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Practical Validation of an Adaptive-Gain Fractional-Order PI Controller for Grid-tied PV Systems

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Abstract

This study investigates energy management in grid-connected photovoltaic (PV) systems, with particular emphasis on the regulation of active and reactive power exchanged with the utility grid under dynamic operating conditions. The intermittent nature of solar energy and grid disturbances requires control strategies capable of ensuring fast response and high-power quality. To address these challenges, an adaptive-gain fractional-order proportional–integral (AG-FOPI) controller is proposed for the inner current control loop of a grid-tied PV inverter. The controller combines the robustness and memory properties of fractional-order integration with an adaptive proportional gain to enhance transient performance while preserving steady-state accuracy. The proposed control strategy is implemented and validated using real-time hardware-in-the-loop (HIL) experimentation based on a TI F28379D digital control platform. Experimental results demonstrate fast and accurate tracking of active and reactive power references, with settling times below 10 ms and negligible overshoot during dynamic transitions. In addition, the injected grid current exhibits low harmonic distortion, with total harmonic distortion consistently maintained below 1.8%. These results confirm the practical suitability of the AG-FOPI controller for grid-tied photovoltaic applications.

Keywords: Grid-tied photovoltaic systems; Fractional-order control; Adaptive proportional gain; Hardware-in-the-loop (HIL); Active and reactive power control.

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1. Introduction

The development of industrial and urban activities is accompanied by a growing energy demand, exerting increased pressure on fossil resources and accentuating environmental problems linked to greenhouse gas emissions. In recent decades, this continuous rise in electricity consumption has further highlighted the limitations of conventional energy systems and reinforced the need for sustainable alternatives [1], [2]. Renewable energies—and photovoltaics (PV) in particular—are becoming a strong solution for a sustainable energy transition. Thanks to their modularity, abundant availability, and steadily falling production costs, PV systems are increasingly being integrated into distribution networks. As deployment accelerates worldwide, PV technology has become a major contributor to distributed generation and a key component of modern power networks [3].

However, photovoltaic energy injection into the electrical grid presents major technical challenges. Due to the intermittent nature of solar radiation and dynamic operating conditions of the grid, managing both active and reactive power in compliance with grid standards is complex. The inverter plays a crucial role in this context: it must ensure a high-quality conversion of DC power into AC while minimizing harmonic distortion (THD) and enabling precise control of energy exchange. These requirements become increasingly stringent with higher PV penetration levels, where voltage fluctuations, fast irradiance variations, and grid disturbances can significantly affect system stability and power quality [4], [5]. Therefore, inverter control strategies must guarantee fast dynamic response while preserving low current distortion and accurate power regulation under varying operating conditions [6].

Conventional Proportional–Integral (PI) controllers remain widely used due to their simple design and effective steady-state performance. Yet, they often suffer from weak disturbance rejection and slow dynamic response in rapidly changing environments. These limitations are particularly critical in grid-connected PV systems, where sudden changes in irradiance, load, or grid voltage require fast and adaptive control actions [7]. Moreover, the fixed-parameter structure of classical PI controllers restricts their ability to cope with nonlinearities and time-varying dynamics inherent to power electronic converters, often leading to overshoot, steady-state errors, and degraded harmonic performance under real operating conditions [8], [9].

To overcome these drawbacks, numerous advanced control strategies have been investigated in the literature, including model predictive control, sliding mode control, adaptive backstepping, feedback linearization, and artificial intelligence–based techniques such as neural networks and fuzzy logic controllers [10–13]. Although these methods can significantly improve dynamic performance and tracking accuracy, they are often associated with high computational complexity, demanding tuning procedures, or reduced suitability for real-time embedded implementation.

Among emerging alternatives, fractional-order control techniques have attracted considerable attention. By extending the integration and differentiation orders from integer to non-integer values, fractional-order PI (FOPI) controllers introduce additional degrees of freedom that allow more precise shaping of system dynamics and improved robustness against parameter uncertainties [14–16]. Several studies have reported superior transient response, enhanced disturbance rejection, and better frequency-domain characteristics of FOPI controllers compared to classical PI controllers, particularly in grid-connected PV applications [17], [18]. Nevertheless, most reported results rely mainly on numerical simulations, and practical validation through real-time experimental platforms remains limited.

