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Hybrid Fuzzy–incremental Conductance MPPT on Spartan-3 FPGA for PV Systems: Implementation of Hardware-in-the-Loop

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Abstract: This work presents an intelligent maximum power point tracking (MPPT) strategy to enhance photovoltaic (PV) energy harvesting under rapidly varying irradiance and temperature conditions. Conventional Perturb-and-Observe (P&O) and Incremental Conductance (INC) methods suffer from steady-state oscillations, drift, and slow dynamic response, leading to power losses. To overcome these limitations, a hybrid MPPT scheme is proposed that combines INC for estimating the instantaneous maximum power point voltage (V_{mpp}) with a Fuzzy Logic Controller (FLC). The FLC processes the tracking error and its variation to generate the duty cycle that controls an interleaved boost converter via a PWM generator. The input and output scaling factors of the FLC are optimally tuned using the Grey Wolf Optimizer (GWO) to improve tracking accuracy and adaptability. Building on a previously developed control strategy, a Hardware-in-the-Loop (HIL) implementation is presented, where the PV array and converter are modeled in MATLAB/Simulink and the controller is executed on an FPGA. Experimental results demonstrate reduced steady-state ripple and improved tracking efficiency compared to conventional methods with 99.65% tracking efficiency and 0.15% steady-state ripple.

Keywords: MPPT, Fuzzy logic controller, Incremental conductance algorithm, Grey wolf optimizer, Hardware in the loop, FPGA.

1. Introduction

Solar Photovoltaics (PV) continue to expand rapidly as a clean electricity source, but the power harvested from PV arrays varies with irradiance, temperature, and operating point. To maintain high efficiency, PV systems employ Maximum Power Point Tracking (MPPT) so that voltage–current operating conditions remain near the array's instantaneous maximum power point. Broad surveys show that modern MPPT research has progressed from classical methods to intelligent and hybrid schemes aimed at faster convergence and lower steady-state ripple under dynamic conditions [1]. Among classical methods, Incremental conductance (INC) is widely used. It exploits the condition $dP/dV=0 \Rightarrow dI/dV=-I/V$ at the MPP to decide whether to increase or decrease operating voltage.

However, fixed step sizes in practical INC implementations can lead to a speed–ripple trade-off during fast irradiance changes [2]. In contrast, Fuzzy Logic Controllers (FLCs) encode heuristic expert rules and have been shown to reduce oscillations and improve tracking smoothness in nonlinear PV dynamics, often outperforming conventional methods in dynamic tests [3]. Building on these strengths, hybrid MPPT structures that combine INC with fuzzy logic (and/or other supervisory elements) have demonstrated superior transient performance while maintaining accurate steady-state tracking [4]. Recent research has increasingly focused on intelligent MPPT methods, employing artificial intelligence (AI) techniques such as fuzzy logic control and neural networks. Despite advancements, these methods often face issues like drifting from maximum power, oscillations, computational complexity and practical implementation challenges.

Optimization techniques, particularly metaheuristics like the Grey Wolf Optimizer (GWO), have shown potential in enhancing MPPT performance.

Recent work on intelligent MPPT has moved from basic FLC toward hybrid, learning-based, and hardware-ready implementations. A number of studies show that FLC MPPT remains attractive because it is model-light and robust to noise; for example, Yahiaoui *et al.* [5] optimize an FLC using a genetic algorithm and report higher harvested energy across irradiance and temperature changes when driving a DC-DC converter, with experimental testing confirming the gains. Beyond pure fuzzy logic, neuro-fuzzy schemes combine neural prediction with fuzzy decision rules to improve convergence and reduce oscillations—Danyali *et al.* [6] demonstrate a neuro-fuzzy MPPT that maintains tracking under partial shading in a grid-connected setup, outperforming conventional techniques in speed and steadiness. Broader surveys agree that intelligent and hybrid MPPT families (fuzzy, ANN/ANFIS, metaheuristics, and their combinations) generally deliver better dynamic behavior than classical P&O/INC, albeit at higher design complexity [7]. Within the hybrid optimization class, several authors couple fuzzy or duty-cycle control with population-based optimizers to tune gains or search the MPP efficiently; an IEEE Access study on a cuckoo-optimized fuzzy controller is a representative example that reports faster tracking and lower ripple across operating conditions [8], while other recent work fuses two optimizers (e.g., Honey Badger algorithm with genetic algorithm) (HBA+GA) to escape local optima under partial shading [9].

Learning-based MPPT has also improved a lot. A large comparative IEEE Access study examines multiple ANN training schemes for MPPT with real irradiance/temperature datasets and provides guidance on algorithm choice and data handling for deployment [10]. On the hardware side, there is growing evidence that intelligent MPPT can meet real-time constraints: an optimized FLC tested experimentally showed practical benefits on converter hardware [5], and the community has pushed toward reconfigurable logic for deterministic, low-latency control; for instance, a 2024 article discusses FPGA-based fuzzy controllers targeting MPPT workloads and motivates FPGAs for parallel, time-critical computation in PV control loops [11]. Finally, system-level studies under partial-shading and multi-string configurations reinforce the need for advanced MPPT to maintain output power and avoid local maxima, supporting the move to intelligent or hybrid strategies in modern PV plants [12].

The traditional MPPT methods that include P&O and INC are popular because of their simple form and low computational cost but they are affected by well-known limitations in a dynamic operating environment. P&O oscillates steadily around the MPP and can wrongly track in the opposite direction when the irradiance is changing rapidly resulting in power loss [13]. Despite the fact that INC has better tracking accuracy with the slope of the power voltage characteristic, it is susceptible to noise in measurements and the step-size must be carefully chosen to trade off convergence speed and stability [2]. The methods based on AI such as FLC can be used to increase robustness and minimize oscillations, although the performance of the methods is highly sensitive to heuristic rule design and membership functions tuning, which restricts reproducibility and flexibility. To address these challenges, this work proposes a hybrid MPPT strategy that combines the analytical strength of INC for MPP estimation with the decision-making capability of FLC, while employing the GWO to systematically tune controller parameters. The proposed approach is implemented on an FPGA and validated through a HIL framework to ensure real-time feasibility and practical relevance under rapidly changing environmental conditions.

This paper extends our previously developed hybrid fuzzy-incremental conductance (FLC-INC) MPPT controller [14] by implementing it on a Spartan-3 FPGA and interfacing it with a Simulink-based PV system through a HIL framework. The PV array and interleaved boost converter are modelled in Simulink, while the FPGA executes the hybrid controller in fixed-point and returns the duty-cycle command each control cycle. Interleaving is selected to reduce input-current ripple and improve conversion quality. The proposed HIL methodology enables deterministic timing with realistic I/O and has been highlighted in recent work as an effective bridge between simulation and hardware for power-electronics control [15]. Using dynamic irradiance/temperature profiles, the FPGA-based hybrid controller achieves faster convergence and lower steady-state ripple compared with the stand-alone INC and stand-alone FLC baselines in the same HIL framework. This improves energy capture during rapid transients while keeping the PV and converter models within Simulink.

Overall, the literature points toward intelligent MPPT—fuzzy, neuro-fuzzy (ANFIS), ANN, and hybrid metaheuristics—as the preferred pathway to reduce steady-state oscillations, speed up transients, and remain robust under fast environmental changes, with growing attention to real-time implementation on DSP/FPGA platforms.

This paper is organized as follows. Section 2 provides the background and motivation that includes a description of photovoltaic systems, MPPT techniques, fuzzy logic control, incremental conductance and the Grey Wolf Optimizer. Section 3 describes the hybrid FLC-INC MPPT strategy and methodology. Section 4 describes the simulation and hardware-in-the-loop experimental design. Section 5 covers the results and performance analysis obtained. Section 6 is the conclusion of the paper, and Section 7 contains the future research directions.

