

Genetic Algorithm Optimized Fractional Order PI Controller for Enhanced Performance in a Grid-Connected PV System

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Abstract — Maximizing energy yield in large-scale grid-connected photovoltaic (PV) systems requires accurate and fast Maximum Power Point Tracking (MPPT), particularly under rapidly changing irradiance. Classical methods such as Perturb and Observe (P&O) and Incremental Conductance (InCond) perform well under steady irradiance but struggle to achieve rapid tracking, low steady-state oscillations, and robustness simultaneously. To address this limitation, a Fractional Order Proportional and Integral (FOPI) controller tuned by a Genetic Algorithm (GA) and coupled with the InCond MPPT technique is proposed. The control architecture comprises three independent FOPI controllers dedicated to the MPPT loop, the DC-link voltage regulation loop, and the grid current control loop. Each loop was optimized separately using a dedicated Integral Time Absolute Error (ITAE) criterion evaluated under the EN50530 dynamic irradiance profile. Validation was conducted through comprehensive time-domain implementations in MATLAB/Simulink using the Simscape Electrical™ toolbox, employing a rigorous test regimen that included irradiance ramps, abrupt steps from 250 W/m² to 1000 W/m², and a staircase profile replicating progressive partial shading. The results demonstrate that the GA-FOPI controller achieves an average MPPT efficiency of 99.7% compared to 98.8% for a conventional integer-order Proportional-Integral (PI) controller. DC-link voltage overshoot drops from 3.0% (515 V) to 0.8% (504 V), with settling time reduced from 0.085 s to 0.06 s. Grid current Total Harmonic Distortion (THD) falls from 2.23% to 2.15%, well within the IEC 61727 limit of 5%. Both controllers respond identically to irradiance steps (0.017 s), but the FOPI eliminates the power overshoot observed with the integer-order PI. The additional degree of freedom introduced by the fractional integration order λ proves particularly effective in rejecting sudden irradiance disturbances. The tuning procedure described, using a genetic algorithm with loop-specific ITAE criteria, can be directly applied to other utility-scale PV configurations without requiring expert knowledge of fractional-order control.

Keywords: MPPT, fractional-order PI, genetic algorithm, grid-connected PV, ITAE

1. Introduction

Grid-connected photovoltaic (PV) installations have expanded at an unprecedented pace over the past decade, with utility-scale plants now routinely exceeding hundreds of megawatts of installed capacity. Several countries already rely on solar PV for a significant fraction of their electricity mix, and this share is expected to grow further as installation costs continue to fall [1]. At this scale, a plant's economic performance depends critically on how efficiently it converts available solar resources into injected energy. A 1% improvement in annual energy yield on a 100 MW installation translates into several GWh of additional production and a measurable improvement in return on investment over the plant lifetime [2].

The component responsible for capturing that yield is the Maximum Power Point Tracking (MPPT) algorithm, which continuously adjusts the PV array's operating point to extract the maximum available power under varying irradiance and temperature conditions. Because both quantities change throughout the day and can change abruptly when clouds pass, the MPPT algorithm must respond quickly without introducing steady-state oscillations that waste the power it is trying to capture. Meeting both requirements simultaneously is the central challenge that motivates this work.

The current-voltage characteristic of a PV array is nonlinear, with a single maximum power point whose location depends on irradiance and temperature. Classical MPPT techniques fall into two broad categories. Direct methods, principally Perturb and Observe (P&O) and Incremental Conductance (InCond) [3], estimate the MPP from instantaneous measurements without a system model. Indirect methods use a closed-loop controller to regulate the PV operating point to a reference generated by a separate algorithm.

P&O is widely used in practice because it is simple to implement and requires no prior knowledge of the array. Its weakness is a fundamental trade-off: a large perturbation step tracks fast but causes large steady-state oscillations; a small step reduces oscillations but slows tracking under rapid irradiance changes, leading to power loss [4]. Recent work has addressed this by combining P&O with simulated annealing to adapt the step size [5], or by using a neural network to predict the optimal step under the EN50530 standardized irradiance profile [6]. Both approaches improve performance but add implementation complexity and, in the neural network case, require representative training data.

More sophisticated control strategies have also been investigated. Fuzzy logic controllers [7] avoid an explicit system model and handle nonlinearity well, but their rule bases require expert knowledge to design. Neural network controllers [8] can learn complex mappings but need offline training and do not generalize easily to modules with different

characteristics. Sliding mode control [9] offers strong robustness to parameter variation but introduces chattering that must be filtered, adding complexity to the power stage design.

Fractional Order Proportional and Integral (FOPI) control has attracted growing interest as an alternative that extends classical PI tuning without requiring a full nonlinear model. Its transfer function is $C(s) = K_p + \frac{K_i}{s^\lambda}$, where the fractional integration order λ is a continuous parameter between 0 and 1. Compared to an integer-order PI, λ provides an independent handle on phase margin: increasing λ adds phase lag at all frequencies, allowing the designer to shape the closed-loop response in ways that are not possible with K_p and K_i alone [10], [11]. This extra degree of freedom is particularly valuable for PV systems, where the small-signal plant gain varies widely with irradiance.

Several research works have applied FOPI to grid-connected PV converters. Bouderrès et al. used Particle Swarm Optimization (PSO) to tune a FOPI controller for the three control loops, but using one objective function [12]. Djellad et al. optimized a FOPI for DC-link voltage control using a multilevel inverter using the Whale Optimization Algorithm (WOA) [13]. Prajapati et al. applied a dual-loop FOPI structure to improve DC microgrid voltage stability [14]. In each case, however, none of the cited authors has applied a separate optimization function for the considered control loops.

The present work proposes the use of FOPI controllers in three control loops, each optimized with a dedicated objective function — a significant contribution. Specifically, the MPPT, DC-link voltage, and grid current control loops are each tuned independently using their respective objective functions. Furthermore, most tuning studies use a single objective function shared across all loops, which prevents loop-specific performance shaping. Validation under the EN50530 standardized dynamic irradiance profile, which includes realistic ramp rates and step amplitudes, is also rare, making it difficult to compare results across studies [6], [15], [16]. This paper addresses these three gaps for a 100 kW three-phase grid-connected PV system. The following contributions are made:

- FOPI controllers are designed for all three control loops, MPPT via the boost converter, DC-link voltage via the Voltage Source Inverter (VSI) outer loop, and grid current via the VSI inner loop, replacing conventional integer-order PI controllers at every level. Unlike [13] and [16], which limited fractional-order control to the boost stage, this work treats the full control hierarchy.
- Each loop is tuned independently using a dedicated Integral Time Absolute Error (ITAE) criterion, evaluated under the EN50530 dynamic irradiance profile. Assigning

a separate objective function to each loop allows performance trade-offs to be resolved at the loop level

- rather than globally, which is not possible when a single cost function is shared across all controllers as in [12].
- The nine controller parameters (K_p , K_i , and λ for each loop) are optimized using a GA, which has shown competitive accuracy against PSO, WOA, and Grey Wolf Optimizer (GWO) on comparable FOPI identification problems [15], [16].
- The resulting controller is validated under the EN50530 dynamic irradiance profile associated with a staircase profile that reproduces the abrupt power steps characteristic of partial shading. The staircase profile is more demanding than those used in [13] and [15] and provides a stress test of disturbance rejection outside the training conditions.

- The proposed GA-FOPI controller is compared against a GA-optimized integer-order PI using four standardized metrics: average MPPT efficiency, response time to a $250 \rightarrow 1000 \text{ W/m}^2$ step, DC-link voltage overshoot, and grid current Total Harmonic Distortion (THD) [17].

