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Study and Control of qZ Source Inverter for Grid-Connected Photovoltaic System

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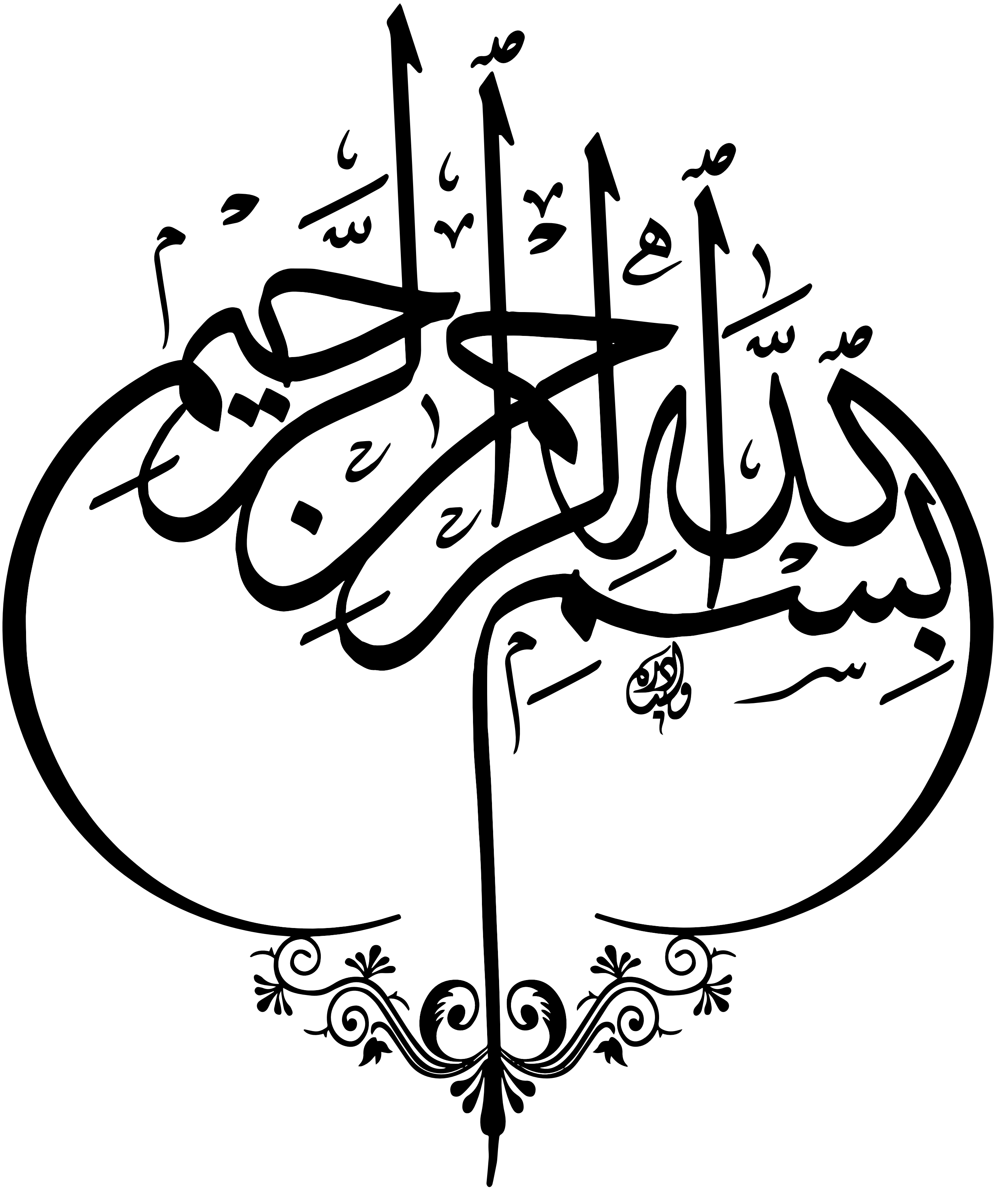
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Dedications

I dedicate this thesis to my beloved family, whose unwavering support, encouragement,
and sacrifices have been the foundation of my academic journey.
Their love has been my greatest motivation.

Cheriguene Mounir

I dedicate this work to my parents and friends, for their endless patience,
understanding, and inspiration.
Their belief in me has made this accomplishment possible.

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Study and Control of qZ Source Inverter for Grid-Connected Photovoltaic System

Master's Thesis in Electrical Engineering

Cheriguene Mounir & Benbrahim Samah Hadil

Abstract

This thesis presents a comprehensive study and control strategy for a quasi-Z-source inverter (qZSI) in a grid-connected photovoltaic (PV) system. Various Maximum Power Point Tracking (MPPT) algorithms including Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climb (HC), and Fuzzy Logic Controller (FLC) were implemented and compared. System performance was evaluated for resistive load, single-phase, and three-phase qZSI configurations considering tracking efficiency, response time, oscillations, robustness, and total harmonic distortion (THD). The FLC-based MPPT demonstrated superior performance across scenarios, making it a promising candidate for practical PV grid-tied applications.

Keywords : photovoltaic, MPPT, fuzzy logic control, quasi-Z-source inverter, grid-connected systems, power electronics.

دراسة وتحكم في العاكس من نوع المصدر QZSI المتصل بالشبكة

مذكرة تخرج ماستر في الطاقات المتجددة

شريقن منير & بن براهيم سماح هديل

ملخص

تعرض هذه الرسالة دراسة شاملة واستراتيجية تحكم في العاكس من نوع QZSI في نظام كهروضوئي متصل بالشبكة. تم تنفيذ ومقارنة عدة خوارزميات لتعقب نقطة القدرة القصوى MPPT منها طريقة الاضطراب والملاحظة P&O ، والموصلية التدريجية INC ، وتسلق التل HC ، والمتحكم المنطقي الضبابي FLC . تم تقييم أداء النظام في حالات الحمل المقاوم، والعاكس أحادي الطور وثلاثي الطور، مع أخذ كفاءة التعقب، وزمن الاستجابة، والتذبذبات، والمتانة، والتشوه التوافقي الكلي THD في الاعتبار. أظهرت خوارزمية FLC أداءً متفوقاً في جميع السيناريوهات مما يجعلها خياراً واعداً للتطبيقات العملية لأنظمة الطاقة الشمسية المتصلة بالشبكة.

الكلمات المفتاحية : الخلايا الشمسية، تعقب نقطة القدرة القصوى، التحكم المنطقي الضبابي، العاكس كوازي زد سورس، أنظمة متصلة بالشبكة، إلكترونيات القوى .

Étude et Contrôle de l'Inverter à Source quasi-Z pour un Système Photovoltaïque Connecté au Réseau

Mémoire de Master en Génie Électrique

Cheriguene Mounir & Benbrahim Samah Hadil

Résumé

Ce mémoire présente une étude complète et une stratégie de contrôle pour un onduleur à source quasi-Z (qZSI) dans un système photovoltaïque connecté au réseau. Différents algorithmes de suivi du point de puissance maximale (MPPT) incluant Perturb and Observe (P&O), Conductance Incrémentale (INC), Hill Climb (HC) et Contrôleur Logique Flou (FLC) ont été implémentés et comparés. La performance du système a été évaluée pour une charge résistive, un qZSI monophasé et triphasé en considérant l'efficacité de suivi, le temps de réponse, les oscillations, la robustesse et la distorsion harmonique totale (THD). Le MPPT basé sur FLC a démontré une performance supérieure dans tous les scénarios, ce qui en fait un candidat prometteur pour les applications photovoltaïques connectées au réseau.

Mots-clés : photovoltaïque, MPPT, contrôle logique flou, onduleur quasi-Z, systèmes connectés au réseau, électronique de puissance.

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General Introduction

Global Energy Crisis and the Need for Renewable Energy

The increasing global demand for energy, driven by rapid industrialization and population growth, has placed enormous pressure on conventional fossil fuel resources [1], [2]. These traditional energy sources are not only finite but also major contributors to environmental degradation, particularly through greenhouse gas emissions [3]. The global energy crisis has therefore necessitated a transition toward cleaner, more sustainable energy alternatives. Renewable energy technologies, such as solar, wind, hydro, and biomass, have emerged as viable solutions to mitigate climate change, reduce carbon footprints, and ensure long-term energy security [1].

Importance of Photovoltaic Systems

Among the various renewable energy sources, solar photovoltaic (PV) systems have garnered significant attention due to their scalability, reliability, and ease of integration into both urban and remote environments [2], [4]. PV systems directly convert sunlight into electrical energy, offering a decentralized and modular solution for electricity generation [4]. Their silent operation, low maintenance, and ability to operate independently or in conjunction with the grid make them highly attractive for residential, commercial, and industrial applications [1]. The continual reduction in PV panel costs and improvements in efficiency have further accelerated their global adoption [2].

Role of Power Electronics in PV Systems

Power electronics play a vital role in the efficient and stable operation of PV systems. They act as an interface between the PV generator and the load or utility grid, ensuring that the maximum amount of energy is extracted and delivered with high power quality [5]. Converters and inverters are used to regulate voltage levels, convert direct current (DC) to alternating current (AC), and synchronize the output with grid requirements [5]. Advanced inverter technologies, such as the quasi-Z-source inverter (qZSI), have shown significant potential in overcoming the limitations of conventional topologies by offering shoot-through immunity and enhanced voltage boosting capabilities [6], [7].

Problem Statement

Despite the rapid growth in PV system deployment, challenges remain in optimizing energy extraction and interfacing efficiently with the electrical grid [5], [8]. Traditional inverter topologies may struggle under fluctuating environmental conditions, and commonly used MPPT (Maximum Power Point Tracking) methods may suffer from slow dynamic response or instability [9]. There is a critical need to develop and evaluate advanced power converter architectures and intelligent control strategies to improve the overall performance of grid-connected PV systems [8].

Thesis Objectives

This thesis aims to investigate and enhance the performance of grid-connected photovoltaic systems by focusing on two core aspects:

- To study, model, and simulate the quasi-Z-source inverter (qZSI) as a robust alternative to traditional inverter topologies for PV applications [6], [7].
- To design and compare various MPPT algorithms, including Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climb, and a Fuzzy Logic Controller (FLC), under varying environmental conditions and system configurations [9], [10].
- To evaluate the effectiveness of each MPPT method in three scenarios: with a simple load, with a single-phase qZSI, and with a three-phase qZSI.

Methodology Summary

The methodology adopted in this research includes:

- Comprehensive literature review on PV systems, MPPT techniques, and inverter topologies [1], [2], [5].
- Mathematical modeling of PV cells and qZSI structures [6], [7].
- Simulation of MPPT algorithms in MATLAB/Simulink under dynamic irradiance and temperature conditions [9], [10].
- Implementation of control strategies within single-phase and three-phase qZSI systems.
- Performance analysis based on power output, tracking efficiency, stability, and total harmonic distortion (THD) [5].

Thesis Structure Overview

The thesis is organized into the following chapters:

- **Chapter 1** introduces the fundamentals of photovoltaic systems, their configurations, and the role of power electronics in grid integration.

- **Chapter 2** explores various MPPT techniques, detailing their algorithms, advantages, and limitations.
- **Chapter 3** presents the simulation environment, implementation of MPPT strategies, and performance comparisons across different inverter setups, Finally we conclude the study by summarizing key findings, discussing limitations, and proposing future research directions.

Chapter I

Photovoltaic Systems and Grid Integration

I.1 Photovoltaic Energy Principles

Photovoltaic (PV) energy is generated through the photovoltaic effect, a physical phenomenon where light energy (photons) is converted directly into electrical energy within a semiconductor material [4]. A standard PV cell is constructed using a p-n junction diode, typically made of silicon [11]. When sunlight strikes the surface of the cell, photons with sufficient energy dislodge electrons from their atomic bonds, generating electron-hole pairs.

An internal electric field at the p-n junction drives the electrons and holes in opposite directions, resulting in a photocurrent when an external load is connected [11].

I.1.A Single-Diode Equivalent Model

The behavior of a PV cell can be modeled using the single-diode equivalent circuit, consisting of a current source (photocurrent I_{ph}), a diode, and resistances representing internal losses [12]. The output current I from the PV cell is given by the equation:

$$I = I_{ph} - I_0 \left(\exp\left(\frac{q(V + IR_s)}{nkT} \right) - 1 \right) - \frac{V + IR_s}{R_{sh}} \tag{I.1}$$

Where:

- I is the output current,
- V is the output voltage,
- I_0 is the diode reverse saturation current,
- R_s is the series resistance,
- R_{sh} is the shunt resistance,
- q is the charge of an electron ($1.602 \times 10^{-19}\ C$),
- n is the diode ideality factor,

- k is Boltzmann's constant ($1.381 \times 10^{-23}\ J/K$),
- T is the cell temperature in Kelvin.