2. Background and motivation

A Photovoltaic (PV) output power exhibits highly dynamic behavior in response to variations in solar irradiance and ambient temperature. As a result, tracking the MPP under rapidly changing environmental conditions remains one of the most challenging tasks in PV systems, since the operating point continuously shifts over time. Although significant scientific and technological progress has led to the development of numerous MPPT algorithms, each technique presents inherent limitations in terms of tracking speed, steady-state oscillations, or robustness under fast weather transients. Consequently, selecting an efficient and reliable MPPT strategy is essential for maximizing energy extraction from PV systems [7, 13].

To address these challenges, hybrid MPPT approaches that combine the strengths of conventional algorithms with intelligent control techniques have gained increasing attention. In particular, integrating FLC with the INC method offers improved adaptability and faster convergence while preserving the reliability of slope-based tracking. Furthermore, implementing such intelligent MPPT schemes on hardware platforms such as field-programmable gate arrays (FPGAs) enables real-time operation with deterministic timing and low latency, making them suitable for practical PV applications. In this work, an FPGA-in-the-loop framework is adopted to evaluate the proposed hybrid FLC-INC MPPT under dynamically varying irradiance and temperature conditions, emulating realistic operating scenarios.

2.1 Photovoltaic systems overview

Photovoltaic (PV) systems convert sunlight directly into electrical energy. They often combine solar panels and a programmable DC/DC converter with power electronic devices to fully use the output characteristics of a solar panel, which is clarified in Fig. 1 MPPT is the feedback control technique

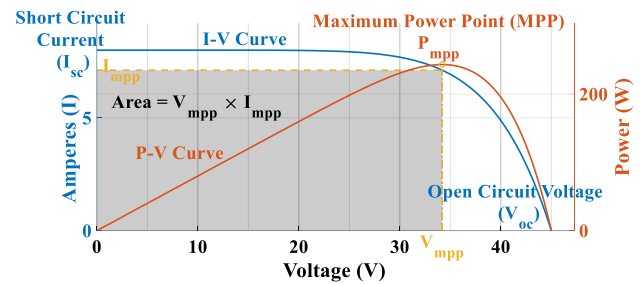


Figure. 1 I-V & P-V characteristics of a solar panel

capable of extracting maximum power from the PV panel [16]. The method has the advantages of easy implementation, high efficiency, and fast response, and can be adapted to fast-changing environmental conditions [17].

The PV system primarily includes a solar array, a DC/DC power converter, and a controller that tracks the MPP of the PV array [18]. Photovoltaic conversion enables the conversion of solar irradiance into electrical energy via solar cells in the PV array. Each cell determines the conversion of a photon modelled as a quantum of energy into an electron (or hole) excited onto the conduction (or valence) band; these electrons and holes then generate a current flow if an external load is connected to the terminals of the cell [19]. Photovoltaic cells withstand an operational voltage of approximately 0.5 V; therefore, several cells are associated both in series and parallel to create a panel having the output voltage and current suitable for the desired application [19]. However, due to the nonlinear current-voltage and power-voltage characteristics of PV arrays, the operating point varies continuously with changes in solar irradiance, temperature, and load conditions. Without appropriate control, the PV system may operate away from the MPP, leading to significant power losses. Therefore, a MPPT controller is required to dynamically adjust the operating voltage or duty cycle of the DC/DC converter, ensuring that the PV array consistently operates at its MPP and delivers the highest possible energy under varying environmental conditions.

Photovoltaic systems convert sunlight into electrical energy using PV arrays consisting of photovoltaic panels connected in series and parallel to achieve the desired voltage and power [19]. A unidirectional DC/DC converter is implemented to step up/down the voltage of the PV system, consisting of power semiconductor switches, diodes, inductors, and capacitors, as shown in Fig. 2 for the interleaved boost converter [20]. The DC/DC converter output powers the load, and the proposed

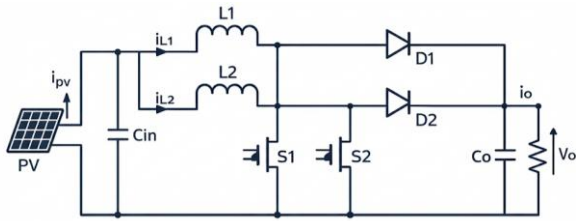


Figure. 2 PV panel with an interleaved boost converter

MPPT algorithm adjusts its duty cycle to operate the PV array at its MPP. The controller computes the duty cycle, which is then supplied to the PWM generator to drive the power switch of the DC/DC converter [21].

2.2 Maximum power point tracking

Current practice relies heavily on the Perturb and Observe (P&O) and INC algorithms, but these algorithms are ineffective under rapidly fluctuating irradiance. Therefore, another method must be developed to achieve better tracking performance [22]. To improve current algorithms, an FLC can be combined with the INC to generate a hybrid FLC-INC algorithm, resulting in higher tracking efficiency at the MPP.

A PV system is a constellation of different components; its principal function is to convert solar energy into electrical energy. The efficiency of the systems depends on many parameters, such as the solar irradiance and the temperature. For this reason, MPPT is required to extract the MPP under different operating conditions. This requirement means that an MPPT algorithm should be used to maximize the energy obtained by the PV system [23].

The MPPT control technique is a fundamental component of a PV system, as it significantly enhances energy conversion efficiency. Since the MPP continuously changes with variations in solar irradiance and cell temperature, numerous MPPT algorithms have been developed to accurately and efficiently track this operating point. Among these algorithms, the Hill-Climbing (HC) or P&O technique and the INC algorithm are commonly used due to their simple structure and ease of implementation [24]. However, the HC technique is not efficient in the case of rapidly changing atmospheric conditions [25]. By comparison, INC is generally more suitable in fast-changing conditions, yet the baseline method can still exhibit longer convergence and even stability issues unless enhanced [26, 27]. Fig. 3 shows the P&O algorithm flowchart, where the controller perturbs the

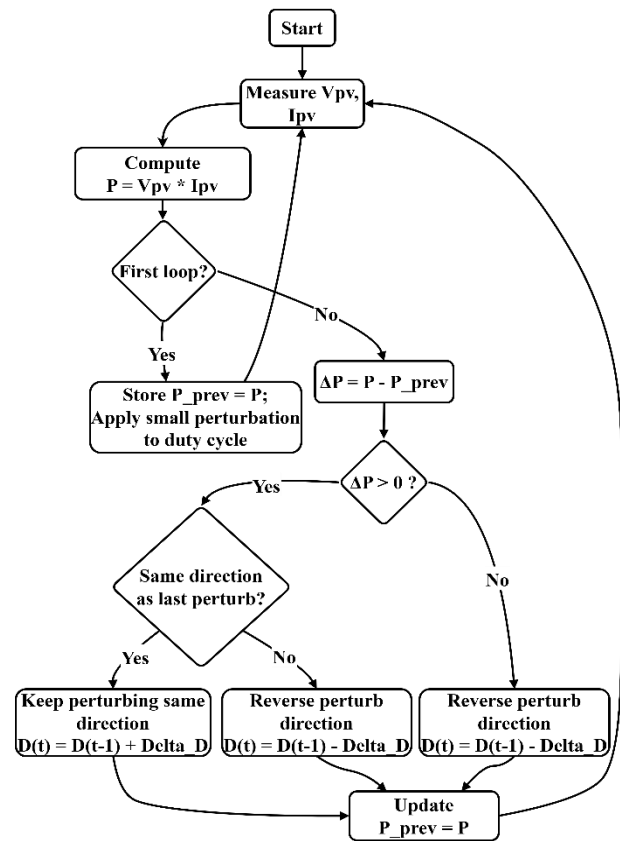


Figure. 3 Flowchart of the P&O MPPT

duty cycle, measures the resulting power change, and keeps or reverses the perturbation direction to climb toward the MPP. Simple and fast, but prone to steady-state oscillation and missteps under rapid irradiance changes. Moreover,

Fig. 4 shows the INC algorithm flowchart, where the controller compares the incremental conductance dI/dV with the instantaneous conductance $-I/V$ to determine whether the operating point is to the left or right of the MPP, then adjusts the duty cycle accordingly. It is more accurate than P&O during fast transients, but typically requires careful slope estimation and variable step sizing for speed.

