ENHANCING SOLAR POWER EFFICIENCY: A COMPARISON OF MPPT TECHNIQUES FOR GRID-TIED PV SYSTEMS

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Abstract

This research investigates the effectiveness of three Maximum Power Point Tracking (MPPT) algorithms—Incremental Conductance (IC), Perturb and Observe (P&O), and Fuzzy Logic Controller (FLC)—in optimizing power output in grid-tied photovoltaic (PV) systems. Each algorithm was tested under varying environmental conditions, focusing on performance in terms of energy extraction, stability, and adaptability to fluctuating irradiance and temperature. Results indicate that FLC offers superior performance, exhibiting reduced power fluctuations and faster responsiveness to environmental changes compared to IC and P&O. These insights contribute to enhancing PV system efficiency and reliability in modern power grids.

Keywords: FLC, IC, MPPT, P&O, PV Energy

1. Introduction

With the continuous increase in global energy demand, the need for alternative, renewable energy sources have become more urgent than ever. Among the various renewable energy technologies, PV systems stand out due to their ability to harness solar energy and convert it directly into electricity (Abidi et al., 2023). Solar energy is a highly attractive solution because it is abundant, clean, and sustainable, making it a key component in efforts to reduce reliance on fossil fuels and mitigate environmental pollution.

Despite the advantages, PV systems face significant challenges in their practical implementation. One major issue is the variability in energy output due to changing environmental conditions, such as temperature fluctuations, varying levels of solar irradiance, shading, and other weather-related factors (Al-Kubragyi, 2023; Alharbi et al., 2023). These conditions can drastically affect the efficiency of PV systems, leading to suboptimal energy production. To address this, maximum power point tracking (MPPT) techniques are employed to optimize the power output of PV panels by continuously adjusting the operating point of the system (Soumana et al., 2022).

MPPT algorithms are essential in grid-tied PV systems, where efficient power extraction is critical for ensuring consistent energy supply and grid stability (Noman et al., 2023). There are several MPPT techniques, each with different complexities and performance levels under varying environmental conditions (Manna et al., 2023). Among the most commonly used methods are the P&O algorithm, the IC algorithm, and more recently, the FLC (Mayouf, 2022).

The P&O method is one of the simplest and most widely implemented MPPT techniques. It works by perturbing the operating voltage of the PV array and observing the effect on power output. However, it can suffer from power oscillations around the maximum power point (MPP) and may struggle in rapidly changing irradiance conditions (Thanh & Le, 2023).

The IC method improves upon the P&O technique by using the derivative of the power with respect to voltage to predict the direction of the maximum power point (Zongo, 2021). Although it performs better under dynamic conditions, its complexity increases with the need for more calculations, which can slow down the response time.

The FLC approach leverages fuzzy logic to handle nonlinear and complex systems. It adapts quickly to changing environmental conditions and provides faster, more accurate tracking of the MPP with fewer fluctuations. FLC are increasingly popular in advanced control applications because of their ability to handle imprecision and uncertainties in input data, making them well-suited for the highly variable nature of solar irradiance and temperature (Azmi et al., 2023; Derbeli et al., 2023).

This paper provides a comparative study of these three MPPT algorithms: P&O, IC, and FLC. The performance of each algorithm is analyzed in a grid-tied PV system under different environmental conditions, specifically focusing on variations in temperature and irradiance levels. The goal is to assess which MPPT technique offers superior performance in terms of maximizing energy extraction while minimizing system instability and power oscillations. The study's findings will contribute to improving the efficiency of PV systems and their integration into modern power grids.

2. System Design

The system proposed in this study is a grid-tied photovoltaic system as in Figure 1, designed to efficiently convert solar energy into electrical power and feed it into a three-phase grid. The model consists of several key components, each of which plays a critical role in ensuring the effective operation of the overall system (Soumana et al., 2022). The design encompasses the PV array, a DC-DC boost converter, a DC-AC inverter, an *RL* filter, a step-up transformer, and the electrical grid. The system also incorporates a controller, which optimizes energy extraction from the PV array under various environmental conditions (Islam et al., 2022). Below is a breakdown of the major components of the system.