To further clarify the novelty of the present work, Table 1 summarizes the key features of recent FOPI-based PV systems studies and compares them with our proposed approach. Unlike previous works, which generally use a single or multiple FOPI controllers optimized with a shared cost function, this paper introduces three independent FOPI controllers (MPPT, DC-link, grid current), each tuned with a dedicated ITAE criterion. Moreover, our optimization explicitly uses the EN50530 dynamic irradiance profile, a standard test condition rarely adopted in comparable studies.

Table 1. Comparison of the proposed controller with recent FOPI-based MPPT studies

Reference	Controller	Control loops	Optimizer	Loop specific cost	EN50530 standard	HIL/Exp.
Bouderres et al [12]	FOPI (MPPT)	1	PSO	NO	NO	NO
Djellad et al	FOPI (DC-link)	1	WOA	NO	NO	NO
Prajapati et al	FOPI (droop)	2	PSO	NO	NO	NO
Issaoui et al	FOPI/FOPID	1	GA	NO	NO	NO
Taibi et al	FOPI (DC-link)	1	GA	NO	NO	NO
Our work	FOPI (MPPT, DC-link, Current)	3	Multi GA	YES (3 loops with specific ITAE)	YES	Planned

The paper is structured as follows: Section 2 presents the system model, including the PV array, boost converter, and VSI with LCL filter. Section 3 describes the FOPI controller structure and the GA optimization setup. Section 4 presents simulation results and the comparative analysis. Section 5 draws conclusions and identifies directions for future work.

2. Mathematical Modeling of the Grid-connected PV System Components

Accurate modeling of the grid-connected photovoltaic system is essential for control design and performance evaluation. This section presents the mathematical models of the main subsystems: the PV array, the DC-DC boost converter, the DC-link, and the three-phase voltage source inverter with its LCL filter. Each model is expressed in a form suitable for control-loop analysis and subsequent optimization of the fractional-order PI controllers. The overall system configuration, including the interconnection of these components, is also described.

2.1 The PV Array Model

The SunPower SPR-305 monocrystalline module, rated at 305 W under Standard Test Conditions (STC: 1000 W/m^2 , 25°C), was selected for this study. Its key electrical parameters are: $V_{oc} = 64.2 \text{ V}$, $I_{sc} = 5.96 \text{ A}$, $V_{mp} = 54.7 \text{ V}$, $I_{mp} = 5.58 \text{ A}$. The array is built by associating N_p parallel strings of N_s series modules to reach the 100 kW target.

Each module is represented by the single-diode equivalent circuit (Figure 1), which balances accuracy and computational cost [18], [19]. The terminal current is:

$$I_{pv} = N_p I_{ph} - N_p I_s \left[\exp \left(\frac{V_{pv} + I_{pv} R_s}{N_s n V_t} \right) - 1 \right] - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \quad (1)$$

where V_{pv} is the terminal voltage, I_{ph} the photocurrent, I_s the diode reverse saturation current, n the diode ideality factor, $V_t = \frac{kT}{q}$ the thermal voltage, and R_s , R_{sh} the series and shunt resistances. N_s and N_p represent the number of series and parallel modules.

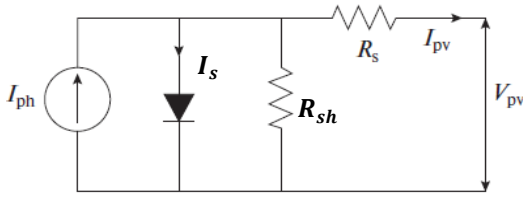


Fig. 1. Equivalent circuit of a PV cell.

2.2 DC-DC Boost Converter Model

A boost converter steps up the PV array voltage to the 500 V DC-link level. Applying state-space averaging to the switching circuit yields two coupled differential equations [20]:

$$L_b \frac{di_{L_b}}{dt} = V_{pv} - (1 - d)V_{dc} \quad (2)$$

$$C_{dc} \frac{dV_{dc}}{dt} = (1 - d)i_{L_b} - i_{inv} \quad (3)$$

where L_b is the boost inductance, C_{dc} the DC-link capacitance, i_{L_b} the inductor current, V_{dc} the DC-link voltage, i_{inv} the inverter input current, and $D \in [0, 1)$ the duty cycle set by the MPPT controller.

2.3 Grid-Side Inverter and LCL Filter Model

A three-level, three-phase VSI transfers power from the DC link to the grid through an LCL filter. Transforming the three-phase variables into the synchronous dq reference frame rotating at the grid angular frequency ω_g gives six state equations [21], [22]:

$$L_1 \frac{di_d}{dt} = V_{d_{inv}} - V_{dc} + \omega_g L_1 i_q \quad (4)$$

$$L_1 \frac{di_q}{dt} = V_{q_{inv}} - V_{qc} - \omega_g L_1 i_d \quad (5)$$

$$C_f \frac{dV_{dc}}{dt} = i_d - i_{gd} + \omega_g C_f V_{qc} \quad (6)$$

$$C_f \frac{dV_{qc}}{dt} = i_q - i_{gq} - \omega_g C_f V_{dc} \quad (7)$$

$$L_2 \frac{di_{gd}}{dt} = V_{dc} - V_{gd} + \omega_g L_2 i_{gq} \quad (8)$$

$$L_2 \frac{di_{gq}}{dt} = V_{qc} - V_{gq} - \omega_g L_2 i_{gd} \quad (9)$$

where L_1 and L_2 are the inverter-side and grid-side filter inductances, C_f the filter capacitor, i_d, i_q the inverter-side currents, V_{dc}, V_{qc} the capacitor voltages, i_{gd}, i_{gq} the grid-side currents, and V_{gd}, V_{gq} the grid voltages.

The VSI switching is controlled by Space Vector PWM (SVPWM), chosen for its lower harmonic content compared to sinusoidal PWM [23]. Grid synchronization relies on a Phase-Locked Loop (PLL) that tracks the grid voltage angle in real time [24]. An outer voltage loop regulates V_{DC} to its 500 V reference and generates the d-axis current reference for the inner current loops. A step-up transformer (260 V / 25 kV)

connects the VSI output to the medium-voltage distribution grid.

2.4 Overall System Configuration

Figure 2 shows the complete power and control structure. The PV array feeds the boost converter, whose duty cycle is set by the MPPT algorithm. The boost converter output charges the DC-link capacitor, from which the VSI draws current to inject three-phase power into the grid. The three control loops, MPPT, DC-link voltage, and grid current, act on separate actuators and are tuned independently, as described in Section 3.

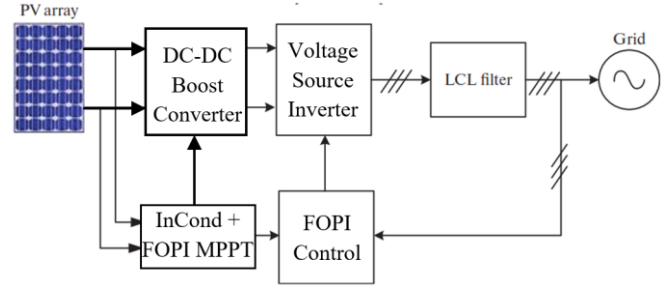


Fig. 2. Overall configuration of the studied grid-connected PV system.

3. Proposed Fractional Order Control of the Grid-Connected PV System

The proposed control strategy employs three independent fractional-order PI controllers, each dedicated to a specific loop within the grid-connected PV system. The first loop integrates the Incremental Conductance MPPT algorithm with a FOPI controller to regulate the boost converter duty cycle, thereby extracting maximum power from the PV array. The second loop maintains the DC-link voltage at its 500 V reference by generating the d-axis current command for the voltage source inverter. The third loop governs the grid-side currents in the synchronous dq frame, ensuring unity power factor operation. Each FOPI controller is tuned independently using a genetic algorithm with a dedicated ITAE objective function, as detailed in Section 3.3. This decentralized tuning approach allows the optimization to address the distinct dynamics of each loop without compromise.

