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Design and Performance Analysis of Dual Stage Multifunctional PV Inverter for Non-Active Current Compensation Using ANFIS Controller

by

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CERTIFICATE OF APPROVAL

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ABSTRACT

The growing integration of renewable energy sources—especially photovoltaic (PV) systems into the power grid has led to significant challenges related to power quality and system stability. In response to these issues, this thesis conducts an in-depth investigation into the design and evaluation of a dual-stage multifunctional PV inverter. The proposed inverter not only delivers clean active power to the grid but also compensates for undesirable current components such as harmonics and reactive power, which typically arise due to nonlinear and inductive loads. The system employs a two-stage configuration: a DC-DC boost converter that regulates the DC-link voltage, followed by a three-phase voltage source inverter (VSI) for interfacing with the grid. To derive the reference currents necessary for harmonic and reactive current compensation, the Instantaneous Reactive Power Theory (IRPT) is utilized. Departing from conventional approaches that rely on Proportional-Integral (PI) controllers, this research adopts an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller to enhance system responsiveness and adaptability under dynamic conditions.

Simulation outcomes confirm the inverter's effectiveness in improving power quality by compensating for non-active current components. The system achieves a notable reduction in total harmonic distortion (THD) to 4.31% and operates at a unity power factor. Moreover, the ANFIS controller demonstrates superior performance over traditional PI controllers by minimizing overshoot, shortening settling time, and providing better harmonic suppression. These results highlight the potential of intelligent control strategies in advancing efficient, stable, and high-performance grid-connected PV systems.

Keywords: MFI, ANFIS, THD, IRPT, Non-active current compensation

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LIST OF ABBREVIATIONS

PV	Photovoltaic
MPPT	Maximum Power Point Tracking
ANFIS	Adaptive Neuro-Fuzzy Inference System
IRPT	Instantaneous Reactive Power Theory
THD	Total Harmonic Distortion
PCC	Point of Common Coupling
APF	Active Power Filter
P&O	Perturb and Observe (MPPT Algorithm)
PI	Proportional-Integral (Controller)
FFT	Fast Fourier Transform
PLL	Phase-Locked Loop
SRF	Synchronous Reference Frame
RES	Renewable Energy Sources
IGBT	Insulated Gate Bipolar Transistor
PQ	Power Quality
RMS	Root Mean Square

CHAPTER ONE: INTRODUCTION

1.1 Background

The global energy landscape is undergoing a significant transformation, driven by the increasing adoption of renewable energy sources to mitigate climate change and reduce dependence on fossil fuels. Among these sources, photovoltaic (PV) systems have emerged as one of the most promising technologies due to their scalability, declining costs, and environmental benefits[1]. However, the integration of PV systems into the power grid presents several challenges, particularly in maintaining power quality and ensuring stable grid operation[2]. The proliferation of nonlinear and unbalanced loads in modern power systems has exacerbated issues such as harmonic distortion, reactive power demand, and current unbalance, which can degrade grid performance and lead to inefficiencies.

To address these challenges, multifunctional grid-connected inverters have been developed, which not only inject clean energy into the grid but also improve power quality by compensating for non-active currents[3]. This work presents a dual-stage multifunctional photovoltaic (PV) inverter that integrates maximum power point tracking (MPPT), active power filtering (APF), and reactive power compensation within a single framework, delivering a cost-effective and reliable solution for modern electrical systems. Designing and controlling such a system involves sophisticated strategies to maintain efficient operation amid fluctuating load demands and grid conditions. The primary focus of this thesis is on the development and evaluation of a multifunctional PV inverter system that addresses non-active current compensation using an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. The system architecture comprises a boost converter responsible for implementing MPPT and regulating the DC-link voltage, followed by a three-phase voltage source inverter (VSI) that connects to the grid, ensuring power quality enhancement. To generate the necessary reference signals for harmonic and reactive current mitigation, the Instantaneous Reactive Power Theory (IRPT) is applied. Replacing the conventional PI controller, the ANFIS-based controller significantly improves system adaptability and dynamic response.

