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A Coordinated Virtual Inertia Control Framework for Frequency Stability Enhancement in Low Inertia Power Systems Using Redox Flow Battery and GWO Optimized Fuzzy PID Control

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Abstract *– The rapid transition toward renewable-dominated power systems has significantly reduced system inertia due to the widespread replacement of conventional synchronous generators with inverter-interfaced renewable energy resources. This reduction in inertia leads to severe frequency stability challenges, including high rate of change of frequency and deep frequency deviations following disturbances. To address these issues, this paper presents a coordinated virtual inertia control framework that integrates a Redox Flow Battery-based virtual inertia mechanism with a Grey Wolf Optimizer-optimized fuzzy PID controller. The proposed framework emulates the inertial response of synchronous generators while providing adaptive secondary frequency regulation under varying operating conditions. The control architecture, mathematical foundation, and coordination strategy are systematically discussed, demonstrating the suitability of the proposed approach for enhancing frequency stability in modern low-inertia power systems.*

Keywords*: Low-Inertia Power System, Frequency Stability, Virtual Inertia Control, Redox Flow Battery, Virtual Synchronous Generator, Fuzzy PID Controller, Grey Wolf Optimizer;*

I. Introduction

The global power sector is undergoing a fundamental transformation driven by increasing electricity demand, environmental concerns, and international climate commitments. Large-scale integration of renewable energy sources such as solar photovoltaic and wind generation has become essential for achieving sustainable and low-carbon energy systems. However, most renewable energy resources are interfaced with the grid through power electronic converters and do not inherently provide mechanical inertia.

System inertia plays a crucial role in resisting sudden frequency changes following power imbalances. In conventional power systems, the rotating masses of synchronous generators naturally provide inertial support, slowing down frequency variations and allowing sufficient time for primary and secondary frequency control mechanisms to act. In contrast, renewable-dominated power systems exhibit low-inertia characteristics, making them highly vulnerable to fast frequency excursions and high RoCoF events [1], [2]. Recent grid disturbances and blackout events have highlighted the limitations of conventional frequency control strategies in low-inertia environments [3]. As renewable penetration increases, maintaining frequency stability has become one of the most critical challenges in modern power system operation. Consequently, advanced control strategies capable of compensating for inertia loss are required. Virtual inertia control has emerged as an effective solution for enhancing frequency stability in low-inertia systems. By emulating the inertial behavior of synchronous generators using control algorithms and fast-acting energy storage systems, virtual inertia enables inverter-interfaced resources to participate actively in frequency regulation [4]. Among various energy storage technologies, Redox Flow Batteries offer unique advantages such as independent power and energy ratings, long cycle life, and suitability for repeated charge–discharge operation [5]. In addition to inertial support, intelligent secondary frequency control is required to restore frequency to its nominal value. Fuzzy PID controllers provide adaptive control capability under nonlinear and uncertain system conditions, while meta-heuristic optimization techniques such as the Grey Wolf Optimizer enable optimal tuning of controller parameters [6]. This paper proposes a coordinated framework combining RFB-based virtual inertia control with GWO-optimized fuzzy PID control for frequency stability enhancement in low-inertia power systems.

II. Frequency Stability Challenges in Low-Inertia Power Systems

Frequency stability refers to the ability of a power system to maintain system frequency within acceptable limits following disturbances. In low-inertia systems, reduced kinetic energy results in rapid frequency deviations and increased RoCoF, which may lead to protection mal-operation and system collapse [7].

Table 1 highlights the key differences between conventional high-inertia systems and modern low-inertia systems.

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Table 1. Characteristics of High- and Low-Inertia Power Systems

Feature	**High-Inertia System**	**Low-Inertia System**
Dominant generation	Synchronous machines	Inverter-based RES
Inertia contribution	High	Very low
RoCoF	Low	High
Frequency nadir	Shallow	Deep
Stability margin	High	Reduced

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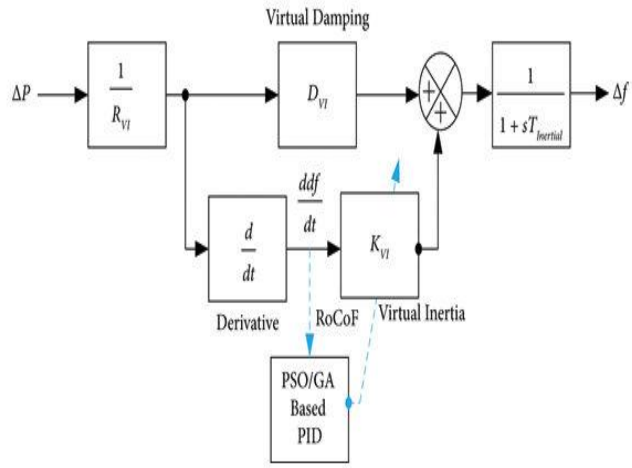
III. Related Work