3.1 Incremental Conductance MPPT Technique

Among the direct MPPT methods, InCond was retained here because it locates the MPP analytically rather than by trial perturbation, which makes it better suited to the rapid irradiance steps present in the EN50530 test profile [25].

The operating principle follows directly from the shape of the $P - V$ curve. Writing $P = V \cdot I$ and differentiating with respect to V gives:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V \frac{dI}{dV} \quad (10)$$

At the MPP, $\frac{dP}{dV} = 0$ by definition, so the tracking condition reduces to:

$$\frac{dI}{dV} = -\frac{I}{V} \quad (11)$$

The left-hand side, $\frac{dI}{dV}$, is the incremental conductance; the right-hand side, $-\frac{I}{V}$, is the instantaneous conductance with a sign change. The algorithm evaluates this inequality at each sampling instant and moves the voltage reference accordingly:

- If $\frac{dI}{dV} > -\frac{I}{V}$, the operating point sits to the left of the MPP and the voltage reference is increased.
- If $\frac{dI}{dV} < -\frac{I}{V}$, the operating point is to the right and the voltage reference is decreased.
- If $\frac{dI}{dV} = -\frac{I}{V}$ within a small tolerance, the MPP has been reached, and the reference is held fixed.
- A fourth case arises when $\frac{dI}{dV} = 0$ while $\frac{I}{V} \neq 0$, which occurs on the nearly flat current plateau of the $V-I$ curve far from the MPP. In that region the algorithm holds the reference unchanged until a change in irradiance shifts the operating point back toward the MPP region.

Compared to P&O, this formulation avoids the ambiguity that arises when a perturbation step and an irradiance change occur in the same sampling interval, since the decision is based on conductance ratios rather than on the sign of a power difference between two successive samples. The InCond flow chart is given in Figure 3 below.

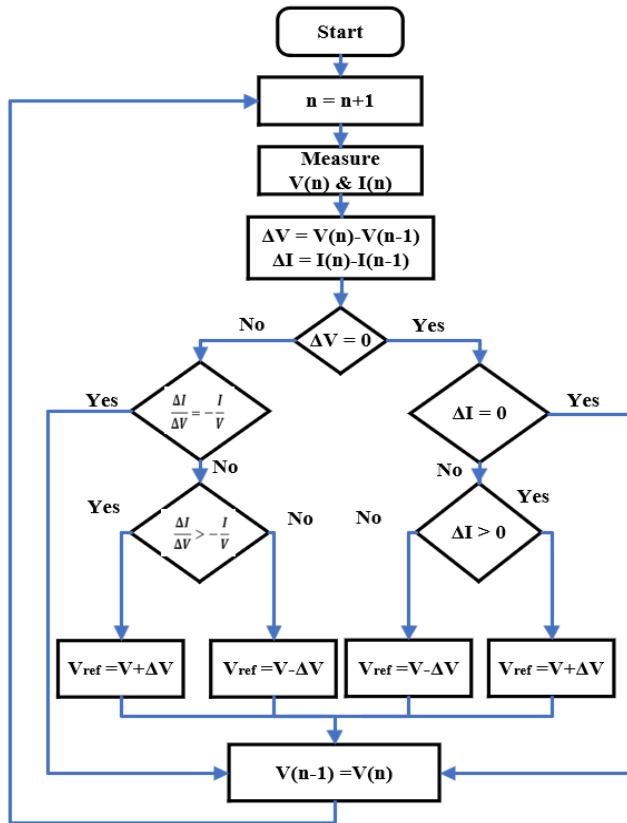


Fig. 3. Flow chart of the Incremental Conductance MPPT technique.

The reference voltage generated by the InCond algorithm is tracked by a FOPI controller, which adjusts the boost converter duty cycle D . For a boost converter, the steady-state relationship between the PV terminal voltage and the DC-link voltage is:

$$V_{dc} = \frac{V_{pv}}{1-D} \quad (12)$$

Where V_{dc} is the DC voltage link at the output of the DC-DC converter and V_{pv} is the PV system's output voltage.

In practice, the FOPI controller computes the duty cycle correction ΔD needed to drive V_{pv} toward the InCond reference. Using a fractional-order controller here rather than a standard PI, reduces the hunting around the MPP that a purely proportional-integral action tends to produce when the plant gain changes with irradiance [25].

3.2 The DC voltage Bus and power control

When irradiance changes, the power balance between the PV array and the grid shifts, causing the DC-link voltage to deviate from its 500 V setpoint. A dedicated FOPI controller monitors this deviation and adjusts the d-axis current reference I_d to restore the voltage. Because the DC-link capacitor acts as a buffer between the two sides of the conversion chain, keeping V_{dc} stable enables the MPPT loop and the grid injection loop to operate independently.

Grid power injection is handled by two current controllers working in the dq frame. The d-axis current controls active power transfer; its reference is derived directly from the DC-link voltage controller. The q-axis current reference is set to zero, forcing the reactive power to zero and keeping the power factor at unity. This arrangement means that all power extracted from the PV array is delivered to the grid with no reactive component, regardless of irradiance level.

3.3 Fractional Order Proportional and Integral Controller Structure

The three controllers share the same structure, known as PI^λ , whose transfer function is [11]:

$$C(s) = K_p + \frac{K_i}{s^\lambda} \quad (13)$$

where K_p is the proportional gain, K_i the integral gain, and $\lambda \in (0, 1)$ the fractional integration order.

The fractional integration order λ provides an additional degree of freedom to the FOPI controller. In a standard Proportional-Integral (PI) controller, the integration order is fixed at 1, which means the phase contribution of the integral term is always -90° . Setting $\lambda < 1$ reduces this phase lag, allowing the designer to increase the gain crossover frequency, and therefore the closed-loop bandwidth, without sacrificing phase margin [10]. For PV converters, whose small-signal plant gain varies by a factor of four or more between 250 W/m^2 and 1000 W/m^2 , this extra degree of

freedom translates into more consistent transient performance across the full irradiance range [26]. Analytically deriving K_p , K_i , and λ from the plant transfer functions of the three loops would require several simplifying assumptions and would not account for the interactions between loops. Parameter selection is therefore treated as an optimization problem, solved using a GA.

3.4 Genetic Algorithm Optimization Framework

The parameter vector for each controller is $x = [K_p, K_i, \lambda]$. Three independent GA runs are performed, one per control loop using a population of 15 candidates evolved over 20 generations. The search bounds are set to $K_p, K_i \in [0, 500]$ and $\lambda \in (0, 1)$.

Each candidate is evaluated by simulating the full system under the EN50530 dynamic irradiance profile and computing a loop-specific ITAE cost function. Assigning a separate cost to each loop rather than a single global criterion as in [12], allows the GA to resolve the performance trade-offs of each loop on its own terms. The three objective functions are:

- For the MPPT loop:

$$J_{MPPT}(x) = \int_0^{t_{sim}} t \cdot \left| \frac{dI}{dV} + \frac{I}{V} \right| dt \quad (14)$$

- For the DC-bus voltage loop:

$$J_{Vdc}(x) = \int_0^{t_{sim}} t \cdot |V_{DC_Ref} - V_{DC_mes}| dt \quad (15)$$

- For the grid current control loop:

$$J_{Current}(x) = \int_0^{t_{sim}} t \cdot |P_{PV} - P_{grid}| dt \quad (16)$$

where t_{sim} is the optimization horizon, V_{DC_Ref} and V_{DC_mes} are the DC-link voltage reference and measurement, and P_{PV} and P_{grid} are the PV output power and the power delivered to the grid.

The ITAE weighting, multiplying the absolute error by time penalizes errors that persist into steady state more heavily than early transients, which naturally rewards both fast initial tracking and low residual oscillation [27].