MPPT techniques for PV systems have been indispensable in making the best use of the available power. The goal of such algorithms remains maximizing the power generated by the PV array for any operating condition and rapidly adapting to new operating points following changes in environmental conditions [28].

Because of the nonlinear current-voltage and power-voltage characteristics of the array, as shown earlier in Fig. 1. The MPP varies with irradiance, temperature, and load conditions; a system incorporating an MPPT routine can effectively

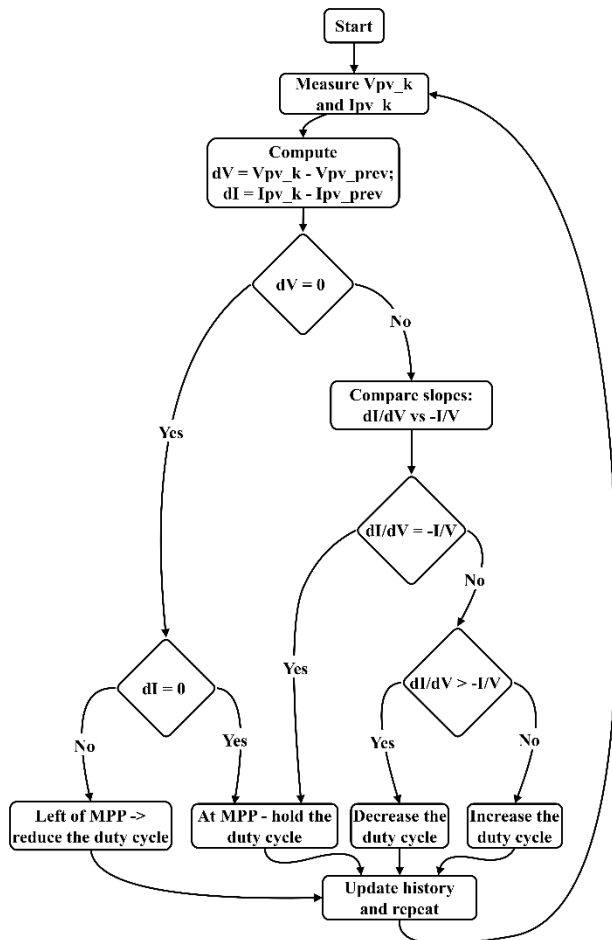


Figure. 4 Flowchart of the INC MPPT

extract more power from the PV array than one without.

Conventional MPPT methods include Open-Circuit Voltage (OCV), Short-Circuit Current (SCC), P&O, and INC. The OCV and SCC methods determine the MPP based on reference voltages and currents derived from the PV array's open-circuit voltage and short-circuit current, respectively [29]. Although these techniques are conceptually straightforward, they necessitate additional sensors to measure array voltage and current accurately. Furthermore, the OCV and SCC methods perform well only under standard conditions, so their functionality in different environments is restricted [30]. The P&O and INC approaches make use of the perturbation principle, whereby the voltage of the PV array is altered gradually, and the changes in the resultant parameters are observed [7]. The P&O algorithm is widely used due to its simplicity and satisfactory performance under steady and uniform operating conditions. However, when solar irradiance or temperature varies rapidly, the method tends to cause persistent oscillations around the MPP, which leads to power losses [31]. In contrast, the INC

method identifies the MPP by exploiting the condition that the derivative of power with respect to voltage becomes zero at the MPP on the power–voltage curve, as illustrated in Fig. 1 [26]. This is achieved by continuously comparing the instantaneous conductance with the incremental conductance, allowing the controller to determine the direction toward the MPP without the steady-state oscillations typically observed in the P&O method. Despite this advantage, the performance of the INC algorithm can degrade under high irradiance levels, where the nonlinear nature of the I–V characteristic makes accurate MPP detection more challenging. To address these limitations, several improvements to the INC technique have been reported in the literature. Variable step-size strategies have been introduced to accelerate the tracking process, although they increase algorithmic complexity and often require retuning when applied to different PV systems [32]. Alternatively, direct control schemes adjust the converter duty cycle directly within the MPPT algorithm, thereby removing additional control loops and improving both transient response and steady-state behavior. Nevertheless, these approaches typically involve increased circuit complexity and cost, reflecting an ongoing trade-off between tracking performance and practical implementation [12].

2.3 Fuzzy logic control in MPPT

Fuzzy Logic Control (FLC) has been widely adopted in MPPT due to its robustness, fault tolerance, and ability to handle nonlinear and time-varying systems without requiring an accurate mathematical model [33, 34]. Unlike conventional controllers, FLC encodes expert knowledge using linguistic rules, making it well suited for PV systems where output power varies continuously with irradiance and temperature [35, 36]. Traditional MPPT methods such as P&O and INC are simple and effective under steady conditions; however, P&O suffers from tracking errors during rapid irradiance changes [37], while INC exhibits slow convergence despite reduced steady-state oscillations [26].

Fuzzy logic operates by assigning degrees of membership between 0 and 1 to linguistic variables such as low, medium, and high through predefined membership functions [38]. This approach enables qualitative reasoning with low computational complexity, making it suitable for real-time control [38]. In MPPT applications, FLC commonly uses variables such as changes in power and voltage instead of precise numerical models, reducing sensitivity to noise and measurement inaccuracies [39,

40]. FLC can also detect the MPP with minimal oscillations under steady-state conditions.

Despite its advantages, FLC design relies heavily on expert knowledge, and there is no standardized method for selecting membership functions and rule bases [41]. Additionally, computational requirements may increase with system complexity, limiting real-time implementation [41]. These challenges motivate hybrid MPPT strategies to achieve improved tracking accuracy, adaptability, and computational efficiency.

In this work, a Mamdani-type FLC is designed using the error between the reference MPP voltage and the PV voltage, along with its change, as inputs as shown in Fig. 5. The controller output adjusts the duty cycle of the DC–DC converter. Fig. 6 shows seven triangular membership functions which are defined for each input and output variable, resulting in a compact 49-rule base shown in Table 1 that ensures fast convergence, reduced steady-state oscillations, and robustness under rapidly changing conditions. The use of simple inference operators and centroid defuzzification provides smooth control behaviour and enables efficient real-time and FPGA-compatible implementation with low latency.

