methods to stabilise power and frequency in microgrids. However, traditional controllers often struggle with slow gain estimation, prompting the use of advanced optimisation techniques to improve their performance. Robust control strategies, while effective, involve complex mathematical formulations that can be challenging to implement instantaneously. Nonetheless, optimisation techniques have proven instrumental in minimising frequency deviations and enhancing the overall stability of isolated microgrid systems.

The primary objectives of this project, as outlined in the reviewed research studies, are as follows:

(a) To design and simulate a PID controller for ALFC to optimise the performance of an isolated microgrid system.

(b) To evaluate the effectiveness of the proposed control strategy through steady-state error sensitivity analysis by examining the impact of varying system load, inertia constants, and performance indices on the overall system dynamics.

This study is divided into five sections. Section 1 introduces the research and sets the context for the work. Section 2 presents a comprehensive literature review, discussing microgrids and their diverse functionalities. The findings from various studies are analysed to extract critical insights relevant to this research. Section 3 provides a detailed explanation of the system under study. The simulation of ALFC for an isolated microgrid, aimed at enhancing transient performance and mitigating frequency deviations, is conducted using MATLAB/Simulink. Section 4 showcases and interprets a variety of simulation results, offering a thorough analysis. Finally, Section 5 concludes the study, summarizing the key findings and implications of the work.

2. Microgrid Controls

A microgrid is a complex network designed to distribute electricity by integrating multiple energy sources with precisely coordinated components. Variations in power generation and interactions among these elements may cause occasional disruptions in power quality for end-users[3,4]. To mitigate these challenges, it is vital to develop specialized control mechanisms tailored to the specific demands of the system. Such adaptive strategies enable the microgrid to respond efficiently to fluctuating conditions, maintain operational stability, and achieve performance objectives with improved reliability and precision.

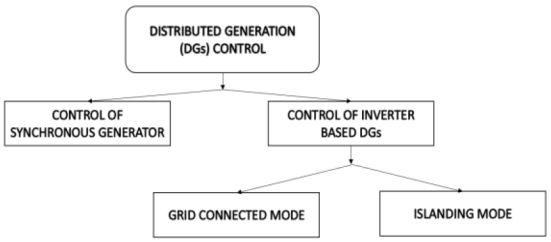


Figure 1. Classification of DGS control of microgrid.

Most systems rely on control methods focused on managing output current and frequency to integrate Distributed Energy Resources (DER) with the utility grid. A common approach involves using current regulations to control the active and reactive power exchanged with the utility. Additional strategies for current control include operating inverters in master/slave configurations, indirect voltage regulation, and implementing voltage and frequency droop controls. Initially, real and reactive power control strategies were utilized, where adjustments in reactive power influenced active power and vice versa. However, as reactive power does not contribute to useful energy in power systems, minimizing reactive power is generally preferred. For systems with non-linear loads, voltage and frequency droop control methods present challenges in regulating output effectively. These methods cannot achieve zero steady-state error and often result in minor output inaccuracies. Droop control is particularly limited in managing harmonic distribution between phases under non-linear load conditions. Furthermore, line impedance significantly affects reactive power in three-phase systems, complicating the application of droop control. While droop control excels in load-sharing management across multiple converters, it is less effective for systems with topological changes, such as intentional islanding, especially when both linear and non-linear loads are present[5,6].

Hybrid systems aim to address the shortcomings of traditional droop control by combining elements of master/slave and droop methodologies. However, these hybrid approaches also struggle in scenarios involving topological changes and operational mode transitions. A

more effective solution for systems integrating DER with utility grids and supporting intentional islanding involves utilizing current injection techniques paired with direct regulation of system states—controlling voltage in islanding mode[7,8].

The control approach discussed in this study is applied to microgrids powered by single AC generators or gas turbines. In such systems, the energy supplied to the prime mover is adjusted to respond to variations in load demand. These changes in load would otherwise result in fluctuations in the generator's speed. By regulating the energy input to the prime mover, the control method ensures that the speed of the generator remains stable, maintaining reliable operation and consistent power output within the microgrid.