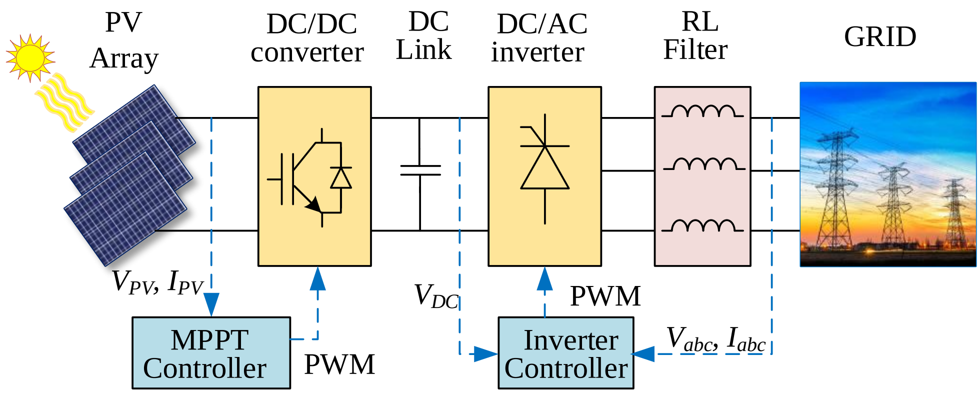

Figure 1. Grid-tied PV system schematic

2.1. PV Panel Modeling

The PV panel is the principal part of the system, responsible for converting sunlight into electrical energy. A PV cell can be represented using an equivalent circuit model consisting of a single diode, a series resistor R_s, and a shunt resistor R_{sh}. This model (Figure 2) is crucial for understanding the electrical behavior of PV cells under different irradiance and temperature conditions (Al-Kubragyi, 2023).

The output current of the PV panel I is given by (Premkumar et al., 2020):

$$I = I_L - I_0\left[e^{\left(\frac{q(V+IR_s)}{N_s AkT}\right)} - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{1}$$

where: I_L is the light-generated current, I_0 is the diode's saturation current, q is the charge of an electron ($1.6\times10^{-19}C$),V is the terminal voltage of the PV panel, R_s is the series resistance, R_{sh} is the shunt resistance, N_s is the number of cells in series, A is the diode ideality factor, k is Boltzmann's constant ($1.38\times10^{-23} J/K$), T is the cell temperature in Kelvin.

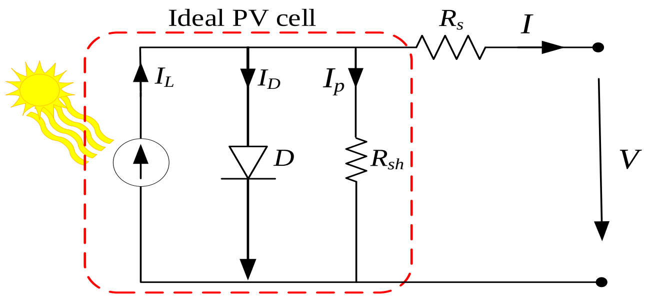

Figure 2. PV cell equivalent circuit

This equation represents the relationship between the current and voltage of a solar cell, factoring in the influence of temperature and irradiance levels on PV performance. The current-voltage (*I-V*) and power-voltage (*P-V*) characteristics are essential for analyzing the efficiency of the PV system under different operating conditions (Premkumar et al., 2020). Figure 3 representing these curves show the effects of various irradiance levels on the system, illustrating the dynamic nature of PV output.

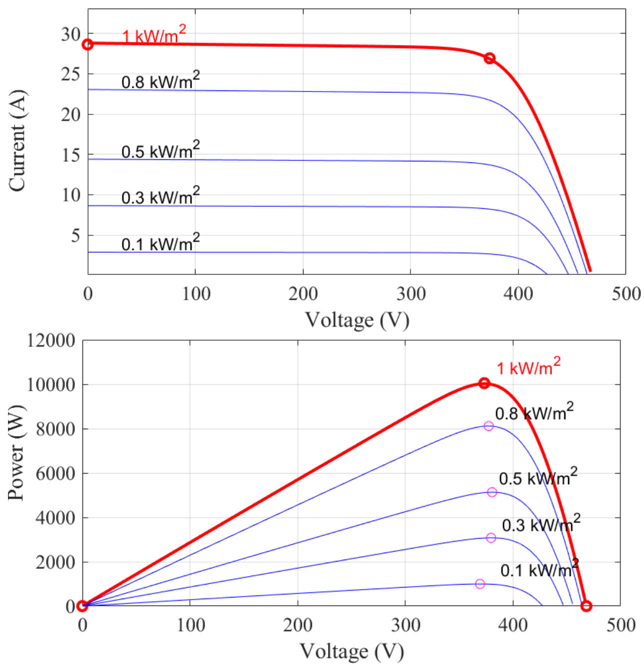

Figure 3. The characteristic curve of the PV module at 25°C and varying irradiant change

2.2. DC-DC Boost Converter Modeling

DC-DC boost converter is used to step up the low DC voltage produced by the PV array to a higher DC voltage that is more suitable for grid integration or battery storage (Singh & Kundu, 2020). The boost converter is placed between the PV array and the load or grid, and it plays a vital role in regulating the voltage to ensure optimal energy transfer.