GA follows a standard generational loop: tournament selection picks parent pairs, single-point crossover produces offspring, and random mutation maintains population diversity. Elitism carries the best candidate from each generation forward without modification. The loop terminates when the maximum generation count is reached. Figure 4 summarizes the full optimization flowchart.

The optimal solution $x^* = [K_p^*, K_i^*, \lambda^*]$ for each loop, the candidate is the one that minimizes its respective cost function over the EN50530 profile. These nine values are then fixed for all subsequent simulations, including the staircase validation profile described in Section 4.

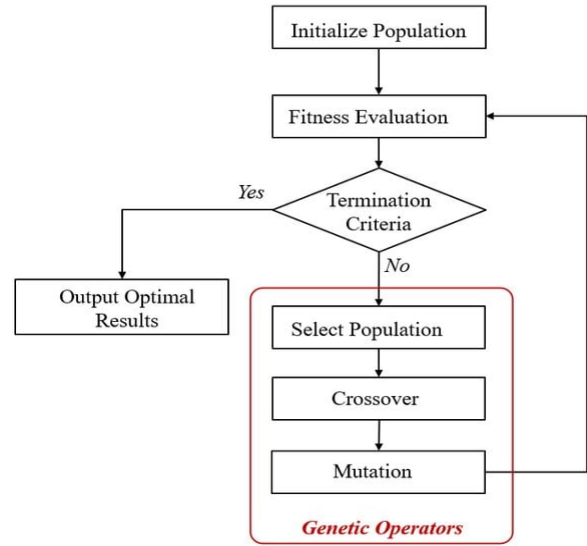


Fig. 4. Flowchart of the Genetic Algorithm optimization process

Figure 5 brings together the three control loops described in Sections III-A through III-E into a single block diagram. Reading left to right: the InCond algorithm generates the voltage reference, the MPPT FOPI controller sets the boost duty cycle, the DC-link voltage controller feeds the d-axis current reference to the VSI inner loop, and the grid current controllers produce the final SVPWM switching signals. The nine GA-optimized parameters for the three per loop are fixed at the values listed in Table 3.

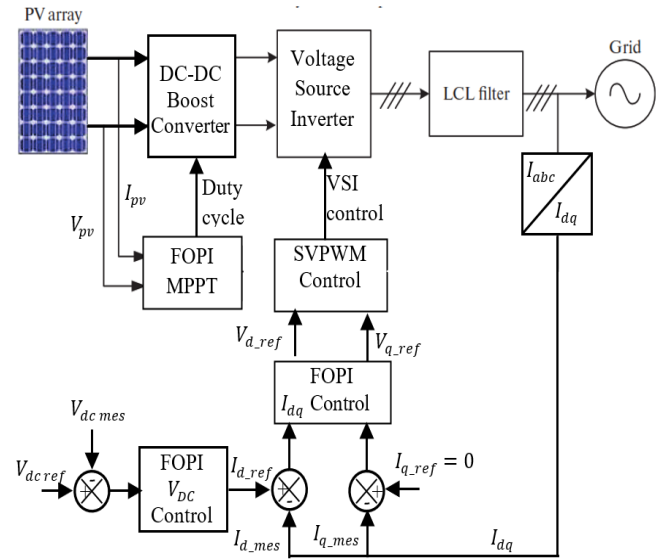


Fig. 5. The proposed control scheme of the grid-connected PV system.

4. Results and Discussion

This section presents the validation results of the proposed GA-optimized fractional-order PI controller applied to the 100 kW three-phase grid-connected PV system. The system parameters, test profiles, and controller settings are first described to establish the validation framework.

Subsequently, the performance of the GA-FOPI controller is compared against a conventional GA-optimized integer-order PI controller across the complete power conversion chain: from PV array power extraction, through DC-link voltage regulation, to grid current injection. Quantitative metrics, including MPPT efficiency, voltage overshoot, settling time, and total harmonic distortion, are extracted from the time-domain waveforms and harmonic spectra. All validation tests were conducted under identical dynamic irradiance profiles comprising ramps, abrupt steps, and a staircase pattern, as prescribed by the EN50530 standard. The section is organized into three integrated subsections: (A) System Under Test and Validation Setup, (B) DC-Link and MPPT Performance, and (C) Grid Integration and Power Quality.

4.1 System Under Test and Validation Setup

The physical system parameters, implementation environment, and dynamic irradiance test profiles must first be established to ensure reproducibility and provide context for the results that follow.

The complete 100 kW grid-connected PV system described in Section 2 uses 305 W monocrystalline modules (SunPower SPR-305) with the following key parameters at Standard Test Conditions (STC: 1000 W/m², 25°C): $V_{oc} = 64.2$ V, $I_{sc} = 5.96$ A, $V_{mp} = 54.7$ V, $I = 5.58$ A. The current-voltage (I-V) and power-voltage (P-V) characteristics of the SunPower SPR-305 PV module under variable irradiation at 25°C are given in Figure 6.

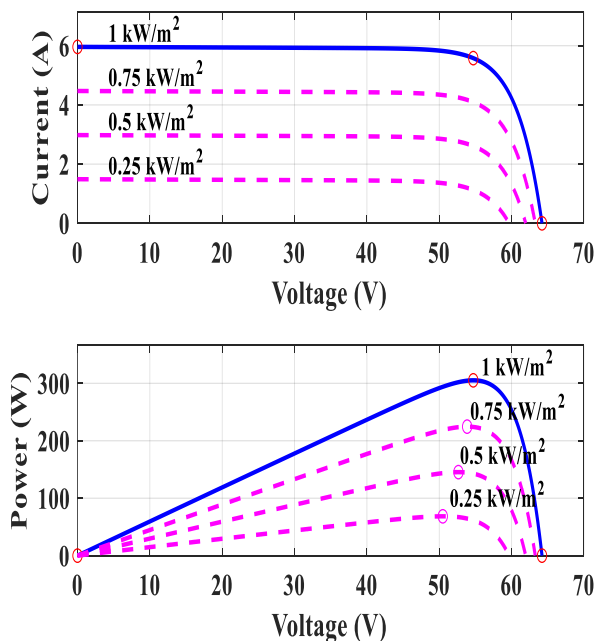


Fig. 6. The I-V and P-V characteristics of the SunPower SPR-305 PV module.

The PV system studied in this paper consists of 66 parallel strings, each composed of 5 series-connected SPR-305 modules. The system parameters are summarized in Table 2.

Table 2. System parameters

Component	Parameter	Value
PV Array (STC)	Rated Power	100.65 kW
	V_{mp} (string)	273 V
	I_{mp} (PV)	368 A
Boost Converter	L	5 mH
	C	100 μ F
DC Link	V_{dc}	500 V
	C	6 mF
LCL Filter	L_1 (Inverter side)	150 μ H
	L_2 (Transformer side)	50 μ H
	C	200 μ F
Transformer	V_1/V_2 line-to-line RMS	260 V / 25 kV
	Rated Power	100 kVA
Grid	Line-to-line RMS voltage	25 kV, 60 Hz

The PV system was implemented in the MATLAB/Simulink environment using the Simscape Electrical™ toolbox, as presented in Figure 7.

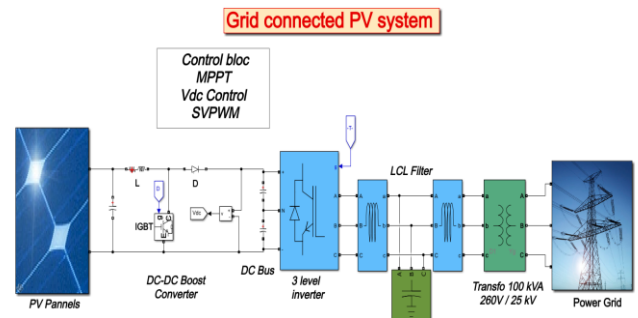


Fig. 7. Implemented control block on MATLAB Simulink.