2.4 Incremental conductance algorithm

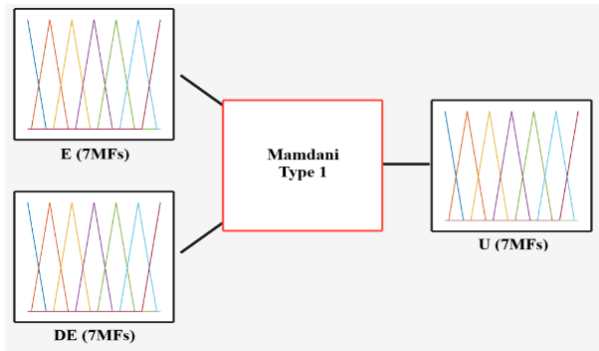


Figure. 5 Fuzzy Logic Controller design

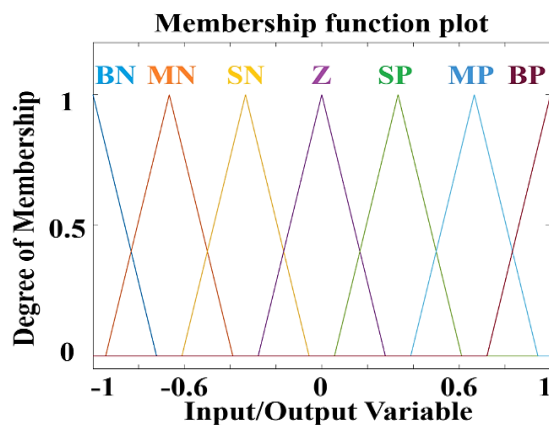


Figure. 6 Membership function plot for inputs and output

Table 1. Rules of the Fuzzy Logic Controller

E \ DE	BN	MN	SN	Z	SP	MP	BP
BN	Z	SN	SN	MN	MN	BN	BN
MN	SP	Z	SN	SN	MN	MN	BN
SN	SP	SP	Z	SN	SN	MN	MN
Z	MP	SP	SP	Z	SN	SN	MN
SP	MP	MP	SP	SP	Z	SN	SN
MP	BP	MP	MP	SP	SP	Z	SN
BP	BP	BP	MP	MP	SP	SP	Z

The incremental conductance algorithm derives the MPP based on the fact that the derivative of output power with respect to voltage is zero at the MPP. Past the MPP, the signs of the derivatives differ, allowing the algorithm to adjust the operating voltage accordingly. If the conductance $-I/V$ equals the incremental conductance $\Delta I/\Delta V$, the MPP has been reached. When $-I/V$ is less than $\Delta I/\Delta V$, the system operates on the left side of the MPP; if greater, it operates on the right side. By comparing $-I/V$ and $\Delta I/\Delta V$, the controller determines the direction of movement for the operating voltage [7]. The power–voltage curve near the MPP is relatively flat; thus, small voltage changes do not induce significant power deviations. Fixed step sizes may cause oscillations around the MPP, whereas large variable steps can lead to divergence [1]. Various strategies, including adaptive step size tuning, have been proposed to balance tracking speed and oscillation amplitude [42]. These challenges motivate integrating FLC with INC to enhance MPPT performance under dynamic conditions.

The incremental conductance method is an accepted technique for MPPT. It computes the ratio dI/dV from measurements of the PV modules' instantaneous current and voltage, compares it with the negative ratio of I/V , and adjusts the operating point of the converter if they are not equal [26]. Fig. 8 and 9 illustrate that the MPP occurs when $dP/dV = 0$, which forms the core principle of the INC algorithm, as demonstrated below with supporting equations [43]:

The power output of the PV array is:

$$P = V_{pv} * I_{pv} \quad (1)$$

Incremental Conductance condition for MPP [43]:

$$\frac{dP}{dV} = \frac{d(V_{pv}I_{pv})}{dV_{pv}} = I_{pv} + V_{pv} \frac{dI_{pv}}{dV_{pv}} \quad (2)$$

At MPP [43]:

$$\frac{dP}{dv} = 0 \Rightarrow \frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \quad (3)$$

The error signal and the rate of error used as inputs to FLC:

$$e(k) = V_{mpp}(k) - V_{pv}(k) \quad (4)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (5)$$

, and FLC output which represents the change in duty cycle:

$$\Delta D(k) = \text{FLC}(e(k), \Delta e(k)) \quad (6)$$

The integrated duty cycle is:

$$D = \Delta D(k) + D(k-1) \quad (7)$$

, where:

P : is the power of the solar panel in watt
 V_{pv} : is the voltage of the solar panel in volt
 I_{pv} : is the current of the solar panel in ampere
 V_{mpp} : is the voltage of the solar panel at MPP in volt
 D : is the duty cycle for the converter

A recent work presents INC MPPT using a novel direct control algorithm that adjusts the duty cycle inside the algorithm, eliminating the control loop of the dc/dc converter and maintaining effective tracking [44]. Steady-state oscillations were reduced, and dynamic performance improved, as shown by simulation results [44]. Yet another recent study proposes an improved INC MPPT method that eliminates the oscillation phenomenon caused by unreasonable step size setting, thereby improving the efficiency of photovoltaic power generation and achieving fast and accurate tracking of the MPP under rapid changes of light intensity [42].

The INC principle is based on the fact that the derivative of power against voltage is zero at the MPP. At MPP, the relation $dP/dV = 0$ can be written as $dI/dV = -I/V$. The classic INC algorithm determines whether the output voltage is to be increased or decreased based on this condition, which is used as the first approach of the hybrid method [26]. The traditional approach however employs a constant step size (ΔV) that may be either small resulting in slow tracking or large resulting in oscillations [45]. To overcome this, the hybrid FLC-INC algorithm employs FLC to adapt the step size.

2.5 Grey wolf optimizer

Grey wolf optimizer (GWO) is a metaheuristic algorithm that is bio-inspired and based on the

leadership hierarchy and cooperative hunting of grey wolves. This was applied in this work to optimize the scaling factors (inputs/output gains) of the FLC to optimize the performance of MPPT in a PV system [46].

The GWO algorithm works by revising the positions of search agents (wolves) with the influence of the best three solutions alpha, beta and delta, and balancing between exploration and exploitation [46]. The optimization was guided by a custom fitness function, which is the mean of the PV power (fitness = mean(Ppv)). In order to improve performance and minimize manual trial-and-error, the FLC scaling gains are optimized with the GWO. To find the minimum of a composite objective in parameter space (e.g. tracking error, steady-state ripple, and settling time), GWO generally searches the parameter space offline. GWO-tuned FLC produces abridged convergence, minimum oscillation, and tracking, and retains the real-time controller lightweight when deployed on the target platform.

To ensure transparency and avoid potential overfitting, the GWO tuning procedure was performed offline using a clearly defined optimization framework. The objective function was formulated to maximize the mean harvested power over the optimization horizon, expressed as:

$$J = \frac{1}{T} \int_0^T P_{pv}(t) dt \quad (8)$$

, where $P_{pv}(t)$ is the instantaneous PV output power and T is the period of evaluation. The optimization by direct maximization of the average extracted power as opposed to minimization of error terms only is an inherent way of considering both transient tracking accuracy and steady-state ripple behaviour.

The FLC input/output scaling factors (K_p , K_d , K_o) are the decision variables constrained by predetermined limits that were chosen to ensure that the controllers operate within a stable range and that the duty-cycle was feasible. The GWO algorithm was run with population size of 20 search agents and 20 iterations.

In order to reduce stochastic bias, the optimization was run several independent times with various random seeds. The last reported scaling factors are the best fitness solution, and the objective value was not very sensitive to the variability of the objective value across runs.

To reduce the risk of overfitting, the optimization was conducted using representative but limited irradiance and temperature profiles. The optimized parameters were subsequently validated on additional disturbance scenarios not used during tuning,

including different ramp slopes and simultaneous irradiance–temperature variations. The controller maintained comparable tracking efficiency and harvested energy under these unseen profiles, demonstrating satisfactory generalization capability.

3. Hybrid approach: FLC-INC

A hybrid fuzzy-incremental algorithm (FLC-INC) of MPPT in PV systems that works under dynamic conditions is suggested. The hybrid technique is a combination of the strength of FLC and the precision of INC and is executed in an FPGA Xilinx Spartan-3. The method is tested with a 10-second test dataset to apply on various scenarios to test the controller, because longer simulations are costly and take a long time to compute. Experimental findings prove the capability of the algorithm to get steady output power and precisely follow the MPP.

