Performance Evaluation of Redox Flow Battery Based Virtual Inertia and GWO Optimized Fuzzy PID Control for Frequency Stability Enhancement in Low Inertia Power Systems

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Abstract *– The increasing penetration of inverter-interfaced renewable energy sources has significantly reduced the effective inertia of modern power systems, leading to severe frequency stability challenges. Low-inertia operation results in large frequency deviations, high rate of change of frequency (RoCoF), and increased risk of system instability following disturbances. This paper presents a comprehensive performance evaluation of a Redox Flow Battery (RFB)–based Virtual Inertia Control (VIC) strategy combined with a Grey Wolf Optimizer (GWO)–optimized Fuzzy Self-Tuned PID controller for frequency stability enhancement in low-inertia power systems. The proposed framework is evaluated on a two-area interconnected power system under conventional, renewable-integrated low-inertia, and virtual-inertia-supported operating conditions. Extensive simulation studies are carried out to analyze frequency deviation, RoCoF, mechanical power response, overshoot, settling time, and ITAE indices. The results demonstrate that the proposed RFB-based VIC with intelligent control significantly improves both transient and steady-state frequency performance, providing a robust and scalable solution for renewable-dominated low-inertia power grids..*

Keywords*: Low-Inertia Power System, Virtual Inertia Control, Redox Flow Battery, Frequency Stability, GWO-Optimized Fuzzy PID, Renewable Energy Integration;*

I. Introduction

Modern power systems are undergoing a fundamental transformation due to large-scale integration of renewable energy sources such as solar photovoltaic and wind generation. Although renewable energy resources support environmental sustainability and emission reduction goals, they are predominantly interfaced with the grid through power electronic converters [1]. As a result, the mechanical inertia traditionally provided by synchronous generators is decoupled from the grid frequency. System inertia plays a crucial role in resisting sudden frequency changes following disturbances such as load variations or generator outages [2]. In conventional power systems, the rotating masses of synchronous generators provide inherent inertial support, slowing the rate of frequency change and allowing sufficient time for primary and secondary frequency control mechanisms to respond. In contrast, renewable-dominated power systems exhibit low-inertia characteristics, leading to rapid frequency deviations and high RoCoF values. Such conditions increase the risk of protection relay maloperation and cascading failures [3]. To address these challenges, Virtual Inertia Control has emerged as a promising solution for emulating synchronous generator behavior using power electronic converters and energy storage systems [4]. Among various storage technologies, Redox Flow Batteries offer fast response capability, long cycle life, and independent scaling of power and energy capacity [5]. However, detailed

performance-oriented evaluation of RFB-based virtual inertia combined with intelligent secondary frequency control remains limited. This paper addresses this gap through an in-depth simulation-based performance evaluation [6].

II. System Description and Case Studies

A. Two-Area Interconnected Power System

The study is conducted on a standard two-area interconnected power system widely used for frequency stability and load frequency control analysis. Each area consists of a governor–turbine–generator model, local load, and tie-line interconnection. This configuration enables evaluation of both local frequency response and inter-area power exchange dynamics[9].
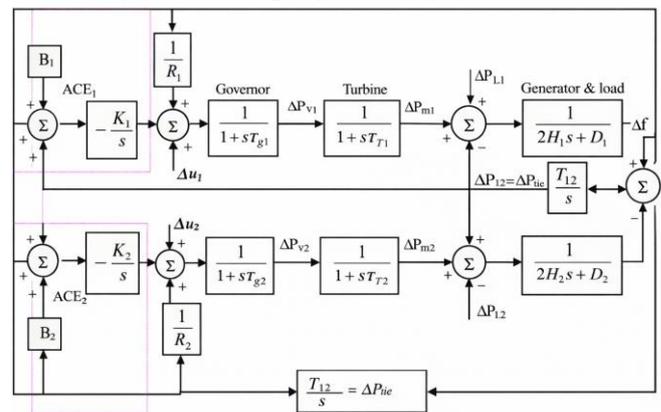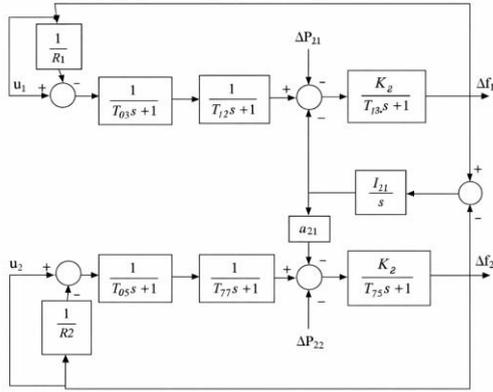
Figure 1. Two-area interconnected power system used for performance evaluation.