In parallel, adaptive control mechanisms have been proposed to further enhance inverter performance by adjusting controller parameters online according to system behavior. Adaptive gain strategies enable aggressive control action during transients while maintaining stability and reduced oscillations near steady state [19]. However, the combination of adaptive gain mechanisms with fractional-order control, and their validation under realistic real-time conditions, is still insufficiently explored in the existing literature.

This work addresses this research gap by investigating the practical implementation and real-time validation of an adaptive-gain fractional-order proportional–integral (AG-FOPI) controller for grid-connected photovoltaic systems.

The proposed controller combines the memory and robustness properties of fractional-order integration with an adaptive proportional gain mechanism to ensure fast transient response and improved steady-state performance. The controller parameters are optimized using the Particle Swarm Optimization (PSO) algorithm to achieve an optimal compromise between dynamic response, stability, and power quality.

A key contribution of this study is the primarily validated through Hardware-in-the-Loop (HIL) experimentation. By implementing the control algorithm on a TI F28379D digital control platform and interfacing it with a real-time simulated power stage, the proposed approach enables realistic assessment of implementation constraints such as sampling delays, quantization effects, and computational limitations, which are often neglected in purely simulation-based studies. Experimental results demonstrate accurate regulation of active and reactive power, reduced total harmonic distortion of grid-injected currents, and improved robustness compared to conventional PI and standard FOPI controllers.

The remainder of this paper is organized as follows. Section 2 presents the modeling of the grid-connected PV system. Section 3 describes the design of the AG-FOPI controller and the PSO-based optimization procedure. Section 4 presents the Hardware-in-the-Loop experimental setup. Section 5 discusses the experimental results. Finally, Section 6 concludes the paper.

2. System Description and Modeling

The overall architecture of the studied single-phase grid-connected photovoltaic (PV) system is depicted in Fig. 1. The system is composed of three main functional blocks: the DC power generation unit, the power conversion and filtering unit, and the control and synchronization unit.

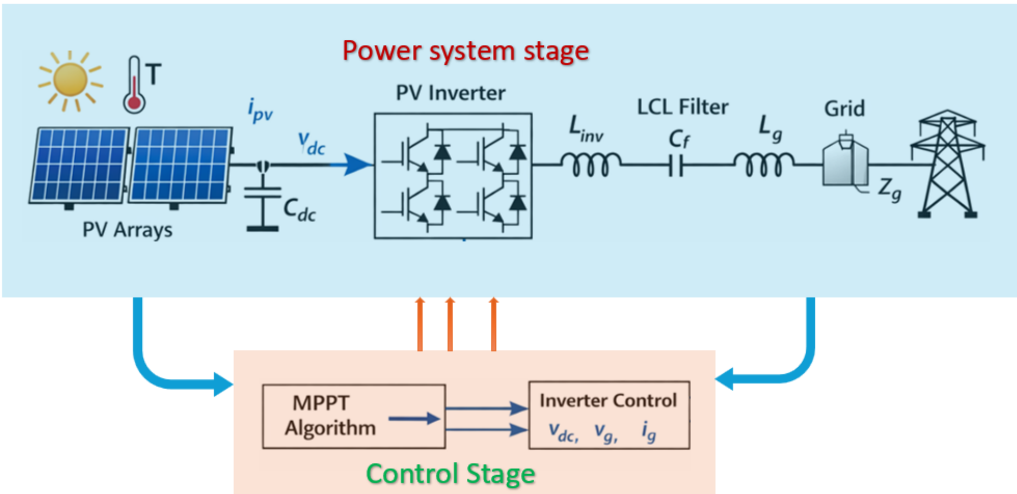

Figure 1. Architecture of the single-phase grid-connected photovoltaic system.

2.1 DC Power Generation Unit

A programmable DC power source is used to emulate the behavior of a photovoltaic generator. This approach allows controlled reproduction of PV operating conditions and facilitates repeatable real-time testing within the HIL environment. A DC-link capacitor $C_{dc}$is connected in parallel with the DC source to ensure power decoupling, stabilize the DC bus voltage, and attenuate high-frequency voltage ripple induced by inverter switching.

The DC-link voltage regulation is essential to guarantee proper inverter operation and to ensure that sufficient energy is available for grid injection under varying load and power demand conditions.

