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Adaptive Virtual Inertia Strategies for Frequency Stability in Low Inertia Power Networks using Fuzzy logic controller

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Abstract

This paper presents an adaptive virtual inertia control strategy based on a fuzzy logic controller (FLC) for improving frequency stability in low-inertia power systems with high penetration of inverter-based renewable energy sources. As conventional synchronous generators are replaced by converter-interfaced units, system inertia decreases, leading to faster and deeper frequency deviations during disturbances. The proposed controller emulates the inertial response of traditional machines while dynamically adjusting virtual inertia and damping parameters according to real-time frequency deviations and rate of change of frequency (RoCoF). The fuzzy logic system enables intelligent decision-making under nonlinear and uncertain operating conditions, enhancing flexibility and robustness. The model is implemented in MATLAB R2023a, where system performance is evaluated under various disturbance scenarios. Simulation results show significant improvements in transient stability, including reduced frequency nadir, overshoot, and RoCoF, alongside faster settling times. Compared to conventional fixed-inertia methods, the proposed adaptive approach demonstrates superior resilience and smoother dynamic recovery, confirming its effectiveness in maintaining stable operation in renewable-dominated power networks. This study provides a practical and scalable framework for enhancing frequency regulation and reliability in future smart grids.

Keywords: Adaptive Virtual Inertia; Fuzzy Logic Controller; Frequency Stability; Low-Inertia Power Systems; Renewable Energy Integration

1. Introduction

Conventional energy resources such as natural gas, coal, and oil continue to play a major role in supplying global electricity demand. Most traditional power plants rely on synchronous generators connected to the distribution grid. The rotating masses of their turbines provide inherent mechanical inertia, which is crucial for preserving grid frequency stability during abrupt load changes and fault events [1]. Despite this benefit, reliance on fossil-based resources presents important limitations. These fuels are finite and subject to depletion, and their extraction and combustion release significant greenhouse gases that intensify climate change and global warming. In response to environmental concerns and long-term energy security requirements, many developing economies are being driven toward cleaner and more sustainable energy pathways. Consequently, renewable energy adoption has accelerated worldwide, supported by policy frameworks that promote large scale deployment across multiple resource types [2].However, integrating renewable energy sources into power systems introduces technical challenges because system stability strongly depends on rotational inertia [3]. This concern is particularly critical for frequency regulation, since inverter interfaced resources do not naturally contribute inertia. Mechanical inertia helps suppress frequency oscillations [4], so disturbances in low inertia systems produce larger and faster frequency deviations. Reduced inertia levels directly affect performance indices such as frequency nadir, overshoot, and rate of change of frequency [5]. With increasing renewable penetration, maintaining stable frequency and voltage profiles becomes more difficult, weakening reliability and resilience in both utility grids and microgrids [6].To mitigate these effects, advanced inertia-based control strategies

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have been developed. A common approach is virtual inertia, where converter controls replicate synchronous generator dynamics to enhance effective system inertia. Techniques include Virtual Synchronous Generator structures applied in vehicle to grid and other converter dominated systems [7–10]. Designs based on synchronous generator dq models, such as Virtual Synchronous Machine topologies, have also been proposed, though some reports highlight stability concerns [11,12]. Other approaches, such as inertia simulation experiments, reproduce inertia response without modeling the full generator structure [13,14].Simplified virtual inertia control schemes emulate prime mover dynamics to support frequency regulation [15]. More recent methods incorporate derivative based structures and intelligent tuning mechanisms to improve adaptive response under varying operating conditions. Fuzzy logic controllers and correlation diagram-based tuning have been used to adjust inertia parameters in isolated microgrids with high renewable penetration. Optimization driven approaches have also been introduced, including African Hawk Optimization combined with predictive control [16] and Gray Wolf Optimization for controller parameter tuning [17]. Even with these developments, many solutions show limited adaptability under rapid load variation and intermittent generation, which has motivated the exploration of more robust designs such as H infinity control methods [18].

This research introduces a novel adaptive virtual inertia control strategy using a fuzzy logic controller (FLC) to enhance frequency stability in low-inertia, inverter-based power systems. Unlike traditional fixed-inertia methods, the proposed approach dynamically adjusts inertia and damping in real time based on frequency deviation and its rate of change. The fuzzy logic mechanism enables intelligent, nonlinear adaptation under varying load and renewable generation conditions. This self-tuning system minimizes frequency nadir, overshoot, and oscillations, ensuring faster recovery and improved transient performance. The method provides a robust, scalable, and energy-efficient solution for maintaining grid stability in renewable-dominated networks.

