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Optimized PID Based Load Frequency Control of a Hybrid Microgrid

S. M. Aminu[1*], Y. Jibrl[2], A. Abdulkarim[3], A. S. Abubakar[4]
[1234]Department of Electrical Engineering, Ahmadu Bello University, Zaria – Nigeria.
[3]Department of Electrical Engineering, KIU, Kampala – Uganda.
(*Corresponding author email:amshehu12@gmail.com*)

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ABSTRACT

This research presents the development of an optimized PID based load frequency control of a hybrid microgrid. The micro-grid (MG) concept allows the renewable energy sources to operate in both synchronized grid and islanded/stand-alone mode. These modes of operations of the MG have made it smart, hence require intelligent coordinated control strategies. The existing control strategies of the MG system is associated with one-point failure problem due to loss in communication, imbalance in frequencies and voltages of the loads on the distributed generators. The PID controller was used for the decentralized system. The PID was tuned using genetic algorithm (GA). The performance criteria used for the tuned GAPID based on the transient and steady state parameters are ISE, ITSE, IAE, ITAE on the system. From the simulation, the ITAE criteria performed better having values of 1.4332 sec for the GA tuned PID, in terms of settling time while for the second scenario IAE criteria performed better for the GA tuned PID, with settling time values of 1.4491 sec. This is in order to achieve a stabilized and robust micro-grid network system.

1. INTRODUCTION

MG can be said to be a cluster of distributed generators (DG), energy storage system (ESS) and other related equipment in the system which can operate both in isolated (island mode) or grid connected (Nguyen et al., 2017) mode [12]. These sources are located at distribution level of the network while they produce an influence on the sustainability, security of the system while adding more stress on the distribution grid (Almasalma *et al*., 2017) [2].

The recent use of RES and DGs penetration in multiple numbers has given rise to the microgrid concept. The basic issue in microgrid control depends on its stability, bidirectional load flow, and the stochastic nature of most of the RES (Arora *et al*., 2024) [3]. Other disturbances which need to be handled in order to have a robust microgrid control are different topology, parametric and communication uncertainties, nonlinear loads and nonlinearities as a result of nonlinear dynamics of the DGs/RES. With the rapid growth of DG technologies, there are two variants of the DG system with a significant presence in the network; which are the renewable energy sources (RES) and combined heat and power (CHP) facilities. The RES system has an environmentally friendly characteristics, and also the CHP has an advantage of easily programmable and high efficiency. Also, both the DG and CHP can be dispatched due to their electrical and thermal functionalities, and based on their demands. However, both RES and CHP have some advantages, the DG have some disadvantages from the control perspective which limits their integration into the microgrid.

Sedhom *et al*., (2020) [16] present based H-Infinity harmony search control in order to improve conventional droop control method. The microgrid power is regulated while maintaining both the voltage and frequency regulations. Simulations results have shown the superiority of the system over other controller. Eydi and Ghazi (2022) [7] proposed a novel communication link-less control method for hybridized microgrid control technique.