The hybrid FLC-INC MPPT algorithm of PV systems in dynamic conditions is designed by developing a conceptual framework. The algorithm design in the framework employs the FLC and INC techniques, which are supposed to enhance the dynamic performance and speed of response of traditional MPPT techniques. FLC takes advantage of the benefits of the fuzzy set theory and expert knowledge, and the INC method computes the voltage at MPP (V_{mpp}) based on the incremental conductance and the instantaneous conductance (dI/dV and I/V). Instead of using a fixed or variable step size, the FLC determines the duty cycle directly following the processing of the error, the panel voltage (V_{pv}) subtracted from V_{mpp} . The simulation outcomes prove that the suggested FLC-INC controller is much more effective than the conventional INC method because it allows PV systems to reach the MPP in a very short time in case of unstable or variable weather conditions and improves stability in urban areas.

The proposed MPPT strategy is a development of the traditional INC method with the addition of an FLC to dynamically control the size of the duty cycle step in response to the error. INC methods have received much interest as stand-alone MPPT strategies to PV systems due to their capability to distinguish power based on voltage and detect the MPP, thus overcoming the oscillation problems that are inherent in the P&O approach. The use of steady-state INC equation using a constant step size results in a slow response and severe oscillations when the irradiance levels are changed. In comparison, FLC allows dynamic tuning of the step size, which improves the capability of the system to quickly and precisely track the MPP in the case of transient

conditions. Duty cycle adjustment to the output of the FLC provides a rapid means to the MPP and the addition of FLC broadens the operation of the method and keeps hardware levels low. Experiments and simulations in a variety of climatic conditions prove that the hybrid FLC-INC algorithm can maintain the effective control of the MPP, which is superior to the steady-state performance of the standard INC method and highlights the advantages of hybridization of PV systems in dynamic conditions. Fig. 7 illustrates the controller samples V_{pv} and I_{pv} of the Simulink plant, calculates the error $e = V_{mpp} - V_{pv}$ and its change, and uses FLC to produce a duty cycle, which is fed to a PWM generator, which drives the interleaved boost converter in the Simulink model (HIL).

The suggested MPPT system combines the INC algorithm and the FLC to enhance the performance of the system in changing irradiance conditions. The INC algorithm estimates the V_{mpp} and the difference between V_{mpp} and the actual V_{pv} is one of the FLC inputs (error), and this error change (Δe) is taken as

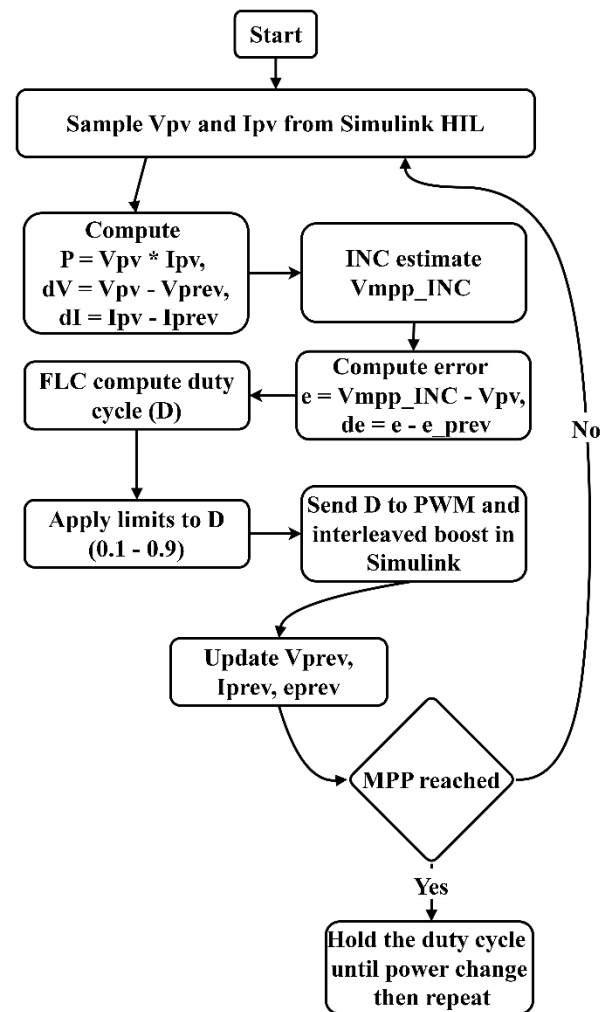


Figure. 7 Flowchart of the FPGA-based hybrid FLC-INC MPPT in HIL

the second input. The FLC employs these two variables to create a change in the duty cycle (ΔD), which is then added to create the actual duty cycle applied to an interleaved boost converter. This method allows rapid dynamic response, and the reduction of steady-state oscillations is reduced. The interleaved boost converter eliminates current ripple, diffusion of thermal load, and efficiency. The structure of the control loop includes gain scaling at the inputs and output of the FLC, which are tuned using the GWO.

Figs. 8 and 9 below show the PV panel characteristics under varying irradiance and temperature levels. These characteristics were generated using the built-in I-V and P-V curve plotting functionality provided by the PV panel block in Simulink, based on the solar panel specifications used in this study's model.

Figs. 8 and 9 illustrate that the MPP occurs when $dP/dV = 0$, which forms the core principle of the INC algorithm, as demonstrated previously with the supporting equations.

4. Simulation and experimental setup

The hybrid FLC-INC MPPT algorithm is assessed using a hardware-in-the-loop (HIL) workflow. The PV array and DC/DC converter are modeled in MATLAB/Simulink as shown in Fig. 10. Fig. 11 shows the solar panel system, which consists

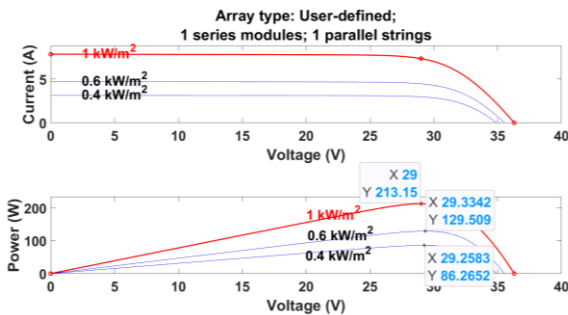


Figure 8 PV characteristics with different Irradiances levels (P-V curve and I-V curve)

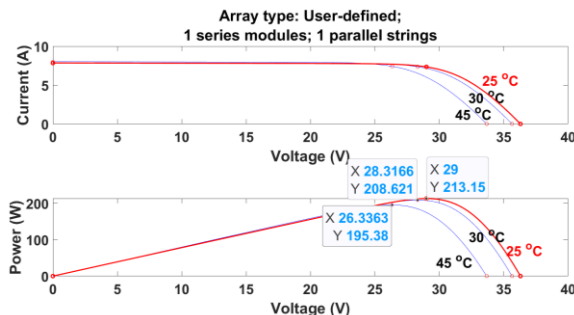


Figure 9 PV characteristics with different temperatures levels (P-V curve and I-V curve)

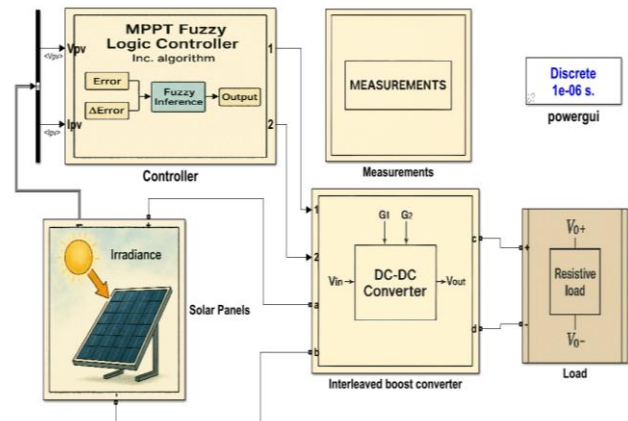


Figure 10 The main Simulink model

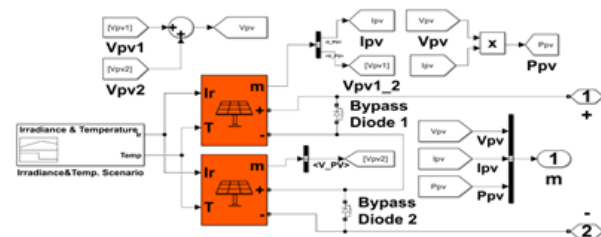


Figure 11 Solar Panels

of two panels exposed to variable irradiance and temperature levels.