1.2 Multifunctional Inverters and Power Quality

A multifunctional inverter (MFI) is a next-generation power electronic interface that not only facilitates the integration of distributed generation (DG) units like PV systems but also actively contributes to enhancing power quality. It achieves this by injecting the desired active power while simultaneously compensating for harmonic and reactive components of the load current. In this way, MFIs help in achieving cleaner grid currents, improving power factor, and complying with regulatory standards such as IEEE 519, which limits harmonic distortion at the point of common coupling.

Conventionally, power quality is improved using dedicated devices like shunt active power filters (SAPFs) or static VAR compensators (SVCs)[4]. However, the use of multifunctional inverters offers a more compact and cost-effective solution by utilizing the same inverter that connects the PV source to the grid. To ensure effective compensation, these inverters must be equipped with robust and adaptive control strategies capable of dynamically adjusting to varying load and grid conditions.

1.3 Control Challenges in Multifunctional Inverters

The control of multifunctional inverters poses several challenges, especially under nonlinear, time-varying, or unbalanced load conditions. Conventional control strategies such as proportional-integral (PI) controllers are widely used due to their simplicity and ease of implementation. However, they often fail to provide satisfactory performance in dynamic environments, particularly when the system parameters vary or when the nature of the load changes abruptly.

To overcome these limitations, intelligent control techniques such as fuzzy logic, artificial neural networks (ANN), and adaptive neuro-fuzzy inference systems (ANFIS) have been introduced. Among them, ANFIS stands out by combining the interpretability of fuzzy logic with the adaptive learning capabilities of neural networks. ANFIS-based controllers can learn from data, self-tune their internal parameters, and offer superior control performance under nonlinear and uncertain conditions.

1.4 Research Motivation

The motivation behind this research arises from the need to develop a high-performance multifunctional inverter that can effectively deal with power quality issues while maintaining efficient integration of PV energy into the grid. Given the shortcomings of traditional control methods, this study explores the use of an ANFIS-based controller for non-active current compensation in a grid-connected PV system. The proposed system is designed to dynamically detect and compensate for harmonic and reactive currents, thereby enhancing power quality and ensuring compliance with grid codes.

Additionally, by comparing the proposed ANFIS-based control strategy with a conventional PI controller, this study aims to quantitatively assess the improvement in system performance. Key performance indicators include THD reduction, power factor correction, overshoot minimization, and transient response.

1.5 Thesis Organization

This thesis is structured as follows:

- **Chapter 2** presents a detailed literature review of existing work on multifunctional inverters, harmonic compensation, and intelligent controllers, with a focus on ANFIS.
- **Chapter 3** describes the system modeling, control design, and simulation setup, including detailed explanation of ANFIS structure and IRPT-based compensation.
- **Chapter 4** provides simulation results and a comparative analysis of ANFIS and PI controllers, discussing their performance in terms of THD, transient response, and power quality metrics.
- **Chapter 5** concludes the study and outlines future research directions for hardware implementation and system optimization.

1.6 Problem Statement

The integration of PV systems into the power grid has introduced several challenges related to power quality and grid stability. The increasing use of non-linear and inductive loads has resulted in harmonic currents that distort the grid voltage and current waveforms, leading to increased losses and equipment malfunction and reactive current that consume reactive power, reducing the power factor and increasing transmission losses.

While multifunctional inverters have been proposed to address these issues, their performance is often limited by the use of traditional control strategies, such as PI controllers, which may not provide the required dynamic response and adaptability under varying operating conditions

1.7 Objectives

The main objective of this project is to Design Dual Stage Multifunctional PV Inverter for Non-Active Current Compensation Using ANFIS Controller for grid integration.

The more specific objectives of this thesis are as follows:

1. Implement Non-Active Current(harmonic and reactive) Compensation using IRPT

2. Develop and train an ANFIS Controller for robust inerter control.
3. Compare performance of ANFIS with conventional PI controllers.

1.8 Scope

The scope of this thesis is to design, simulate, and analyze a dual-stage multifunctional photovoltaic (PV) inverter integrated with an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller for non-active current compensation. The system aims to achieve the following objectives:

- Design a PV array model to generate maximum power under varying environmental conditions.
- Develop a multifunctional inverter capable of injecting active power into the grid while compensating for non-active currents.
- Utilize the Instantaneous Reactive Power Theory (p-q Theory) to identify and compensate for non-active currents.
- Replace traditional PI controllers with an ANFIS controller for improved dynamic response and accuracy.
- Validate the proposed system by comparing its performance with traditional control methods.