3. Designing of Isolated Microgrid System

The isolated microgrid system analyzed in this research is structured using established models from existing literature. It encompasses multiple components, including a diesel engine generator (DEG), a battery energy storage system (BESS), solar power generation (SPG), Biomass Power Generation (BPG), and wind power generation (WPG)[9,10]. Comprehensive models for SPG and WPG are detailed in references[11-17], which offer valuable insights into their functionality and integration within the microgrid framework. These references form a foundation for understanding the dynamics and interactions of renewable energy sources within the system.

Table 1. Microgrid parameter

S. No.	Parameters	Value assigned
1	Rated Capacity	0.6MW
2	G_{Pp1}	12OHz/p.u.MW
3	t_{Pp1}	0.09s
4	B_{11}	0.425p.u.MW/Hz
5	R_{11}	2.361Hz/p.u.MW
6	D_{11}	$8.333*10^{-3}$

3.1 Diesel Engine Generator Transfer Function

A DEG integrates a diesel engine with an electric generator to produce electrical energy, functioning as a reliable non-renewable power source. It is commonly employed in isolated microgrid systems to ensure a consistent and dependable electricity supply. The DEG plays a crucial role in compensating for power imbalances caused by the variability of renewable energy sources such as solar and wind[18,19]. By using a speed governor control mechanism, the system adjusts the fuel input to the engine, enabling it to maintain steady generator performance and system stability. For analytical and simulation purposes, the dynamics of the DEG are often represented as a first-order transfer function model, which simplifies its operational characteristics. The DEG unit in this study has a generation capacity of 0.3 MW, emphasizing its effectiveness in supporting the operational needs of microgrid systems[20,21].

$$G_{DEG1}(s) = \frac{G_{D1}}{1+st_{D1}} * \frac{G_{DEG1}}{1+st_{DEG1}} \quad (1)$$

where, $G_{DEG1} = 1, G_{D1} = 1$ and $t_{DEG1} = 2\ s$, $t_D = 20\ s$ are the gain and time constants.

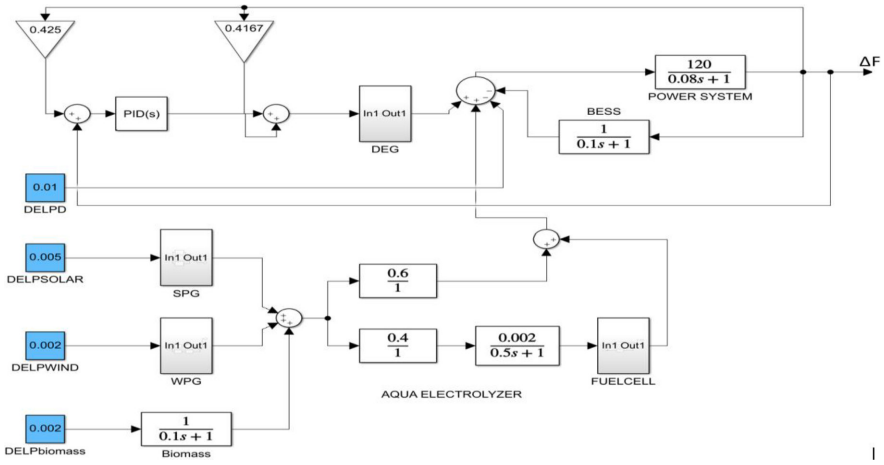


Figure 2. Simulation block of an isolated microgrid system.

3.2 Wind Power Generation Transfer Function

In isolated microgrids, wind energy is harnessed through wind turbines to generate electricity. The behaviour of the system is often modelled using a transfer function, which characterizes the relationship between the wind speed and the power output of the turbine. This model helps to analyze how variations in wind speed impact electricity generation and how the system adjusts to these changes. For a wind power system to function effectively in an isolated microgrid, it must accommodate fluctuations in wind patterns while ensuring the generated power is seamlessly integrated into the grid. By studying and refining this transfer function, it becomes possible to optimize the performance of the wind power system, allowing it to complement other energy sources within the microgrid and ensuring an uninterrupted and stable energy supply[22]. The Wind Power Generation (WPG) system in this study has a capacity of 0.09 megawatts, with three wind turbine units being considered as part of the multi-microgrid setup.