The controller is synthesized on a Xilinx Spartan-3 FPGA and connected to the model through real-time I/O. In each control cycle, the simulated PV voltage and current are streamed to the FPGA; the FPGA executes the hybrid MPPT in fixed-point and returns the duty-cycle command to the Simulink converter/PWM block. The test campaign applies ramp irradiance and temperature scenarios within Simulink to verify adaptability and robustness of the controller. Comparative runs against stand-alone INC and stand-alone FLC baselines show that the FPGA-based hybrid controller achieves faster convergence, smoother power, and lower oscillations around the MPP under rapidly changing conditions, while preserving deterministic real-time behavior.

Fig. 12 Shows the FLC-INC with a PWM generator and 2 gate signals for the interleaved boost converter built in Simulink, while Fig. 13 shows it built in Xilinx FPGA blocks. The FLC scaling gains $K_p = 0.5$, $K_d = 0.1$, and $K_o = 0.005$ are obtained through GWO tuning and kept constant during all experiments.

Fig. 14 shows how the FLC is implemented in the FPGA with a look-up table methodology.

The proposed MPPT architecture combines the INC algorithm with a FLC. The INC block estimates the instantaneous maximum power point voltage V_{mpp} ,

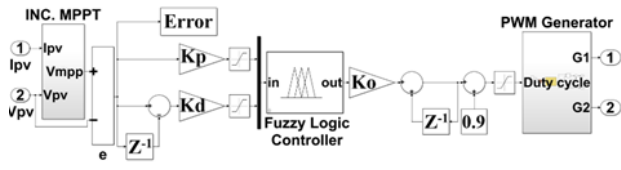


Figure 12 FLC-INC Controller

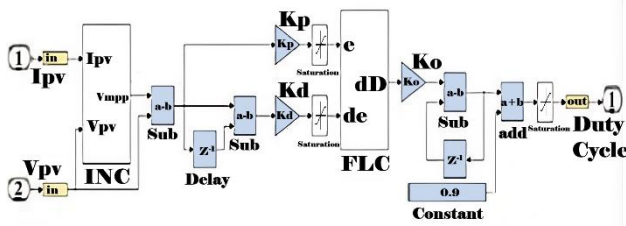


Figure 13 FLC-INC Controller Built in Xilinx Blocks

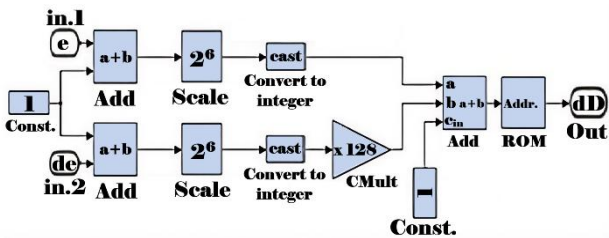


Figure 14 FLC implemented in the FPGA

from which the control error (e) and its variation (Δe) are derived, normalized, and applied to the FLC. Based on the predefined rule base, the FLC generates an incremental duty cycle command (ΔD), which is accumulated to get the duty cycle (D) and limited to ensure stable converter operation with reduced steady-state oscillations.

For FPGA implementation, the FLC is realized using fixed-point arithmetic and a ROM-based inference approach, where the scaled input variables are mapped to a unique memory address and the corresponding control output is retrieved without on-line fuzzy computations. This structure guarantees deterministic execution, low computational complexity, and efficient real-time operation, making the proposed controller well suited for FPGA-in-the-loop MPPT applications.

The controller operates with a fixed sampling period of $T_s = 1\mu s$ (1 MHz update rate). The power converter is driven by a PWM generator operating at 5 kHz, resulting in 200 MPPT updates per PWM period. At each control cycle k , the FPGA execution follows a deterministic sequence: (i) latching of $V_{pv}[k]$ and $I_{pv}[k]$; (ii) power computation and incremental conductance evaluation using ΔV and ΔI ;

(iii) estimation of the reference voltage $V_{mpp}[k]$; (iv) error computation $e[k] = V_{mpp}[k] - V_{pv}[k]$ and $\Delta e[k]$; (v) fuzzy inference to generate the duty increment $\Delta D[k]$; and (vi) duty-cycle integration and update. The resulting duty command is recorded and implemented at the following PWM frame boundary so that causal and repeatable behaviour can be exhibited.

The HIL interface presents a limited and deterministic latency of one control cycle, such that:

$$D_{\text{applied}}[k] = D_{\text{computed}}[k - 1]. \quad (9)$$

Zero-order hold is used to sample input signals and buffer them at FPGA registers and output commands are fed synchronously to the PWM generator.

All FPGA computations are realized using fixed-point arithmetic with a 16-bit word length. Intermediate products retain extended precision before rounding and truncation, and saturating arithmetic is employed throughout to prevent overflow. The duty-cycle command is explicitly constrained to

$$0.1 \leq D \leq 0.9, \quad (10)$$

with the incremental update limited to

$$|\Delta D| \leq 0.01, \quad (11)$$

ensuring stable operation under fast irradiance changes and mitigating quantization-induced oscillations.

The design was synthesized using Xilinx ISE 14.7 targeting the specified Spartan-3A DSP device. Post-place-and-route analysis confirms that all control computations meet timing closure and are completed within a single control cycle, with sufficient margin.

Figs. 15 and 16 show the interleaved boost converter and the system load, which is a resistive load here.

The HIL validation platform is shown in Fig. 17. The controller is deployed on the Xilinx Spartan-3 FPGA, while the photovoltaic array and interleaved boost converter are modelled in MATLAB/Simulink and executed on the host PC. Signal exchange between both domains is performed at each control cycle.

This HIL configuration provides deterministic timing from a real FPGA controller while keeping the PV and power stage in Simulink, enabling safe, fast,

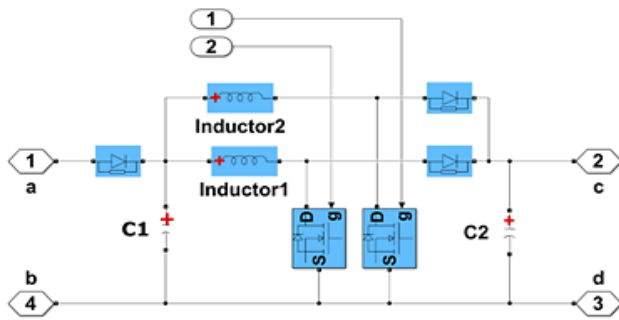


Figure. 15 Interleaved boost converter

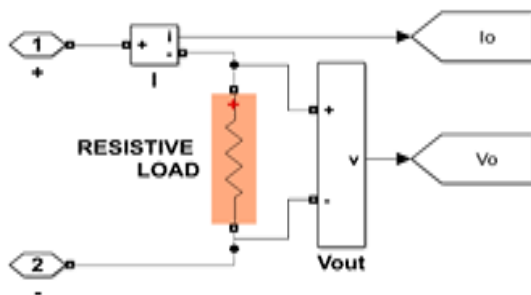


Figure. 16 Resistive Load



Figure. 17 HIL System Wiring

and repeatable testing of the hybrid MPPT across diverse dynamic scenarios.

