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Semantic-AI–Enhanced LFC for PV-Integrated Grids Using a TFOID-(PDN+1) Framework

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ABSTRACT

As photovoltaic (PV) penetration increases, reduced system inertia intensifies frequency stability challenges in interconnected power grids. Conventional proportional integral derivative–based and single-loop fractional-order load frequency control schemes often exhibit limited disturbance rejection and robustness under stochastic PV fluctuations and parameter uncertainties. This paper proposes a cascaded tilted fractional-order integral–derivative–(PDN+1) load frequency control framework for a two-area PV–storage-integrated system, enhanced by a semantics-guided intelligent optimization strategy. A modified multi-objective function combining integral squared time absolute error and squared control effort embeds control semantics related to disturbance persistence and energy limitation. The lemur optimizer is employed for parameter tuning. Simulation results demonstrate faster response, smaller frequency deviations, and improved robustness compared with Proportional–Integral–(Proportional–Derivative+1), functional-order–proportional integral derivative, and single-objective integral squared time absolute error–based controllers, while maintaining engineering feasibility for future low-inertia power systems.

KEYWORDS

Photovoltaic, Load Frequency Control, TFOID-(PDN+1), Modified Objective Function, Parameter Optimization

INTRODUCTION

Driven by global carbon neutrality goals, large-scale photovoltaic (PV) generation has become a key means of optimizing the power mix. By the end of 2022, global PV capacity exceeded 843 GW, accounting for over 28% of new power additions, and is projected to supply more than 17% of global electricity by 2030 (Gilabert-Torres et al., 2025; Zhang et al., 2025). However, PV intermittency and the low inertia of inverter-based PV systems significantly reduce grid inertia, increasing frequency deviation risks and weakening disturbance tolerance in interconnected power systems (Astereki et al., 2026; Z. U. Khan et al., 2024; Yousef et al., 2024).

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Consequently, significant research efforts have been directed toward load frequency control (LFC) algorithms for interconnected power systems with large-scale PV integration. While conventional proportional-integral-derivative (PID) controllers remain widely used in LFC applications because of their simplicity and efficiency, their linear structure offers limited disturbance rejection capabilities, making them inadequate for systems with high PV penetration (Abomazid et al., 2022; Ekinci et al., 2024; Fu et al., 2024; Irfan et al., 2024; Wadi et al., 2024; Yıldız et al., 2024). To mitigate PV output fluctuations, Yang et al. (2025) integrated solar radiation data with a fractional-order (FO) PID controller for frequency regulation; however, the single-loop architecture of functional-order–proportional integral derivative (FOPID) constrains its effectiveness in improving frequency quality. In comparison, advanced control techniques such as sliding mode control, model predictive control, and deep reinforcement learning generally demand substantial computational resources and high-fidelity system models, which can limit their practical applicability under real-time constraints and in the presence of model uncertainties (Li et al., 2021; Li & Cui., 2025 Ma et al., 2024; Nagi et al., 2025; Wang & Huang, 2024;). In contrast, intelligent optimization algorithms (IOA) offer a more direct and tractable approach to LFC optimization. Rather than constructing intricate mathematical models, IOA utilize a Simulink simulation model derived from the system transfer function, along with a suitably formulated objective function, to facilitate the efficient identification of effective controller parameters. As a result, the use of novel IOA to optimize innovative controller designs has emerged as an active and promising research direction in the field of power system LFC (Ahmed et al., 2022; I. A. Khan et al., 2024).

In terms of controller structural innovations, cascade control has demonstrated considerable potential owing to its hierarchical architecture, which employs an outer loop for global optimization and an inner loop for rapid disturbance rejection (Behera et al., 2019; Nour et al., 2023; Sharma & Singh, 2024; Tavakoli et al., 2024; Wang et al., 2025; Yang et al., 2022). For instance, a Proportional–Integral (PI)– (Proportional–Derivative) PD cascade controller was developed for thermal power systems (Irshad & Ali, 2020); however, this design did not account for the coordinated operation of hydro, gas, and renewable energy units in modern power systems. A Fractional-Order Proportional–Integral–Derivative–Tilted Integral–Derivative cascade controller tuned via the squirrel search algorithm (SSA) was proposed for a wind–diesel hybrid system, while a PI–(PD+1) cascade controller optimized using particle swarm optimization (PSO)was applied to an interconnected system with PV and flywheel energy storage (Guha et al., 2022; Wang et al., 2023). Nevertheless, both approaches overlooked the impact of generation rate constraints (GRC) on dynamic performance. Furthermore, a PDN–PI controller based on the coyote optimization algorithm was introduced, yet its inner-loop design neglected the influence of regional frequency deviation on control performance (Abou El-Ela et al., 2022).

The objective function serves as a fitness function in IOA and is directly used for controller parameter optimization, allowing evaluation of control strategy performance (Zhang & Fu, 2025). Researchers have employed single-objective tuning formulas, such as integral time absolute error, integral absolute error, integral square error (ISE), and integral time square error, in power system LFC (Agwa et al., 2022; Ali et al., 2025; Yang et al., 2024). In contrast, a multi-objective formulation incorporating ISE, control signal, and regulation time, as proposed in some studies, is applicable only to conventional PID controllers and has not been validated for complex cascade control structures (Khalil et al., 2023). Another multi-objective method based on integral squared time absolute error (ISTAE) and input signals for individual units has been applied to cascaded PID–PID control; however, it is limited to islanded microgrids and has not been tested in modern regional interconnected grids (Khalil et al., 2024).

In addition to control algorithm design, the deployment of energy storage systems has become a widely adopted auxiliary approach for enhancing frequency regulation. Among various storage technologies, such as electrochemical, flywheel, and virtual inertia systems, hydrogen-based energy