2.2 Power Conversion and Filtering Unit

The DC/AC conversion stage consists of a single-phase two-level Voltage Source Inverter (VSI). The inverter is followed by an LCL filter composed of inverter-side inductance L_{inv}, grid-side inductance L_g, and filter capacitor C_f, where L_{inv}, L_g, and C_f denote the inverter-side inductance, grid-side inductance, and filter capacitor, respectively. The LCL filter is designed to attenuate switching harmonics while maintaining low total harmonic distortion (THD) in the grid-injected current, ensuring compliance with grid interconnection standards.

An autotransformer may be used to adapt voltage levels and improve coupling with the utility grid, particularly in laboratory or experimental setups.

2.3 Control and Synchronization Unit

The control structure adopts a hierarchical dual-loop strategy. The outer voltage control loop regulates the DC-link voltage $v_{dc}$by comparing it to its reference value v_{dc}^*. The inner loop controls the grid-injected current i_g, ensuring accurate tracking of the reference current i_g^*, which is derived from the active and reactive power setpoints $P^*$and Q^*. This loop incorporates the proposed Adaptive-gain Fractional-Order PI (AG-FOPI) controller, whose role is to enhance transient response, improve robustness, and reduce steady-state error under dynamic operating conditions.

To ensure proper synchronization with the grid, a Phase-Locked Loop (PLL) is employed to estimate the grid voltage phase angle θ. The estimated angle enables transformation of system variables from the stationary frame to the rotating dq reference frame, using Clarke and Park transformations. In the dq frame, the inverter dynamics are simplified, allowing decoupled control of active and reactive power.

2.4 Dynamic Model in the dq Reference Frame

The inverter current dynamics expressed in the dq reference frame are given by:

$$\begin{cases} \dot{I}_d = -\frac{R}{L} I_d + \omega I_q - \frac{1}{L} V_d + \frac{V_{dc}}{L} S_d \\ \dot{I}_q = -\frac{R}{L} I_q - \omega I_d - \frac{1}{L} V_q + \frac{V_{dc}}{L} S_q \end{cases} \tag{1}$$

where $S_d$and $S_q$are the modulation signals generated by the control law, $V_d$and $V_q$are the grid voltage components in the dq frame, $\omega$is the grid angular frequency, and $R$and Lrepresent the equivalent resistance and inductance of the filter.

Switching and conduction losses are neglected in this modeling stage for control design purposes. Nonlinear coupling terms are compensated using feedforward techniques, which allows independent regulation of the current components.

Under these assumptions, the active and reactive powers injected into the grid can be expressed as:

$$\begin{cases} P = \frac{3}{2}(V_d I_d + V_q I_q) \\ Q = \frac{3}{2}(V_q I_d - V_d I_q) \end{cases} \tag{2}$$

These expressions clearly demonstrate that, under grid-oriented control where $V_q \approx 0$, active power is primarily controlled through I_d, while reactive power is governed by I_q. This property forms the theoretical basis for the decoupled control strategy adopted in this work.

2.5 Summary of the Control-Oriented Model

The proposed system architecture enables efficient energy injection into the utility grid with independent regulation of active and reactive power. The use of the dq reference frame simplifies control design and allows the proposed AG-FOPI controller to operate effectively within the inner current loop.

3. AG-FOPI Controller Design

To ensure robust and high-performance control of the grid-injected current, this work proposes an Adaptive-Gain Fractional-Order Proportional–Integral (AG-FOPI) controller. The controller is specifically designed for the inner current loop of a grid-connected PV inverter, where fast dynamic response and robustness against disturbances are critical. The proposed approach combines the memory properties of fractional-order calculus with a nonlinear adaptive mechanism applied to the proportional gain, enabling improved performance under varying operating conditions.

3.1 Control Law Formulation

The control input $u(t)$applied to the inner current loop is defined as:

$$u(t) = k_p(e(t)) \cdot e(t) + k_i \cdot D^{-\lambda} e(t) \tag{3}$$

where:

- $e(t) = i_g^*(t) - i_g(t)$is the current tracking error,
- $D^{-\lambda}$denotes the fractional-order integral operator of order $\lambda$with $0 < \lambda \leq 1$,
- $k_i$is the constant integral gain,
- $k_p(e)$ is an adaptive proportional gain that adjusts according to the error magnitude.

Unlike classical PI and standard FOPI controllers with fixed gains, the proposed AG-FOPI structure dynamically adjusts the proportional action, allowing the controller to react aggressively during transients while maintaining smooth behavior near steady state.