The system was developed in order to address the problem of power sharing, battery state of charge (SOC), Frequency and voltage stability. It's can be integrated in a multi sub-grid micro grid due to its ability to encourage expandability and modularity in order to improve various DC buses voltages and different frequencies. Simulation was done in MATLAB/Simulink environment, and the results showed that the system is stable in terms of analysis of small signal and nonlinear model as well as to maintain frequency and voltage deviation, SOC batteries balancing and dispatch power appropriately to a satisfactory level. Lee *et al*., (2022) [10] develop a Generic Microgrid Controller which provides a self-healing capability in order to improve microgrid resilience and reliability during islanding so as to serve critical loads. The system is provided with recent redundances that comprises redundant lines and new switch yards. The self-healing includes service restoration, fault location and isolation, controller Computational limits and time constraints were dealt with through the expert system implementation. The system has a simple and practical application. However, the approach is cost effective. Onaolapo *et al.*, (2023) [13] proposed a communication-based controller in order to maintain current and voltage at reference level, power sharing and stability. The drawback of conventional droop control of power sharing, current control, voltage regulation has been addressed by this method and the robustness of the system has been shown by the real time simulation through different operating conditions to obtain the control objectives. Toularoud *et al*., (2023) [18] developed a multi-layer interactive controller to improve the performance of the MGs based distributed energy resources (DERs). The developed controller ensured the stability, reliability and efficiency of the active/reactive power and voltage/frequency of the MGs. The first layer, which is the voltage/frequency layer, an internal voltage and current controller was combined in the power droop controller (PDC) to stabilize the MG from load oscillations quickly. The second layer, which is the secondary layer was based on distributed finite-time control (DFTC) was implemented on the MG in order to modify and restore the control system. Sahu *et al*., (2023) [15] conducted research to implement a grade-2 fuzzy cascaded (G2-FCC) controller to stabilizes a hybrid system consisting high uncertainty in regards to frequency and stability. The system is equipped with energy storage device and battery energy management as well, in order to improve frequency profile. The approach has shown that G2-FCC and A-DQN (advanced deep-Q network) algorithm are very effective in terms of parameter optimal design and settling time respectively. Khan and Aamir (2023) [9] design a consensus based distributed controller in order for the DG units to be able to regulate their power and frequency while maintaining phase angle and voltage magnitude variation. A back propagation based proportional integral controller was used to make the fixed gain parameters of the secondary controller to be flexible. Additionally, steepest descent based fuzzy logic controller and fuzzy proportional integral controller was use to provide seamless synchronization and signals compensation correction. Simulation results show effectiveness of the system under different setups. Tabassum *et al*., (2024) [17] developed an integrated technique for islanded microgrid using model-based and model-free methods. A two-tied technique which involve artificial intelligent data driven strategies were used for the control of the MG. The MG considered in the article is a combination of an AC load, two electric vehicles (EVs), and a diesel generator. Distributed management system (DMS) was used for supervision of the MG. Support vector machine (SVM) classifier was used when identifying false data injection (FDI) attacks on the MG system. The performance criteria used was integral of time absolute error (ITAE), integral of squared error (ISE) and integral of absolute error (IAE) which will also be the evaluation criteria of this paper. The simulation results showed satisfactory results, with a high accuracy rate.

The article is structured as follows; section one presents the introduction, while section two gives the methodology used for the development of the article. section three presents the results and discussion. The conclusion is given in section four and finally, the references is listed.

2.0 METHODOLOGY

The increase evolution of the RES and DGs penetration in multiple numbers give rise to the concept of micro-grid. The basic challenges in micro-grid control lies on stability, bidirectional load flow, low inertia and stochastic nature of most of the RES (Bhadu *et al.,* 2017) [5]. Other disturbances that need to be handled in order to have robust performance by the micro-grid includes nonlinear loads, nonlinearities as a result of nonlinear dynamics of the DGs/ RES, different topology, parametric and communication uncertainty (Baghaee *et al*., 2017) [4]. The challenges in environmental pollution due to the use of fossil fuel has led to the development of these new energy resources, which serve as an alternative to conventional energy sources for being clean and environmentally friendly (Alfergani & Khalil, 2017) [1]. Concentration has now turn to renewable energy source (RES). In order to address the challenges of rise in energy demand, increase in price of conventional energy sources and the harmful effect in respect to environment (Alfergani & Khalil, 2017) [1]. Wind turbines, photovoltaic panels, diesel generators and fuel cells are categorized under distributed or Renewable energy source technology. These technologies devise a means of arranging DC/AC inverters in parallel for both high load capacity and load sharing in order to form a network. This structure is what is known as Micro grid (MG) (Alfergani & Khalil, 2017) [1], which is shown in Figure 1. The named MG sources was used in this article. The wind turbine was adopted from [21], for the PV model and fuel cells. they were adopted from [24], and the energy storage system from [23].

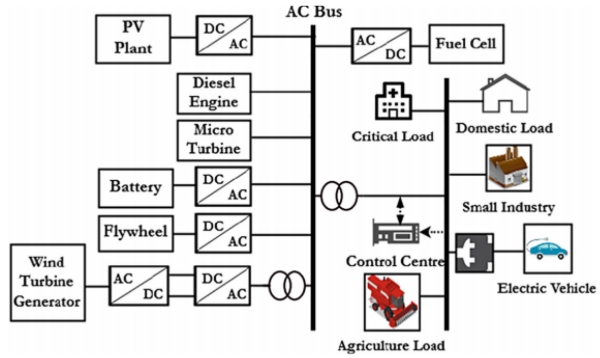

Figure 1: Microgrid Structure [25]

2.2 PID Controller Design

The PID controller was developed to minimize the frequency deviation of the hybrid microgrid system

modelled in equations (1 – 5). The PID controller was designed in Simulink based on:

$$U_{PID} = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

Where U_PID is the controller manipulated variable that act on the hybrid microgrid system based on the generated error e(t) and Kp, Ki, and Kd are the proportional, integral, and derivative gains. The values of these controller gains determine the controller's performance and can be obtained using several tuning methods. Commonly used values are obtained based on the following error criteria, as shown in Figure 2.