$$G_{WPG1}(s) = \frac{G_{WPG1}}{1 + st_{WPG1}} \tag{2}$$

where, gain and time constants are $G_{WPG1} = 1$, $t_{WPG1} = 1.5s$

3.3 Solar Power Generation Transfer Function

In isolated microgrids, solar energy generation is essential for harnessing renewable power by converting sunlight into electricity using Photovoltaic (PV) panels. The system's behaviour can be described using a transfer function that models the connection between solar radiation levels and the generated electrical output. This transfer function enables the prediction of how variations in solar irradiance influence the power produced by the panels and how the system responds to these changes. For isolated microgrids, it is crucial for the solar generation system to adjust to fluctuations in sunlight while ensuring that the produced electricity is effectively integrated into the microgrid's network. By refining this transfer function, the solar power system can be optimized to maintain consistent operation, complementing other energy sources within the microgrid, and ensuring uninterrupted and reliable electricity supply[23]. The Solar Power Generation (SPG) plant in this study has a capacity of 0.085 megawatts. This research models a microgrid system that incorporates two solar power generating units.

$$G_{SPG1}(s) = \frac{G_{S1}}{1 + st_{S1}} * \frac{G_{T1}}{1 + st_{T1}} \tag{3}$$

where, $G_{S1} = 1.8$, $G_{T1} = 0.3$ are the gain constants and $t_{S1} = 1s$, $t_{T1} = 1s$ are time constants.

3.4 Biomass Power Generation Transfer Function

Biomass power generation plays a key role in providing sustainable energy by converting organic materials, such as agricultural waste or plant matter, into electricity through methods like combustion or biogas production. The behaviour of this power generation system is often represented by a transfer function, which models how inputs—like the biomass feed rate or the amount of organic matter—affect the electrical output. This mathematical relationship helps predict how variations in fuel supply or combustion effectiveness influence the produced power and how the system adapts to these fluctuations. In isolated microgrids, the biomass-based generation system must ensure consistent output, despite the challenges posed by changes in fuel quality or availability. The transfer function considers critical factors such as fuel efficiency, thermal response time, and the control systems in place to manage the energy conversion process. In this study, the Biomass Power Generation (BPG) system has a capacity of 0.03 megawatts.

$$G_{BPG1}(s) = \frac{G_{BPG1}}{1 + st_{BPG1}} \tag{4}$$

where, $G_{BPG1} = 1$ and $t_{BPG1} = 1s$ are gain and time constants.

3.5 Battery Energy Storage System and Flywheel Energy Storage System Transfer Function

A Battery Energy Storage System (BESS) is essential for stabilizing isolated microgrids by storing surplus energy when generation exceeds demand and discharging it during high demand periods. The operation of a BESS is often modeled using a transfer function, which outlines how the rate of charge and discharge impacts the system's power output and its ability to adapt to fluctuations in power supply and demand[24]. This mathematical model

establishes the connection between input factors, such as the battery's charge state or the energy input/output, and the resulting electrical output. In microgrids, particularly those operating in isolation, it is vital for the BESS to effectively manage variations in power generation and consumption, ensuring that sufficient energy is available when needed.

In contrast, Flywheel Energy Storage Systems (FESS) use an electric motor to spin the flywheel at high speeds, storing energy in its rotational motion. Operating in a high-vacuum environment, FESS boasts high cycle efficiency, typically between 85% and 95%, and has minimal friction losses, along with low maintenance needs. The BESS in this case has a capacity of 0.025 megawatts.

$$G_{BESS1}(s) = \frac{G_{BESS1}}{1 + st_{BESS1}} \tag{5}$$

$$G_{FESS1}(s) = \frac{G_{FESS1}}{1 + st_{FESS1}} \tag{6}$$

where, $G_{BESS1} = 1, G_{FESS1} = 1$ are gain constant and $t_{BESSS1} = 0.1\ s$, $t_{FESS1} = 0.1\ s$ are time constant.