The boost converter presented in Figure 4 comprises several key components: IGBT (Insulated Gate Bipolar Transistor): Used as a switching device, controlled by pulse-width modulation (PWM) signals to regulate the duty cycle; Inductor (*L*): Stores energy during the switch's ON state and releases it during the OFF state, thereby boosting the voltage; Diode: Prevents the reverse flow of current; Capacitor (*C*): Smoothens the output voltage by filtering the ripple produced by switching (Thanh & Dai, 2023).

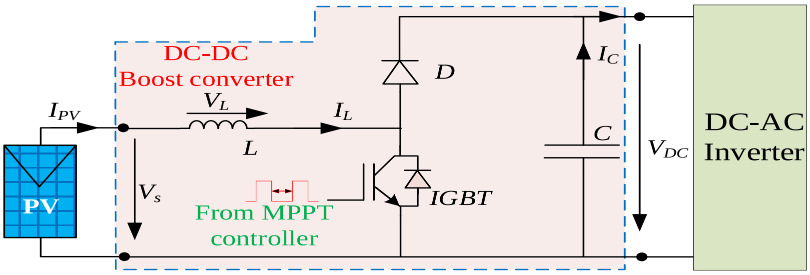

Figure 4. DC-DC Boost converter diagram

The relationship governing the boost converter's operation is expressed as:

$$V_{DC} = V_{out} = \frac{V_s}{1-D} \tag{2}$$

where: $V_{DC} = V_{out}$ is the output voltage of the boost converter, V_s is the input voltage from the PV array, D is the duty cycle of the PWM signal, ranging from 0 to 1. The duty cycle D controls the amount of voltage boost, and it is dynamically adjusted by the MPPT algorithm to ensure that the PV array operates at its MPP (Thanh & Dai, 2023). The boost converter is critical in ensuring that the voltage from the PV array is sufficiently stepped up for further processing by the inverter.

2.3. DC-AC Inverter

The DC-AC inverter is one of the most important components in a grid-tied PV system. It converts DC-electricity produced by the PV array into AC, which can be fed into the electrical grid or used to power AC loads (Soumana et al., 2022). This conversion is necessary because the grid and most household appliances operate on AC, not DC.

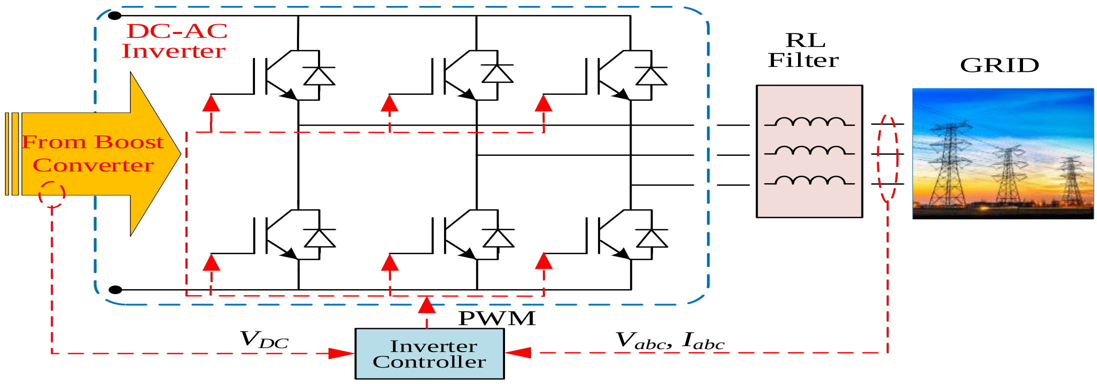

Figure 5. DC-AC Inverter diagram

In this design, a three-phase inverter is used to match the requirements of a grid-tied system presented by Figure 5 (Gawhade & Ojha, 2021; Islam et al., 2022). The inverter is equipped with advanced control systems that ensure the smooth integration of the solar power generated with the grid, while also maintaining power quality and synchronizing the frequency and voltage of the PV system with those of the grid.

The inverter operates by using switching devices (e.g., MOSFETs or IGBTs) to create an alternating waveform from the DC input (Soumana et al., 2022). The efficiency and stability of the inverter are critical, as poor inverter performance can lead to energy losses and power quality issues, such as harmonic distortion.