3.2 Adaptive Proportional Gain Mechanism

The adaptive proportional gain is defined using a hyperbolic tangent function:

$$k_p(e) = k_{p0} + \Delta k_p \cdot \tanh(\alpha \mid e(t) \mid) \quad (4)$$

where:

- $k_{p0}$is the nominal proportional gain,
- Δk_pdetermines the maximum gain variation,
- αcontrols the sensitivity of the gain adaptation.

This nonlinear adaptation law ensures a smooth and bounded variation of the proportional gain**.** For large tracking errors, the gain increases rapidly, providing strong corrective action and improving transient response. As the error decreases, the gain gradually saturates toward its nominal value, which helps reduce steady-state oscillations and prevents excessive control effort**.**

The adaptive mechanism therefore provides:

- Fast transient response under sudden disturbances or reference changes**;**
- Reduced steady-state ripple and improved stability near equilibrium**;**
- Enhanced robustness against parameter uncertainties and grid disturbances**.**

3.3 Advantages of Fractional-Order Integration

The fractional-order integral term $D^{-\lambda}e(t)$introduces a distributed memory effect that cannot be achieved with classical integer-order integration. This property allows more flexible shaping of the closed-loop dynamics by adjusting the order λ**.**

Compared to conventional PI controllers, the fractional-order formulation:

- Improves the trade-off between response speed and steady-state accuracy**;**
- Enhances robustness to system parameter variations**,** particularly in the presence of grid impedance uncertainty;

- Provides smoother dynamic behavior under rapidly changing operating conditions**,** such as fluctuating irradiance or grid disturbances.

These characteristics make fractional-order control particularly suitable for grid-connected PV applications, where system dynamics are inherently nonlinear and time-varying.

3.4 Parameter Optimization Using PSO

The AG-FOPI controller parameters $\{k_{p0}, \Delta k_p, k_i, \lambda, \alpha\}$ are optimized using the Particle Swarm Optimization (PSO) algorithm**.** PSO is selected due to its simplicity, fast convergence, and ability to handle nonlinear, multi-objective optimization problems without requiring gradient information**.**

The objective function minimized by PSO is defined as:

$$J = w_1 T_s + w_2 M_p + w_3 \text{ISE} \quad (5)$$

where:

- $T_s$is the settling time,
- $M_p$is the maximum overshoot,
- ISEis the integral of the squared error,
- $w_1, w_2, w_3$are weighting coefficients reflecting control priorities.

This cost function ensures a balanced optimization that simultaneously addresses transient performance, overshoot limitation, and steady-state accuracy. The weighting coefficients are selected to favor fast response while maintaining acceptable power quality and stability.

3.5 Digital Implementation Aspects

The AG-FOPI controller is implemented in discrete time using the Grünwald–Letnikov approximation for the fractional-order integral term. This approximation is well suited for real-time digital implementation and provides a good compromise between accuracy and computational complexity**.**

The controller is deployed within the inner current loop of the dual-loop control architecture, while the outer loop regulates the DC-link voltage using a conventional PI controller.

4. Hardware-in-the-Loop Experimental Setup

Hardware-in-the-Loop (HIL) testing is a real-time validation technique that enables the evaluation of control algorithms on actual digital hardware while the physical power system is simulated in real time. This approach provides a realistic compromise between offline simulation and full-scale experimental testing, allowing safe, repeatable, and cost-effective validation under conditions close to real grid operation.

In this work, the HIL platform is used to validate the proposed AG-FOPI controller. The power stage of the grid-connected PV system—including the photovoltaic source, single-phase voltage source inverter, LCL filter, and utility grid—is modeled in MATLAB/Simulink and executed in real time on a host computer. The control algorithm is implemented on a TI F28379D digital signal controller, which interfaces with the simulated plant through a UART communication interface over a USB connection, ensuring closed-loop operation under real-time constraints.

This configuration allows realistic assessment of embedded implementation constraints, such as sampling delays, quantization effects, and computational limitations, which are typically neglected in purely simulation-based studies. The HIL platform operates at a sampling frequency of 5us, which is sufficient to capture the fast dynamics of power electronic converters and current control loops.

The overall architecture of the HIL setup is illustrated in Fig. 2, showing the interaction between the real controller hardware and the simulated power stage. This setup ensures that the controller behavior observed during testing closely reflects real-world operating conditions.