3.6 Fuel Cells and Aqua Electrolyzers Transfer Function

Fuel Cells (FC) and Aqua Electrolyzers (AE) are essential components in advanced energy systems, particularly in isolated microgrids, where they contribute to efficient energy storage and power generation. A fuel cell generates electricity by converting hydrogen through an electrochemical reaction, producing water and heat as byproducts, making it a clean and sustainable energy source. It ensures a consistent power supply during periods when renewable energy generation is insufficient. Aqua electrolyzers complement fuel cells by producing hydrogen through the electrolysis of water, utilizing excess energy from renewable sources[25,26]. This process enables energy storage during periods of surplus generation, which can later be utilized to meet demand during low production intervals. Together, fuel cells and electrolyzers form an integrated hydrogen-based energy storage and generation system. This system balances energy supply and demand, supporting the stability of isolated microgrids. By fine-tuning the operational parameters of these components, the microgrid can achieve enhanced energy efficiency, improved response to fluctuations, and reliable integration with other renewable energy sources.

$$G_{AE1}(s) = \frac{G_{AE1}}{1 + st_{AE1}} \tag{7}$$

$$G_{FC1}(s) = \frac{G_{FC1}}{1 + st_{FC1}} \tag{8}$$

where, $G_{AE1} = 0.002, G_{FC1} = 0.002$, are the gain constants and $t_{AE1} = 0.5\ s, t_{FC1} = 4\ s$ are the time constants

3.7 Dynamic Controller Transfer Function

A dynamic PID controller, when configured using a systematic tuning approach like the Ziegler-Nichols method, offers robust and adaptable control for systems experiencing changing conditions. This method determines the optimal proportional, integral, and derivative gains by analyzing the system's response to controlled adjustments[27,28]. Initially, the integral and derivative actions are deactivated, and the proportional gain is increased until the system reaches a state of consistent oscillation. From this critical point, the tuning parameters are calculated to enhance the controller's performance. This adaptability makes them ideal for applications such as microgrids or industrial automation, where stability and precision are vital despite fluctuating inputs. By employing a Ziegler-Nichols tuned dynamic PID controller, systems can achieve faster response times, reduced errors, and improved overall reliability in dynamic and complex operational scenarios. In this context, r(t) represents the reference or set point for the microgrid system, y(t) is the system's actual output, and u(t) denotes the final output produced by the controller[29,30].

$$u_1(t) = G_{p1}e(t) + G_{i1}\int e_1(t)dt + G_{d1}\frac{de(t)}{dt} \tag{9}$$

where, G_{p1}, G_{i1} and G_{d1} are the gains of the PID controller. $e_1(t)$ is the controller error input,

$$e_1(t) = r_1(t) - y_1(t) \tag{10}$$

Reducing IAE_1, $ITAE_1$, ISE_1, and $ITSE_1$ is the main objective of fine-tuning a PID controller's settings. This is defined as:

$$Min\left(IAE_1 + ITAE_1 + ISE_1 + ITSE_1\right) \tag{12}$$

4. Results and Discussions

In the simulation studies, a microgrid system is utilized to demonstrate the effectiveness of the PID controller. The performance of the PID controller is evaluated through

the operation of the microgrid under various scenarios, showcasing its robustness and adaptability in handling different conditions. These cases highlight the controller's ability to maintain system stability and efficiently manage power distribution across the microgrid.

4.1 Simulation Results

Case 1: In this case of isolated microgrid, a 10% increase in step load demand leads to a notable shift in system dynamics, particularly in the frequency response. The transient behaviour of the system is observed and analyzed to evaluate its ability to manage such load changes. The frequency response, as illustrated in Figure 3, highlights the system's capability to adapt to the increased load by minimizing the time required for frequency stabilization. Enhancing the settling time of frequency fluctuations significantly improves the overall system performance. Summarized performance metrices are presented in Table 2, reflecting the system's efficiency in maintaining stability and reliability under changing load conditions.