In order to ensure that quantization and latency do not have a significant impact on the reported results, the controller was tested at the same irradiance and temperature profiles with both floating-point and fixed-point versions. The fixed-point implementation had a tracking efficiency deviation less than 1%, and no noticeable stability, transient response or steady-state ripple degradation. Further simulations using a clear one-cycle command delay verified that the controller is stable and still has a performance advantage over the traditional MPPT techniques. Moreover, bit-true comparison of the FPGA output with the fixed-point software model indicated that

there was an agreement in the first LSB, which is a true indication of faithful hardware realization.

In order to provide fair and reproducible assessment, the stand-alone INC, stand-alone FLC and the proposed hybrid FLC-INC optimized by GWO were run and tested in the same HIL conditions. All the controllers were implemented on the same Xilinx Spartan-3A DSP FPGA, and the PV array and interleaved boost converter were modelled in MATLAB/Simulink and connected to the FPGA-in-the loop.

All the experiments had identical control sampling period ($T_s = 1\mu s$), PWM frequency (5 kHz), 16-bit fixed-point arithmetic, minimum and maximum duty-cycle ($D_{min} = 0.1$, $D_{max} = 0.9$), PV model parameters, converter component, load conditions, and equivalent irradiance and temperature profiles. The controller logic was the only one that was varied across test cases.

In the case of the INC baseline, the updated duty-cycle was determined by the sign of the incremental conductance (dP/dV) using a constant step size ($\Delta D = 0.01$). Derivatives were computed using backward finite differences with low-pass filtering, and identical saturation constraints were applied. The stand-alone FLC employed the same input variables and membership functions as the hybrid controller, representing a conventional fuzzy MPPT.

Performance metrics, including tracking efficiency and steady-state ripple were computed using identical definitions and evaluation windows for all controllers.

5. Results and discussion

The performance of the hybrid FLC-INC MPPT was evaluated using a HIL arrangement: the PV array and interleaved boost converter were modelled in MATLAB/Simulink, while the controller ran on a Xilinx Spartan-3 FPGA. Tests targeted tracking efficiency and steady-state ripple under programmed irradiance and temperature profiles. Three representative scenarios were applied in Simulink: (i) uniform operating conditions, (ii) increasing irradiance ramps, and (iii) decreasing irradiance ramps.

The first test scenario involves a 425 W solar panel model subjected to dynamically changing irradiance ($400\text{--}1000\text{ W/m}^2$) and constant temperature (25°C). Fig. 18 illustrates the irradiance and temperature profiles applied to the system, and Fig. 19 shows the real-time power response of the PV array and the load.

The second test scenario involves the solar panel

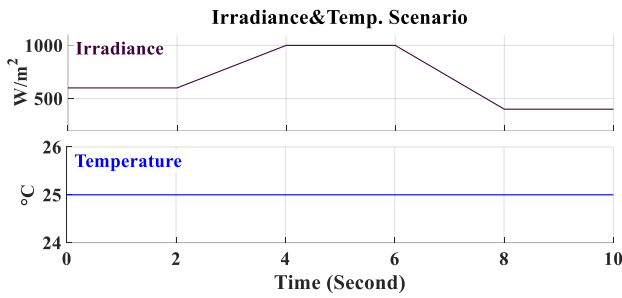


Figure 18 Irradiance and temperature scenario 1

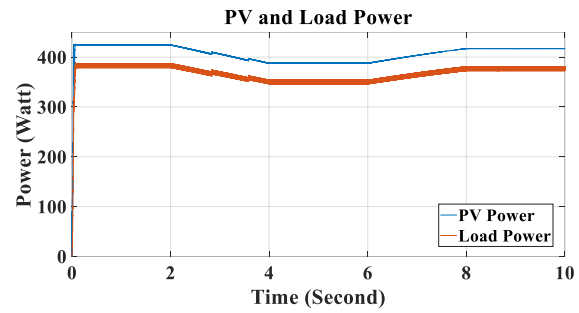


Figure 21 PV and Load powers – scenario 2

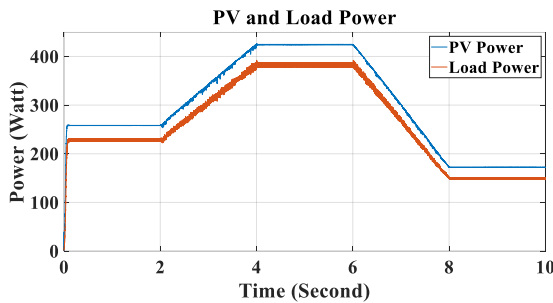


Figure 19 PV and Load powers – scenario 1

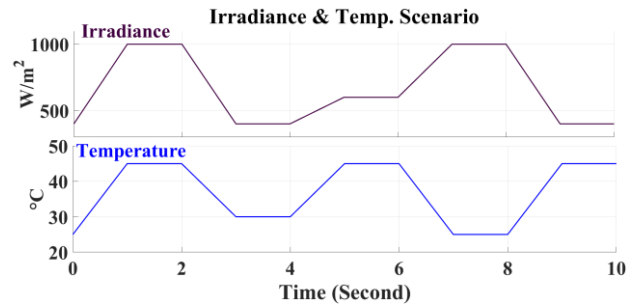


Figure 22 Irradiance and temperature scenario 3

model subjected to dynamically changing temperature (25–45 °C) and constant irradiance (1000 W/m²). Fig. 20 illustrates the irradiance and temperature profiles applied to the system, and Fig. 21 shows the real-time power response of the PV array and the load.

To further strengthen the robustness evaluation, an additional benchmark profile was implemented as shown in Fig. 22 including simultaneous irradiance and temperature variations with different transition rates. Unlike the previous cases where one parameter was varied at a time, this extended scenario applied concurrent irradiance ramps (slow and fast slopes) together with dynamic temperature changes to emulate realistic environmental disturbances. The controller maintained stable and accurate tracking with fast convergence and short settling time, and no deviation from the theoretical MPP was observed throughout the applied disturbance profiles. The

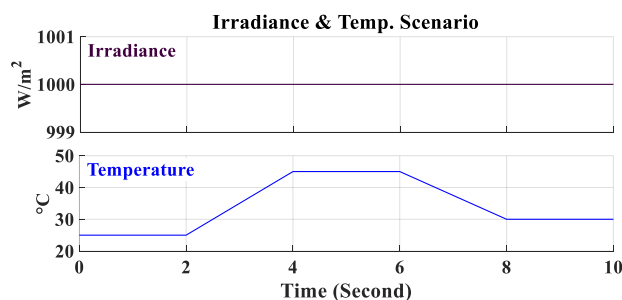


Figure 20 Irradiance and temperature scenario 2

harvested energy under this extended benchmark remained comparable to the high tracking efficiency observed across the evaluated cases, confirming that the hybrid FLC–INC controller maintains its effectiveness beyond specific operating scenarios.

Moreover, measurement disturbances were also tested by adding noise to the sensed PV voltage and current signals in the HIL interface. The added noise was mostly on the INC slope estimation step which caused some small transient oscillations. Nevertheless, by adding a first order low-pass filter in the measurements path the oscillatory response reduced without compromising tracking rate or steady state. These extended experiments show that the developed FPGA-based hybrid controller is more stable, provided with higher tracking accuracy, and ripple suppression in a wider range of realistic operating profiles, which therefore validates the claimed robustness of the HIL environment.