2.4. RL Filter

The *RL* filter, consisting of a resistor (*R*) and an inductor (*L*) connected in series, is an essential component used to eliminate unwanted harmonics and smooth out the voltage and current waveforms produced by the inverter (Soumana et al., 2022). These harmonics, generated during the DC-AC conversion process, can lead to power quality issues and reduce the overall efficiency of the PV system if not properly filtered.

The inductor in the *RL* filter stabilizes the variations in voltage and current by storing energy in its magnetic field, while the resistor dissipates excess energy as heat, ensuring that only clean, high-quality AC power is fed into the grid (Soumana et al., 2022). The *RL* filter plays a crucial role in improving the power factor and reducing the total harmonic distortion (THD) of the system.

3. Maximum Power Point Tracking Techniques

The efficiency of a photovoltaic (PV) system largely depends on its ability to extract maximum power from the solar panels under varying environmental conditions such as temperature and solar irradiance. The power-voltage (*P-V*) curve of a PV array has a unique point known as the MPP (Al-Kubragyi, 2023), where the system generates the most electrical power. However, due to the changing environmental factors, the MPP shifts continuously, requiring dynamic tracking mechanisms to adjust the system's operating point and ensure maximum power output. Three MPPT algorithms are evaluated in this study.

3.1. P&O MPPT Technique

P&O is a simple method that adjusts the operating voltage of the PV array and observes the effect on power output, making small perturbations to find the MPP (Thanh & Le, 2023). Figure 6 depicts the flowchart of the P&O algorithm, showing how the decision-making process operates. The operation of this technique can be summarized:

Step 1: The algorithm measures the current (*k*) power output (P_{current}) of the PV system.

Step 2: It compares this with the previous (*k*-1) power measurement (P_{previous}).

Step 3: If the power has increased ($P_{\text{current}} > P_{\text{previous}}$), the system continues to perturb the operating voltage in the same direction.

Step 4: If the power has decreased ($P_{\text{current}} < P_{\text{previous}}$), the perturbation direction is reversed.

This process continues iteratively, with the operating voltage oscillating around the MPP.

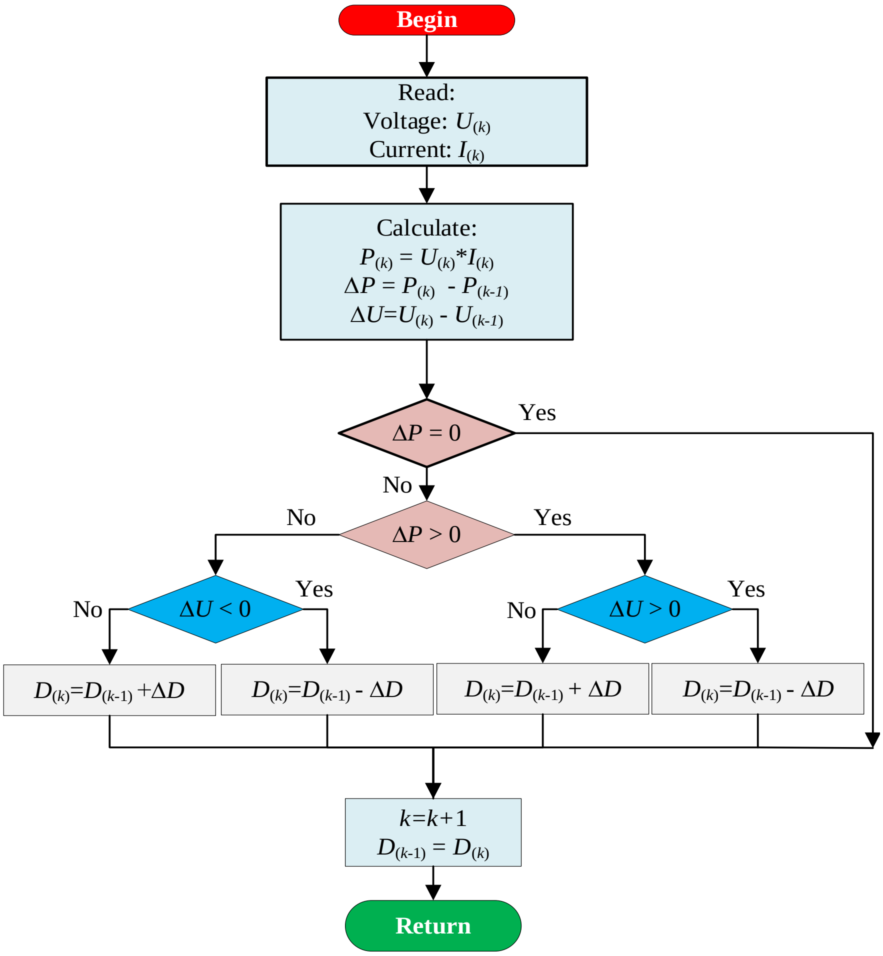

Figure 6. P&O operation flow chart

3.2. IC MPPT Technique

The IC method is more advanced and accurate than the P&O technique, particularly under rapidly changing environmental conditions. This method improves upon P&O by calculating the derivative of power with respect to voltage $\left(\frac{dP}{dV}\right)$ to determine the position of the operating point relative to the MPP (Thanh & Dai, 2023). Figure 7 illustrates the operation of the IC algorithm, showing how the system tracks the MPP by evaluating the slope of the *P-V* curve and can be expressed as:

Step 1: If $\frac{\Delta I}{\Delta V} = -\frac{I}{V}$, the system is at the MPP.

Step 2: If $\frac{\Delta I}{\Delta V} > -\frac{I}{V}$, the system is to the left of the MPP, so the voltage should be increased.

Step 3: If $\frac{\Delta I}{\Delta V} < -\frac{I}{V}$, the system is to the right of the MPP, the voltage should be decreased.

The IC method eliminates many of the disadvantages of P&O, particularly when dealing with rapidly changing irradiance. It is more stable and accurate because it directly uses the slope of the power curve rather than simply perturbing the voltage blindly (Kebbab et al., 2022). However, the increased accuracy comes with a higher computational cost, as the algorithm requires more complex mathematical calculations and more precise measurements.

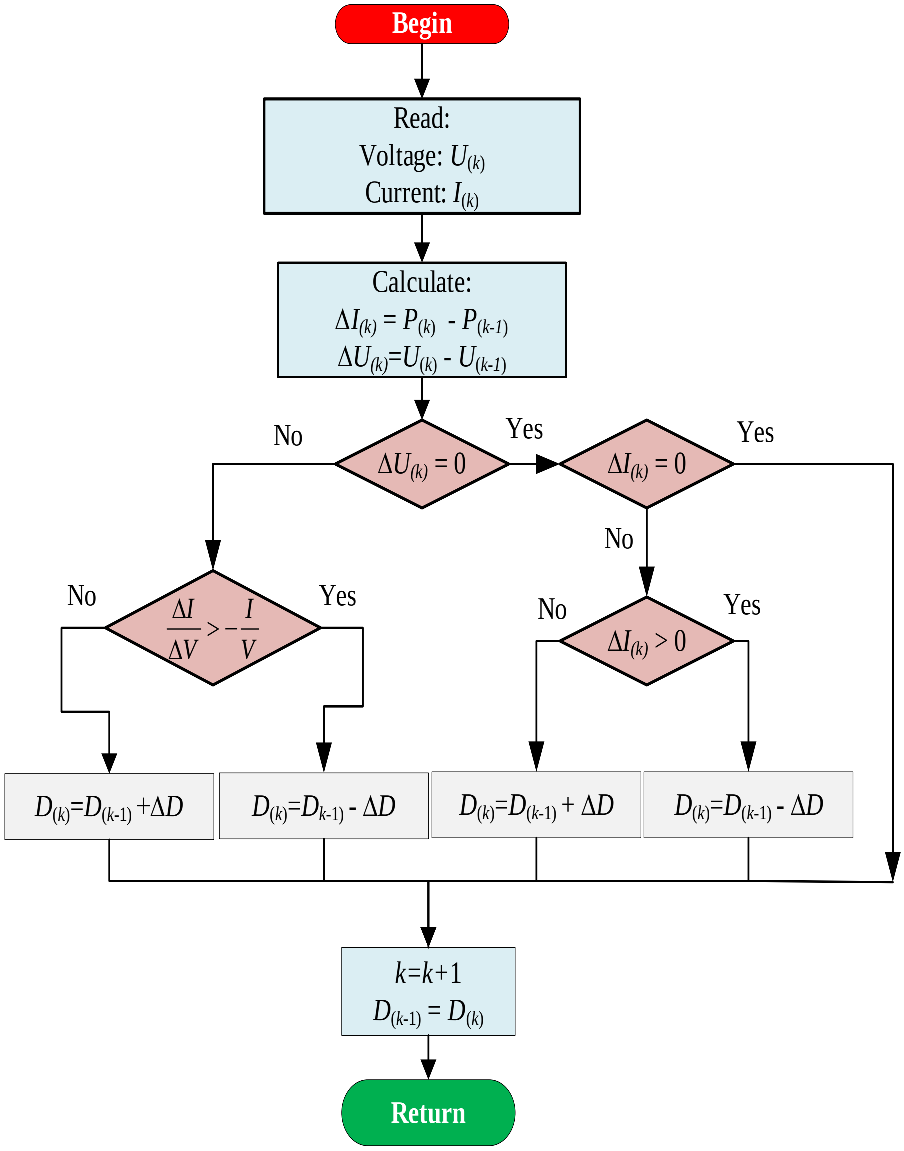

Figure 7. IC operation flow chart

3.3. Fuzzy Logic Controller (FLC) Algorithm

The FLC is a more sophisticated MPPT technique designed to handle non-linear and uncertain systems, which makes it highly suitable for PV systems where environmental conditions are highly variable. Unlike P&O and IC, which rely on precise mathematical models, the FLC method uses a set of linguistic rules and fuzzy logic to make decisions, making it more flexible and robust under dynamic conditions (Azmi et al., 2023; Thanh & Dai, 2023). A regular FLC has four components: Fuzzier to converts the numerical inputs into fuzzy linguistic; Rule - base is the core of FLC consists of “IF-THEN” rules, which govern how the system should behave as presented in Table 1; Inference Engine uses the rule base to decide how to adjust the system’s control parameters; and the

