

# An Adaptive PID Load Frequency Control of Islanded Microgrids Based on Iterative Learning Control

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## Abstract

The deviation in frequency could be a major issue in power system operation because it can affect the stability of the system. Load frequency control (LFC) is needed to control the deviation so that system stability can be maintained. The LFC is often referred to as an automatic generator control (AGC) microgrid in islanded mode. In this paper, an adaptive PID control based on iterative learning control (ILC) is proposed to handle power system dynamics in islanded mode of microgrid. The results show that the proposed PID controller has better performance under various disturbances, such as load changes and penetration of external generation, and renewable presence such as wind power, while adhering to the 2% overshoot and 2% steady state band constraints. During simulation, the proposed controller has demonstrated its superiority over the classical PID tuning.

## 1. Introduction

The human objective of reducing greenhouse gas emissions has led to the introduction of renewable energy generators [1]. However, the generators increase the complexity of the power system's operation [2]. Therefore, this makes the reality that a power system is a system with high dynamics in the world [3]. Because of the dynamics, the power system might never reach its steady state, and so the stability of the power system might be a crucial issue in its operation. Frequency deviations in the power system could cause a variety of issues for devices connected to the system. Reports indicate that frequency variations can impact the operation and speed control of both synchronous and asynchronous motors. These changes can lead to increased reactive power consumption and reduced load performance. Furthermore, frequency fluctuations can result in transmission line overloads and disrupt system protection mechanisms [4].

Due to the rapid growth of renewable energy sources such as wind and solar, frequency stability has become a major issue in the operation of power systems. The operation of a multi-area power system is becoming progressively more complicated. Load frequency control (LFC) is a crucial component of a power system for minimizing frequency variation by sustaining power exchange between power system zones. The LFC, often referred to as automatic generator control (AGC) in islanded mode of microgrid, works stand-alone. Many researchers have worked to find a better performance controller to solve the LFC problems in [5]–[12]. Based on the research, an adaptive controller gives better solutions for the LFC system. However, the iterative gain evaluation method is not found in the list.

A PID controller is a classic and simple controller that is easy and cheap to implement in controlling a plant. The major problems with a PID control are hard to tune and to face in a non-linear plant. This problem might be solved by adaptively tuning the controller to face the change in system dynamics. Model-based controllers such as model predictive control, neural networks, and other controllers have been used in many cases to overcome

the drawbacks of PID controllers. On the other hand, the PID control can also run at maximum performance by properly tuning its gain. The famous tuning method, the Ziegler-Nichols (ZN) method, might not give a better solution in some cases, so other tuning methods have been used, such as fuzzy [13], and neural networks [14], etc.

As a model-free control, iterative learning control (ILC) has a simple structure and does not require specific model parameters [15]. Iterative gain evaluation has been proposed in references [15]–[21], but extending the proof to a variety of system types, developing a discrete version, and establishing gain convergence bounds required significant effort. The structure of these early algorithms has subsequently been augmented and expanded [16].

This paper focuses on the simplest methods, which not only serve as a foundation for more advanced algorithms but also play a crucial role in promoting the broader adoption of this control system design approach. In this paper, an adaptive PID control has been proposed to handle the nonlinearity of the LFC. The objectives of this work included: 1) setting the controller algorithm to a LFC system; 2) evaluating the LFC system's performance under load variation; and 3) examining the controller's performance in the presence of noisy renewable penetration.

## 2. Problem Statement

Adaptive control has been used in load frequency control (LFC) by many different researchers in the past. Among these researches, the last three years research on adaptive control of the LFC are provided in references [5]–[8].

Reference [5] demonstrates an adaptive PI LFC control technique based on teaching learning-based optimization (TLBO) methods. The proposed controller is tested on two-area systems, including PV and Wave Energy Conversion System (WECS), subjected to various disturbances such as load fluctuations and the inherent intermittency of the WECS. The results demonstrate that the controller effectively improved the system's response across these different types of disturbances. The controller also shows superiority over other classical schemes.