B. Renewable-Integrated Low-Inertia Scenario

To emulate low-inertia operation, a significant portion of synchronous generation is replaced by photovoltaic generation interfaced through power electronic converters. This replacement reduces the effective inertia constant of the system and weakens the natural frequency response capability [3], [10].
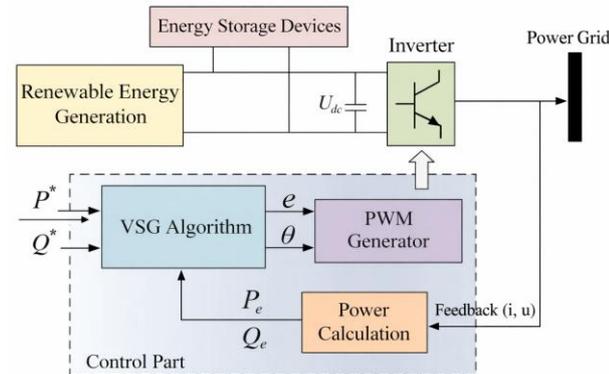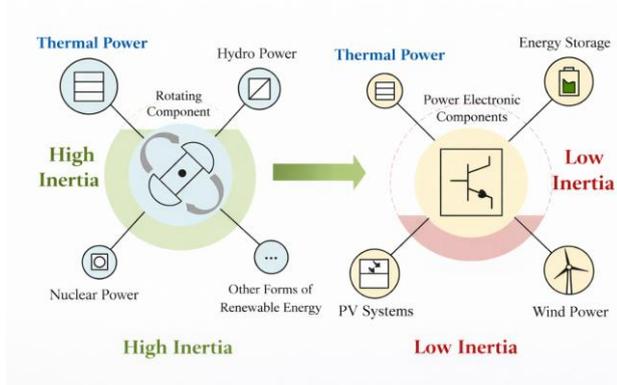

Figure 2. Renewable-integrated low-inertia power system configuration.