Several studies have investigated frequency stability enhancement in renewable-dominated power systems. Virtual synchronous generator and synchronverter-based approaches have been proposed to replicate synchronous generator dynamics using power electronic converters [8]. Energy storage-assisted virtual inertia schemes have demonstrated effective mitigation of frequency deviations and RoCoF [9]. Redox Flow Batteries have gained attention for grid-scale frequency regulation due to their scalability and durability [10]. Intelligent control strategies such as fuzzy logic controllers have been applied to load frequency control problems to handle nonlinearities and parameter uncertainties [11]. Furthermore, optimization-based tuning of fuzzy controllers using meta-heuristic algorithms, including PSO and GWO, has shown improved control performance [12]. Despite these advancements, limited work has focused on the coordinated integration of RFB-based virtual inertia with GWO-optimized fuzzy PID control in low-inertia interconnected power systems, which motivates the present study.

IV. Proposed Coordinated Control Framework

In The proposed framework integrates renewable generation with a Redox Flow Battery (RFB) through a bidirectional power electronic converter for frequency stability enhancement in low-inertia power systems. System frequency and its rate of change are used to generate coordinated virtual inertia and secondary frequency control actions.



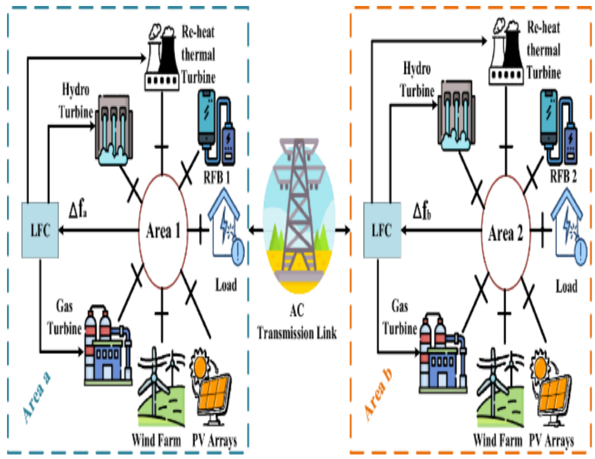
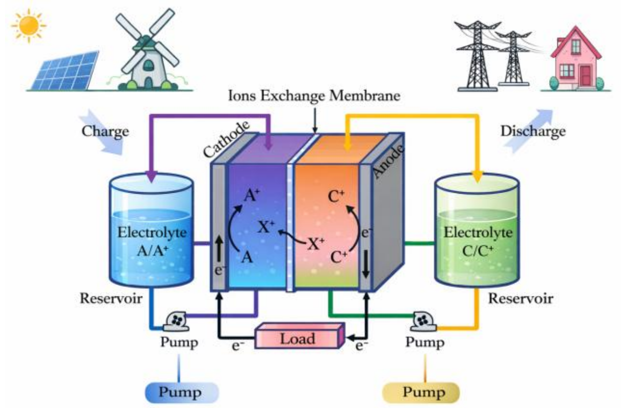


Figure 1. Overall architecture of the proposed coordinated virtual inertia and frequency control framework.

Redox Flow Battery-Based Virtual Inertia Control

The virtual inertia controller enables the RFB to emulate synchronous generator inertia by injecting or absorbing active power proportional to frequency deviation and RoCoF. This provides fast inertial support during transient disturbances in low-inertia systems.



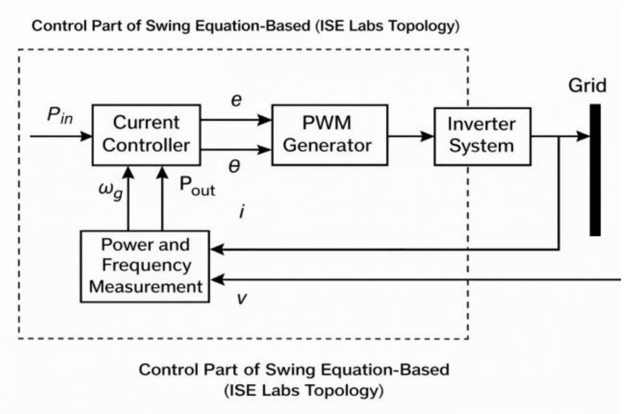


Figure 2. Virtual inertia control mechanism implemented using Redox Flow Battery energy storage.