Reference [6] presents an adaptive control technique based on optimization methods of Jaya and compares it with the Practical Swarm Optimization Algorithm to tune a PI controller for serving a single area LFC system via on-line tuning. A microgrid consisting of a 20 MW diesel generator and a 17 MW demand load is used to test the proposed controller. Simulation results show that the best performance controller is given by Jaya optimization.

Reference [7] introduces an adaptive load frequency control method applied to both an isolated microgrid power system and two interconnected microgrids (MGs). The Jaya optimization algorithm is enhanced with the Balloon Effect (BE) modification to improve its sensitivity. The proposed controller has been evaluated under various conditions, including step changes, variable load demands, and parameter variations. Simulation results demonstrate that the controller tuned with the Jaya + BE technique outperforms other approaches, including conventional controllers and adaptive controllers tuned with the standard Jaya algorithm.

Reference [8] proposes an adaptive MPC controller via Internal Model Control (IMC) type 1 that only updates the IMC internal model and IMC type 2 that updates both the internal model and MPC gain. The adaptive method lied in the online controller gain update based on the least squares method. Both IMC types 1 and 2 are then simulated and compared in a two-area LFC system. The simulation results indicate that adjustments in the gain and time constant of the internal model have ensured enhanced performance of the proposed controller. From the system responses, it is evident that the IMC controller type 2 outperforms both the MPC controller and the IMC type 1 controller, demonstrating its superior effectiveness.

An iterative learning control (ILC) method was first proposed by Kawamura et al. in [16] that uses information obtained from previous learning to construct control inputs for subsequent learning, thereby accelerating the learning process. Several subsequent studies on ILC have focused primarily on demonstrating the convergence of the learning algorithm, learning speed, and learning law structure, as well as the robustness, analysis method, initial value, and application of the learning process, all of which led to the enhancement of the method [15]–[21]. Compared to the latest findings in the ILC method, the virtual time-response-based iterative gain evaluation and redesign (V-Tiger) method offers an interesting approach. This method tunes a PID controller gain by using frequency component settings. It does so while setting constraints for overshoot and the steady-state band. This method is claimed to deliver not only high performance but also an optimal solution under some constraints that are typically not possible to solve with a classic PID controller.

Adaptive controls have shown better performance in controlling the power system dynamics of an LFC system compared to static controllers based on these studies. On the other hand, a V-Tiger-based ILC control method has never been reported in previous studies. This research will apply the V-Tiger-based ILC method in an LFC system and continue to simulate and investigate the effectiveness of adaptive ILC control in an LFC system of an islanded microgrid.

### 3. Methods

#### 3.1 Iterative Learning Control

Iterative Learning Control (ILC) is a control mechanism for systems that perform repeatedly the same task or action. In this manner, it can use prior control signals to construct the current control action. This characteristic sets ILC apart from most other control techniques, allowing it to achieve superior results with less information about the plant compared to other control methods. Typically, practical testing of ILC algorithms has been conducted to validate a specific algorithm within theoretical frameworks. However, exceptions are found in publications that present experimental work, although these often fail to adequately justify the selected algorithm or are focused on highly specialized areas where the application of broader ILC methods is not feasible [15]–[21].

The ILC algorithms used in [15]–[21] for various purposes consisted of a correction term comprising some measure of the error from the same instant in the previous trial:

$$u_{k+1}(t) = u_k(t) + \Gamma e_k(t) \quad (1)$$

Where  $\Gamma$  is the learning gain, while  $u_k(t)$  and  $e_k(t)$  are the control signal and the tracking error at the  $k$ -th iteration. The ILC D-type Algorithm, in which the error derivative  $\dot{e}_k(t)$  is used, is given in equation (2) [16].

$$u_{k+1}(t) = u_k(t) + \Gamma \dot{e}_k(t) \quad (2)$$

It has been determined that feedback controllers are extremely useful for stabilizing the plant during the ILC process, and they have been incorporated into a variety of control structure positions [16].