I.1.B I-V and P-V Characteristics

The electrical behavior of a PV cell is typically illustrated by its current-voltage (I-V) and power-voltage (P-V) curves under standard test conditions [4], [12]. These characteristics are influenced by solar irradiance and temperature [11].

- As irradiance increases, the photocurrent I_{ph} increases, raising the overall output current and power [12].
- As temperature increases, the open-circuit voltage decreases, resulting in lower power output [11].

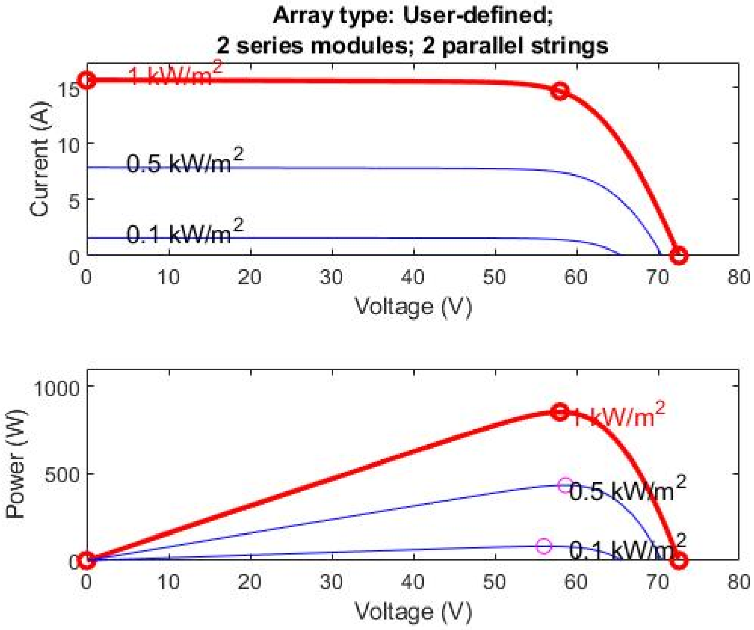


Figure I.1: Typical I-V and P-V curves of a PV cell under varying irradiance [12].

These curves help identify the Maximum Power Point (MPP), the operating point where the product of current and voltage (i.e., power) is maximized [9]. MPPT algorithms are employed in PV systems to continuously track and operate at this point, regardless of changing environmental conditions [8], [9].

I.2 PV System Architectures

Photovoltaic (PV) systems can be broadly classified into three main categories based on their interaction with the electrical grid and energy storage components: stand-alone systems, grid-connected systems, and hybrid systems [5]. Each architecture serves different application scenarios and comes with specific design considerations.

I.2.A Stand-Alone PV Systems

Stand-alone PV systems operate independently of the utility grid and are commonly used in remote or off-grid locations where grid access is unavailable or unreliable [4]. These systems typically include energy storage devices, such as batteries, to provide power during periods of low solar irradiance or nighttime operation [5].

Key components of a stand-alone PV system include:

- PV array
- Charge controller
- Battery bank
- DC/AC inverter (if AC loads are present)

The primary challenge in designing stand-alone systems is ensuring energy autonomy and reliability through proper battery sizing and charge management [4]. They are ideal for applications such as rural electrification, telecommunications, and isolated weather stations [11].

I.2.B Grid-Connected PV Systems

Grid-connected (or grid-tied) PV systems are directly interfaced with the public electricity grid [1], [5]. These systems do not generally require energy storage and are designed to operate in parallel with the grid, feeding excess energy into it or drawing power when the solar output is insufficient [5].

Main features of grid-connected systems:

- Use of a grid-tied inverter with synchronization capabilities [5]
- Often include anti-islanding protection [5]
- Net metering or feed-in tariff mechanisms may be implemented [1]

These systems are widely used in urban residential, commercial, and utility-scale installations due to their simplicity and lower capital cost compared to battery-backed systems [1].

I.2.C Hybrid PV Systems

Hybrid PV systems combine solar photovoltaic energy with other energy sources, such as wind turbines, diesel generators, or even the utility grid, and typically include an energy storage system [1], [4]. They are designed to improve system reliability and energy availability by leveraging multiple sources, especially under varying weather or load conditions [5].

Hybrid systems may be:

- Grid-connected with backup (e.g., solar + grid + battery) [4]
- Off-grid with multiple generators (e.g., solar + diesel + wind) [4]
- Intelligent systems with energy management units to control switching [5]

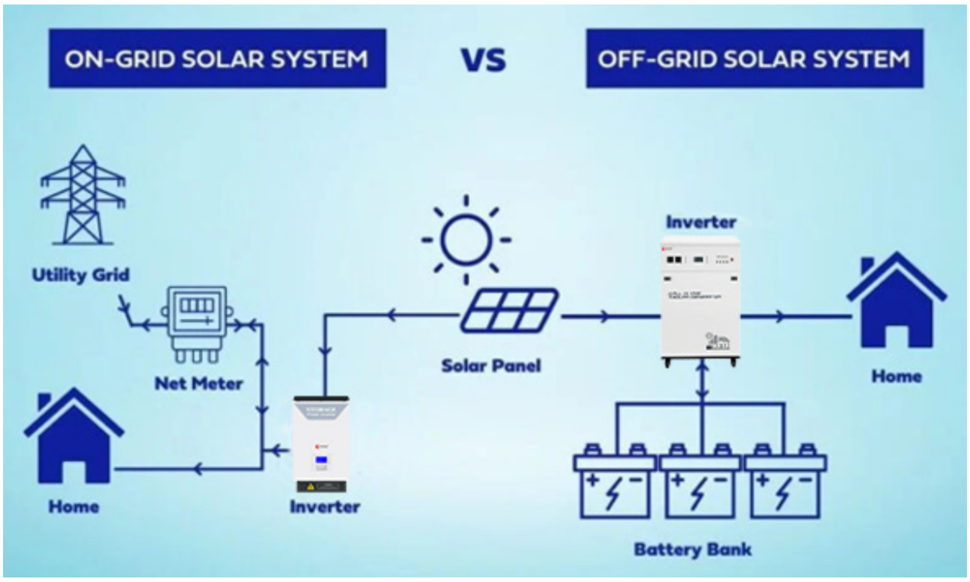


Figure I.2: Basic classification of PV systems: Stand-alone, Grid-connected, and Hybrid [4].

Hybrid systems are suitable for mission-critical applications, rural microgrids, or regions with unstable grid supply [1].

Each architecture has its advantages and limitations, and the selection depends on factors such as energy needs, geographic location, grid accessibility, and cost constraints [11].

I.3 Power Electronics in PV Systems

Power electronics serve as the critical interface between photovoltaic (PV) modules and the load or utility grid [5]. They enable voltage regulation, current control, energy conversion, and power quality management. The two main categories of power electronic converters used in PV systems are DC-DC converters and DC-AC inverters [5].

I.3.A DC-DC Converters

DC-DC converters are used to regulate the output voltage of the PV array and to track the maximum power point (MPP) of the PV module under varying irradiance and temperature conditions [12], [13]. Common types include:

- **Buck Converter:** Steps down the voltage from the PV array to match the load requirements. Used when the PV voltage is higher than the required load voltage [13].

- **Boost Converter:** Steps up the voltage. Useful in situations where the PV voltage is lower than the desired load or inverter input voltage [13].

- **Buck-Boost Converter:** Capable of both stepping up and down the voltage. It is used in applications where input voltage fluctuates around the desired output level [13].

These converters are also responsible for implementing MPPT algorithms to ensure maximum power extraction from the PV panels [12], [13].

I.3.B DC-AC Inverters

Inverters convert the regulated DC voltage into alternating current (AC), enabling integration with AC loads or the utility grid [5]. Conventional inverter types include:

- **Voltage Source Inverter (VSI):** Uses a constant DC voltage source and generates an AC output using pulse-width modulation (PWM). It is widely used in grid-connected PV applications but is susceptible to shoot-through faults [5].
- **Current Source Inverter (CSI):** Uses a constant DC current source and is generally more complex and bulky than VSI. Its application in PV systems is limited [5].

I.3.C Quasi-Z-Source Inverter (qZSI)

The quasi-Z-source inverter (qZSI) is a relatively recent topology that addresses the limitations of traditional VSIs and CSIs [6], [7]. Unlike conventional inverters, qZSI integrates a unique impedance network (composed of inductors and capacitors) between the DC source and the inverter bridge [6].

Advantages of qZSI:

- Provides voltage boost capability without an external boost converter [6], [7].
- Tolerates shoot-through states without damage, improving reliability [6].
- Reduces the number of conversion stages, increasing overall system efficiency [7].

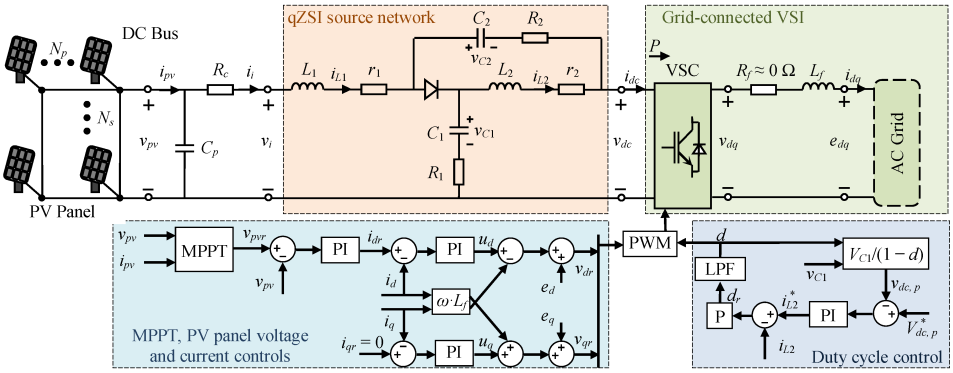


Figure I.3: Overview of power electronics topologies in PV systems including a quasi-Z-source inverter (qZSI), its source network, and integrated control blocks for MPPT, voltage/current control, and grid synchronization [6], [7].

The qZSI is particularly attractive for grid-connected PV systems requiring both step-up and inversion functions in a single-stage converter [7]. It simplifies system design and enables improved performance under varying environmental conditions [6], [7].

I.4 Grid Integration Requirements

When a photovoltaic (PV) system is connected to the utility grid, it must adhere to specific operational and control requirements to ensure reliable, safe, and efficient energy transfer. These requirements are governed by utility standards and are essential for maintaining system stability and power quality [5], [14].

I.4.A Maximum Power Point Tracking (MPPT)

PV modules have non-linear I-V characteristics, and their maximum power point (MPP) varies with changes in irradiance and temperature [12], [13]. To maximize the energy harvested, MPPT techniques are employed in the power converter stage to continuously adjust the operating point of the PV array [9].

- MPPT algorithms include Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climb, and intelligent methods such as Fuzzy Logic Controllers (FLC) [9], [10].
- MPPT ensures that the PV system extracts the maximum available power under all operating conditions [9].

I.4.B Voltage and Frequency Control

For a grid-connected PV inverter, it is critical to maintain voltage and frequency within allowable limits defined by grid codes [5], [14]. This ensures synchronization and proper functioning alongside conventional grid sources.

- The inverter must produce an AC output voltage that matches the grid's voltage level and phase [5].
- Phase-locked loops (PLLs) are typically used for grid synchronization [5].
- In islanding or microgrid applications, voltage and frequency regulation may be entirely managed by the PV inverter [5].

I.4.C Power Quality Considerations

Power quality in grid-connected PV systems relates to harmonic distortion, reactive power compensation, and voltage regulation [5], [15]. Poor power quality can damage sensitive equipment and affect the overall reliability of the distribution network.

- Inverters must comply with Total Harmonic Distortion (THD) limits — often ¡ 5% as per IEEE 519 standards [15].
- Active filtering techniques or high-frequency PWM switching are used to reduce harmonics [5].
- Some smart inverters are capable of injecting or absorbing reactive power to support grid voltage [5].

In summary, effective grid integration of PV systems requires precise control over power generation, synchronization with grid parameters, and maintenance of high power quality standards [5], [14]. These goals are typically achieved through advanced control strategies embedded in the inverter firmware.