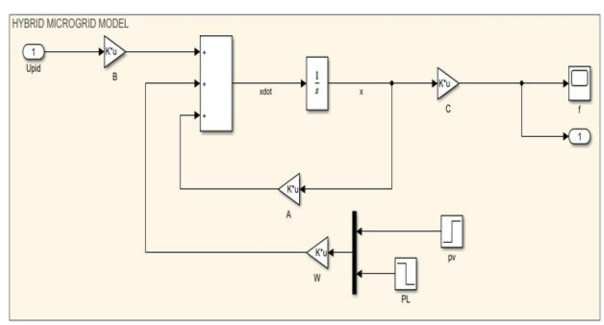

Figure 2: Hybrid Microgrid Model

$$\left.\begin{aligned} J_{IAE} &= \int_0^t (|\Delta f| + |\Delta P_{tie}|)dt \\ J_{ITAE} &= \int_0^t t(|\Delta f| + |\Delta P_{tie}|)dt \\ J_{ISE} &= \int_0^t (\Delta f^2 + \Delta P_{tie}{}^2)dt \\ J_{ITSE} &= \int_0^t t(\Delta f^2 + \Delta P_{tie}{}^2)dt \end{aligned}\right\} \quad (2)$$

Where IAE, ITAE, ISE, ITSE are the integral absolute error, integral time absolute error, integral square error, and integral time square error. $J_{IAE}, J_{ITAE}, J_{ISE}$, and J_{ITSE} are the objective function based on the error criteria (IAE, ITAE, ISE, ITSE). Δf is the frequency deviation defined as:

$$\Delta f = f_{desired} - f_{actual} \quad (3)$$

$$U_{PID} = K_p(f_{desired} - f_{actual}) + K_i \int_0^t (f_{desired} - f_{actual})\, dt + K_d(\dot{f}_{desired} - \dot{f}_{actual}) \quad (4)$$

$$\left.\begin{aligned} &\min J \\ &subject: \\ &K_p^{min} \le K_p \le K_p^{max} \\ &K_i^{min} \le K_i \le K_i^{max} \\ &K_d^{min} \le K_d \le K_d^{max} \end{aligned}\right\} \quad (5)$$

Equations (3) was modelled in Simulink as shown in Figure 3.

2.3 Genetics Algorithm

The GA is one of the metaheuristic algorithms which has the capability of solving a wide range of optimization problems. Its modelled based on natural selection, evaluation and genetic [22]. A number of modifications are been carried out to suite various both linear and nonlinear problems this is shown in Figure 3.

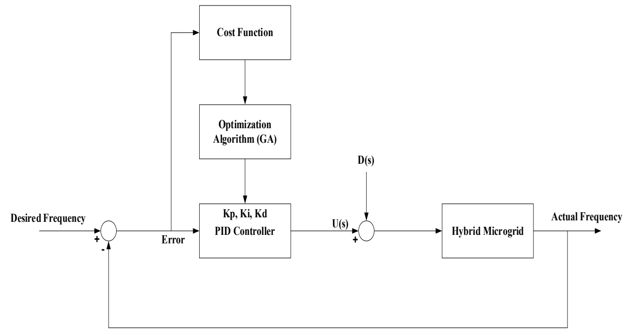

Figure 3: The Tunning process of parameters of the PID

When hybridize there are some superior characteristics ranging from ranking, selection, crossover and mutation. It has the ability of parallel, manipulating modern computing resources to improve performance and effectiveness. Genetic Algorithms are powerful tools for optimization problems, especially in complex and dynamic environments. However, challenges such as computational cost, parameter tuning, and the potential for suboptimal solutions. Their efficiency frequently depends on the specific application and individual in designing and implementing the algorithm.

3.0 RESULT AND DISCUSSION

The result obtained from the objectives are discuss in this section

4.1 System Response of the Dynamic Model of the Hybrid Microgrid

The open loop response of the system was generated to understand the system characteristics and the stability analysis was done using a bode plot. The results are respectively presented in Figures 4 and 5.

From Figure 3, it can be seen that the system response does not follow that of an underdamped system and the frequency deviation is not within the acceptable range.

From Figure 4, it can be seen that the system is not stable which also confirmed the system is not operational as reported in the system specifications.