#### 3.2 Frequency Control in Microgrids

The recent surge in population, household utilities, industrial activities, and digitalization has led to a significant rise in power demand. However, traditional energy sources like fossil fuels, diesel, and coal are inadequate to meet this growing demand. Consequently, there is increasing interest in and development of alternative energy sources, such as wind, solar, and hydro-based power plants, to bolster the foundation of energy generation [22]. Innovations, advancements, and improvements in small-scale power generation and distribution have promoted the use of distributed power sources at low voltage levels. The concept of integrating distributed sources into distribution networks has prompted the establishment of microgrids to address power demand [23].

A microgrid is a basic power system that includes power sources, loads, and/or storage devices, operating as a self-contained, controllable unit. It can function autonomously in both grid-connected and isolated operation modes. By managing the entire process of power generation, distribution, and consumption, microgrids serve as a backup system for end users, providing power in case of a main grid failure [6].

In electric power system operations, frequency stability is a major stability issue that is closely related to active power deviation [24]. The deviation is mostly due to load variation that is unpredictable. Load Frequency Control is a controller used to control the active power flow to meet the demand power, which is triggered by load variations. Fig. 1 shows a single-area LFC system that is used to model an islanded microgrid.

A single-area power system based on Fig. 1 consists of three system states, including frequency deviations  $\Delta f$ , governor deviation  $\Delta P_g$ , and prime mover deviation  $\Delta P_m$ . Each system state is written in formulations, as in equations (3), (4), and (5) [6], [8].

$$\Delta \dot{f} = \frac{\Delta P_m}{M} - \frac{\Delta P_L}{M} - \frac{D}{M} \Delta f \quad (3)$$

$$\Delta \dot{P}_m = \frac{\Delta P_g}{T_t} - \frac{\Delta P_m}{T_t} \quad (4)$$

$$\Delta \dot{P}_g = \frac{\Delta P_c}{T_g} - \frac{\Delta f}{RT_g} - \frac{\Delta P_g}{T_g} \quad (5)$$

In the equations 3-5,  $\Delta f$ ,  $\Delta P_m$ ,  $\Delta P_L$ , and  $\Delta P_g$  refer to the deviations of frequency (Hz), prime mover (pu), loads (pu), and governor (pu). The other constants of  $D$ ,  $M$ ,  $T_g$ ,  $T_t$ , and  $R$  are the equivalent damping coefficient (pu/Hz), inertia constant (pu.s), governor time constant (s), turbine time constant (s), and frequency drop (Hz/pu), respectively.

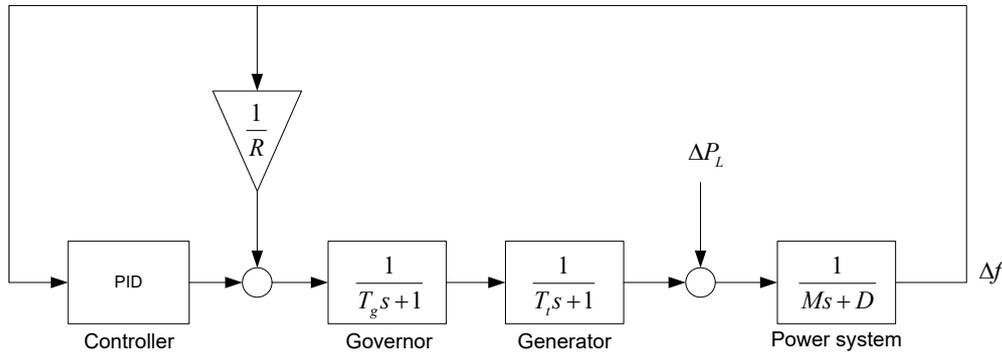


Fig. 1 Single area LFC diagram

## 4. Result and Discussion

### 4.1 System Setup

A microgrid power system is used to test the effectiveness of this proposed method, as shown in Fig. 1, consisting of a 20 MW diesel generator and a 17 MW load. The base parameters of the system are given in Table 1 [6].