A dynamic irradiance profile, including both low- and high-irradiance ramps, was used to test the MPPT algorithms under realistic conditions, as shown in Figure 8. The validation was performed under variable solar irradiation profiles comprising three distinct test scenarios. First, an ascending then descending ramp between 30% and 100% of nominal irradiation (per EN50530 standard) assessed the controller response to gradual changes. Second, an abrupt step from 250 W/m² to 1000 W/m² emulated severe, sudden variations typical of significant panel shadowing. Finally, a staircase profile was modeled to replicate progressive partial shading across the PV array.

The genetic algorithm was configured with a population size of 20 elements and 15 generations, executed with parameters specified in Section 3.4 for both integer-order and fractional-order PI controllers. The convergence of the best fitness value (ITAE) over generations yielded the optimal controller parameters, as given in Table 3. The optimized FOPI controller was then used for all subsequent validations.

Both controllers were tested over a five-second period under identical dynamic irradiance profiles. The resulting waveforms are presented in Figures 9 through 19.

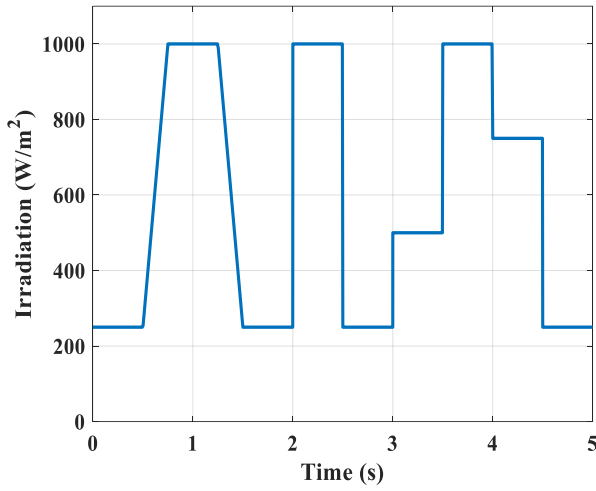


Fig. 8. Irradiance profile.

Table 3. Optimal controllers' parameters

Controller	Control loop	parameter
Integer order PI	MPPT control	$K_p = 75.3, K_i = 17.5$
	V_{dc} control	$K_p = 27, K_i = 453$
	Current control	$K_p = 3.1, K_i = 20$
Fractional order PI	MPPT control	$K_p = 216.7, K_i = 109.8, \lambda = 0.57$
	V_{dc} control	$K_p = 45, K_i = 246, \lambda = 0.81$
	Current control	$K_p = 13.7, K_i = 3.1, \lambda = 0.84$

4.2 DC-Link and MPPT Performance

The MPPT loop and the DC-link voltage regulation are physically coupled through the boost converter and are therefore analysed together to reflect their interaction in the actual system.

Figure 9 illustrates the impact of the irradiance profile on PV output voltage. Variations in irradiance induce substantial changes in PV output voltage, challenging the control system's ability to track the Maximum Power Point (MPP).

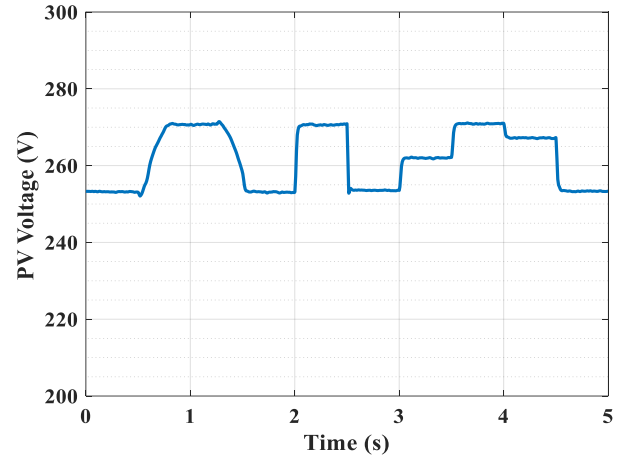


Fig. 9. PV output voltage.

Figure 10 presents the power generated by the PV system under the variable irradiance profile shown in Figure 8. The response of the GA-optimized integer-order PI controller is compared against that of the proposed GA-optimized fractional-order PI controller. Two regions of interest, where the integer-order PI exhibits noticeable deviations from the optimal power curve, are circled for closer examination.

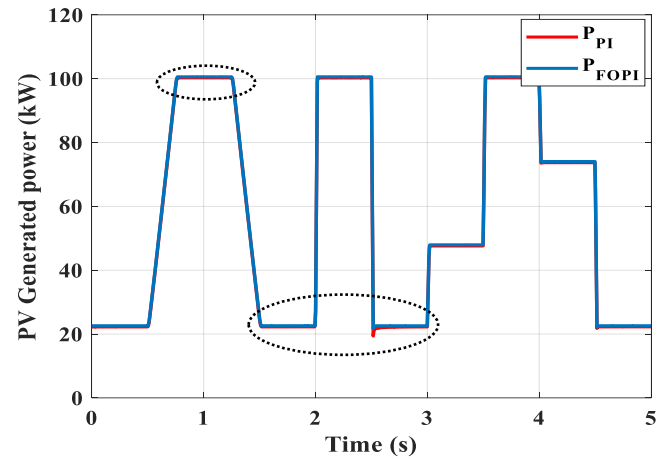


Fig. 10. PV Power generated.

Both controllers demonstrate excellent tracking of the maximum power point, with fast response times during abrupt irradiance variations. However, as observed in the two circled regions, the integer-order PI controller's response exhibits a clear deviation from the optimal power curve accompanied by significant power overshoot during irradiance steps. The two circled regions from Figure 10 are enlarged in Figures 11(a) and 11(b) to provide a detailed view of the overshoot behavior.

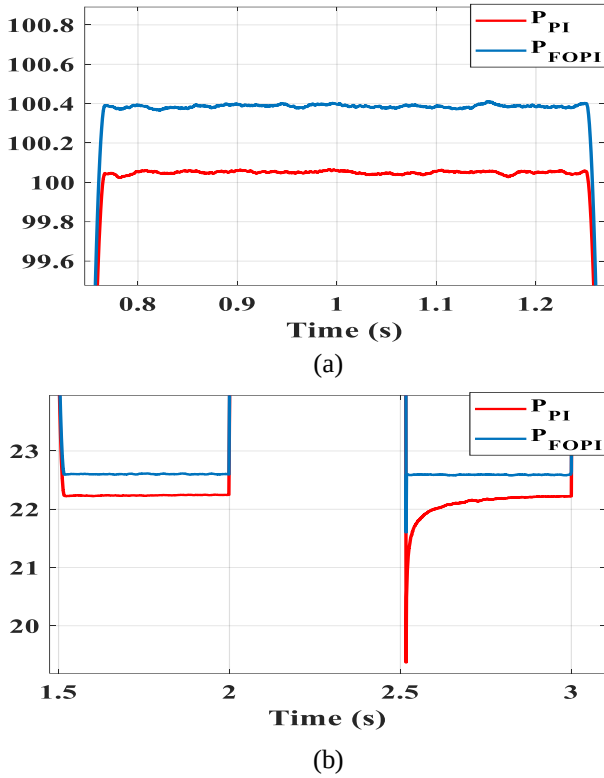


Fig. 11. Zoom on PV Power generated: (a) first circled region and (b) second circled region from Figure 10.

The zoomed views confirm that the integer-order PI controller suffers from pronounced power overshoot following sudden irradiance steps. In contrast, the fractional-order PI controller tracks the optimal power curve more smoothly, eliminating the overshoot entirely. This drawback of the integer-order PI controller can significantly affect the generated power and degrade overall PV system efficiency. Both integer-order and fractional-order controllers provide effective maximum power point tracking under the tested irradiance profile; however, the FOPI controller exhibits consistently better performance. Specifically, at 1000 W/m^2 , the maximum achievable power is 100.65 kW , yielding an efficiency of 99.6% for the FOPI controller compared to 99.4% for the integer-order PI. At 250 W/m^2 , the advantage becomes more pronounced: the FOPI controller achieves approximately 99.8% efficiency, whereas the integer-order PI reaches only 98.2% .