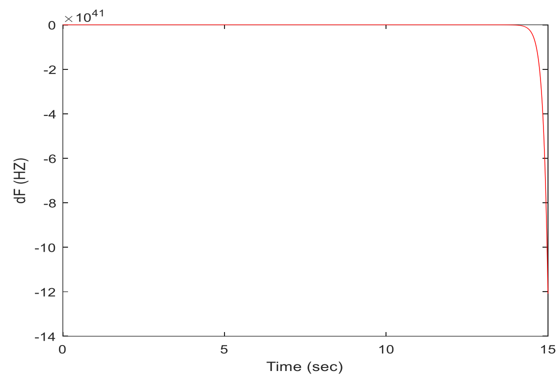

Figure 4: Transient Response of the System of a normal operational system.

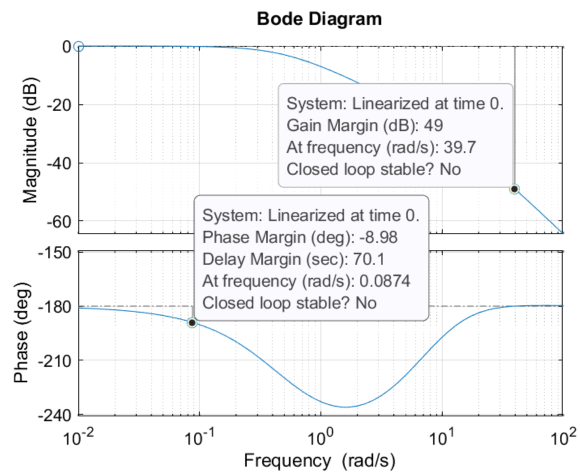

Figure 5: Stability Analysis of the System

The summarized data obtained for the system is shown in Table 1.

Table 1: Transient Parameters of the System without Controller

Transient Parameters					Steady State Analysis	
Rise Time (s)	Settling Time (s)	Overshoot (%)	Undershoot (%)	Peak (Hz)	Frequency Deviation (Hz)	System Stability
0.3178	14.9971	0	0	1.2089e+42	1.2089e+42	Unstable

3.1 PID Controller Tuning

The simulation parameters used for the simulation of the GA-PID is given in Table 2.

Table 2: GA Simulation Parameters

S/N	**Parameters**	**Value**
1	Population Size	50
2	Number of Variables	3
3	Maximum Iterations	1000
4	[alpha, beta, gamma]	[0.5 0.2 1]
8	Lower Boundary	[0 0 0]
9	Upper Boundary	[200 200 200]
10	Crossover Function	Adaptive Feasible
11	Mutation Function	Arithmetic

Also, the aims of the optimized PID controllers applied to Area I (called GA-PID Controller) as recorded based on the four performance measures (ISE, ITSE, IAE, and ITAE), are presented in Table 3.

Table 3: Optimized PID Controller Gains for Area I

Error Criteria	GA-PID Controller		
	K_p	K_i	K_d
ISE	99.9775	8.2644	9.9798
ITSE	99.8966	46.0839	97.9722
IAE	99.9970	22.5048	59.7083
ITAE	99.9694	25.0431	13.6198

The transient response of the hybrid microgrid control system in Area I with the application of the GA-PID controllers is shown in Figures 6:

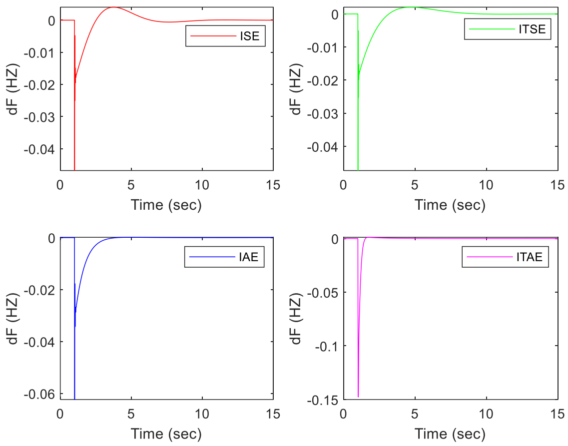

Figure 6: Area I Transient Response for GA-PID Controller

Figure 3 presents the ISE (Top-Left), ITSE (Top-Right), IAE (Bottom-Left), and ITAE (Bottom-Right) response with the desired frequency deviation of zero Hz.