Table 1 Base parameters of a microgrid

| $D$<br>(pu/Hz) | $M$<br>(pu.s) | $R$<br>(Hz/pu) | $T_g$<br>(s) | $T_d$<br>(s) |
|----------------|---------------|----------------|--------------|--------------|
| 0.015          | 0.08335       | 3              | 0.08         | 0.4          |

Based on Fig. 1, the system model will be changed after load and/or external generator penetration. Therefore, the adaptive PID feature of the proposed method will be based on the changes. A classical PID control based on Ziegler-Nichols (ZN) is provided to validate the results. The ZN method was also used previously to tune and validate the given method in [6], [14], [25], while reference [8] uses Model Predictive Control (MPC), which comes with its own tuning method and does not use this ZN tuning method.

Simulation and validation will be carried out to find out how effective the proposed controller is by comparing the results with those of non-adaptive classical PID tuning. The simulation will be carried out in three cases: 1) continuous load changes; 2) penetration from an external generator; and 3) noisy power injections from renewables.

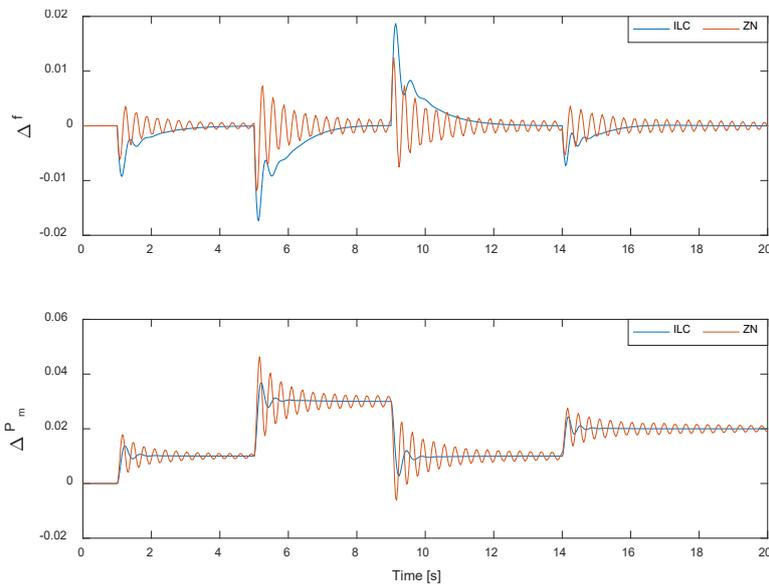
### 4.2 System Underload Changes

In simulating the system with this change in demand load, the demand changes will be made several times within 20 s. Data from this simulation is given in Table 2. Furthermore, the results showing the frequency and prime-mover deviations are given in Fig. 2.

The iterative learning control (ILC) method is used to tune the proposed PID control by limiting maximum overshoot to 2% and steady-state band to 2%. With these constraints, the tuning results show a relatively low PID gain, as given in Table 2. However, the simulation results show that the proposed PID controller with the ILC method does not exceed the 2% constraint at each given load step, as shown in the  $\Delta f$  curve in Fig. 2. In this case, the figure shows that the longest time to reach steady state is 4 s, which occurs at each released load; in contrast, the time to reach steady state is less than 3 s when the load is entered. This response can also be seen in the change of the  $\Delta P_m$  curve, which, on average, can reach steady state when the load changes in less than 1 second. On the other hand, it takes a little longer when the load is released, but it does not reach 2 s. This condition can be caused by excessive overshoot damping action on the  $K_i$  gain, which is almost the same as the  $K_p$  gain. The PID gain that is not too large causes the controller to be quieter in dealing with changes in load, resulting in faster steady-state achievement. Even with a higher overshoot, the values shown still meet the required constraint limits.