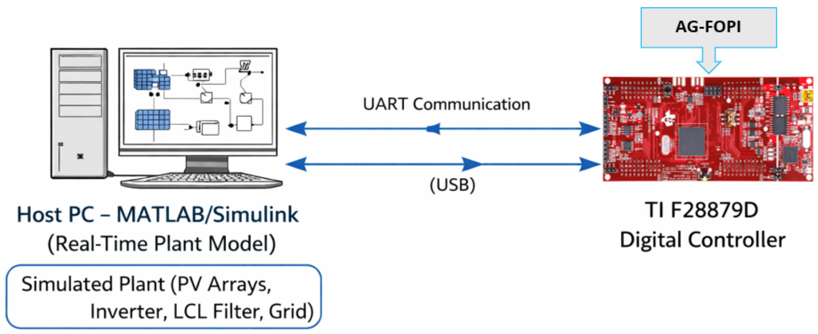

Figure 2. Hardware-in-the-loop experimental setup for the grid-connected PV system.

5. Results and Discussion

This section presents and discusses the experimental results obtained from the HIL validation of the proposed AG-FOPI controller. The results focus on dynamic performance, power quality, decoupling capability, and comparison with conventional PI control, under identical operating conditions.

5.1 Active and Reactive Power Control Performance

Fig. 3 illustrates the active and reactive power injected into the grid under step changes in the P Q reference. The AG-FOPI controller achieves fast and accurate tracking of both active and reactive power references. Settling times are approximately 10 ms, with negligible overshoot, demonstrating the effectiveness of the adaptive proportional gain during transient conditions. This behavior is mainly attributed to the adaptive proportional gain, which increases the control action during transient conditions and smoothly decreases near steady state.

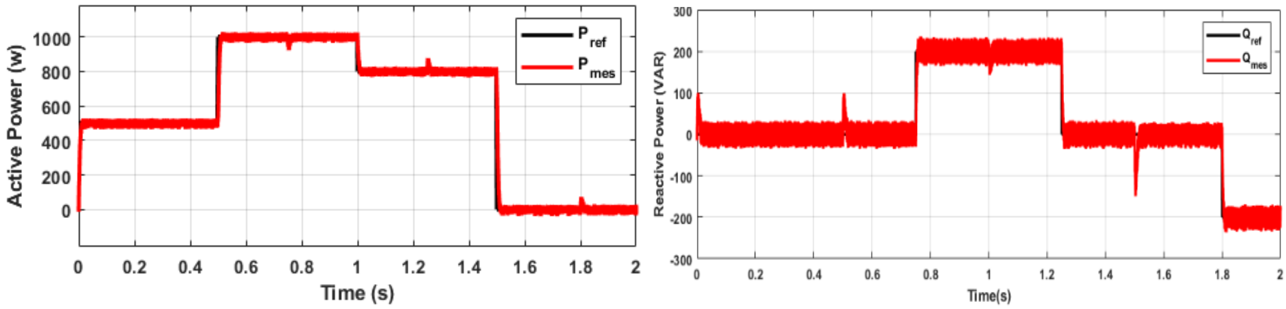

Figure 3. Active and reactive power responses.

The decoupled control capability is clearly observed, as variations in the active power reference P^* have minimal influence on the reactive power response Q, and vice versa. This confirms the suitability of the dq-based control structure combined with the AG-FOPI controller for independent regulation of power components.

5.2 Grid Voltage and Current Waveforms

Fig. 4 presents the grid voltage and injected current waveforms. The injected current remains sinusoidal and synchronized with the grid voltage, even during abrupt changes in power references. This indicates effective phase synchronization through the PLL and accurate current regulation by the inner control loop.