Defuzzifier responds for converting output from the inference engine back into numerical value. In this MPPT, it takes two inputs: the error (E_k) between the current operating point and the MPP, and the change in error (ΔE_k). Based on these inputs, the FLC adjusts the duty cycle of the DC-DC converter to track the MPP. Figures 8 depicts the membership functions used in the FLC method, showing how the error and change in error are classified into linguistic variables and how the control output is determined.

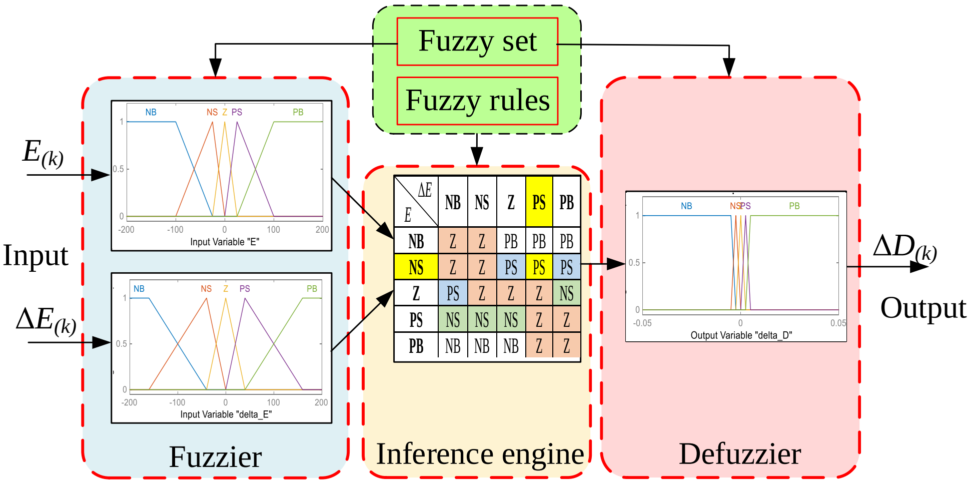

Figure 8. FLC block's structure

TABLE 1. Rules for the fuzzy logic controller

$E_{(k)}$ \ $\Delta E_{(k)}$	**NB**	**NS**	**Z**	**PS**	**PB**
NB	Z	Z	PB	PB	PB
NS	Z	Z	PS	PS	PS
Z	PS	Z	Z	Z	NS
PS	NS	NS	NS	Z	Z
PB	NB	NB	NB	Z	Z

4. Simulation Results

To validate the effectiveness of the three MPPT algorithms: P&O, IC, and FLC - a detailed simulation was carried out using MATLAB/Simulink for a 10kWp PV system with grid-connected in Figure 9. The simulation aimed to assess the performance of each technique under environmental conditions, particularly focusing on changes in solar irradiance. These simulations were crucial in understanding how each algorithm adjusts the operating point of the PV system to ensure maximum power output under different scenarios.