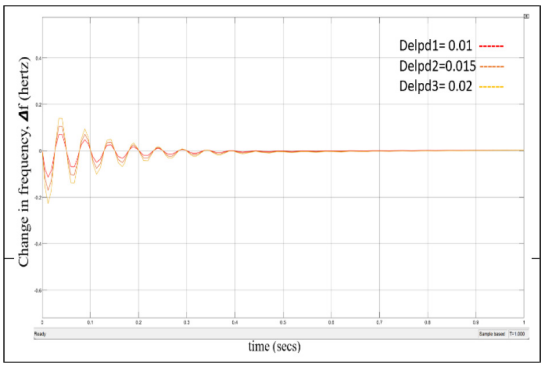


Figure 3. Isolated microgrid frequency deviation under load variation.

Table 2. Performance metrices of frequency deviation

S. No.	Sensitivity analysis indices	Δf
1	Settling time (s)	8.2828
2	CE_1	0.001651
3	IAE_1	0.01978
4	$ITAE_1$	0.03606
5	ISE_1 ($X10^{-5}$)	4.479
6	$ITSE_1$($X10^{-5}$)	8.493

Case 2: In this case of isolated microgrid, A sensitivity analysis of steady-state error was performed to assess whether the PID controller's tuning parameters were appropriate for real-time operation. In this study, the isolated microgrid system's performance was examined by adjusting key parameters, such as the inertia constant, from their default settings. The system's inertia was modified by 10% both above (H = 4.5) and below (H = 3.5) its initial value of H = 4. These frequency changes, resulting from the modifications in inertia, are represented in Figure 4, highlighting the controller's effectiveness in maintaining system stability and minimizing frequency deviations even under varying operational scenarios.

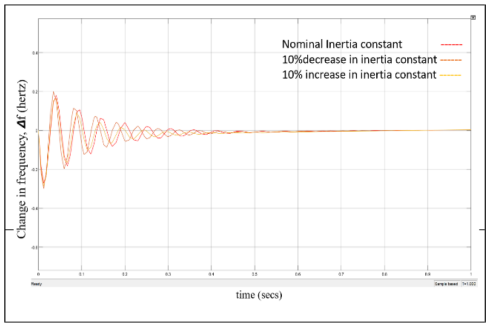


Figure 4. Isolated microgrid frequency deviation under inertia variation.

4.2 Experimental Results

The ZN-PID controller is evaluated using Software-In-Loop (SIL) simulation. This is accomplished through the integration of RT-LAB, OPAL-RT software, and MATLAB Simulink, enabling seamless interaction between the simulation models and the actual system environment. RT-LAB offers a flexible platform, delivering robust solutions for a wide range of power system applications. In this study, the OPAL-RT OP4510 simulator is used to verify the effectiveness of the Automatic Load Frequency Control (ALFC) in an isolated microgrid, with the results related to frequency deviations presented in Figure 5.

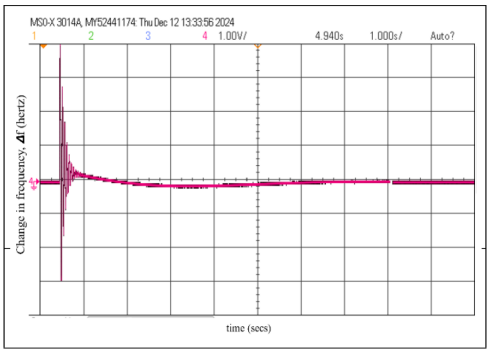


Figure 5. Response of isolated microgrid frequency deviation for sudden disturbances.

5. Conclusion

This study investigates the performance of a Ziegler-Nichols (ZN)-tuned PID controller applied to the ALFC of an isolated microgrid system, incorporating energy storage and renewable energy sources, alongside microgrid operation management. Based on the data gathered, the ZN-PID controller effectively reduces load fluctuations and mitigates system uncertainties, leading to improvements in performance metrics such as IAE1, ITAE1, ISE1, and ITSE1 for frequency stability. The findings highlight that the tailored controller gains successfully address the system's uncertainties, optimizing its operation. The results are validated using the RT simulator, ensuring the accuracy and reliability of the simulation outcomes in real-time conditions.

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