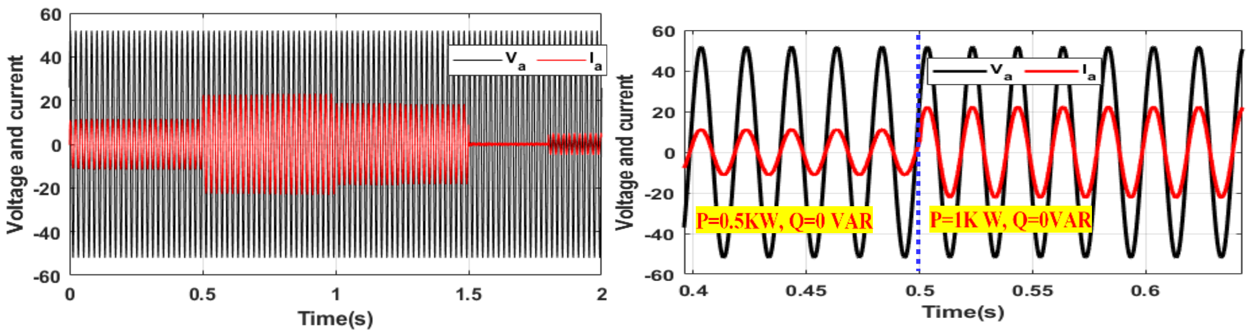

Figure 4. grid voltage and injected current waveforms under P, Q change

5.3 Harmonic Performance Analysis

The harmonic performance of the injected grid current is evaluated using Total Harmonic Distortion (THD) analysis. Fig. 5 shows the measured THD under various operating scenarios. The THD remains consistently below 1.8%, satisfying typical grid code requirements and confirming the controller's ability to maintain high current quality.

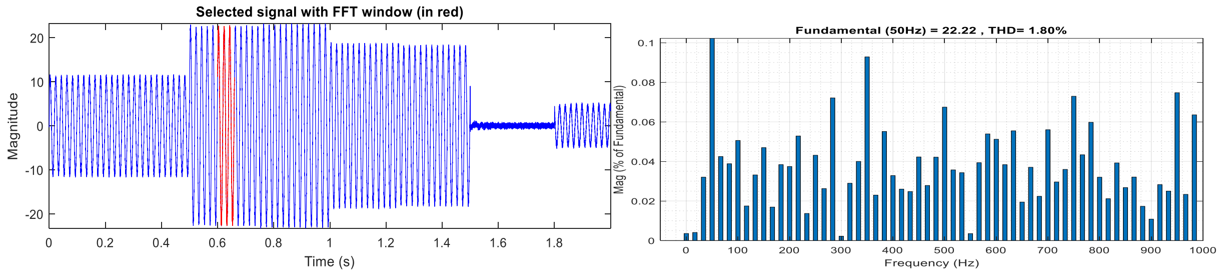

Figure 5. THD Current injected

This low THD level demonstrates the advantage of combining fractional-order integration with adaptive gain control, which improves dynamic response without sacrificing steady-state harmonic performance.

5.4 Comparative Analysis with Classical PI Control

To further highlight the benefits of the proposed approach, a comparative study is conducted between the AG-FOPI controller and a conventional PI controller under identical test conditions. Table I summarizes the comparison in terms of settling time, overshoot, steady-state error, injected current THD, robustness against disturbances, and coupling between active and reactive power.

The AG-FOPI controller exhibits a significantly faster settling time and reduced overshoot compared to the classical PI controller, while maintaining lower THD and improved robustness. The adaptive proportional gain enables aggressive response during transients while preserving smooth steady-state behavior, which cannot be achieved with fixed-gain PI control.

Table 1. Performance comparison of classical PI and AG-FOPI controllers

Performance Criterion	Classical PI	AG-FOPI
Settling time	~80 ms	~10 ms
(P/Q) Overshoot	high	Low to none
Steady-state error	Very low	Very low
Injected current THD (%)	~1.3%	~1.8%
Robustness against disturbances	Moderate	High
Coupling between P and Q	Slight	decoupled
Tuning complexity	Low	Moderate

Overall, the experimental results confirm that the AG-FOPI controller outperforms conventional PI control in dynamic performance, power quality, and robustness, making it a suitable solution for grid-connected PV applications.

6. Conclusion

This work proposed and experimentally validated an adaptive-gain fractional-order proportional–integral (AG-FOPI) control strategy for grid-connected photovoltaic (PV) systems. The controller was designed for the inner current loop to improve dynamic response and power quality under varying operating conditions. Hardware-in-the-loop (HIL) experiments were conducted using a TI F28379D digital control platform to assess the real-time performance of the proposed approach. The experimental results demonstrated fast and accurate tracking of active and reactive power references, with settling times below 10ms and negligible overshoot. In addition, the injected grid current exhibited low harmonic distortion, with THD values consistently below 1.8%, satisfying typical grid code requirements. Compared with conventional PI control, the AG-FOPI controller showed enhanced transient performance, improved robustness, and better decoupling between active and reactive power, while maintaining moderate implementation complexity suitable for real-time embedded systems. These results confirm the practical effectiveness of the proposed controller for grid-tied PV applications. Future work will focus on extending the proposed approach to three-phase systems and grid-disturbance scenarios.

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