**Table 2** PID gain under load variation

| Time (s) | $\Delta P_L$ (p.u) | Proposed PID Gain |        |        | Classical PID Gain |         |        |
|----------|--------------------|-------------------|--------|--------|--------------------|---------|--------|
|          |                    | $K_p$             | $K_i$  | $K_d$  | $K_p$              | $K_i$   | $K_d$  |
| 1        | 0.02               | 1.8247            | 2.1936 | 0.8999 | 7.9584             | 14.7624 | 1.0726 |
| 5        | 0.04               | 2.8799            | 0.5412 | 0.5605 | 7.9584             | 14.7624 | 1.0726 |
| 9        | 0.01               | 1.8869            | 1.8404 | 0.5972 | 7.9584             | 14.7624 | 1.0726 |
| 14       | 0.02               | 1.8247            | 2.1936 | 0.8999 | 7.9584             | 14.7624 | 1.0726 |

**Fig. 2** Controller response under load variation

Compared to the same system under the same treatment in previous research [6], which only used  $K_i$  gain and the gain will be adjusted based on the error that appears, The controller response is very slow in reaching steady state, as shown in the response of the system: with a load change of 0.02, it can reach a steady state in 6 s, and the overshoot is more than 10%.

The result of tuning with the classical PID method is a high  $K_p$  gain that is offset by more attenuation at a fairly high  $K_i$  and  $K_d$  gain. This condition gives an aggressive system response and oscillates around the setpoint over a long damping time. Furthermore, this condition resulted in high oscillations in  $\Delta P_m$ . Even so, the resulting overshoot tends to be quite low when compared to the overshoot with the proposed PID tuning.

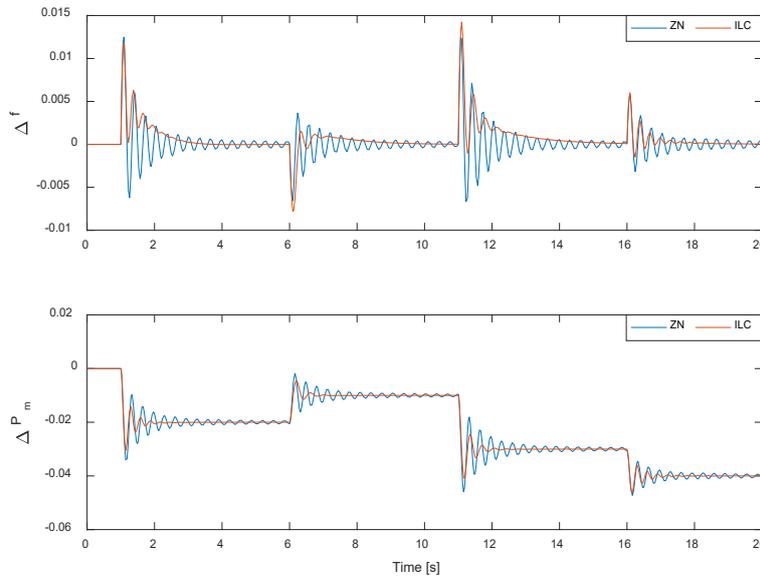
### 4.3 External Generator Penetration

In contrast to the response system during the changeover, the increase in capacity with an external generator causes the main generator to reduce the capacity of production while continuing to increase the power, and the load is fully supplied by the external generator. The theoretical response is also shown in reference [8].

**Table 3** PID gain under generation change

| Time (s) | $\Delta P_L$ (p.u) | Proposed PID Gain |        |        | Classical PID Gain |         |        |
|----------|--------------------|-------------------|--------|--------|--------------------|---------|--------|
|          |                    | $K_p$             | $K_i$  | $K_d$  | $K_p$              | $K_i$   | $K_d$  |
| 1        | 0.02               | 3.8383            | 4.3083 | 1.3133 | 7.9584             | 14.7624 | 1.0726 |
| 6        | 0.01               | 5.0392            | 3.0532 | 1.2217 | 7.9584             | 14.7624 | 1.0726 |

|    |      |        |        |        |        |         |        |
|----|------|--------|--------|--------|--------|---------|--------|
| 11 | 0.03 | 2.3441 | 1.9659 | 0.6937 | 7.9584 | 14.7624 | 1.0726 |
| 16 | 0.04 | 3.8383 | 4.3083 | 1.3133 | 7.9584 | 14.7624 | 1.0726 |