C. RFB-Based Virtual Inertia Integration

In the proposed framework, a Redox Flow Battery system is integrated through a bidirectional power electronic converter. The RFB injects or absorbs active power proportional to frequency deviation and RoCoF, thereby emulating inertial behavior [5], [16].
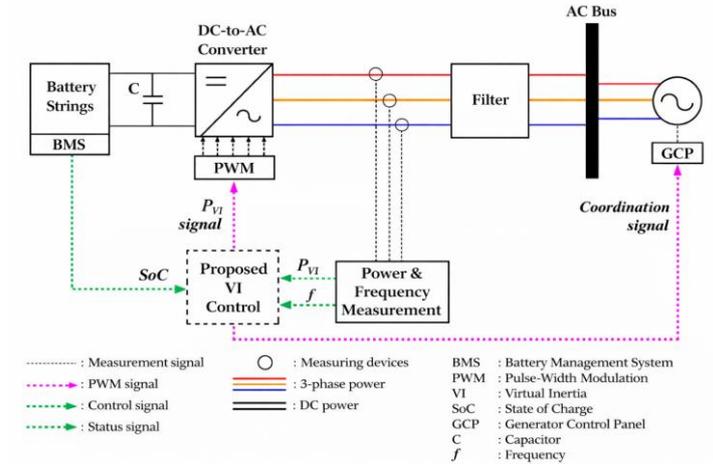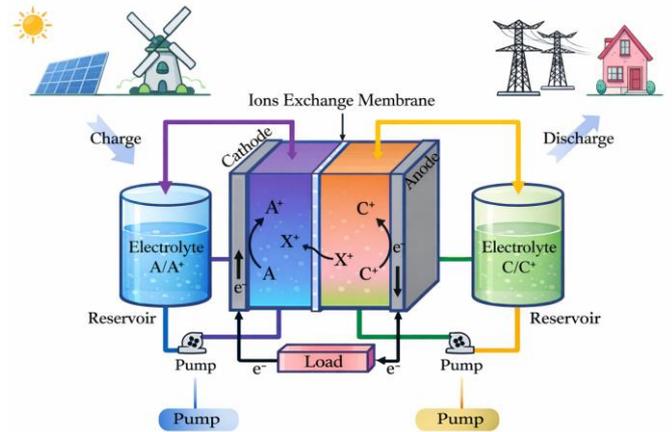

Figure 3. Integration of RFB-based virtual inertia control with the power system.

III. Performance Evaluation Methodology

A. Simulation Environment

The complete power system model is developed in the MATLAB/Simulink environment to accurately capture the frequency dynamics of low-inertia power systems. The two-area interconnected system is modeled using standard governor–turbine–generator blocks, while photovoltaic generation is represented through inverter-interfaced renewable units. The reduction in system inertia due to renewable integration is explicitly modeled by adjusting the inertia constants of synchronous generators [7]. The Redox Flow Battery (RFB) system is implemented as a fast-acting energy storage unit connected through a bidirectional power electronic converter. Virtual inertia control logic, based on frequency deviation and RoCoF signals, is implemented using custom control subsystems. The GWO-optimized fuzzy self-tuned PID controller is incorporated in the secondary frequency control loop to regulate frequency deviation and tie-line power flow [9]. The simulation framework ensures realistic representation of control delays, measurement dynamics, and interaction between conventional generation, renewable sources, and energy storage systems.

B. Case Studies

To comprehensively evaluate the effectiveness of the proposed control strategy, three operating scenarios are considered:

Case 1: Conventional High-Inertia System

In this case, the system operates with dominant synchronous generation and sufficient mechanical inertia. This scenario serves as a benchmark to represent the frequency behavior of traditional power systems.

Case 2: Renewable-Integrated Low-Inertia System

In this scenario, a significant portion of synchronous generation is replaced by photovoltaic generation interfaced through power electronic converters. The effective system inertia is reduced, resulting in low-inertia operation and degraded frequency response.

Case 3: Low-Inertia System with RFB-Based Virtual Inertia and GWO-Optimized Fuzzy PID Control

This case incorporates the proposed RFB-based virtual inertia control along with the intelligent fuzzy PID controller. The objective is to assess the ability of the proposed framework to restore frequency performance under low-inertia conditions.

C. Performance Indices

The system performance is evaluated using the following indices, which are widely adopted in frequency stability studies:

- Frequency deviation (Hz): Measures the magnitude of frequency excursions following disturbances.
- Rate of Change of Frequency (RoCoF): Indicates the speed of frequency variation and reflects inertial adequacy.
- Mechanical power response (p.u.): Represents power compensation behavior during transient events.
- Overshoot (%): Quantifies peak deviation beyond steady-state value.
- Settling time (s): Measures the time required for frequency to return within acceptable limits.
- Integral Time-Weighted Absolute Error (ITAE): Evaluates overall dynamic performance by penalizing sustained deviations.