The PV system generates direct current, which must be converted to alternating current before being transmitted to the electrical grid. The DC bus plays a crucial role in this stage, as it decouples the boost converter output from the inverter input. The stability of the DC bus voltage is essential to ensure smooth, stable, and optimal power flow. Figure 12 presents the DC bus voltage profiles for both controllers over the entire five-second simulation period, with the reference set to 500 V . Two regions of interest, where transient disturbances cause visible deviations from the reference, are circled for closer examination.

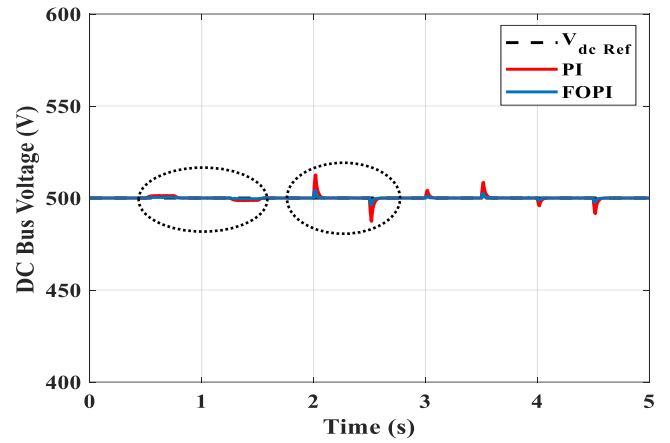


Fig. 12. DC bus voltage.

Both controllers maintain the DC bus voltage relatively stable around its 500 V reference throughout most of the simulation. However, irradiation transients propagate through the MPPT loop and the DC-link dynamics, leading to more pronounced voltage fluctuations, particularly with the integer-order PI controller. As indicated by the two circled regions, the integer-order PI exhibits larger amplitude deviations and slower recovery compared to the FOPI controller. These regions are presented in detail in Figures 13(a) and 13(b), respectively.

The two circled regions from Figure 12 are enlarged in Figures 13(a) and 13(b) to provide a detailed view of the DC bus voltage dynamics during sudden irradiance steps. Figure 13(a) captures the response during an ascending step, while Figure 13(b) captures the response during a descending step.

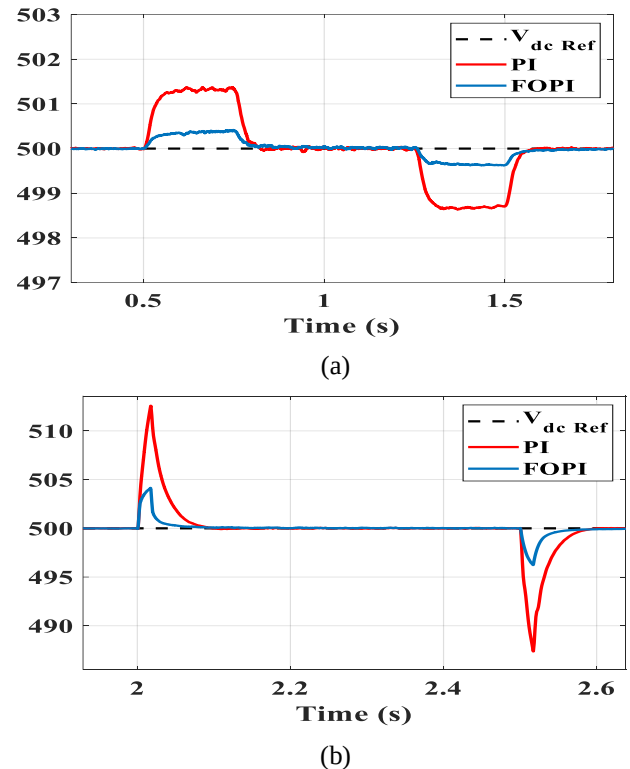


Fig. 13. Zoom on DC bus voltage: (a) first circled region and (b) second circled region from Figure 12.

The zoomed views confirm that the FOPI controller exhibits superior disturbance rejection, achieving faster damping and minimal deviation from the 500 V reference. In contrast, the integer-order PI controller exhibits significant overshoot and a prolonged settling time. Quantitatively, during a sudden irradiance step, the DC bus voltage experiences an overvoltage peak of 515 V (3.0% overshoot) for the integer-order PI controller, whereas it does not exceed 504 V (0.8% overshoot) for the FOPI controller. The settling time after the disturbance is reduced from 0.085 s with the integer-order PI to 0.06 s with the FOPI. These results demonstrate the superior voltage regulation capability of the fractional-order controller under transient irradiance conditions.

4.3 Grid Integration and Power Quality

The final stage of the power conversion chain involves the inverter, the grid filter, and compliance with power quality standards. These elements are examined together to assess how cleanly and efficiently the extracted PV power is delivered to the utility grid.

Grid integration of the PV system requires a three-phase inverter and a step-up transformer to adapt the inverter output voltage (approximately 260 V) to the medium-voltage utility grid level (25 kV). In this study, a three-level three-phase inverter controlled by space vector pulse width modulation (SVPWM) was employed to achieve optimal power transfer with high power quality. Figure 14 presents the inverter output voltage waveforms for both controllers at the transformer primary side.

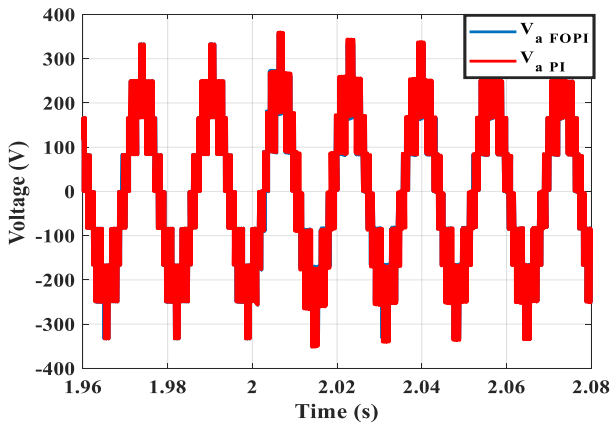


Fig. 14. Output inverter voltage.

The voltage waveforms are nearly identical for both controllers, as the SVPWM switching strategy remains unchanged. The sinusoidal shape is well-maintained with minimal distortion, confirming proper inverter operation. The amplitude remains stable regardless of irradiance variations because the DC-link voltage is actively regulated to 500 V.

Figure 15 illustrates the inverter output current waveforms supplying the step-up transformer for the integer-order PI and FOPI controllers, respectively. The current amplitude directly reflects the power extracted from the PV array, as the inverter

operates at unity power factor. A region of interest, where the integer-order PI exhibits current overshoot following a sudden irradiance step, is circled for closer examination.