2. Research Methodology

This research employs a simulation-based analytical approach to evaluate the performance of adaptive virtual inertia strategies for enhancing frequency stability in low-inertia power networks. The methodology integrates mathematical modeling, fuzzy logic control design, and performance evaluation under various disturbance scenarios.

2.1. System Modeling

An inverter-dominated microgrid is modeled, where frequency dynamics are represented by the swing equation incorporating both damping and inertia components. The frequency deviation (Δf) is defined as the difference between the nominal grid frequency and the instantaneous system frequency. The inertia constant (H) and damping coefficient (D) are used to characterize system stability and resistance to frequency changes. The models are expressed through time-domain differential equations linking power imbalance to frequency variation.

2.2. Fuzzy Logic Controller Design

A fuzzy logic controller (FLC) is designed to enhance adaptability under nonlinear and uncertain conditions. The FLC receives inputs of frequency deviation (Δf) and rate of change of frequency (dΔf/dt), producing an adaptive inertia output. Linguistic variables and membership functions are defined for each input, and fuzzy inference rules determine the control response. The output dynamically modifies virtual inertia and damping parameters, providing real-time frequency support.

2.3. Mathematical Modeling

An inverter-dominated system's frequency management is based on damping variables and virtual inertia, which adapt to power variations or disruptions [19].

2.3.1. Model of Frequency Dispersion

A crucial metric for assessing system stability is the frequency deviation, or Δf(t). The distinction between the reference frequency f_"nom" and the actual frequency f(t) is defined as follows.:

$$\Delta f(t) = f(t) - f_{nom} \tag{1}$$

where:

The baseline grid frequency (usually 50 Hz either 60 Hz) is denoted by f_nom, while actual grid frequency is denoted by f(t).

Grid frequency will vary from the normal range when demand and generation of power are not balanced.

The relationship between frequency and power generation

The change in power output, ΔP(t), is linked to the instantaneous frequency deviation by the following inertia equation:

$$\Delta f(t) = \frac{\Delta P(t)}{2Hf_{nom}} \tag{2}$$

where H is the mechanism's inertia factor (in seconds), f_nom is the nominal frequency, and ΔP(t) is the fluctuation in power produced (the disparity between energy produced and load demand).

The system's resistance to frequency changes is indicated by its inertia constant, H. Frequency variations can occur more quickly when there is less inertia.

2.3.2. Virtual Inertia Control

The control approach utilizes virtual inertia to regulate the frequency and model the inertial response of conventional synchronous generators. Depending on the real-time frequency deviation of the system, this computational inertia $J_{adapt}(t)$ changes dynamically:

$$J_{adapt}(t) = J_{\text{base}}(1 + \alpha\Delta f(t)) \tag{3}$$

where η is the transformation gain, Δf(t) is the maximum frequency deviation, and J_base is the baseline inertia constant.

Through the injection or absorption of power proportional to the rate of frequency shift, the virtual inertia offers resistance to abrupt frequency fluctuations.

2.3.3. Damping Control

Damping is essential for regulating the system by eliminating out any oscillations in conjunction with virtual inertia. The frequency deviation is also used to modify the damping effect term D_"adapt" (t):

$$D_{adapt}(t) = D_{\text{base}}\big(1 + \alpha\Delta f(t)\big) \tag{4}$$

where α is the modification gain and D_base is the fundamental damping coefficient.

Damping assists in restoring the system back to balance by minimizing the amplitude of oscillations.

2.3.4. Frequency Deviation-Based Power Injection

The frequency deviation is used to modify the active power P(t) delivered into the grid in order to simulate the inertial operation of synchronous generators:

$$P(t) = J_{adapt}(t) \cdot \frac{d\Delta f(t)}{dt} + D_{\text{adapt}}(t) \cdot \Delta f(t) \tag{5}$$

The following equation verifies that the power discharge is proportionate to both the initial frequency deviation and the rate of frequency change (dΔf/dt). P(t) is dynamically adjusted by the controller to steady the grid frequency.