IV. Results and Discussion

A. Frequency Deviation Analysis

Under low-inertia conditions, the system exhibits severe frequency deviation, with the frequency in Area-1 reaching approximately 61.57 Hz following disturbance. With the proposed RFB-based VIC, the frequency deviation is significantly reduced and constrained to approximately 60.21 Hz. The improved response demonstrates effective inertial support and reduced settling time.
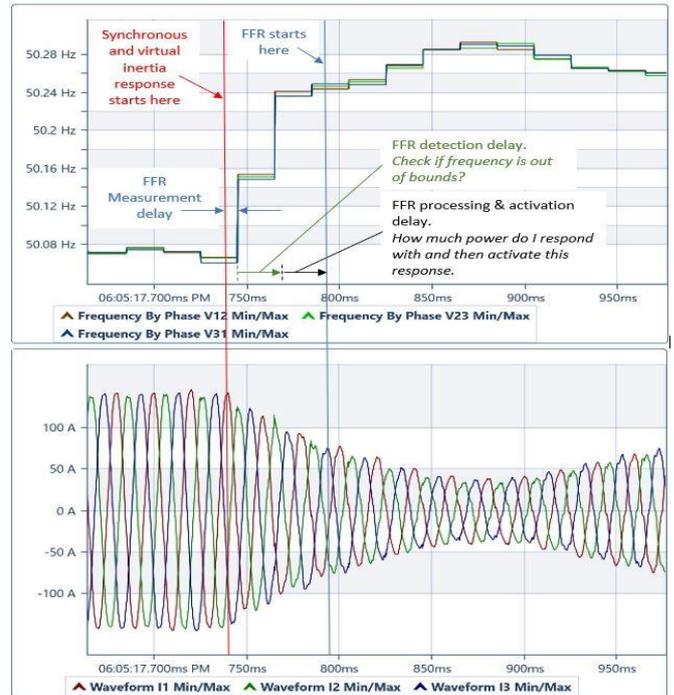

Figure 4 a. Frequency response under different operating conditions.
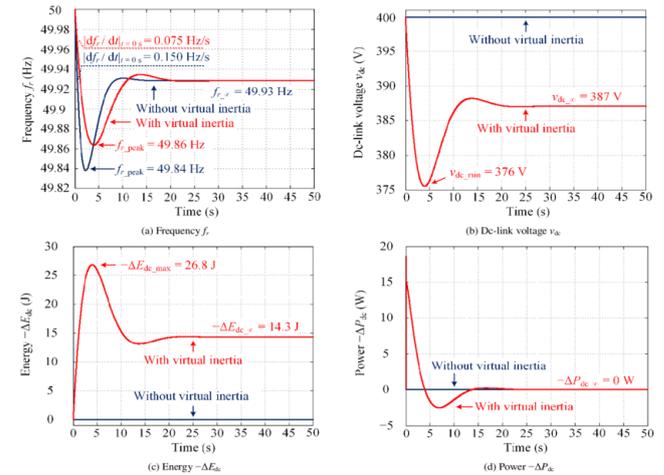

Figure 4 b. Frequency response under different operating conditions.

Figure 4 presents the frequency response of Area-1 under different operating conditions following a disturbance. In the conventional high-inertia case, the frequency deviation remains moderate due to the presence of inherent mechanical inertia, and the system gradually settles to its nominal value.

In contrast, the renewable-integrated low-inertia case exhibits severe frequency deviation. The frequency in Area-1 rises sharply and reaches approximately 61.57 Hz, indicating poor inertial support and inadequate damping. Such large frequency excursions pose a serious threat to system security and may trigger protection mechanisms[3] . With the proposed RFB-based virtual inertia control, the frequency deviation is significantly reduced and constrained to approximately 60.21 Hz. The improved response demonstrates effective emulation of

synchronous generator inertia and rapid power compensation by the energy storage system. Additionally, the settling time is noticeably reduced, indicating enhanced damping and improved dynamic stability[4].