It can be seen from the figure that the system attained the desired frequency deviation based on the ISE, ITSE, IAE, and ITAE performance measures with different transient properties. To evaluate the performance of the designed controllers, the transient parameters and the steady state error obtained for the hybrid MG control system based on the four error criteria are recorded in Table 3.

Table 3: Area I Transient Parameters and the Steady State Error for GA-PID Controller

The results in Table 3 show that the ITAE-based controller generates a better realistic transient response than the other three controllers for frequency deviation control. Thus, the ITAE-based GA-PID controller was selected for the frequency deviation control. The results in Table 4 show that the ITAE-based controller generates a better realistic transient response than the other three controllers for frequency deviation

Table 4: Area I Transient Parameters and the Steady State Error for GA-PID Controller

Error Criteria	Rise Time (s)	Settling Time (s)	Overshoot (%)	Undershoot (%)	Peak (Hz)	Steady State Error
ISE	8.2621	5.7006	4.7702	4.1177	0.0468	9.8113e-
ITSE	9.4721	6.8958	4.2074	1.8114	0.0473	1.1248e
IAE	3.3143	2.9384	1.5840	3.1695	0.0623	3.9357E-
ITAE	5.8369	1.4332	2.1290	1.5912	0.1476	6.9312e-

control. Thus, the ITAE-based FFA-PID controller was selected for the frequency deviation control. The optimized parameters for GA-PID and FFA-PID controllers for area 2 microgrid system is shown Table 5:

Table 5: Optimized PID Controller Parameters for Area II

Error Criteria	GA-PID Controller		
	K_p	K_i	K_d
ISE	99.9075	99.4304	99.9675
ITSE	99.9348	50.3856	95.8374
IAE	99.9977	25.1953	13.0948
ITAE	99.9978	25.6491	8.6454

Figure 4.5 presents the ISE (Top-Left), ITSE (Top-Right), IAE (Bottom-Left), and ITAE (Bottom-Right) response with the desired frequency deviation of zero Hz. It can be seen from the figure that the system attained the desired frequency deviation based on the ISE, ITSE, IAE, and ITAE performance measures with different transient properties. The transient response of the hybrid microgrid control system in Area II with the

application of the GA-PID controllers is shown in Figures 7:

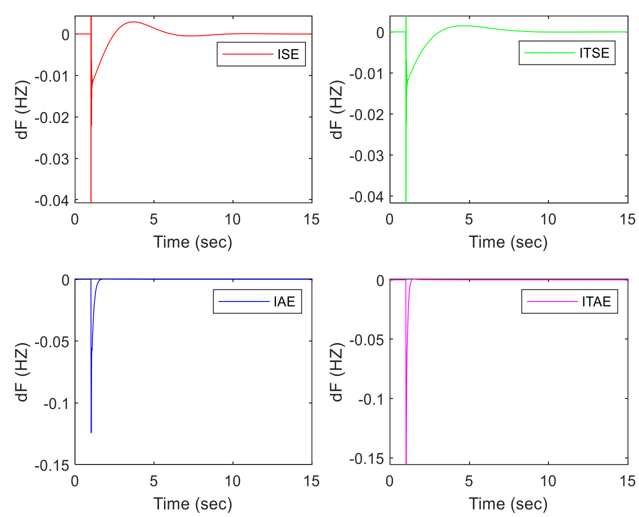

Figure 7: Area II Transient Response for GA-PID Controller

To evaluate the performance of the designed controllers, the transient parameters and the steady state error obtained for the hybrid MG control system based on the four error criteria are recorded in Table 6.

Table 6: Area II Transient Parameters and the Steady State Error for GA-PID Controller

Error Criteria	Rise Time (s)	Settling Time (s)	Overshoot (%)	Undershoot (%)	Peak (Hz)	Steady State Error (HZ)
ISE	7.7006	5.4033	3.7124	3.9555	0.0407	1.0971
ITSE	1.0343	6.4362	2.8274	2.6266	0.0417	1.4736
IAE	1.0996	1.4491	5.4107	4.6468	0.1243	2.6743
ITAE	4.4912	1.2938	7.5117	1.9621	0.1558	7.9385

Table 6: Area II Transient Parameters and the Steady State Error for GA-PID Controller

4.0 Conclusion

Results shows that GA-PID effectively improves frequency regulation, with future work exploring Model Predictive Control (MPC) for enhanced robustness. The study developed a GA-tuned PID controller for load frequency control in hybrid microgrids. The ITAE-based controller demonstrated the best transient response and system stability among various performance criteria.

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