As shown in Fig. 19, Figs. 21 and 23, the system effectively tracks the MPP with minimal steady-state oscillations. For example, at an irradiance of 1000 W/m², the system produces 425 W (from two panels). When the irradiance drops to 600 W/m² and 400 W/m², the output power decreases accordingly to 258 W and 171.6 W, as shown in Fig. 19. Similarly, the system responds well to temperature changes: at 25°C, 30°C, and 45°C, it generates 425 W, 417 W, and 390.7 W respectively.

The above results give the following efficiency for each case:

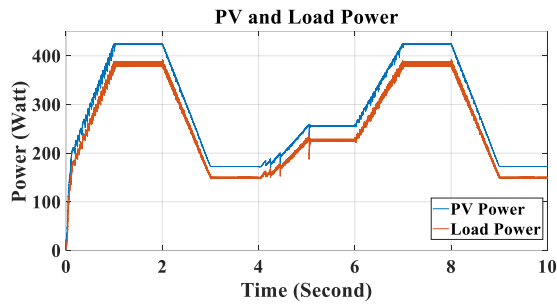


Figure. 23 PV and load powers – scenario 3

, where the efficiency is calculated as the ratio of the MPP obtained by the controller to the theoretical MPP determined from the PV characteristics, as shown in Figs. 8 and 9. It is given by:

$$\text{Efficiency} = \frac{\text{obtained MPP}}{\text{Theoretical MPP}} * 100\% \quad (12)$$

The efficiencies in Table 2 refer only to tracking efficiency in steady-state, not to overall power-conversion efficiency. Converter and sensing losses are deliberately excluded so that competing MPPTs could be compared on equal footing, in line with the methodology adopted by the other's works.

Table 3 presents a direct performance comparison between the stand-alone INC, stand-alone FLC, and the proposed hybrid FLC–INC optimized by GWO, all evaluated under identical HIL conditions. Therefore, the differences observed in efficiency and steady-state ripple behaviour are solely attributed to the control strategy rather than variations in hardware, modelling, or test conditions.

While INC achieved 89.5% efficiency with 1% ripple, the standalone FLC exhibited large oscillations 10% ripple, since it was not designed to operate as a standalone MPPT. In contrast, the hybrid FLC–INC achieved the highest efficiency (99.69%) with minimal ripple (0.15%).

Performance comparisons with other related methods verify that the hybrid algorithm outperforms other techniques in dynamic conditions. Significant benefits of hybridization are reported throughout the paper.

Table 2. Efficiency of the proposed controller with different irradiance and temperature levels

Irradiance (W/m ²)	1000	600	400	1000	1000
Temperature (°C)	25	25	25	30	45
Efficiency (%)	99.69	95.9	99.46	98.46	99.98

Table 3. Comparative performance of INC, FLC, and proposed FLC–INC evaluated under identical conditions

Method	Efficiency %	Power Ripple
INC	89.5%	1%
FLC	91.32%	10%
FLC-INC	99.69%	0.15%

Performance evaluation in this work is primarily based on tracking efficiency, defined as the ratio of the energy harvested to the theoretical maximum energy available from the PV array over a given test profile. Tracking efficiency is computed in an energy-based, profile-averaged manner over a fixed 10 second evaluation window for each irradiance and temperature scenario, rather than as an instantaneous power ratio, thereby directly reflecting the energy-maximization capability of the MPPT under dynamic operating conditions.

PV voltage, current, and output power are measured at the HIL interface using 16-bit fixed-point representations consistent with the FPGA implementation, inherently accounting for quantization effects. Sensor noise is not explicitly modeled in order to isolate controller-induced performance differences under identical test conditions. In addition to tracking efficiency, steady-state power ripple is reported as a secondary performance indicator. Transient response indicators such as overshoot and settling time are of secondary relevance in the context of power-based MPPT operation and do not materially influence performance evaluation adopted in this work. Since the objective of MPPT is to maximize harvested energy, controller performance is more appropriately assessed through energy-oriented metrics. Accordingly, emphasis is placed on tracking efficiency and steady-state power behavior, which more directly reflect the effectiveness of the MPPT.

6. Conclusion

This work presented a hybrid FLC–INC MPPT realized on a Xilinx Spartan-3 FPGA and evaluated in a HIL setup, where the PV array and interleaved boost converter were modelled in MATLAB/Simulink. The INC stage estimates the instantaneous V_{mpp} online, while the FLC uses the tracking error $e = V_{mpp} - V_{pv}$ and its variation to generate the PWM duty cycle. When evaluated under identical FPGA/HIL conditions, the proposed controller achieved a peak tracking efficiency of 99.69%, outperforming stand-alone INC and stand-alone FLC baselines implemented in this work.

Table 4. Comparative table with recent works

Ref.	Method	Platform / Implementation	Efficiency %	Converter type	Output Ripple
Khan et al., 2021 (International Journal of Engineering Works) [47]	P&O	Simulation (MATLAB/Simulink)	87.3%	SEPIC	Very low
	INC	Simulation (MATLAB/Simulink)	91.5%		Very low
	FLC	Simulation (MATLAB/Simulink)	93%		Very low
Sun et al., 2022 (Scientific Reports) [26]	INC (variable step)	Simulation (MATLAB/Simulink)	97.38%	Boost	Very low
Ullah et al., 2023 (Results in Engineering) [3]	FLC	Simulation (MATLAB/Simulink)	98.9%	Boost	Low
Yahiaoui et al., 2023 (Mathematical Problems in Engineering) [5]	GA-optimized FLC	Experimental Setup	98.66%	Boost	Very low
Deghfel et al., 2024 (Scientific Reports) [8]	GA/WOA optimized ANFIS	Simulation (MATLAB/Simulink)	98.736-99.996%	Boost	Very low
Çakmak et al., 2025 (Energies) [39]	Hybrid FLC–P&O	Simulation (MATLAB/Simulink)	98.47%	Boost	1% voltage ripple
Hasan et al., 2025 (Results in Engineering) [48]	Hybrid GA-INC	Simulation (MATLAB/Simulink)	98.8%	Boost	-----
Proposed work	FLC-INC	Xilinx Spartan-3 (FPGA), HIL with Simulink	99.69%	Interleaved boost	0.15% Power Ripple

Efficiency values reported from recent literature are included for qualitative reference only, as direct quantitative comparison is limited by differences in PV models, converter topologies, sampling rates, and metric definitions. In addition, the use of an interleaved boost converter resulted in very low output ripple and improved steady-state stability, while the FPGA realization ensured deterministic real-time execution without modifying the plant model. The HIL results confirm that the proposed FPGA-based hybrid MPPT controller provides higher harvested energy and superior steady-state behavior under rapid irradiance and temperature variations.

7. Future work directions

Future work will target global MPPT under partial shading conditions (PSC) and converter enhancements. We will integrate a two-stage global–local MPPT on the FPGA: a low-rate global search

(triggered by PSC detection) to locate the optimal region, followed by the existing fast FLC–INC tracker to minimize ripple. A lightweight GWO-based supervisor will periodically refine fuzzy membership functions instead of the gains only after transients to sustain low ripple with short settling times. On the power stage, we will evaluate synchronous interleaved boost and higher-gain variants (e.g., coupled-inductor/quadratic boost) and add digital current-mode control with phase management to improve dynamic response and efficiency. A PSC scenario will be used in HIL to quantify energy gains, convergence speed, and steady-state ripple.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, methodology, software, formal analysis, investigation, data curation, visualization, and original draft preparation: Mohannad Omar Abdullah; validation, review and editing, supervision, resources, funding acquisition, and project administration: Mohammed Y. Hassan and Nagham Saeed. All authors have read and agreed to the final version of the manuscript.

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