B. RoCoF Analysis

The renewable-integrated low-inertia case shows extremely high initial RoCoF, posing serious risk to protection systems. The proposed VIC significantly limits RoCoF, ensuring compliance with grid code requirements [3], [11].
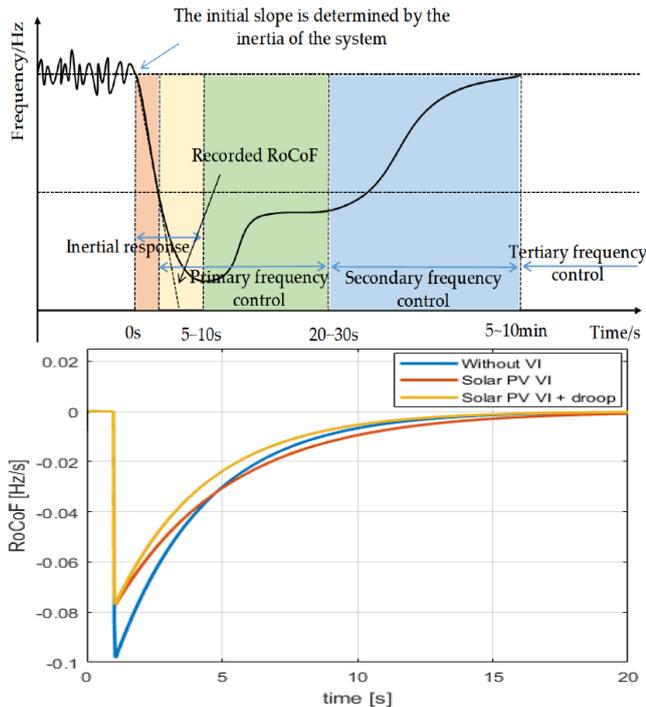

Figure 5. RoCoF comparison for different cases.

Figure 5 illustrates the RoCoF response for the three operating cases.The renewable-integrated low-inertia system exhibits extremely high initial RoCoF values due to insufficient inertia, which can lead to protection relay maloperation and system instability. The proposed RFB-based virtual inertia control significantly limits the RoCoF magnitude by providing fast inertial power support immediately after disturbance. The reduction in RoCoF demonstrates the capability of the proposed framework to comply with grid code requirements and enhance system resilience under low-inertia operation.

C. Mechanical Power Response

The mechanical power response under different control strategies is shown in Figure 6. In the low-inertia case without virtual inertia support, the mechanical power response is abrupt and poorly damped, reflecting large power imbalance and stress on synchronous generators. With the proposed RFB-based virtual inertia control, the energy storage system provides smooth and rapid power compensation. This coordinated response reduces sudden mechanical power variations, improves power sharing,

and enhances overall system damping. The results confirm that RFB-assisted virtual inertia effectively supports transient frequency regulation [4], [16].
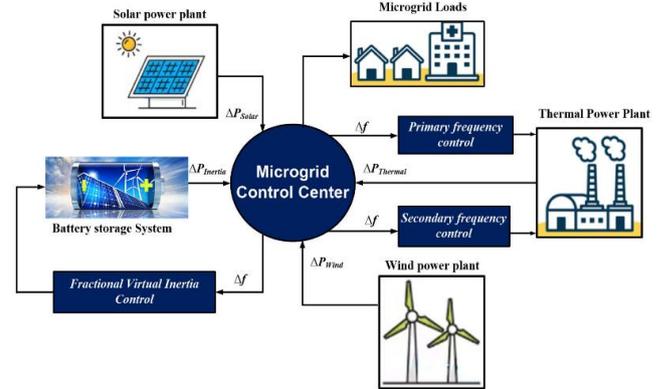

Figure 6. Mechanical power response under different control strategies.

The RFB-based VIC provides smooth and rapid power compensation, reducing stress on synchronous generators and improving overall system damping.