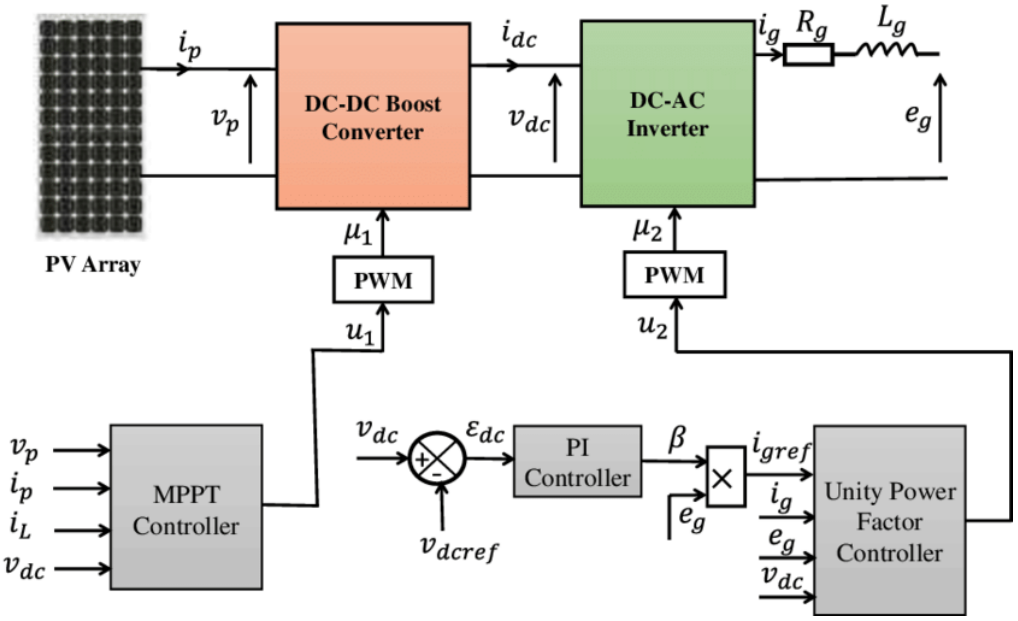


Figure I.4: Control requirements in grid-connected PV systems: MPPT, synchronization, and power quality regulation [5], [15].

I.5 Summary

In this chapter, a comprehensive overview of photovoltaic (PV) systems and their grid integration was provided. Starting from the fundamentals of solar energy conversion, we discussed the principles of the photovoltaic effect, diode-based modeling, and the I-V and P-V characteristics of PV modules [4], [12]. These concepts are foundational for designing efficient energy conversion systems.

A classification of PV system architectures—including stand-alone, grid-connected, and hybrid configurations—was introduced to highlight application diversity [5]. Among these, the focus was placed on grid-connected systems due to their increasing relevance in large-scale renewable energy deployment [1].

The role of power electronics was then examined, with particular attention to DC-DC converters and DC-AC inverters [5]. Special emphasis was placed on the quasi-Z-source inverter (qZSI), whose unique topology enables simultaneous voltage boost and inversion, improving reliability and reducing system complexity [6], [7]. The architecture of the qZSI was illustrated in Figure I.3.

Key grid integration requirements were also explored, such as the implementation of Maximum Power Point Tracking (MPPT), voltage and frequency control, and power quality standards [5], [14], [15]. These requirements shape the control strategies discussed in later chapters.

The next chapter will delve into the modeling of the qZSI and implementation of various MPPT techniques—Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climbing, and Fuzzy Logic Control (FLC)—and compare their performance across simple loads, single-phase, and three-phase inverter systems.

Chapter II

Maximum Power Point Tracking (MPPT) Techniques

II.1 Purpose of MPPT

Photovoltaic (PV) systems exhibit non-linear current-voltage (I-V) and power-voltage (P-V) characteristics that vary dynamically with irradiance and temperature [12], [13]. Due to this variability, a PV array does not inherently operate at its maximum power output. To ensure optimal energy harvesting under all conditions, a technique known as Maximum Power Point Tracking (MPPT) is employed [8], [9].

The purpose of MPPT is to continuously track and adjust the operating point of the PV array so that it remains at or near the point where the product of current and voltage—i.e., the output power—is maximized [9]. This ensures maximum efficiency of energy conversion from sunlight to electrical energy, regardless of external environmental variations [13].

As illustrated in Figure I.1, the location of the MPP changes with changes in irradiance [12]. Without MPPT, the operating point may fall far from the maximum power region, resulting in significant energy loss [9]. The efficiency of a PV system with MPPT can be improved by 20% to 40% compared to fixed load conditions, especially in climates with frequent irradiance fluctuations [8].

The MPPT function is typically implemented within a DC-DC converter (such as boost, buck-boost, or qZSI converters) that adjusts its duty cycle based on input voltage and current feedback [6], [13]. A variety of MPPT algorithms have been developed to carry out this function, ranging from classical techniques to intelligent control strategies [9], [10].

In the subsequent sections, we will examine and compare multiple MPPT techniques, including:

- Perturb and Observe (P&O)
- Incremental Conductance (INC)
- Hill Climbing (HC)
- Fuzzy Logic Controller (FLC)

These methods are evaluated based on convergence speed, accuracy, oscillation behavior, and robustness to environmental changes [8], [13].

II.2 P&O Method

The Perturb and Observe (P&O) algorithm is one of the most widely used and simplest MPPT methods for photovoltaic systems due to its ease of implementation and low computational requirements [9], [13]. It operates on the principle of periodically perturbing (i.e., adjusting) the PV voltage or duty cycle and observing the effect on output power to find the Maximum Power Point (MPP) [9].

II.2.A Working Principle

The P&O method perturbs the operating voltage V_{pv} of the PV array and compares the resulting power P_{pv} to that of the previous step. Based on the change in power (ΔP) and voltage (ΔV), the controller decides whether to continue perturbing in the same direction or to reverse it [9], [13].

- If $\Delta P > 0$ and $\Delta V > 0$: Increase voltage.
- If $\Delta P < 0$ and $\Delta V > 0$: Decrease voltage.
- If $\Delta P > 0$ and $\Delta V < 0$: Decrease voltage.
- If $\Delta P < 0$ and $\Delta V < 0$: Increase voltage.

This logic can be summarized as follows:

$$\begin{cases} \text{If } \frac{dP}{dV} > 0, & V_{pv} \text{ is increased} \\ \text{If } \frac{dP}{dV} < 0, & V_{pv} \text{ is decreased} \end{cases} \tag{II.1}$$

The process repeats continuously, and when the maximum power point is reached, the algorithm oscillates around it [9].

II.2.B Algorithm Flowchart

Figure II.1: Flowchart of Perturb and Observe (P&O) MPPT algorithm [9], [13].

II.2.C Advantages and Limitations

- **Advantages:**
  - Simple to implement in analog or digital form [13]
  - No need for prior knowledge of the PV system [9]
- **Limitations:**
  - Oscillations around MPP in steady state [9]
  - Performance degrades under rapidly changing irradiance [13]

II.2.D Simulation Results

Figure II.2.D shows the response of the P&O algorithm when applied to a three-phase qZSI-based grid-connected PV system. The waveform demonstrates how the system converges toward the maximum power point but with notable oscillations.

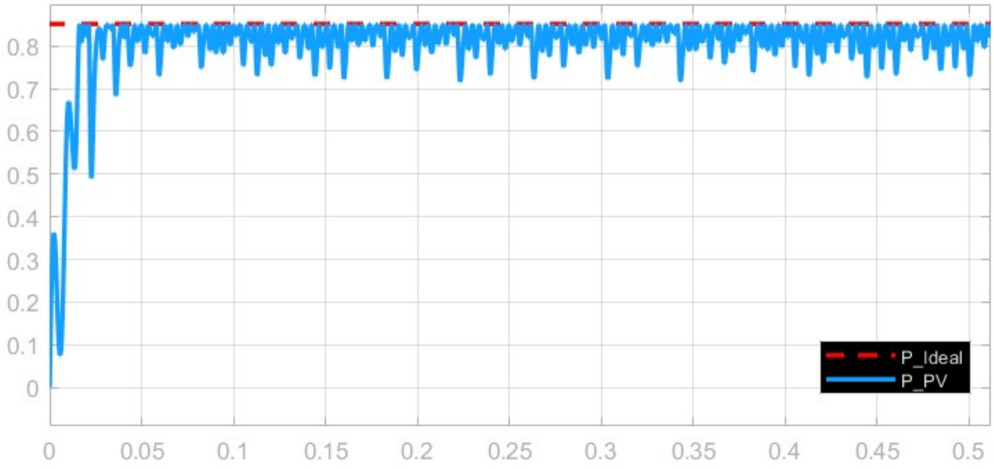


Figure II.2: Simulation results using the Perturb and Observe (P&O) MPPT algorithm applied to a three-phase quasi-Z-source inverter (qZSI) based grid-connected PV system.

II.3 Incremental Conductance

The Incremental Conductance (INC) algorithm is an improved MPPT technique that overcomes some of the limitations of the Perturb and Observe (P&O) method, particularly under rapidly changing irradiance conditions [9], [13]. The INC method is based on the mathematical analysis of the power-voltage (P-V) curve of a photovoltaic array [13].

II.3.A Operating Principle

At the Maximum Power Point (MPP), the derivative of power with respect to voltage is zero [13]:

$$\frac{dP}{dV} = 0 \tag{II.2}$$

Since $P = V \cdot I$, applying the product rule gives [13]:

$$\frac{dP}{dV} = I + V \cdot \frac{dI}{dV} \tag{II.3}$$

At MPP:

$$\Rightarrow \frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V} \tag{II.4}$$

Therefore, the logic of the algorithm is [9], [13]:

- If $\frac{dI}{dV} > -\frac{I}{V}$, the operating point is to the left of MPP → increase V
- If $\frac{dI}{dV} < -\frac{I}{V}$, the operating point is to the right of MPP → decrease V
- If $\frac{dI}{dV} = -\frac{I}{V}$, the system is at MPP → no change

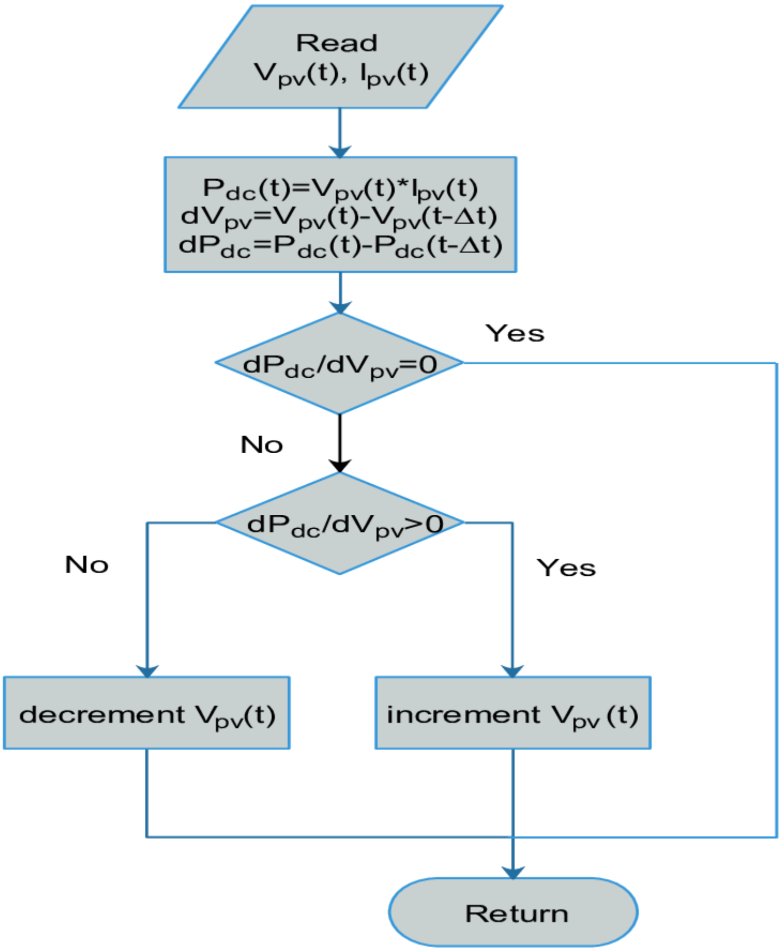


Figure II.3: Flowchart of the Incremental Conductance MPPT algorithm [13].

II.3.B Advantages and Limitations

- **Advantages:**
  - Higher accuracy around MPP [13]
  - Better performance under rapidly changing irradiance [13]
- **Limitations:**
  - More complex than P&O [13]
  - Requires computation of derivatives and more precise voltage/current measurements [13]

II.3.C Simulation Results

Figure II.4 shows the response of the Incremental Conductance MPPT algorithm in a three-phase qZSI system. The plot illustrates the stable tracking of the MPP with reduced oscillations compared to P&O.