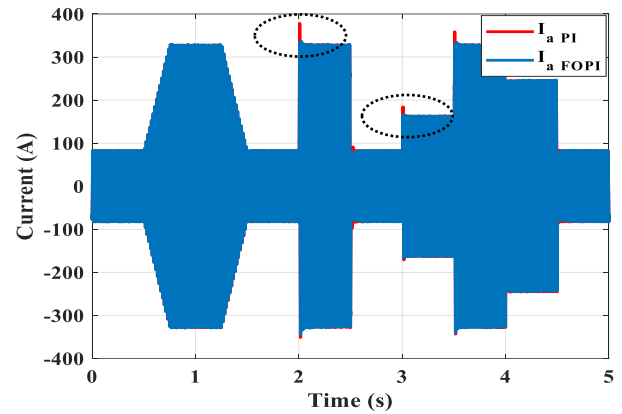
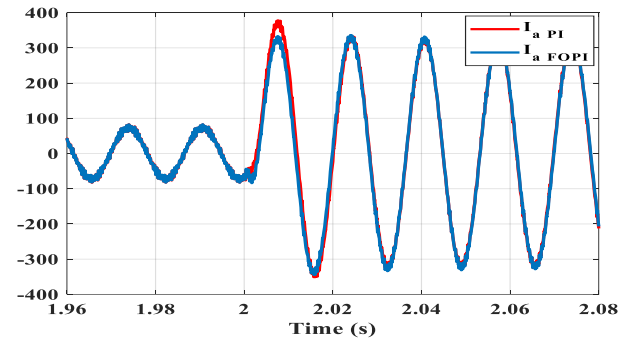


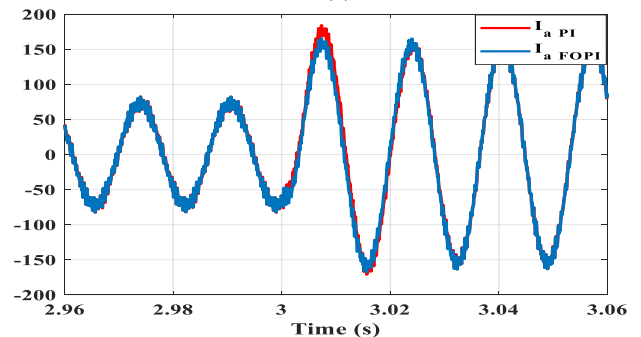
Fig. 15. Output inverter current.

For both controllers, the current amplitude dynamically tracks variations in solar irradiance, ensuring optimal and seamless power transfer from the PV system to the utility grid. However, as indicated by the circled region, the integer-order PI controller exhibits a noticeable current overshoot due to sudden steps in solar irradiance. This overshoot is absent from the FOPI controller's response, indicating superior transient current regulation.

The two circled regions from Figure 15 are enlarged in Figures 16(a) and 16(b) to provide a detailed view of the inverter current overshoot behavior during irradiance steps.



(a)



(b)

Fig. 16. Zoom on inverter current; (a) first circled region, (b) second circled region from Figure 15.

The zoomed views confirm that the integer-order PI controller suffers from a pronounced current overshoot

immediately following sudden irradiance increases. In contrast, the fractional-order PI controller responds smoothly without exceeding the steady-state value. This overshoot in the integer-order PI controller can affect the quality of the power delivered to the grid.

Power quality is a critical factor in electrical grids. The international standard IEC 61727 requires the injected current's total harmonic distortion to be below 5% at the point of common coupling. Compliance with this standard is therefore essential for grid-connected PV systems [17], [28].

Fast Fourier Transform (FFT) analysis is performed to quantify the harmonic distortion of the current injected into the utility grid. Figures 17 and 18 present the harmonic spectra of the inverter output current for the FOPI and integer-order PI controllers, respectively. The THD values obtained from these spectra are compared against the IEC 61727 limit of 5% to assess power quality compliance.

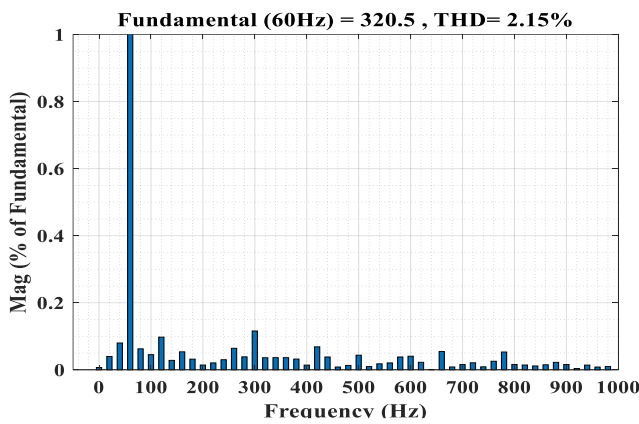


Fig. 17. THD of the inverter output current with FOPI controller.

The FOPI controller achieves a THD of 2.15% at the fundamental frequency of 60 Hz. All harmonic components are well suppressed, and the measured THD is significantly below the 5% compliance threshold. This confirms that the proposed fractional-order control strategy delivers high-quality grid current with minimal harmonic pollution.

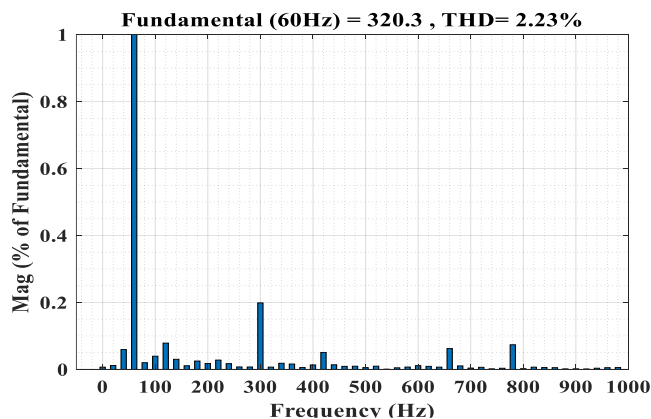


Fig. 18. THD of the inverter output current with integer order PI controller.

The integer-order PI controller yields a THD of 2.23%, which also satisfies the IEC 61727 requirement. However, compared to the FOPI controller, the harmonic distortion is slightly higher. This marginal increase is consistent with the larger oscillations and overshoot observed earlier in the time-domain current waveforms (Figures 15 and 16). The FOPI controller's additional degree of freedom (λ) enables smoother current regulation, directly contributing to the measured reduction in THD.

Finally, Figure 19 overlays the inverter output voltage and current waveforms to verify the unity power factor operation. The current and voltage are perfectly in phase, confirming that the q-axis current reference is maintained at zero and that all active power extracted from the PV array is delivered to the grid without reactive power circulation.

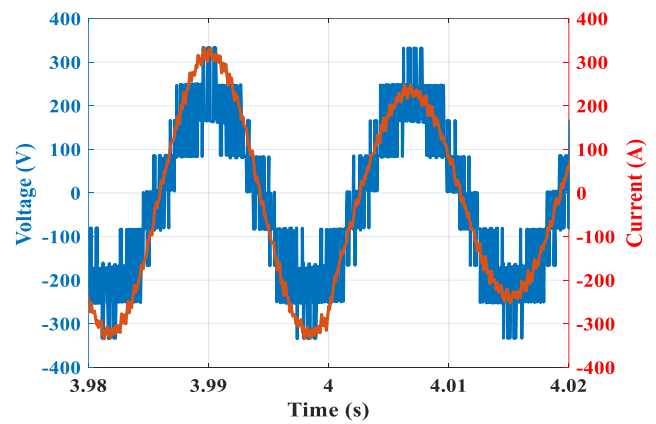


Fig. 19. Zoom on inverter current and voltage.

Table 4 consolidates the key performance metrics obtained for both controllers under identical operating conditions.

Table 4. Performance comparison between integer-order PI and FOPI controllers

	Integer PI	FOPI
Average MPPT efficiency (%)	98.8	99.7
Response time to a 250→1000 W/m ² (s)	0.017	0.017
DC voltage overshoot (%)	3.0	0.8
Setting time (s)	0.085	0.06
THD (%)	2.23	2.15

The proposed GA-FOPI controller achieves an average MPPT efficiency of 99.7%, an improvement of 0.9 percentage points over the integer-order PI (98.8%), with the largest gain observed at low irradiance. Both controllers respond identically to a 250→1000 W/m² irradiance step, settling in 0.017 s; however, the FOPI eliminates the power overshoot that accompanies the integer-order PI response. The DC-link voltage overshoot is reduced from 3.0% (515 V) to 0.8% (504 V), and the settling time improves from 0.085 s to 0.06 s. Grid current THD decreases from 2.23% to 2.15%, remaining well

within the IEC 61727 limit of 5%. These results confirm that the additional degree of freedom provided by the fractional integration order λ enables superior disturbance rejection and reduced steady-state oscillations without compromising tracking speed.