**Fig. 3** Controller response under generation change

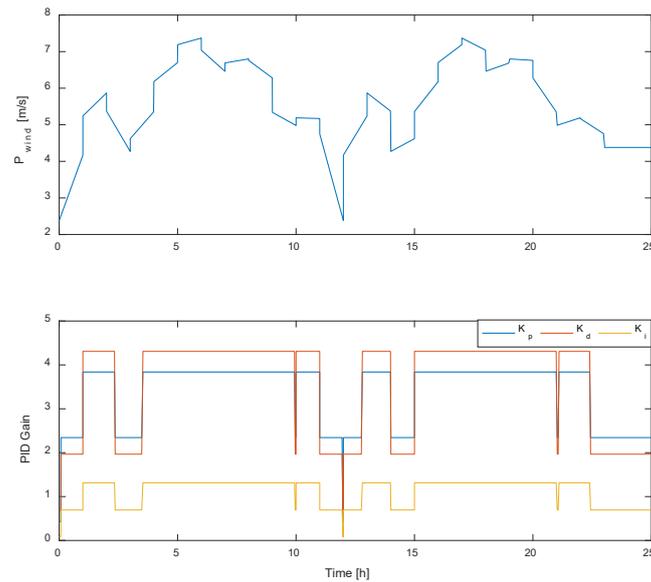
The results of tuning with the classical PID method in this method show the same gain for the step load as in the previous case, so that whatever generation power is given, it will give excessive oscillations. This tuning gain has resulted in similar controller behavior to that of the system during load changes in the previous case. In both cases, the controllers are very aggressive, causing such large frequency oscillations that they affect every state variable in the LFC system, as also shown in the  $\Delta P_m$  curve. On the other hand, the penetration of the external generator, the result of the proposed controller tuning in this case, shows a larger PID gain.

The frequency response for the proposed PID has a fairly good overshoot, and on the other hand, it is even better than the classical PID method. Another benefit is that this method makes the transition to a steady state smoother and faster, and oscillations can be dampened better. This also has an impact on the  $\Delta P_m$  response, which looks better in terms of overshoot and oscillation as well as steady state setting time.

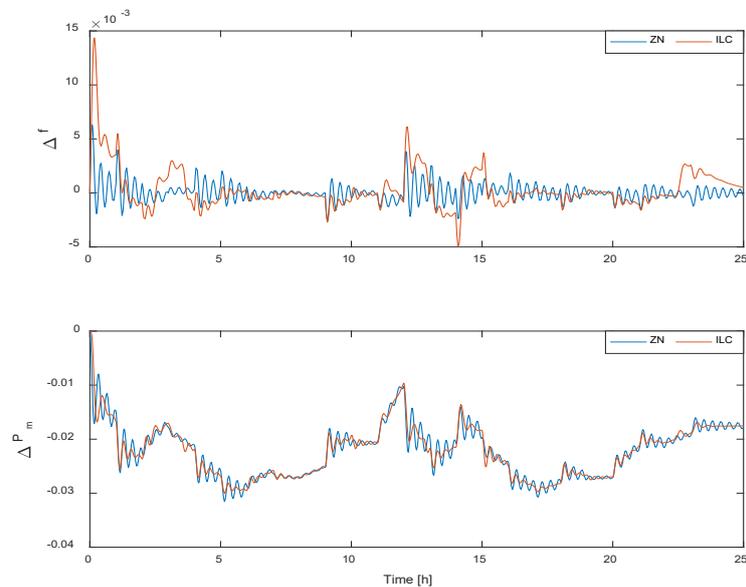
#### 4.4 Presence of Renewable

The penetration from wind power plants is presented in this case. Wind power data were obtained from NASA [26] at latitude -1.4032 and longitude 131.0219. Wind power data shows the most power is generated in January and February 2023. In this case, wind power is converted and injected into the system, as shown by the  $P_{wind}$  curve in Fig. 4.