CHAPTER TWO: LITERATURE REVIEW

The photovoltaic systems connected into the grid has become a critical area of research due to the global shift toward renewable energy sources. However, the intermittent nature of solar energy and the presence of nonlinear and unbalanced loads in the grid pose significant challenges, such as harmonic distortion, reactive power demand, and voltage instability. To address these issues, researchers have proposed various control strategies, topologies, and intelligent techniques for PV inverters. This section provides a comprehensive review of the literature on PV systems, dual-stage inverters, non-active current compensation, and intelligent control techniques, with a focus on recent advancements and research gaps.

Multifunctional inverters (MFIs) act as both active power injectors and power quality enhancers by compensating harmonics and reactive power. Various control strategies and hardware topologies have been proposed in the literature. Domingos et al. in paper [5] proposed a multifunctional inverter for harmonic current compensation based on IRPT. Their work achieved improved current quality but lacked adaptive control for dynamic loads. Wang et al. in paper [6] implemented a VSI-based inverter using predictive current control in PV systems. While effective under linear loads, it showed performance degradation under nonlinear and rapidly changing conditions.Different multifunctional inverter architectures are reviewed in paper[3] and highlighted the growing need for intelligent adaptive control systems in PV-grid integration. Most systems used static controllers like PI and lacked adaptability under nonlinear/unbalanced load conditions.

Power quality degradation arises from Harmonic distortion caused by nonlinear loads, Reactive power demand from inductive or capacitive loads. The IEEE 519 standard recommends THD less than 5% at PCC and Unity power factor for efficient grid operation.Several researchers have focused on power quality improvements using passive filters, active power filters (APFs), and hybrid solutions. However, these solutions often increase system cost and complexity. In paper [7] Reduction of current harmonics using active power filters by instantaneous reactive power theory is used which increases extra cost of active power filters. Design and performance analysis of grid connected photovoltaic (GCPV) based DSTATCOM are proposed in paper [8] for power quality improvements. Using the inverter already present in the PV system for current compensation reduces hardware cost and improves efficiency, making multifunctional inverters a practical alternative.

Dual-stage power conversion systems, consisting of a DC-DC boost converter and a DC-AC inverter, are commonly used in grid-connected PV systems. The boost converter steps up the PV voltage, while the inverter converts DC power to AC for grid integration.Paper[9] highlights the importance of a stable DC-link voltage (600 V) for efficient inverter operation. The dual-stage topology ensures better voltage regulation, improved power quality, and enhanced system reliability compared to single-stage systems. Recent studies have explored the use of advanced DC-DC converter topologies, such as interleaved boost converters and cascaded H-bridge converters, to reduce switching losses and improve efficiency. Paper [6] proposes a dual-stage interleaved boost converter with a high-frequency transformer, achieving higher efficiency and power density compared to conventional designs.

Non-active currents, including harmonic, reactive, and unbalanced currents, degrade power quality and increase losses in the grid. Instantaneous Reactive Power Theory (IRPT) is most used method for identifying and compensating for these currents.Paper [10] discusses the application of p-q theory in multifunctional inverters to achieve low total harmonic distortion (THD) and unity power factor. The theory decomposes the load current into active and non-active components, enabling precise compensation.IRPT, also known as p–q theory, is widely used for non-active current detection. It transforms three-phase currents and voltages into the alpha-beta stationary reference frame using Clarke transformation and calculates: Instantaneous active power (p) and Instantaneous reactive power (q) then Low-pass filtering isolates oscillating components (non-active power), which are then used to reconstruct the compensating current references. Akagi et al. originally proposed Instantaneous Reactive Power Theory (p-q Theory) or IRPT for active power filter (APF) control[11]. In paper [12] applied IRPT in grid-connected inverters and demonstrated fast detection of non-active currents.