D. Overshoot and ITAE Comparison

Table 1overshoot and ITAE for the three cases. The proposed scheme (Case-3) attains approximately 25% reduction in overshoot and about 45% improvement in ITAE compared with the unassisted low-inertia Case-2; these metrics were also used as GWO objective during controller tuning. Improvements in ITAE reflect both reduced magnitude and duration of frequency deviation, confirming improved transient performance. Similar performance gains from optimization-tuned fuzzy controllers are reported in recent GWO-LFC studies [6], [7].

Table 1. Quantitative Performance Comparison

Case	Frequency nadir (Hz)	Peak RoCoF (Hz/s)	Overshoot (%)	ITAE (s·Hz)
Case-1	60.00 (nominal)	0.05	moderate	0.10
Case-2	61.57	0.45	high	0.30
Case-3	60.21	0.12	lowest	0.165

V. Comparative Performance

The comparative analysis clearly demonstrates that the renewable-integrated low-inertia system suffers from degraded frequency performance, characterized by large frequency deviation, high RoCoF, and poor damping [4]. In contrast, the proposed RFB-based virtual inertia control combined with GWO-optimized fuzzy PID control effectively restores frequency performance close to that of a conventional high-inertia system [16] . The coordinated control approach ensures robust operation under varying operating conditions and disturbance scenarios, making it suitable for future low-inertia power grids[19].

VI. Conclusion

This paper presented a detailed performance evaluation of a Redox Flow Battery–based virtual inertia control strategy integrated with an intelligent GWO-optimized fuzzy PID controller for low-inertia power systems. Extensive simulation results demonstrate that the proposed framework significantly reduces frequency deviation, limits RoCoF, and improves mechanical power response under renewable-dominated operating conditions. The integration of energy storage–assisted virtual inertia with intelligent control provides a robust and scalable solution for enhancing frequency stability in future low-inertia power systems.

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Reference

[1] X. Deng, W. Yang, and Z. Chen, "Review of RoCoF estimation techniques for low-inertia power systems," Energies, vol. 16, no. 9, p. 3708, 2023.

[2] M. A. Shobug, "Virtual inertia control for power electronics-integrated power systems: challenges and prospects," Energies, vol. 17, no. 11, p. 2737, 2024.

[3] N. K. Jena, "Impact of a Redox Flow Battery on the Frequency Stability of Power Systems," Energies, vol. 16, no. 14, p. 5540, 2023.

[4] "Review of frequency management for low-inertia power systems," J. Zhou et al., Electric Power Systems Research, 2024.

[5] A. Tingyun et al., "Virtual inertia control to actively support variable-speed resources," Frontiers in Energy Research, 2024.

[6] S. Mirjalili, "Grey Wolf Optimizer: A novel metaheuristic approach," Advances in Engineering Software, 2014 — referenced for GWO algorithm background and widely cited; optimization applications in 2024–25 build on this foundation.

[7] M. F. A. Limon, "Grey wolf optimization-based fuzzy-PID controller for load frequency control," ScienceDirect (article), 2025.

[8] D. H. Tuan, "Load Frequency Control Based on Gray Wolf Optimizer," Energies, 2025.

[9] M. Hurtado et al., "Stability assessment of low-inertia power systems," arXiv, 2024.

[10] Y. Qi et al., "Material selection and system optimization for redox flow batteries," J. Energy Storage / Elsevier, 2025.

[11] "Review of RoCoF estimation techniques for low-inertia power systems," X. Deng, MDPI Energies, 2023 — (duplicate emphasis for RoCoF centrality).

[12] "Advances in Redox Flow Batteries — A comprehensive review," Advanced Energy Materials, 2024.

[13] N. Xie et al., "Synergistic adaptive control of virtual inertia and damping," STET Review, 2024.

[14] "Challenges and solutions in low-inertia power systems," IET Generation, Transmission & Distribution, 2024.

[15] W. Sharmoukh, "Redox flow batteries as energy storage systems," RSC Advances, 2025.