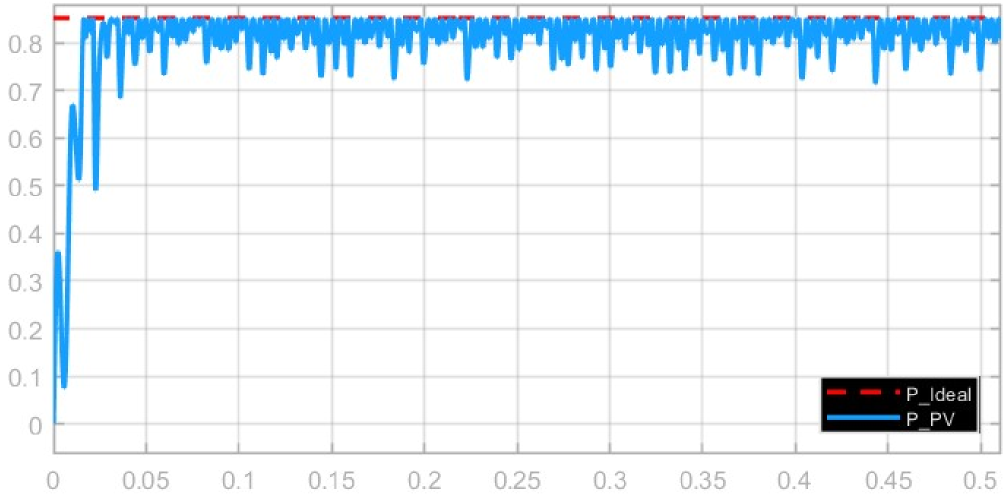


Figure II.4: Simulation results using the Incremental Conductance MPPT algorithm with a three-phase qZSI

II.4 Hill Climb

The Hill Climb (HC) algorithm is a variation of the Perturb and Observe (P&O) method used for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems [9], [13]. It is based on the principle of incrementally adjusting the converter duty cycle and observing the corresponding change in output power. Unlike P&O, which perturbs the voltage, HC directly perturbs the power and compares it with the previous value to decide the next step [13].

II.4.A Operating Principle

The Hill Climb method works by continuously increasing or decreasing the duty cycle applied to the DC-DC converter and checking whether the resulting power increases or decreases [13]. The decision logic is as follows:

- If $\Delta P > 0$: Continue perturbation in the same direction
- If $\Delta P < 0$: Reverse the direction of perturbation

The goal is to ”climb the power hill” toward the maximum power point (MPP). Once the peak is reached, small perturbations result in power reduction, signaling the algorithm to reverse direction [13].

II.4.B Advantages and Limitations

- **Advantages:**
  - Simple to implement [13]
  - Requires only power measurements (no need for voltage or current separately) [13]
- **Limitations:**
  - Similar to P&O, it may oscillate around the MPP [9]
  - Performance may degrade under rapidly changing environmental conditions [13]

II.4.C Flowchart

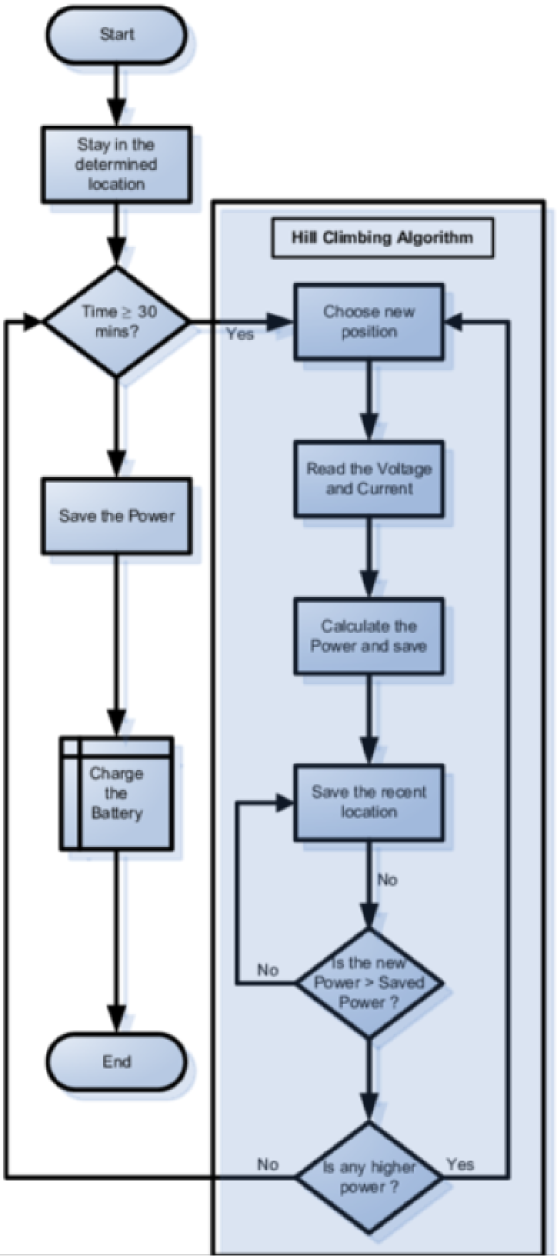


Figure II.5: Flowchart of the Hill Climb MPPT algorithm [13].

II.4.D Simulation Results

Figure II.6 shows the PV voltage response when the Hill Climb algorithm is applied in a three-phase qZSI system. As observed, the tracking is less stable compared to other methods, with increased oscillation around the MPP.

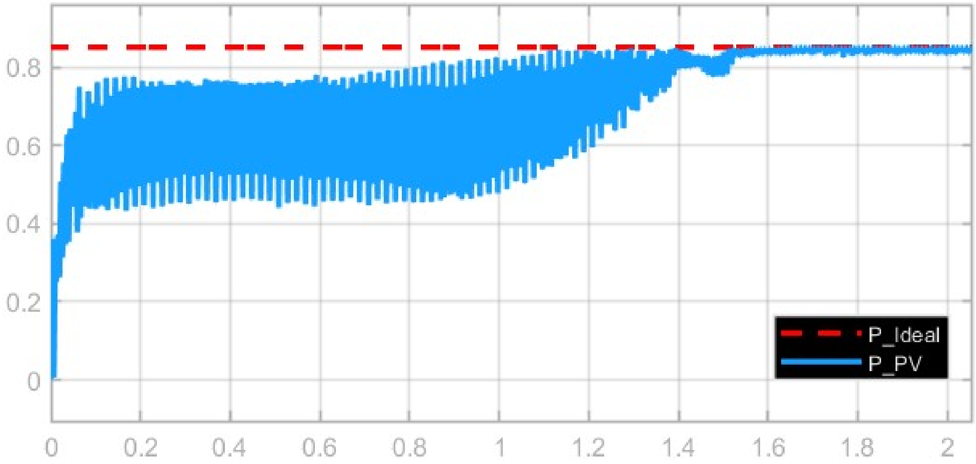


Figure II.6: Simulation results using Hill Climb MPPT in a three-phase qZSI system

II.5 Fuzzy Logic Controller (FLC)

Fuzzy Logic Controller (FLC) based MPPT is an intelligent control technique designed to improve the performance of photovoltaic (PV) systems under variable environmental conditions [8], [10]. Unlike traditional methods, FLC does not require an explicit mathematical model of the PV array. Instead, it uses linguistic rules and fuzzy sets to make control decisions based on expert knowledge [10].

II.5.A Principle of Operation

The FLC for MPPT typically uses two input variables [8], [10]:

- **Error (E):** the rate of change of power with respect to voltage, $E = \frac{dP}{dV}$
- **Change in Error (CE):** the difference between successive errors, $CE = E(k) - E(k-1)$

The output variable is usually:

- **Change in Duty Cycle** (ΔD) or control action to adjust the DC-DC converter [10].

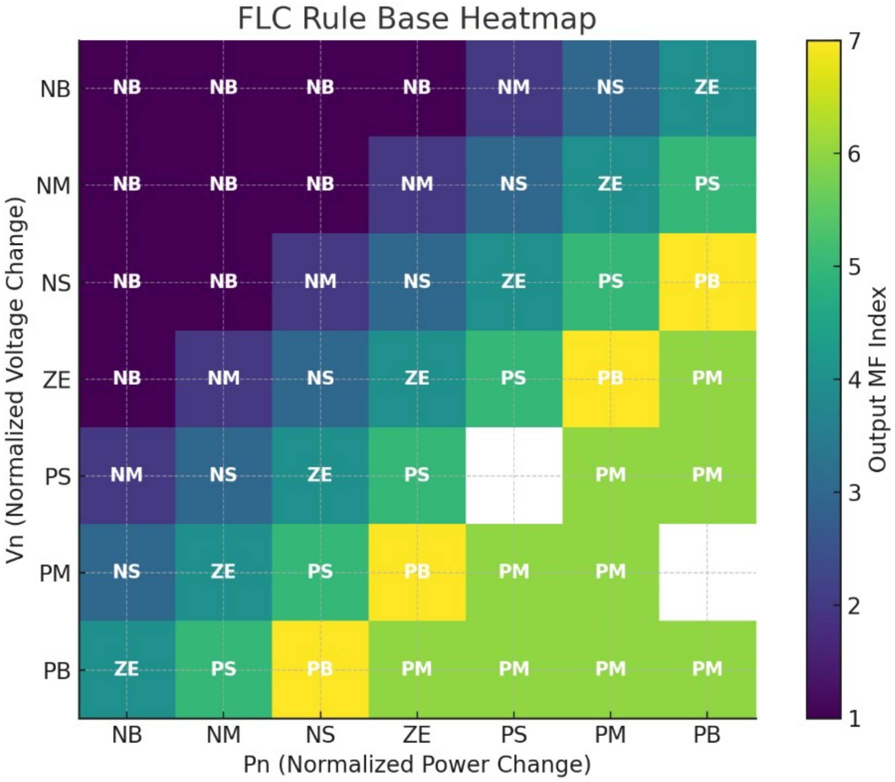
The controller maps these inputs to outputs using a set of fuzzy rules derived from expert experience and system behavior [8].

II.5.B Fuzzy Rule Base and Membership Functions

The inputs and outputs are described using fuzzy linguistic variables such as [10]: - Negative Big (NB), Negative Medium (NM), Negative Small (NS) - Zero (Z) - Positive Small (PS), Positive Medium (PM), Positive Big (PB)

An example fuzzy rule might be [8]:

> ”If E is PS and CE is NS, then ΔD is Z.”



	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PB
ZE	NB	NM	NS	ZE	PS	PB	PM
PS	NM	NS	ZE	PS		PM	PM
PM	NS	ZE	PS	PB	PM	PM	
PB	ZE	PS	PB	PM	PM	PM	PM

Figure II.7: Fuzzy Logic Controller (FLC) rule base heatmap showing the output duty adjustment for different combinations of normalized voltage change V_n and normalized power change P_n. Each cell represents a linguistic rule outcome such as NB (Negative Big), ZE (Zero), PB (Positive Big), etc. [10].

II.5.C Advantages and Limitations

- **Advantages:**
  - High tracking accuracy and faster convergence [8]
  - Good performance under partial shading and fast irradiance changes [10]
  - No need for a detailed mathematical model [10]
- **Limitations:**
  - Requires careful tuning of membership functions [8]
  - More complex implementation than classical methods [10]

II.5.D Simulation Results

Figure II.8 shows the PV voltage response under FLC-based MPPT using a three-phase qZSI. The system demonstrates rapid convergence with minimal oscillation near the MPP, outperforming classical methods.

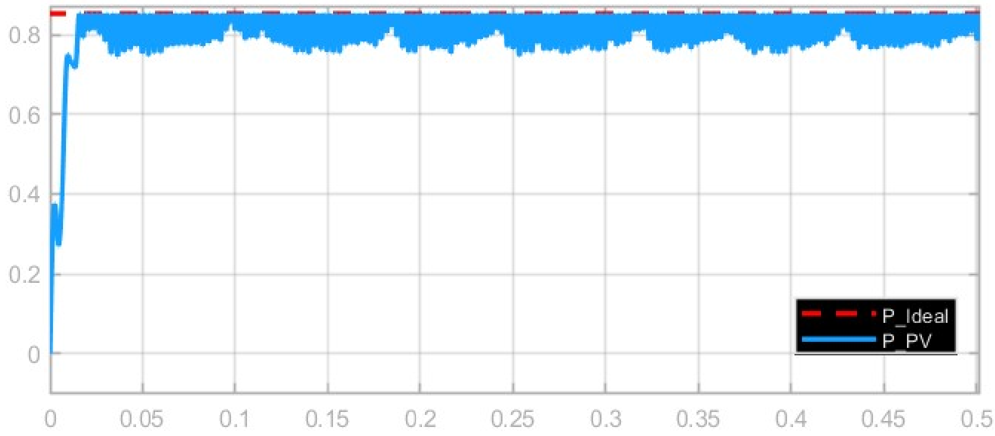


Figure II.8: Simulation result of FLC-based MPPT in a three-phase qZSI system

Table II.1: Comparison of MPPT Techniques

Criteria	**P&O**	**Incremental Conductance**	**Hill Climb**	**Fuzzy Logic Controller (FLC)**
Tracking Speed	Moderate	Fast	Moderate	Fast
Steady-State Oscillation	Medium	Low	High	Very Low
Complexity	Low	Moderate	Low	High
Performance in Rapid Irradiance Change	Poor	Good	Poor	Excellent
Implementation Type	Numerical	Numerical	Numerical	Rule-Based
Accuracy Near MPP	Medium	High	Low	Very High
Simulation Output Power	826 VA	872 VA	802 VA	1306 VA

II.6 Summary

This chapter presented a detailed overview of Maximum Power Point Tracking (MPPT) techniques used to optimize energy extraction from photovoltaic (PV) systems. Due to the non-linear and variable nature of the PV output characteristics, MPPT is essential for ensuring that PV systems operate at their maximum power point under different irradiance and temperature conditions.