As the classical PID gain did not change in the previous two cases, it is also fixed in this case. In the previous two cases, however, the proposed controller gain tends to change with the join or release of the load or the injection of an external generator. As shown in Fig. 5, the conditions cause the proposed controller gain to fluctuate in response to these changes. Fig. 5 shows that the PID gain tends to increase and decrease in response to changes in wind power penetration. The figure shows that  $K_p$  gain dominates  $K_i$  and  $K_d$  gain, whereas  $K_d$  gain is the lowest gain when tuning with the ILC method. This is because the controller must be tuned in accordance with the constraints. An increase in  $K_p$  gain, on the other hand, will slow the controller's ability to reach steady state.



**Fig. 4** PID gain under wind power presence



**Fig. 5** Controller response under wind power presence

The simulation outcomes based on the wind farm's input have implications for fluctuations in system frequency, as illustrated by the  $\Delta f$  curve in Fig. 5. In general, the fluctuation frequency of the classical PID is the same as that of the proposed PID. However, it can be seen that the proposed PID is slower to respond to changes in penetration, resulting in some overshoot. This is due to the fact that the proposed controller gain, unlike classical PID gain, is relatively fixed and slightly aggressive. In contrast to the  $\Delta f$  curve, the  $\Delta P_m$  curve tends to be more stable and follows system changes made by the proposed controller with smaller oscillations because the controller is not as aggressive as the classical PID. It is validated in reference [6] that every adaptive controller can respond differently to the system under renewable presences.

In a multi-area load frequency control (LFC) application, the proposed adaptive control can be effectively used as decentralized controllers within each area of the multi-area LFC systems to manage areas independently. The approach is based on the fact that a standard PID controller is not designed for controlling multi-input multi-output (MIMO) systems directly, as in a multi-area LFC. Then, the proposed adaptive PID controller is used as a single controller for each area within the multi-area LFC framework.

## 5. Conclusion

An iterative learning control (ILC) application was developed in this paper to achieve the best possible gain for PID control on an islanded microgrid. This proposed controller is used to manage frequency stability in an islanded microgrid, which was investigated through a single-area load frequency control (LFC) built as an islanded microgrid. System changes caused by loads or external generator penetration have disrupted the system model. This disruption requires the adaptation of the PID gain where the proposed PID controller handles this adaptation. The proposed PID is constrained to a 2% overshoot and a 2% steady-state band range.

The proposed controller kept frequency deviations within the 2% band during load changes, reaching steady state within 4 seconds during load release and within 3 seconds when loads were applied. Compared to classical PID tuning, which showed higher oscillations and longer settling times, the proposed controller allowed for smoother control with reduced overshoot. The proposed controller has adjusted gain values in each change of the system, resulting in effectively minimizing oscillations and leading to stable frequency control and faster transitions to steady state compared to classical PID, which showed significant oscillations and prolonged damping.

In scenarios with wind power fluctuations, the proposed controller effectively managed frequency deviations, maintaining smaller oscillations in the prime mover deviations compared to classical PID, which displayed more aggressive and less stable behavior. The proposed controller maintained frequency deviations within  $\pm 0.015$  Hz under varying renewable inputs, showing overshoot reductions to less than 1.5% and steady-state times under 5 seconds, significantly outperforming classical PID controllers, which often exceeded these limits.

Overall, the findings validate that the proposed controller, utilizing ILC, offers significant improvements over classical PID controllers in terms of both performance and reliability in microgrid frequency control applications. This approach not only enhances system stability but also provides a scalable and adaptable solution for modern power systems increasingly reliant on renewable energy sources.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** A. B. Rehiara; **data collection:** H. A. B. Lesnussa, A. Z. Patiran; **analysis and interpretation of results:** A. B. Rehiara; **draft manuscript preparation:** P. Sarungallo, Y. Rumengan. All authors reviewed the results and approved the final version of the manuscript.

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