Recent research has focused on improving the accuracy and robustness of non-active current compensation techniques. Paper [13] proposes a modified p-q theory-based algorithm that accounts for grid voltage distortions, achieving better compensation performance under distorted grid conditions. Additionally, advanced filtering techniques, such as adaptive filters and wavelet transforms, have been integrated with p-q theory to enhance harmonic detection and compensation.

Traditional control methods, such as PI controllers, have limitations in handling the dynamic and nonlinear nature of PV systems and grid disturbances[14]. Intelligent control techniques, such as fuzzy logic, neural networks, and Adaptive Neuro-Fuzzy Inference System (ANFIS), have been proposed to overcome these limitations.Paper [15] demonstrates the effectiveness of ANFIS controllers in non-active current compensation, highlighting their ability to adapt to varying operating conditions and provide superior performance compared to conventional methods.

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is an intelligent control approach that combines the strengths of fuzzy logic and artificial neural networks to achieve improved learning and decision-making capabilities. First introduced by Jang in 1993, Paper [16] explained that ANFIS is based on a Sugeno-type fuzzy inference system, where fuzzy rules are used to model system behavior, and neural networks are used to optimize rule parameters through learning algorithms. Fuzzy Logic offers human-readable rules and reasoning and Neural Networks provide learning and generalization capabilities. ANFIS adapts to changing environments and system nonlinearities which Suitable for real-time control in nonlinear and uncertain systems[14].

Recent research has focused on optimizing the design and training of ANFIS controllers for PV systems. Paper [4] proposes a hybrid training algorithm combining particle swarm optimization (PSO) and gradient descent, achieving faster convergence and better accuracy in ANFIS-based MPPT and grid synchronization. Additionally, in paper [17] the integration of ANFIS with other intelligent techniques, such as genetic algorithms and reinforcement learning, has been explored to further enhance system performance.

2.1 Dual-Stage Grid-Connected PV System

In photovoltaic (PV) power systems, the conversion of solar energy into usable electrical power typically involves interfacing circuits that perform DC–DC and DC–AC conversion. Depending on the topology and functional requirements, PV systems are generally classified into single-stage and dual-stage architectures[6]. The choice between these architectures depends on the desired control flexibility, voltage regulation, and type of application whether grid-connected or isolated. A dual-stage PV system incorporates two distinct power conversion stages: a DC–DC converter stage followed by a DC–AC inverter stage. In this configuration, the PV array first feeds a boost converter that steps up and regulates the DC voltage. This stage is usually controlled to track the maximum power point (MPP) of the PV array using algorithms like Perturb and Observe (P&O) or Incremental Conductance. The regulated DC output is then fed to a voltage source inverter (VSI) that converts the DC power into synchronized AC power suitable for the utility grid or local AC loads. single-stage PV system integrates the MPPT and grid interface functions into a single inverter without an intermediate DC–DC stage. While this configuration reduces the component count and improves overall efficiency by eliminating one conversion stage, it suffers from limited control flexibility. In single-stage systems, the inverter must simultaneously perform MPPT and manage the grid current injection, which can result in trade-offs between tracking accuracy and power quality. Moreover, in scenarios with varying irradiance or rapidly changing loads, the system may struggle to maintain stable operation or desired power factor.

The advantage of dual-stage systems lies in the decoupling between MPPT and grid control. Since the DC–DC converter maintains the PV operating point independently of grid conditions, the inverter stage can focus solely on grid synchronization, power quality control, and current regulation. This modular control structure enables higher system stability, better performance under dynamic irradiance, and easier integration of advanced functionalities such as harmonic compensation and reactive power injection.

In a grid-connected configuration, the PV system operates in parallel with the utility grid. The main objectives are to inject active power into the grid and ensure that the power delivered meets grid code requirements, including limits on voltage distortion, frequency variation, and current harmonics. In such systems, synchronization with the grid voltage is critical and is often achieved using a phase-locked loop (PLL). Moreover, in advanced configurations like multifunctional inverters, the system also supplies reactive power and mitigates harmonic pollution, thus actively improving grid power quality.An isolated or off-grid PV system operates independently of the utility grid and is commonly used in remote or rural areas. These systems are typically connected to local AC loads and often include battery storage for energy reliability. In isolated systems, the inverter must act as the primary voltage and frequency source, often referred to as a grid-forming inverter. This requires more complex control strategies, including droop control and voltage regulation loops.