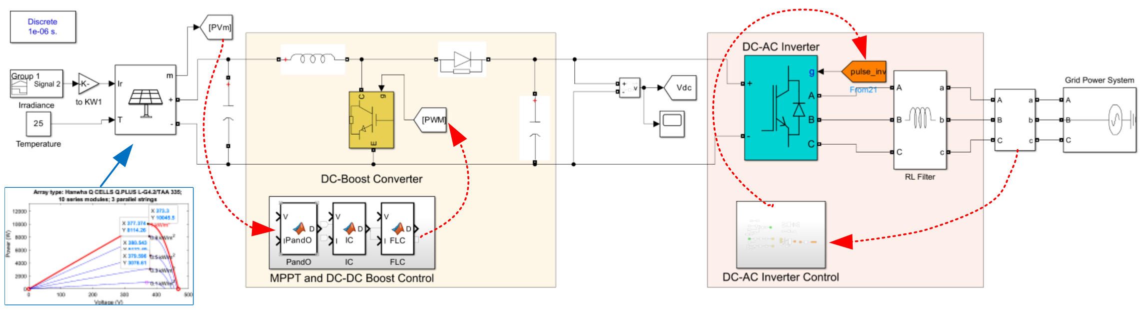

Figure 9. 10kWp PV grid-connected system

The following sections provide an in-depth discussion of the results, focusing on the impact of temperature and solar radiation variations on the PV system's performance.

In this study, the temperature is fixed at 25ºC while the irradiance varies over time, as shown in Figure 10. We'll examine a bell-shaped variant of irradiance, which also includes the presented disturbances. The efficiency of the three techniques can be compared by evaluating the PV array power output and the electricity injected into the grid, as illustrated in Figures 11 and 12.

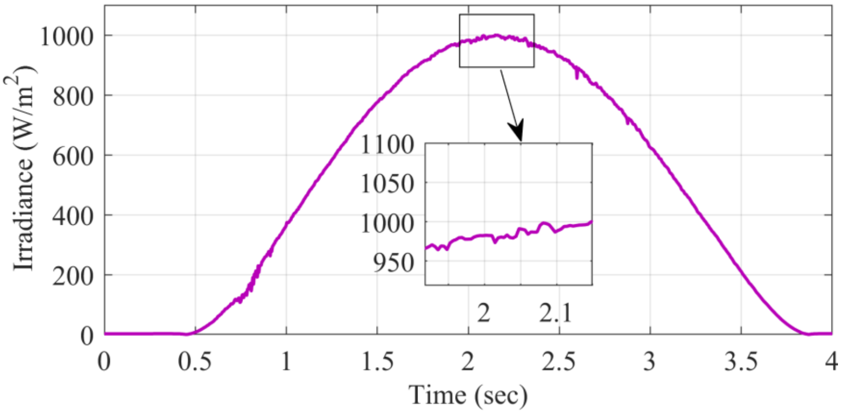

Figure 10. Variant of irradiance for a PV system operating at a fixed temperature of 25ºC