6. GWO-Optimized Fuzzy PID Controller

A fuzzy PID controller optimized using the Grey Wolf Optimizer is employed for secondary frequency regulation. The fuzzy controller processes frequency error and its derivative, while GWO optimally tunes controller parameters to improve damping and robustness under varying operating conditions.

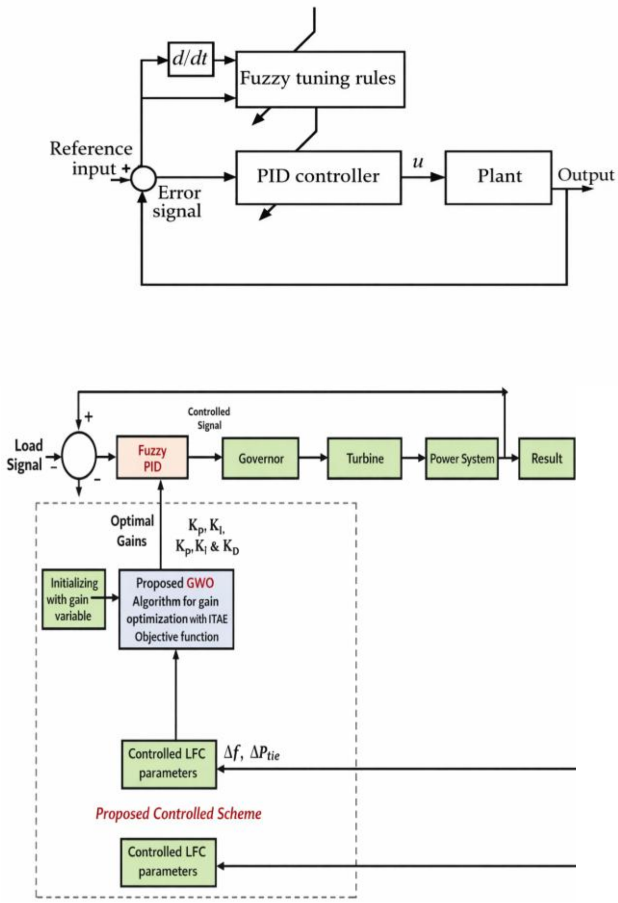


Figure 3. Structure of the GWO-optimized fuzzy PID controller for secondary frequency control.

Conceptual Frequency Response Analysis

The conceptual frequency response indicates that the proposed control framework reduces RoCoF, improves frequency nadir, and enhances damping compared to low-inertia systems without virtual inertia support, thereby improving overall frequency stability.

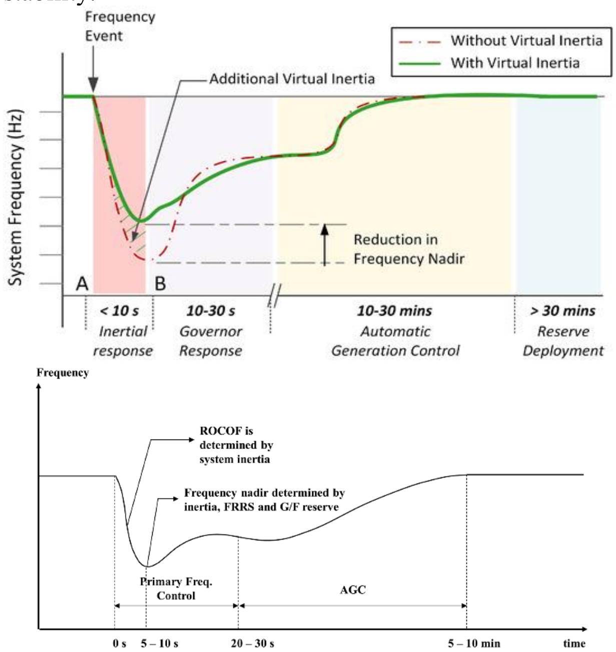


Figure 4. Conceptual frequency response comparison with and without virtual inertia support.

V. Conclusion

This paper presented a coordinated virtual inertia control framework for frequency stability enhancement in low-inertia power systems. By integrating Redox Flow Battery-based virtual inertia with a GWO-optimized fuzzy PID controller, the proposed approach effectively addresses the challenges associated with reduced system inertia and renewable intermittency. The conceptual architecture and control strategy demonstrate how fast inertial support and adaptive secondary frequency regulation can be coordinated to improve system resilience. The proposed framework provides a solid foundation for future implementation and performance validation in renewable-dominated power systems.

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