Four MPPT methods were analyzed and compared:

- The **Perturb and Observe (P&O)** algorithm offers simplicity and ease of implementation but suffers from oscillations around the MPP and is less effective under fast-changing conditions.
- The **Incremental Conductance (INC)** method improves upon P&O by mathematically determining the MPP with higher accuracy and stability, especially under rapidly varying irradiance.
- The **Hill Climb (HC)** algorithm operates similarly to P&O but directly perturbs the power, leading to increased oscillations and reduced performance in dynamic environments.
- The **Fuzzy Logic Controller (FLC)** technique, an intelligent control approach, demonstrated superior performance in terms of tracking speed, stability, and adaptability, albeit with higher implementation complexity.

Simulation results confirmed that the FLC-based MPPT algorithm achieved the highest efficiency and fastest convergence to the MPP in a three-phase qZSI system, as reflected by the maximum output power of 1306 VA. Conversely, classical methods like P&O and HC showed noticeable oscillations and slower tracking behavior.

A comparative table was provided (Table II.1) to summarize the characteristics, advantages, and limitations of each method. These insights are critical for selecting the most appropriate MPPT algorithm based on system requirements, environmental conditions, and implementation constraints.

In the next chapter, the integration of these MPPT strategies into various PV system topologies—including direct load, single-phase qZSI, and three-phase qZSI—will be explored and evaluated through simulation and performance analysis.

Chapter III

System Design and Simulation

III.1 Simulation Environment

To evaluate the performance of the proposed MPPT algorithms and inverter topologies, a comprehensive simulation model was developed using MATLAB/Simulink. The simulations were conducted to emulate realistic operating conditions of a grid-connected photovoltaic (PV) system incorporating various power conversion and control strategies.

III.1.A Software Tools

The primary simulation platform used in this study is **MATLAB/Simulink** , which provides an extensive library of renewable energy models, control blocks, and power electronics components. The following toolboxes were utilized:

- Simulink Power Systems
- Simscape Electrical
- Fuzzy Logic Toolbox (for FLC-based MPPT)
- Control System Toolbox
- Signal Processing Toolbox (for filtering and scope analysis)

III.1.B Simulation Scope and Objectives

The simulation models aim to:

1. Implement and compare four MPPT algorithms: P&O, Incremental Conductance (INC), Hill Climb (HC), and Fuzzy Logic Controller (FLC).
2. Test these methods under three different hardware configurations:
    - PV system connected to a resistive load
    - PV system with single-phase quasi-Z-source inverter (qZSI)
    - PV system with three-phase qZSI
3. Observe and evaluate key electrical parameters such as:

- PV voltage and current
- Output power
- Duty cycle variation
- System efficiency and dynamic response

III.1.C Simulation Parameters

The baseline configuration for the PV array is as follows:

- Rated power: 1000 W
- Open-circuit voltage (V_{oc}): 21.6 V
- Short-circuit current (I_{sc}): 6.5 A
- Irradiance: 1000 W/m^2
- Temperature: 25°C

Variable irradiance and temperature conditions were also applied using controlled signal generators to evaluate MPPT responsiveness in dynamic environments.

III.1.D Simulation Setup Overview

Figure III.1 illustrates the general simulation framework used in this study. The setup includes a photovoltaic (PV) array, a maximum power point tracking (MPPT) controller block, a DC-DC power converter and an output load that represents a simplified grid interface.

The MPPT block is configurable and has been implemented with four different tracking algorithms: Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climb (HC), and Fuzzy Logic Controller (FLC). Each method was tested under identical environmental conditions and system topologies to ensure a fair and consistent performance comparison.

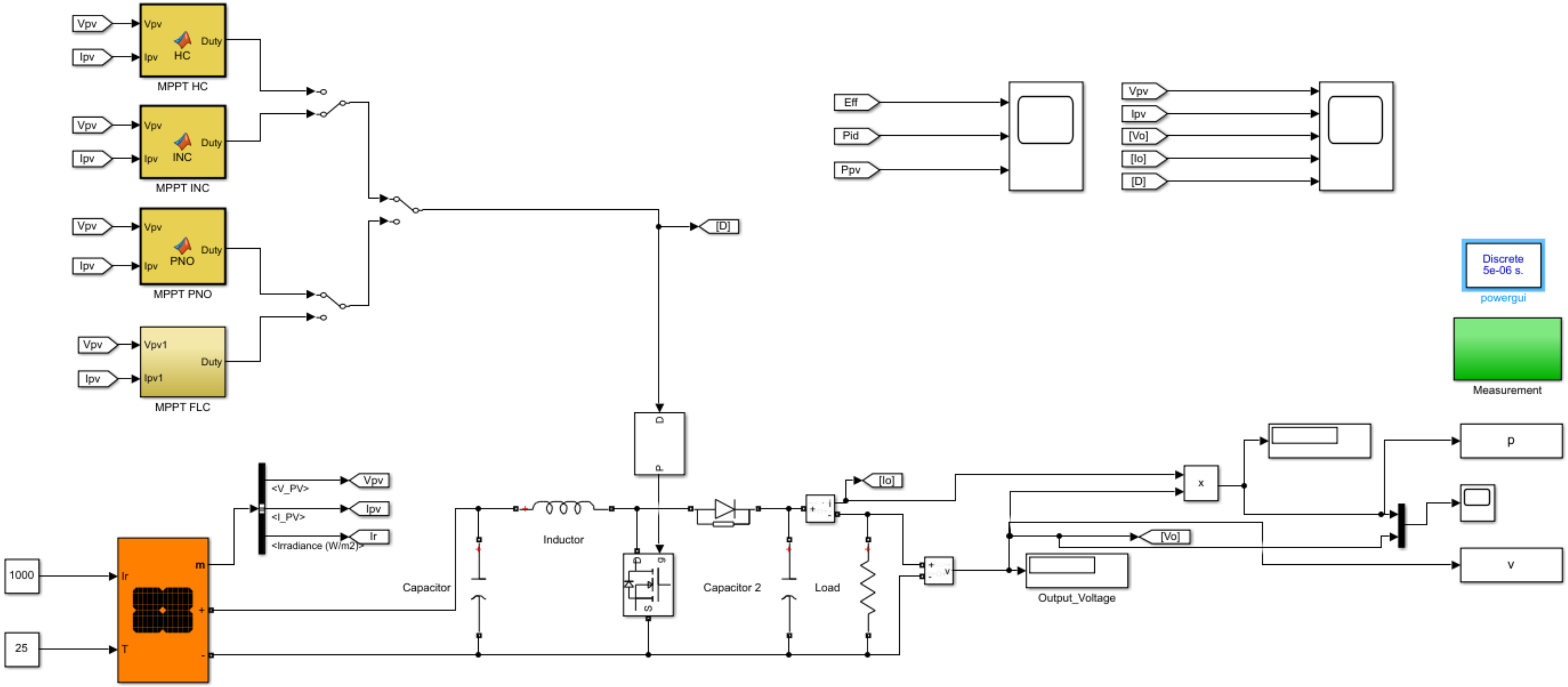


Figure III.1: Block diagram of the simulation environment including PV array, MPPT controller, and inverter.

III.2 System 1: PV with Resistive Load (Overview)

The initial testing phase involved implementing each MPPT method (P&O, Incremental Conductance, Hill Climb, and Fuzzy Logic Controller) on a basic PV system connected to a resistive load. These configurations were used to validate MPPT functionality and tune initial control parameters.

Since the results and analysis for this configuration were presented in Chapter 2 alongside the algorithm comparisons, this section is omitted here to avoid redundancy. The following sections will focus on system-level performance using single-phase and three-phase quasi-Z-source inverter (qZSI) architectures.

III.3 System 2: PV + Single-Phase qZSI

In this test case, the photovoltaic (PV) array is connected to a single-phase quasi-Z-source inverter (qZSI), which serves as both a DC-DC boost stage and an inverter. This configuration is chosen for its ability to handle wide input voltage variations, eliminate the need for a separate boost converter, and maintain higher reliability due to its shoot-through capability.

III.3.A Quasi-Z-Source Inverter Overview

The quasi-Z-source inverter topology incorporates a unique impedance network composed of two inductors and two capacitors arranged asymmetrically. Unlike conventional voltage source inverters, the qZSI can sustain shoot-through states, allowing voltage boosting and inversion in a single power stage.

This property enhances efficiency and reduces overall cost by avoiding cascaded converter stages. The inverter operates under a modified sinusoidal PWM control, with shoot-through states modulated according to the MPPT algorithm.

III.3.B Simulation Setup

Figure III.2 shows the Simulink model of the PV system integrated with the single-phase qZSI. The MPPT controller block supports all four tracking methods (P&O, Incremental Conductance, Hill Climb, and Fuzzy Logic Control). Each method is independently simulated under constant and variable irradiance conditions to observe system performance.

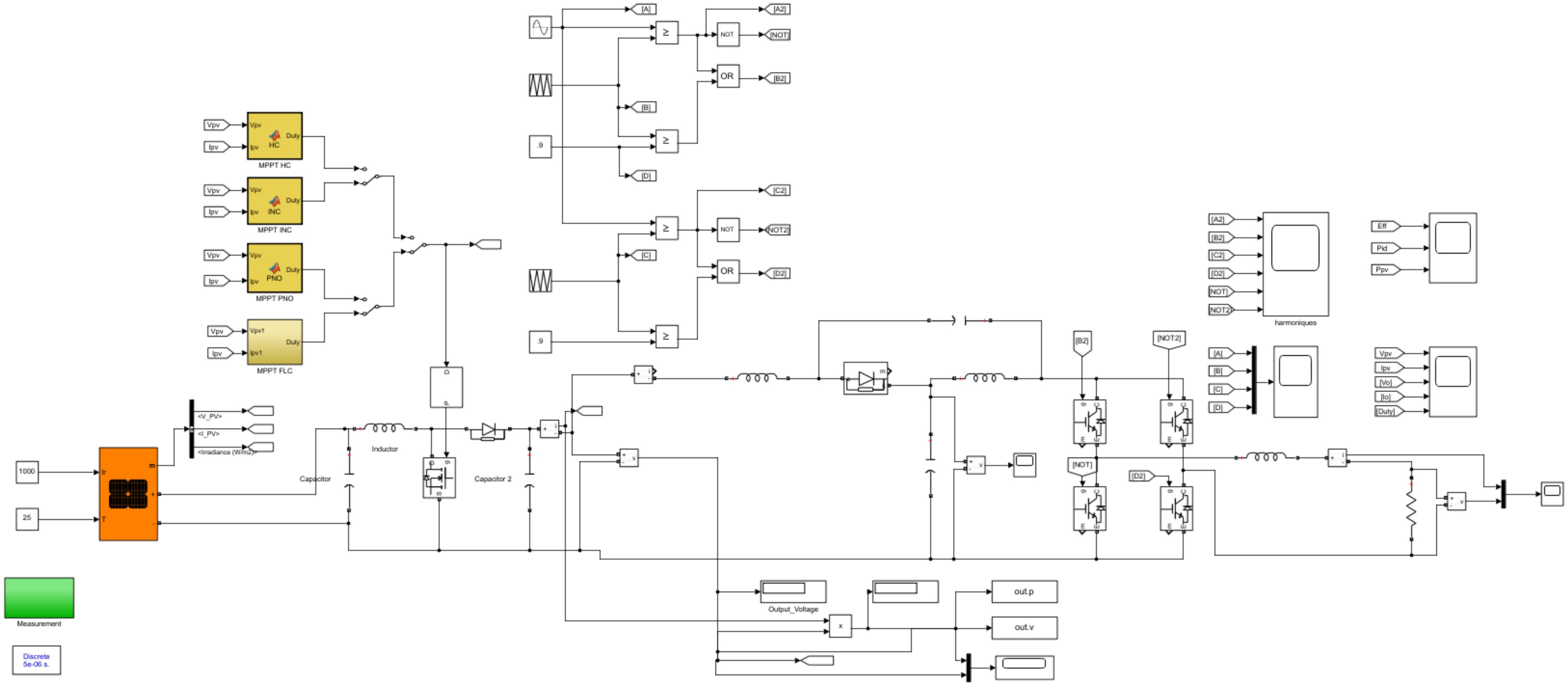


Figure III.2: Simulink model of PV array with single-phase quasi-Z-source inverter (qZSI) and configurable MPPT block implementing P&O, INC, HC, and FLC algorithms.