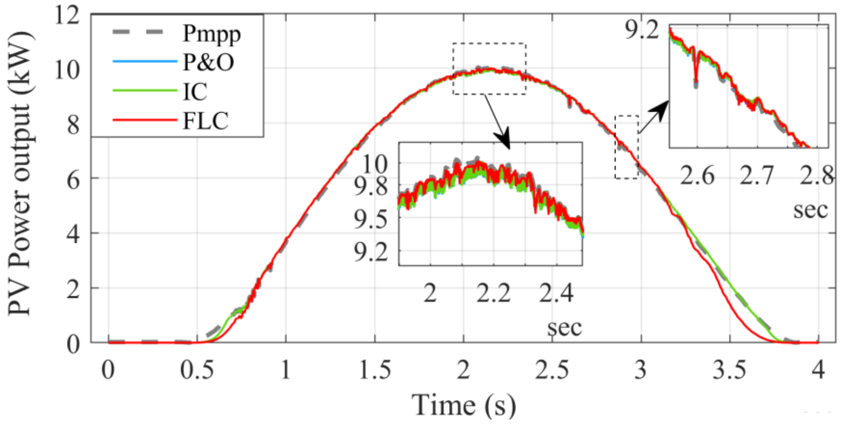

Figure 11. DC - power output of PV

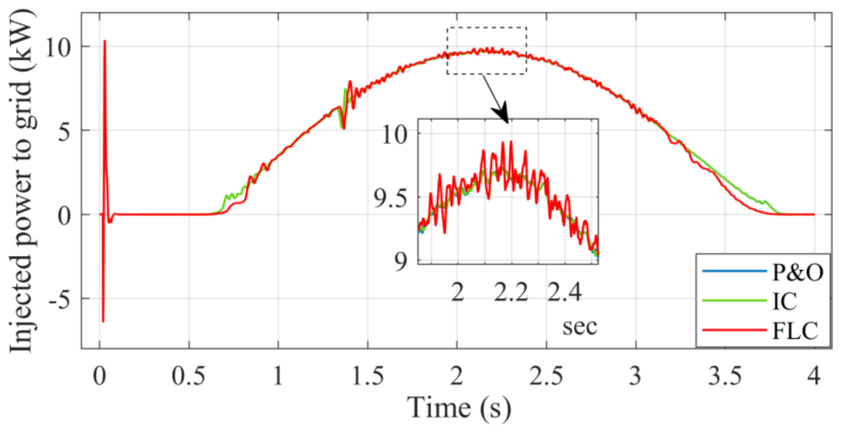

Figure 12. AC - power injected into grid of PV

In Figure 11, in response to the complex changes in irradiance, all three MPPT techniques demonstrate their ability to track the MPP of the PV system. Among them, IC and P&O yield fairly similar results, while FLC, due to ΔD_k being updated each cycle, performs better with fewer fluctuations and closer alignment to the PV maximum power curve. However, considering the AC power injected into the grid, FLC, in its effort to maximize PV power extraction, exhibits greater fluctuations compared to P&O and IC. Nonetheless, in terms of energy efficiency at higher power levels, as shown in Figure 12, the FLC technique proves to be more effective than the other two.

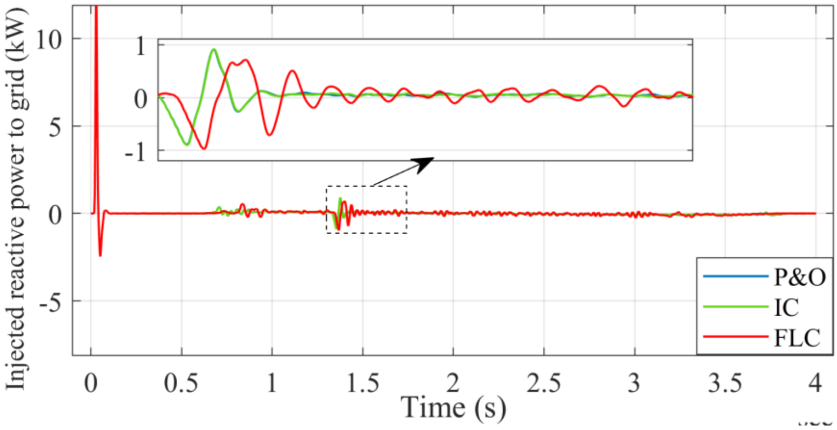

Figure 13. AC - reactive power injected into grid of PV

The reactive power injected into the grid by the system is set in the inverter controller to maintain a power factor close to 1, as shown in Figure 13. The PWM values controlling the DC chopper from the three MPPT techniques are also displayed in Figure 14. FLC technique calculates the PWM values at stable operating points with fewer fluctuations compared to P&O and IC; FLC also responds more quickly, ensuring the system efficiently tracks the MPP.

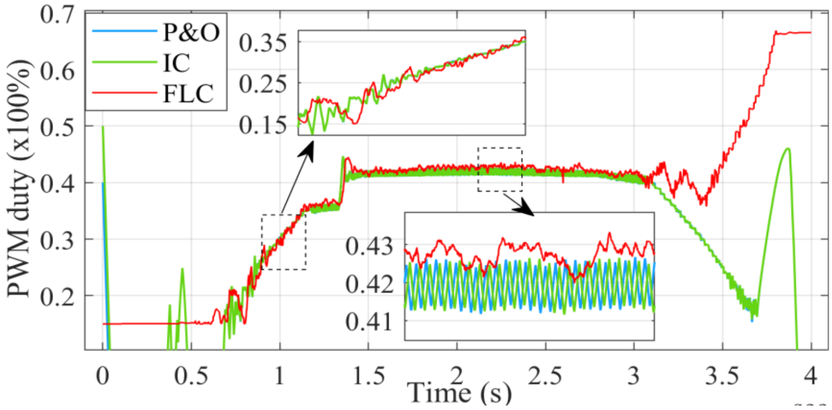

Figure 14. PWM duty values

5. Conclusion

This study examined the performance of three MPPT algorithms: P&O, IC, and FLC in a 10kWp grid-tied PV system under varied environmental conditions. Through a MATLAB/Simulink simulation, each algorithm's efficacy in optimizing energy extraction from solar arrays was assessed, particularly in response to changing irradiance levels. The findings indicate that while all three algorithms are capable of tracking the MPP, the FLC method exhibited superior efficiency in reducing power fluctuations and responding to irradiance variability. This stability makes FLC a promising approach for applications requiring rapid adaptation to environmental changes.

However, FLC's enhanced tracking performance comes at the cost of increased computational demand, which may affect implementation in systems with limited processing resources. Despite this, FLC's advantages suggest it is well-suited for advanced grid-connected PV systems where high accuracy and stability are critical. Future work could explore hybrid approaches that combine the simplicity of P&O and IC with the robustness of FLC, potentially offering a balanced solution for efficient solar power management in diverse conditions.

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