4.4 Genetic Algorithm convergence and parameter sensitivity analysis

To verify the stability of the optimization process, the evolution of the three FOPI parameters (K_p , K_I , λ) over the 20 GA generations is plotted for each control loop in Figures 20(a)–20(c). In the MPPT loop (Figure 20(a)) and the DC bus voltage loop (Figure 20(b)), all parameters converge to stable values after approximately 15 generations, with only minor adjustments thereafter. However, the grid current loop (Figure 20(c)) exhibits a smooth convergence profile, with all parameters settling well before generation 18.

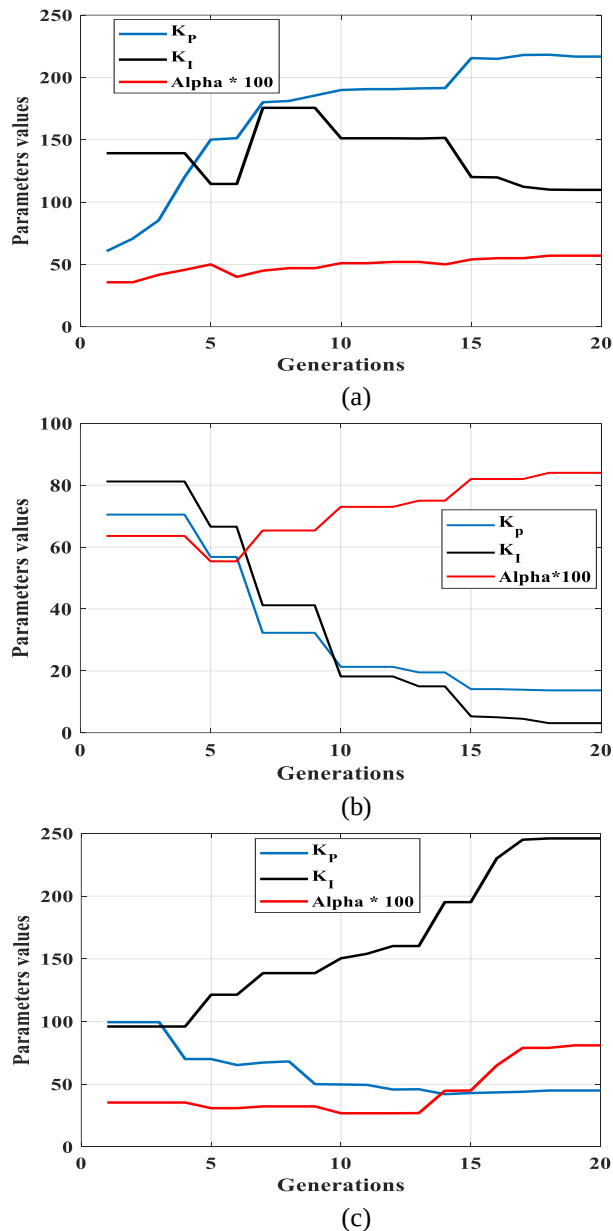


Fig. 20. Evolution of the FOPI parameters during GA optimization

(a) MPPT loop, (b) DC-bus voltage loop, (c) current loop

Figure 21 presents the convergence of the best fitness (ITAE) for the three control loops over the 20 generations. The cost function decreases rapidly during the first 10 generations and then reaches a clear plateau before generation 15 for the MPPT and DC bus loops, and before generation 18 for the current loop. This indicates that the chosen GA settings (population size 15, 20 generations) are sufficient to obtain optimal or near optimal parameters. Extending the optimization beyond 20 generations would not bring a significant improvement, while increasing the computational cost.

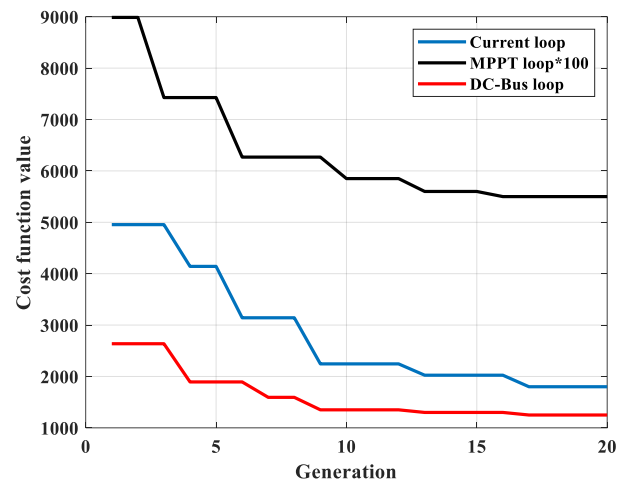


Fig. 21. Convergence of the best fitness (ITAE) for the three control loops over 20 generations.

5. Conclusion

This paper proposed a GA-optimized fractional-order proportional-integral controller for a 100 kW three-phase grid-connected photovoltaic system. The control architecture comprised three independent FOPI controllers, each dedicated to a specific loop: the maximum power point tracking loop (combined with the Incremental Conductance algorithm), the DC-link voltage regulation loop, and the grid current control loop in the synchronous dq frame. Each controller was tuned separately using a dedicated Integral Time Absolute Error cost function evaluated under the EN50530 dynamic irradiance profile, enabling loop-specific performance shaping that is not possible with a single shared objective function.

Validation of the proposed control framework was conducted through comprehensive time-domain simulations using MATLAB/Simulink with the Simscape Electrical™ toolbox, employing a rigorous test regimen that included irradiance ramps, abrupt steps from 250 W/m² to 1000 W/m², and a staircase profile replicating progressive partial shading. The results consistently demonstrate that the GA-FOPI framework outperforms a conventional integer-order PI controller optimized under identical conditions. The average MPPT efficiency improved from 98.8% to 99.7%, with the most notable gain occurring at low irradiance (250 W/m²),

where efficiency rose from 98.2% to 99.8%. Under sudden irradiance steps, the DC-link voltage overshoot was reduced from 3.0% (515 V) to 0.8% (504 V), and the settling time shortened from 0.085 s to 0.06 s. The grid current total harmonic distortion decreased from 2.23% to 2.15%, remaining well below the IEC 61727 limit of 5%, while unity power factor operation was maintained throughout. Both controllers achieved identical response times of 0.017 s to a 250→1000 W/m² irradiance step; however, the FOPI controller eliminated the power overshoot and deviation from the maximum power point observed with the integer-order PI.

These improvements are attributed to the fractional integration order λ , which provides an additional degree of freedom compared to conventional PI tuning. This extra parameter enables better phase-margin shaping and more consistent transient performance across the wide range of plant gains encountered under varying irradiance. The tuning procedure described herein, using a genetic algorithm with loop-specific ITAE criteria, can be directly applied to other utility-scale PV configurations without requiring expert knowledge of fractional-order control.

Building on these findings, future work will focus on experimental validation using a hardware-in-the-loop platform, extending the controller to partial shading scenarios and weak grid conditions, and integrating with advanced control strategies such as model predictive control.

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Author Contributions

Samir Metatla and Abdelhakim Bendakir contributed to the research methodology, writing original draft as well as the formal analysis and references.

Youcef Soufi and Ali Almaktoof contributed to the data curation, methodology, supervision, writing-review & and drafting of the first version.

All authors have read and approved the published version of the article.

Conflict of Interest

The authors declared no potential conflicts of interest.

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