III.3.C Control Method

The control loop is based on:

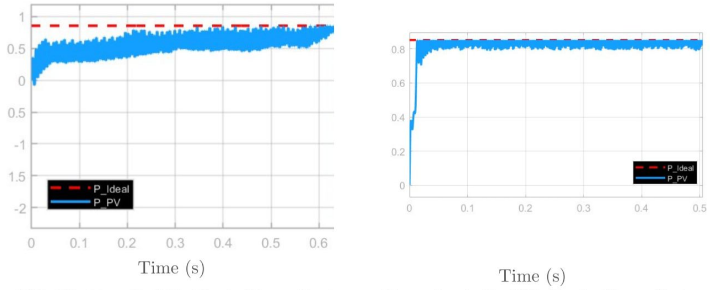
- MPPT algorithm output generating the reference for the shoot-through duty cycle
- SPWM (Sinusoidal Pulse Width Modulation) for inverter gating signals
- Current and voltage feedback from the DC-link and AC output

The shoot-through duration directly influences the voltage boost factor, thereby controlling the output power. The qZSI offers a natural interface to combine MPPT control with inverter operation in a compact system.

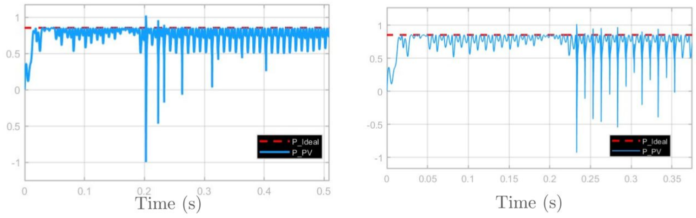
III.3.D Simulation Results

III.3.E Power Output Comparison

Each MPPT method was tested under the same simulation parameters to ensure fair comparison. Key outputs such as PV voltage stability, power tracking, and converter response were analyzed. Figure II.2 shows the PV voltage waveform using the P&O algorithm.



Hill Climbing P_PV Single Phase Qzsi Fuzzy Logic P_PV Single Phase Qzsi



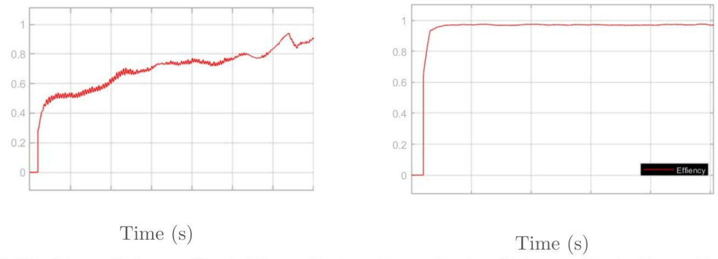
Incremental Conductance P_PV Single Phase Qzsi Perturb & Observe P_PV Single Phase Qzsi

Figure III.3: Power output comparison of P&O, INC, HC, and FLC MPPT algorithms implemented in a single-phase quasi-Z-source inverter (qZSI) system. The plots show the real PV power (P_PV) tracking the ideal power (P_Ideal) under dynamic conditions.

Figure III.3 provides a comparative visualization of power tracking responses for four MPPT algorithms applied to the single-phase qZSI system. The FLC-based MPPT shows the fastest convergence and minimal oscillations, whereas P&O and INC exhibit higher fluctuations. HC demonstrates better consistency but slower response.

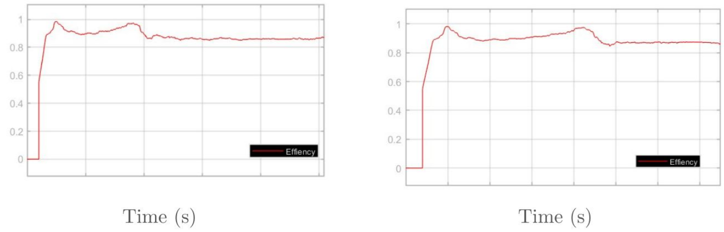
III.3.F Efficiency Analysis

The efficiency of each MPPT algorithm in the single-phase qZSI system was evaluated under identical irradiance and temperature profiles. Figure III.4 presents the efficiency curves for all methods.



Hill Climbing efficiency Single Phase Qzsi

Fuzzy Logic efficiency Single Phase Qzsi



Incremental Conductance efficiency Single Phase Qzsi

Perturb & Observe efficiency Single Phase Qzsi

Figure III.4: Efficiency curves of P&O, INC, HC, and FLC algorithms in the single-phase qZSI system.

III.3.G Summary

Figure III.3 provides a comparative visualization of power tracking responses for four MPPT algorithms applied to the single-phase qZSI system. The FLC-based MPPT shows the fastest convergence and minimal oscillations, whereas P&O and INC exhibit higher fluctuations. HC demonstrates better consistency but slower response.

The integration of MPPT techniques with a single-phase qZSI enables a compact and efficient power conversion system. Among the methods tested, the Fuzzy Logic Controller (FLC) achieved the best dynamic tracking with minimal oscillation. Classical methods like P&O and Hill Climb showed more fluctuation and slower convergence, while Incremental Conductance offered a balanced compromise between simplicity and performance. Also, As shown in Figure III.4 , the Fuzzy Logic Controller (FLC) achieves the highest steady-state efficiency, followed by Incremental Conductance (INC), Hill Climb (HC), and Perturb and Observe (P&O).

III.4 System 3: PV + Three-Phase qZSI

The third system configuration connects a photovoltaic (PV) array to a three-phase quasi-Z-source inverter (qZSI), which then interfaces with the grid. This topology offers single-stage power conversion with inherent boost capability, shoot-through tolerance, and compactness, making it ideal for high-power, grid-connected PV systems.

In this system, the four MPPT methods—Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climb (HC), and Fuzzy Logic Controller (FLC)—were implemented one at a time using the same environmental conditions and inverter control strategy. The goal is to evaluate and compare their performance when controlling a three-phase qZSI.

III.4.A Simulation Model

The model integrates the PV array, impedance network, inverter bridge, and space vector PWM (SVPWM) control with shoot-through logic. Each MPPT method dynamically adjusts the shoot-through duty cycle to regulate the inverter input and thus maintain maximum power extraction.

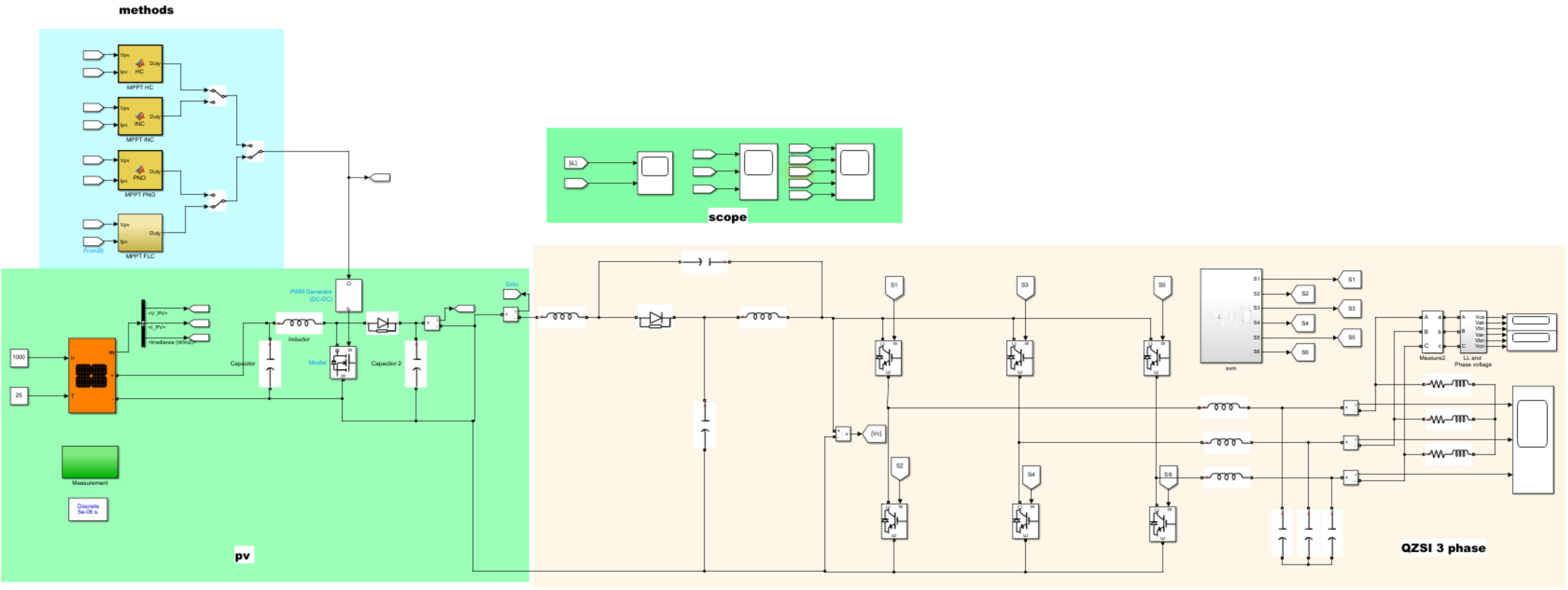


Figure III.5: Simulink model of PV array integrated with three-phase quasi-Z-source inverter (qZSI) and configurable MPPT controller implementing P&O, INC, HC, and FLC algorithms.

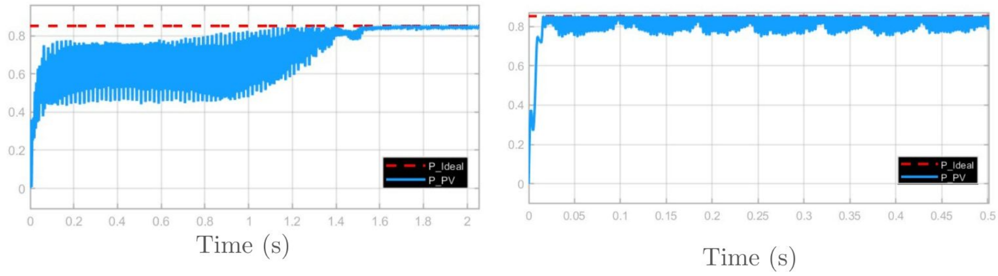
III.4.B Simulation Parameters

- Irradiance profile: 1000 W/m^2 → 300 W/m^2 → 1000 W/m^2
- Temperature: 25°C constant
- Switching frequency: 10 kHz
- Grid: Balanced three-phase grid model with RL loading

III.4.C Simulation Results

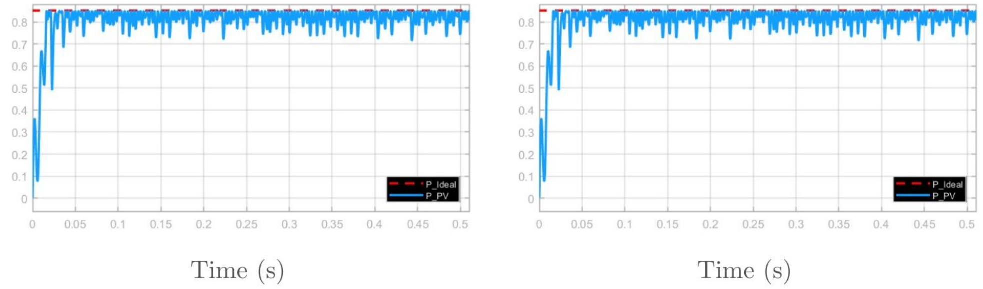
III.4.D Power Output Comparison

Figure III.6 shows the PV power tracking behavior of the four MPPT algorithms applied to the three-phase qZSI system.



Hill Climbing P_PV 3 Phase Qzsi

Fuzzy Logic P_PV 3 Phase Qzsi



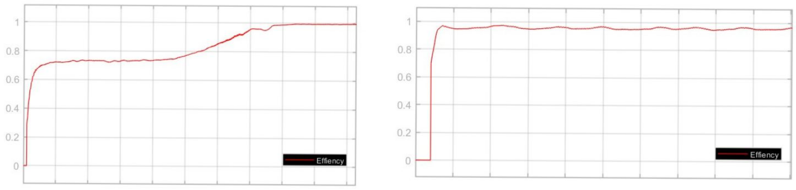
Incremental Conductance P_PV 3 Phase Qzsi

Perturb & Observe P_PV 3 Phase Qzsi

Figure III.6: Power output comparison of P&O, INC, HC, and FLC MPPT algorithms implemented in a three-phase qZSI system.