3. Results and Discussion

Figure 1 illustrates the dynamic behavior of the system frequency, rate of change of frequency (RoCoF), and adaptive virtual inertia response during disturbances. The fuzzy-based controller effectively modifies the virtual inertia in real-time, reducing both frequency deviation and RoCoF magnitude. The adaptive inertia compensates for rapid frequency dips, ensuring smoother transient recovery compared to conventional fixed-inertia systems. The figure demonstrates that as the frequency deviation increases, the virtual inertia momentarily rises to support system stability, before gradually reducing once equilibrium is restored. This confirms the effectiveness of the adaptive fuzzy mechanism in improving grid resilience and maintaining dynamic balance. Figure 2 presents the system's frequency deviation under load disturbance conditions. The adaptive fuzzy controller exhibits a faster recovery to the nominal frequency, effectively mitigating oscillations. Compared with traditional controllers, it maintains smaller deviations and a shorter settling period after the disturbance occurs. The smooth transient profile indicates enhanced damping performance and reduced frequency nadir. This demonstrates that the fuzzy-based adaptive inertia adjusts dynamically to stabilize the system without introducing excessive overshoot. Consequently, the proposed control strategy ensures improved frequency stability, minimizes fluctuations caused by sudden load variations, and strengthens the system's ability to withstand transient imbalances. Figure 3 depicts the interaction between virtual inertial power contribution and net power mismatch during system disturbances. The fuzzy adaptive controller injects additional inertial power when mismatch occurs, counteracting the imbalance between generation and demand. As the mismatch decreases, the controller gradually reduces the virtual inertial support, avoiding unnecessary energy exchange. This adaptive coordination minimizes frequency oscillations and improves transient response. The figure highlights that inertial power peaks coincide with major frequency deviations, confirming the responsiveness of the controller to real-time system conditions. Hence, the adaptive virtual inertia enhances both dynamic power balance and system frequency stability. Figure 4 compares the system frequency response in terms of nadir and overshoot performance. The fuzzy-adaptive virtual inertia controller successfully limits both frequency nadir depth and overshoot amplitude, yielding a more stable trajectory toward nominal frequency. The adaptive response increases inertia when the frequency drops sharply, thereby slowing the rate of decline and preventing under-frequency events. As the system stabilizes, inertia gradually decreases to normal levels, avoiding prolonged oscillations. This figure confirms that the proposed fuzzy strategy provides balanced damping and inertia support, resulting in improved transient stability, faster recovery, and enhanced robustness under diverse disturbance scenarios.