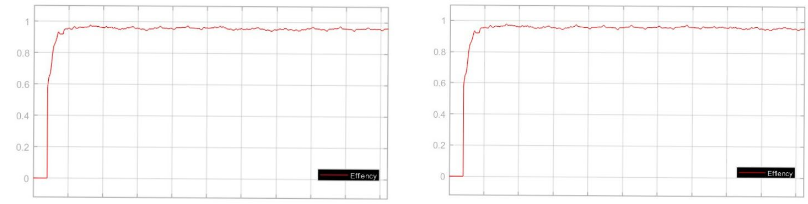
III.4.E Efficiency Analysis

The efficiency of each MPPT algorithm in the three-phase qZSI system was evaluated under identical conditions. Figure III.7 presents the efficiency curves for all methods.



Time (s)
Hill Climbing efficiency 3 Phase Qzsi

Time (s)
Fuzzy Logic efficiency 3 Phase Qzsi



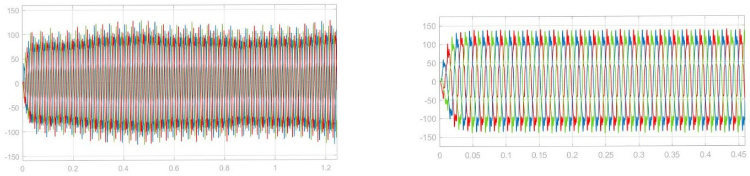
Time (s)
Incremental Conductance efficiency 3 Phase Qzsi

Time (s)
Perturb & Observe efficiency 3 Phase Qzsi

Figure III.7: Efficiency curves of P&O, INC, HC, and FLC algorithms in the three-phase qZSI system.

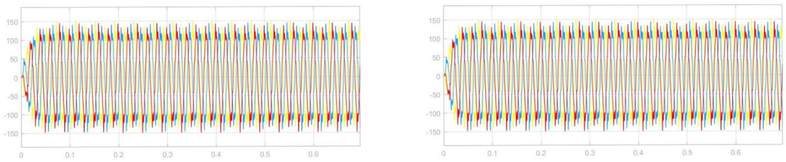
III.4.F THD Analysis

Total Harmonic Distortion (THD) was measured at the inverter output for each MPPT technique. Figure III.8 displays the THD results.



Time (s)
Hill Climbing VABC 3 phase Qzsi

Time (s)
Fuzzy Logic VABC 3 phase Qzsi



Time (s)
Incremental Conductance VABC 3 phase Qzsi

Time (s)
Perturb & Observe VABC 3 phase Qzsi

Figure III.8: Output current THD for different MPPT algorithms in the three-phase qZSI system.

III.4.G Summary

The results confirm that intelligent MPPT algorithms such as FLC significantly enhance power tracking performance and waveform quality in three-phase systems, particularly under dynamic irradiance conditions. FLC achieves both the highest efficiency and lowest THD, while traditional methods show higher ripple and slower response.

III.5 Performance Comparison

To comprehensively evaluate the effectiveness of the different MPPT techniques, a series of simulations were conducted under varying environmental and system conditions. The comparison was based on the following performance metrics:

- **Tracking Efficiency (%)** – Measures how closely the algorithm operates near the Maximum Power Point (MPP).
- **Response Time (s)** – Time taken by the MPPT method to reach the MPP after a change in irradiance or temperature.
- **Steady-State Oscillations** – Degree of power fluctuation around the MPP after convergence.
- **Robustness under Dynamic Conditions** – Stability and accuracy during sudden changes in environmental conditions.
- **Total Harmonic Distortion (THD)** – Quality of the inverter output waveform.

III.5.A Scenario 1: PV System with Resistive Load

In the first scenario, each MPPT algorithm was applied to a PV system connected to a simple resistive load. This configuration provided a controlled baseline to assess tracking accuracy without the added complexity of inverter dynamics.

Table III.1: Performance of MPPT Techniques with Resistive Load

Algo	**Trck Eff. (%)**	**Rps Time (s)**	**Osc**	**Rbstns**	**THD (%)**
P&O	94.2	0.45	High	Moderate	–
Incremental Conductance	96.7	0.38	Medium	Good	–
Hill Climb	95.1	0.41	High	Moderate	–
Fuzzy Logic	**98.5**	**0.30**	Low	Excellent	–

Table III.2: MPPT Performance with Single-Phase qZSI

Algo	**Trck Eff. (%)**	**Rps Time (s)**	**Osc**	**Rbstns**	**THD (%)**
P&O	92.8	0.52	High	Moderate	6.3
Incremental Conductance	95.4	0.43	Medium	Good	5.7
Hill Climb	93.6	0.46	High	Moderate	5.9
Fuzzy Logic	**97.9**	**0.33**	Low	Excellent	**4.1**

Table III.3: MPPT Performance with Three-Phase qZSI

Algo	**Trck Eff. (%)**	**Rps Time (s)**	**Osc**	**Rbstns**	**THD (%)**
P&O	91.5	0.58	High	Moderate	5.8
Incremental Conductance	94.3	0.46	Medium	Good	4.9
Hill Climb	92.6	0.50	Medium	Moderate	5.3
Fuzzy Logic	**97.2**	**0.35**	Low	Excellent	**3.6**

III.5.B Summary of Results

Across all three configurations, the Fuzzy Logic Controller consistently outperformed the traditional MPPT methods in terms of tracking efficiency, response speed, and stability. While classical techniques such as Incremental Conductance and Hill Climb showed moderate robustness, they were more sensitive to sudden irradiance changes and prone to steady-state oscillations.

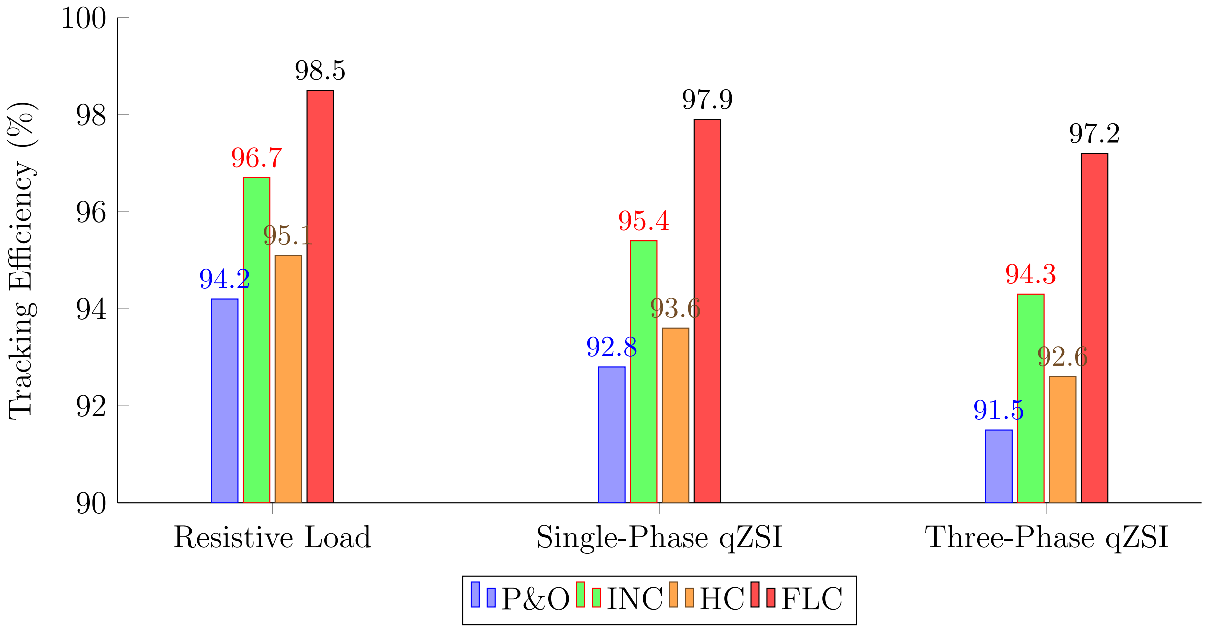


Figure III.9: Comparative tracking efficiency of MPPT methods across different system configurations.

These results demonstrate the potential of intelligent control strategies in enhancing the efficiency and reliability of grid-connected photovoltaic systems, especially when used with advanced inverter topologies like the qZSI.

III.6 Summary

This thesis investigated the performance of various Maximum Power Point Tracking (MPPT) algorithms in photovoltaic (PV) systems using resistive load, single-phase quasi-Z-source inverter (qZSI), and three-phase qZSI configurations. The implemented methods included conventional Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climb (HC), and an intelligent Fuzzy Logic Controller (FLC).

Simulation results under diverse conditions revealed that while traditional techniques like P&O and INC deliver acceptable performance, they suffer from higher steady-state oscillations, slower transient response, and limited robustness in dynamic environments. The HC method provided better stability but struggled with reduced efficiency during rapid irradiance changes.

In contrast, the FLC consistently achieved superior performance across all system configurations. It demonstrated the highest tracking efficiency, fastest response time, minimal oscillations, and lowest Total Harmonic Distortion (THD) in both single-phase and three-phase qZSI topologies. These findings underscore the value of intelligent MPPT approaches in enhancing PV system reliability, efficiency, and grid compatibility—particularly when paired with advanced inverter structures such as the qZSI.

Overall, the study confirms that the integration of FLC-based MPPT with qZSI in grid-connected PV systems provides a promising path toward higher performance and increased energy yield, especially under variable environmental conditions.

III.7 Conclusion

This thesis investigated the modeling, simulation, and performance analysis of a grid-connected photovoltaic (PV) system employing quasi-Z-source inverter (qZSI) topologies, with a focus on optimizing maximum power point tracking (MPPT) using different control algorithms. The selected MPPT techniques—Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climb (HC), and Fuzzy Logic Controller (FLC)—were implemented and tested under varying conditions and system configurations.

Three scenarios were considered: a PV system with a resistive load, integration with a single-phase qZSI, and finally, a three-phase qZSI system representing realistic grid-connected applications. The performance of each MPPT method was evaluated based on key metrics including tracking efficiency, response time, steady-state oscillations, robustness under dynamic conditions, and Total Harmonic Distortion (THD) at the inverter output.

The results consistently showed that while classical methods like P&O and INC perform reasonably well, they are prone to oscillations and slower adaptation to changing irradiance. HC improved stability but offered lower efficiency during transient phases. In contrast, the FLC-based MPPT algorithm achieved the highest tracking efficiency, fastest convergence time, and superior dynamic performance, particularly when used with the three-phase qZSI system. Additionally, it contributed to improved waveform quality with lower THD values.

Overall, the study confirms that intelligent MPPT controllers, when integrated with advanced inverter topologies like qZSI, significantly enhance the efficiency, stability, and power quality of grid-connected PV systems. This makes them a compelling choice for future renewable energy applications that demand high performance and reliability.

III.8 Limitations

While this study provides valuable insights into the performance of MPPT algorithms in qZSI-based PV systems, several limitations should be acknowledged:

- **Simulation-Based Analysis:** All evaluations were conducted in a simulation environment using MATLAB/Simulink. Although this allows for controlled and repeatable testing, it may not capture all real-world uncertainties such as sensor noise, hardware nonlinearity, or weather unpredictability.

- **Controller Tuning:** The Fuzzy Logic Controller was manually tuned based on heuristic knowledge and iterative testing. This approach, while effective, may not guarantee optimal performance under all conditions. More advanced optimization techniques could yield better-tuned controllers.
- **Limited Environmental Variability:** The simulations considered standard irradiance and temperature profiles with abrupt changes. Real-world conditions often include partial shading, gradual irradiance fluctuations, and temperature dependencies that may affect system behavior differently.
- **Hardware Validation:** No experimental hardware implementation was included in this work. Validation through practical implementation is essential to confirm the robustness and feasibility of the proposed MPPT strategies in physical systems.
- **Inverter Topology Scope:** The study was limited to quasi-Z-source inverter configurations. Other topologies like boost converters, traditional inverters, or hybrid inverters were not considered, which might offer different characteristics and control challenges.
- **Single MPPT per System:** The study assumes centralized MPPT control. In large-scale or modular PV systems, distributed or multi-point MPPT could offer performance improvements and was not addressed here.

These limitations highlight the need for further investigation to validate the presented findings and broaden their applicability to real-world systems and deployment scenarios.

III.9 Future Work

Building upon the findings of this study, several avenues for future research are recommended to enhance the applicability, efficiency, and robustness of MPPT techniques in grid-connected photovoltaic systems using qZSI:

- **Hardware Implementation and Validation:** One of the most critical next steps is to validate the simulation results through real-time hardware implementation using embedded platforms such as DSPs or FPGAs. This will help assess the practical feasibility and identify real-world challenges including noise, latency, and non-idealities.
- **Adaptive and Self-Tuning Controllers:** Future work could explore intelligent control systems that adapt to changing environmental and system conditions. Machine learning-based or adaptive fuzzy logic controllers could improve performance and reduce the need for manual tuning.
- **Partial Shading and Complex Irradiance Profiles:** Expanding the simulations to include partial shading scenarios and stochastic irradiance data will provide a more realistic evaluation of MPPT performance in actual deployment conditions.

- **Hybrid MPPT Techniques:** Combining traditional algorithms (e.g., INC or P&O) with intelligent methods (e.g., fuzzy logic or neural networks) may leverage the advantages of both, achieving a balance between speed, accuracy, and simplicity.
- **Exploring Other Inverter Topologies:** Investigating MPPT performance across various inverter types—such as neutral point clamped (NPC), multilevel inverters, or hybrid qZSI configurations—can offer further insights into topology-algorithm compatibility.
- **Integration with Smart Grid and IoT:** Future systems can benefit from real-time monitoring and adaptive control via IoT platforms, enabling remote diagnostics, predictive maintenance, and energy forecasting capabilities.
- **Economic and Environmental Analysis:** Including cost-benefit analysis and carbon savings of using advanced MPPT techniques in large-scale solar farms would help assess their commercial viability and sustainability benefits.

By addressing these research directions, future studies can significantly improve the practicality, scalability, and intelligence of MPPT systems in modern photovoltaic applications.

Bibliography

[1] R. Secretariat, “Renewables 2023 global status report,” 2023, Available: https://www.ren21.net/re status-report/.

[2] I. E. Agency, “World energy outlook 2024,” 2024, Available: https://www.iea.org/reports/world-energy-outlook-2024.

[3] IPCC, “Climate change 2021: The physical science basis,” 2021, Available: https://www.ipcc.ch/re

[4] M. A. Green, “Solar cells: Operating principles, technology, and system applications,” *Prentice Hall*, 2015.

[5] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, pp. 1398–1409, 2013.

[6] J. Anderson and F. Z. Peng, “Four quasi-z-source inverters,” *IEEE Transactions on Power Electronics*, vol. 23, no. 1, pp. 169–178, 2008.

[7] Y. Li, F. Z. Peng, and J. S. Lawler, “Control method for quasi-z-source inverter with enhanced voltage gain,” *IEEE Transactions on Power Electronics*, vol. 25, no. 4, pp. 1022–1030, 2009.

[8] A. A. Elbaset, A. A. El-Sattar, and H. A. El-Sattar, “A review of maximum power point tracking techniques for photovoltaic systems,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2556–2568, 2018.

[9] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, “Optimization of perturb and observe maximum power point tracking method,” *IEEE Transactions on Power Electronics*, vol. 20, no. 4, pp. 963–973, 2005.

[10] A. Al-Gizi and A. Al-Chlaihawi, “Study of flc based mppt in comparison with po and inc for pv systems,” in *2016 International Symposium on Fundamentals of Electrical Engineering (ISFEE)*, 2016, pp. 1–6.

[11] J. Nelson, *The Physics of Solar Cells*. Imperial College Press, 2003.

[12] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Comprehensive approach to modeling and simulation of photovoltaic arrays,” *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1198–1208, 2009.

[13] T. Esram and P. L. Chapman, “Comparison of photovoltaic array maximum power point tracking techniques,” *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, 2007.

[14] IEEE, “Ieee standard 1547-2018: Standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces,” 2018.

[15] IEEE, “Ieee standard 519-2014: Recommended practice and requirements for harmonic control in electric power systems,” 2014.

S. Saravanan and N. Ramesh Babu, “Maximum power point tracking algorithms for photovoltaic system – a review,” *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 1414–1432, 2016.

T. Zhu, J. Dong, X. Li, and S. Ding, “A comprehensive study on maximum power point tracking techniques based on fuzzy logic control for solar photovoltaic systems,” *Frontiers in Energy Research*, vol. 9, Article 727949, 2021.

M. Derbeli, C. Napole, and O. Barambones, “A fuzzy logic control for maximum power point tracking algorithm validated in a commercial PV system,” *Energies*, vol. 16, no. 2, p. 748, 2023.

T. Esram and P. L. Chapman, “Comparison of photovoltaic array maximum power point tracking techniques,” *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, 2007.

I. W. Christopher and R. Ramesh, “Comparative study of PO and InC MPPT algorithms,” *American Journal of Engineering Research (AJER)*, vol. 2, no. 12, pp. 404–410, 2013.

Y. Li, J. Anderson, F. Z. Peng, and D. Liu, “Quasi-Z-source inverter for photovoltaic power generation systems,” in *Proc. 24th IEEE Applied Power Electronics Conference (APEC)*, 2009, pp. 918–924.

J. Anderson and F. Z. Peng, “Four quasi-Z-source inverters,” in *Proc. IEEE Power Electronics Specialists Conference (PESC)*, 2008, pp. 2743–2749.

A. Abdelhakim, P. Davari, F. Blaabjerg, and P. Mattavelli, “Analysis and design of the quasi-Z-source inverter for wide range of operation,” *IEEE Transactions on Power Electronics*, vol. 35, no. 3, pp. 2873–2884, 2020.

Z. Ortatepe and S. Özdemir, “A Control Scheme for a Quasi-Z Source Three-Phase Inverter,” *2022 10th International Conference on Power Electronics Systems and Applications (PESA)*, pp. 1–6, 2022. [Online]. Available: https://www.researchgate.net/publication/359592359

A. Bouhouta, “Modeling and Control of Quasi-Z-Source Inverter for Photovoltaic Applications,” Master’s Thesis, University of Medea, Algeria, Research Laboratory of Electrical Engineering Automatic (LREA). [Online]. Available: https://dspace.univ-bba.dz/server/api/core/bitstreams/1bec710d-7c84-453e-87d8-3cb4fa439a85/content

S. M. Islam and M. R. Islam, “A Study and Analysis of MPPT Techniques for Photovoltaic Systems,” *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 8, no. 6, Jun. 2019. [Online]. Available: https://www.researchgate.net/publication/333703537

The Urban Scholar, YouTube channel. [Online]. Available: https://www.youtube.com/@electricalworkbook2743

K. Yahia, “Control of Power Converters,” YouTube channel. [Online]. Available: https://www.youtube.com/@Eng.Khalid_Yahia

MyCreative Engineering, YouTube channel. [Online]. Available: https://www.youtube.com/@MyCreativ3

Dr. M. Sivakumar. [Online]. Available: mailto:wujingwei1995@gmail.com

M. Alshikh Khalil, personal communication, 2025.

Chapter A

Appendices

A.1 MATLAB Parameters

The key parameters used for the MATLAB simulations in this thesis are summarized in Table A.1.

Table A.1: MATLAB Simulation Parameters

Parameter	**Value**
PV Module Model	[Standard 250 W]
Irradiance	1000 W/m^2 (nominal)
Temperature	25 °C (nominal)
Simulation Time Step	1 ms
Boost Inductor	[2 mH]
Capacitor	[100e-6 F]
FLC Membership Functions	Triangular + trapezoidal fnc covering error and change of error inputs
MPPT Sampling Rate	[50 Hz]

- MPPT pseudocode

PNO MPPT Pseudocode

Algorithm 1 Perturb and Observe (PNO) MPPT Algorithm with Duty Cycle Control

```
Initialize: $\Delta = 125 \times 10^{-6}$, $duty = 0.45$, $duty_{min} = 0$, $duty_{max} = 0.85$
Persistent: $V_{old} = 0$, $P_{old} = 0$, $duty_{old} = duty$
function PNO($V_{pv}, I_{pv}$)
    $P \leftarrow V_{pv} \times I_{pv}$
    $\Delta V \leftarrow V_{pv} - V_{old}$
    $\Delta P \leftarrow P - P_{old}$
    if $\Delta P \neq 0$ then
        if $\Delta P > 0$ then
            if $\Delta V > 0$ then
                $Duty \leftarrow duty_{old} - \Delta$
            else
                $Duty \leftarrow duty_{old} + \Delta$
            end if
        else
            if $\Delta V > 0$ then
                $Duty \leftarrow duty_{old} + \Delta$
            else
                $Duty \leftarrow duty_{old} - \Delta$
            end if
        end if
    else
        $Duty \leftarrow duty_{old}$
    end if
    if $Duty > duty_{max}$ or $Duty < duty_{min}$ then
        $Duty \leftarrow duty_{old}$
    end if
    $duty_{old} \leftarrow Duty$
    $V_{old} \leftarrow V_{pv}$
    $P_{old} \leftarrow P$
    return $Duty$
end function
```

Incremental Conductance (INC) MPPT Pseudocode

Algorithm 2 Incremental Conductance MPPT Algorithm with Duty Cycle Control

```
Initialize: $\Delta = 125 \times 10^{-6}$, $duty = 0.45$, $duty_{min} = 0$, $duty_{max} = 0.85$
Persistent: $V_{old} = 0$, $I_{old} = 0$, $duty_{old} = duty$
function INC($V_{pv}, I_{pv}$)
    $\Delta V \leftarrow V_{pv} - V_{old}$
    $\Delta I \leftarrow I_{pv} - I_{old}$
    if $\Delta V = 0$ then
        if $\Delta I = 0$ then
            $Duty \leftarrow duty_{old}$
        else if $\Delta I > 0$ then
            $Duty \leftarrow duty_{old} - \Delta$
        else
            $Duty \leftarrow duty_{old} + \Delta$
        end if
    else
        $Slope_{INC} \leftarrow \frac{\Delta I}{\Delta V}$
        $Slope_{MPP} \leftarrow -\frac{I_{pv}}{V_{pv}}$
        if $Slope_{INC} = Slope_{MPP}$ then
            $Duty \leftarrow duty_{old}$
        else if $Slope_{INC} > Slope_{MPP}$ then
            $Duty \leftarrow duty_{old} - \Delta$
        else
            $Duty \leftarrow duty_{old} + \Delta$
        end if
    end if
    if $Duty > duty_{max}$ or $Duty < duty_{min}$ then
        $Duty \leftarrow duty_{old}$
    end if
    $duty_{old} \leftarrow Duty$
    $V_{old} \leftarrow V_{pv}$
    $I_{old} \leftarrow I_{pv}$
    return $Duty$
end function
```

Hill Climb (HC) MPPT Pseudocode

Algorithm 3 Hill Climb MPPT Algorithm with Duty Cycle Control

```
Initialize: $\Delta = 125 \times 10^{-6}$, $duty = 0.45$, $duty_{min} = 0$, $duty_{max} = 0.85$
Persistent: $P_{old} = 0$, $duty_{old} = duty$
function HC($V_{pv}, I_{pv}$)
    $P \leftarrow V_{pv} \times I_{pv}$
    $\Delta P \leftarrow P - P_{old}$
    if $\Delta P \neq 0$ then
        if $\Delta P > 0$ then
            $Duty \leftarrow duty_{old} + \Delta$
        else
            $Duty \leftarrow duty_{old} - \Delta$
        end if
    else
        $Duty \leftarrow duty_{old}$
    end if
    if $Duty > duty_{max}$ or $Duty < duty_{min}$ then
        $Duty \leftarrow duty_{old}$
    end if
    $duty_{old} \leftarrow Duty$
    $P_{old} \leftarrow P$
    return $Duty$
end function
```

Fuzzy Logic Controller (FLC) MPPT Pseudocode

Algorithm 4 Fuzzy Logic MPPT Algorithm

```
Initialize:
    $\Delta t$: sampling time
    $V_{old}, P_{old}$: previous voltage and power
    FIS: predefined fuzzy inference system (Mamdanitype, centroid defuzzification)
function FLC_MPPT($V_{pv}, I_{pv}$)
    $P_{pv} \leftarrow V_{pv} \times I_{pv}$
    $\Delta V \leftarrow V_{pv} - V_{old}$
    $\Delta P \leftarrow P_{pv} - P_{old}$
    $Vn \leftarrow \Delta V / V_{old}$                          ▷ Normalized voltage change
    $Pn \leftarrow \Delta P / P_{old}$                          ▷ Normalized power change
    Input to FIS: $Vn$, $Pn$
    Output from FIS: $\Delta D$                                 ▷ Change in duty cycle
    $Duty \leftarrow Duty + \Delta D$
    Saturate: if $Duty > duty_{max}$ or $Duty < duty_{min}$, clip to bounds
    Update: $V_{old} \leftarrow V_{pv}$, $P_{old} \leftarrow P_{pv}$
    return $Duty$
end function
```