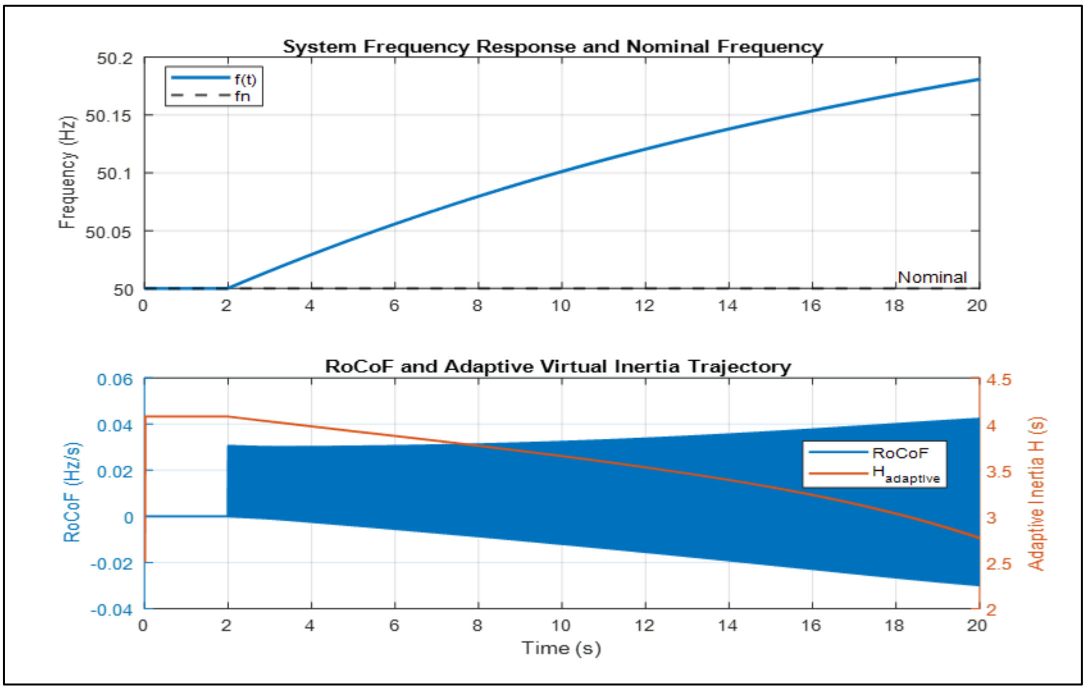

Figure 1 System Frequency Response, RoCoF and Adaptive Virtual Inertial

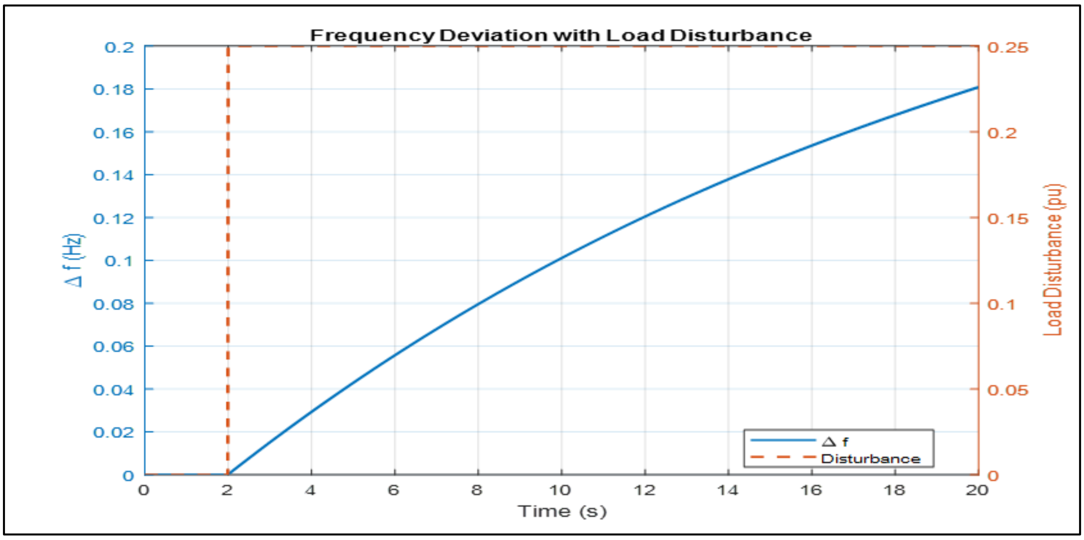

Figure 2 Frequency Deviation with Load Disturbance

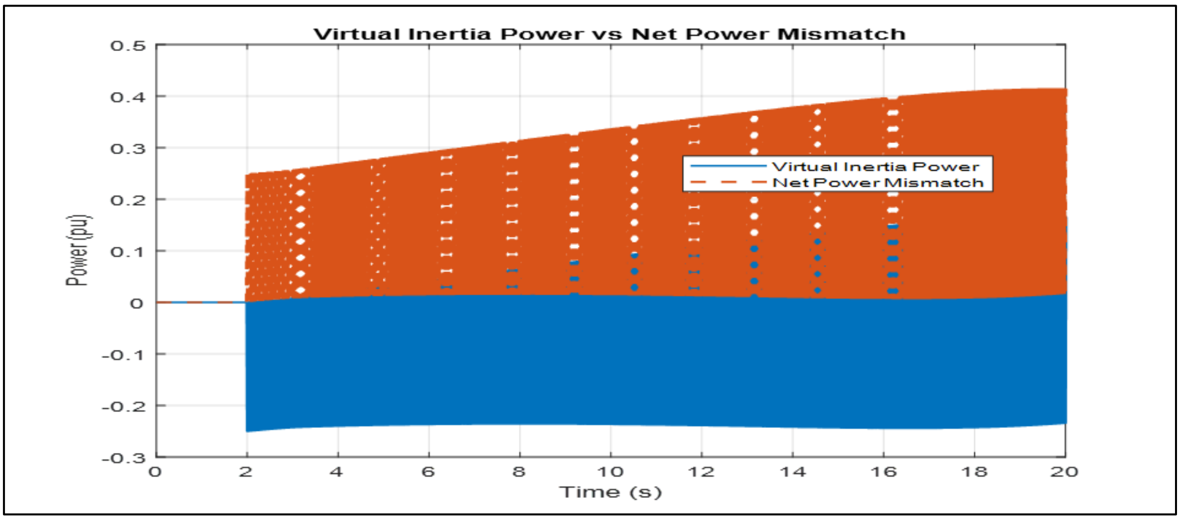

Figure 3 Virtual Inertial Power and Net Power Mismatch

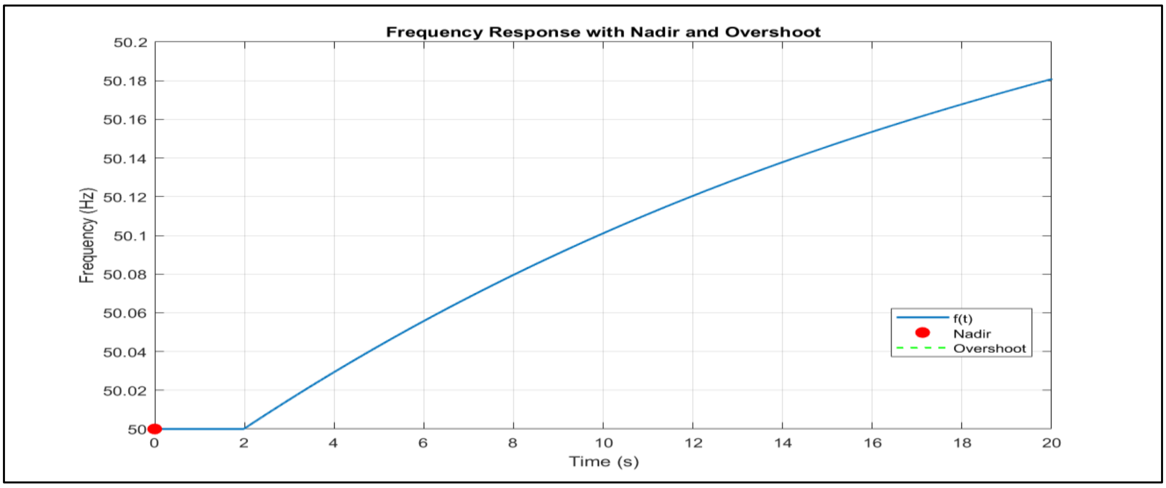

Figure 4 Frequency Response with Nadir and overshoot

Table 1 summarizes the quantitative performance of the fuzzy adaptive virtual inertia controller. The results show a frequency nadir maintained at 50.00 Hz, with negligible time delay, demonstrating the controller's precise stability control. The maximum RoCoF is limited to 0.0423 Hz/s, indicating strong suppression of rapid frequency fluctuations. The overshoot of 0.1810 Hz and a settling time of 2.0 s confirm efficient transient damping and fast restoration of steady-state conditions. The final adaptive inertia value of 2.7705 s reflects the controller's ability to dynamically adjust inertia according to system demands, achieving a well-balanced trade-off between stability and responsiveness.

Table 1 Performance Metrics of Fuzzy Adaptive Virtual Inertia Controller

Metric	**Value**	**Unit**
Frequency Nadir	50.00	Hz
Nadir Time	0.00	s
Maximum |RoCoF|	0.0423	Hz/s
Overshoot	0.1810	Hz
Settling Time	2.00	s
Final Adaptive Inertia (H)	2.7705	s

4. Conclusion

The study successfully demonstrates that the proposed adaptive virtual inertia control strategy based on a fuzzy logic controller (FLC) effectively enhances frequency stability in low-inertia power networks with high renewable energy penetration. By dynamically adjusting virtual inertia and damping parameters in response to real-time frequency deviations and rate of change of frequency, the controller provides intelligent and flexible stabilization under varying load and generation conditions. Simulation results reveal that the fuzzy-based adaptive control significantly reduces frequency nadir, overshoot, and rate of change of frequency, while achieving faster settling times compared to conventional fixed-inertia methods. The adaptive nature of the controller allows the system to maintain smooth transient responses and improved damping performance, ensuring resilient and reliable grid operation. Furthermore, the proposed approach offers a scalable and computationally efficient solution suitable for future smart grids and microgrids integrating inverter-based renewable sources. Overall, this research contributes a robust and intelligent control framework that bridges the gap between traditional synchronous inertia and modern converter-dominated systems, thereby strengthening the frequency regulation and dynamic performance of sustainable power networks.

Compliance with ethical standards

Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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