Dual-stage grid-connected systems offer an effective platform for such multifunctional operations. The DC–DC stage ensures a stable DC-link voltage required by the inverter, while the inverter stage can perform real-time compensation of non-active currents. This dual-control loop architecture is ideal for intelligent controllers like ANFIS, where adaptive current control is essential for dynamic compensation and compliance with standards such as IEEE 519 and IEEE 1547.

2.1.1 Maximum Power Point Tracking (MPPT) and Boost Converter in PV Systems

Maximum Power Point Tracking (MPPT)

Photovoltaic (PV) systems are inherently nonlinear in nature, and their power output varies with changes in solar irradiance and temperature. Each PV module has a specific operating point, known as the maximum power point (MPP), at which it delivers the highest possible power. The MPP is not fixed; it shifts continuously due to environmental fluctuations[18]. Hence, for a PV system to operate efficiently under all conditions, a dynamic mechanism is required to continuously track and adjust to this optimal point. This process is known as Maximum Power Point Tracking (MPPT). MPPT algorithms are implemented in the control system of PV converters to extract the maximum available power from the solar array at any given time. Various algorithms have been developed for MPPT, ranging from simple methods like Perturb and Observe (P&O) and Incremental Conductance (INC) to more advanced approaches involving fuzzy logic, neural networks, and ANFIS. Among these, P&O is widely used due to its simplicity, ease of implementation, and good performance under slowly varying conditions.

Perturb & Observe (P&O) algorithm is the most widely used method due to its simplicity. The algorithm Perturb i.e. Adjust PV voltage (V) in small steps and Check power change (P): If P increases then keep perturbing in the same direction. If P decreases then reverse perturbation direction.

Incremental Conductance algorithm is More accurate than P&O, avoids steady-state oscillations. It is based on the condition at MPP given by:

$$\frac{dP}{dV} = I + V\frac{dI}{dV} = 0 \tag{2.1}$$

If $dI/dV > -I/V$, move right increasing the voltage; otherwise, move left decreasing value of voltage.It has faster response under changing irradiance conditions but more computationally complex than P&O.

The MPPT controller adjusts the operating voltage of the PV array by varying the duty cycle of the connected DC-DC converter. By observing the change in power output corresponding to small perturbations in voltage, the controller determines the direction in which to adjust the operating point to maximize power extraction. When properly tuned, MPPT significantly enhances the energy harvesting efficiency of the PV system.

Boost Converter

A boost converter, also known as a step-up converter, is a type of DC–DC power electronic converter that increases the input voltage to a higher output voltage level. In photovoltaic (PV) systems, the voltage generated by the PV modules often does not meet the required DC-link voltage for inverter operation. Therefore, a boost converter is typically employed between the PV array and the inverter stage to regulate and elevate the voltage to a desirable level[7].

The fundamental operation of a boost converter is based on two switching modes: when the switch (usually a MOSFET or IGBT) is turned ON, current flows through the inductor, and energy is stored in its magnetic field. When the switch is turned OFF, the inductor releases the stored energy through a diode to the output capacitor and load. This process increases the voltage seen at the output terminals of the converter. The relationship between the input and output voltage of an ideal boost converter in continuous conduction mode (CCM) is given by:

$$V_{\mathrm{out}} = \frac{V_{\mathrm{in}}}{1-D} \tag{2.2}$$

where V_{out} is the output voltage, V_{in} is the input voltage from the PV array, and D is the duty cycle of the switching signal.

The boost converter thus serves as an essential interface for voltage regulation and energy harvesting efficiency. The design of the converter includes careful selection of inductor and capacitor values, which influence the ripple voltage, transient response, and overall system stability. Moreover, a high switching frequency is typically chosen to minimize the size of passive components and improve dynamic performance. When integrated with the MPPT controller, the boost converter ensures a steady DC voltage suitable for grid interfacing via an inverter, thereby playing a critical role in the dual-stage PV system architecture.

2.1.2 Multifunctional Inverter (MFI)

A Multifunctional Inverter (MFI) is a power electronic device that not only enables the injection of active power from a distributed energy resource such as a photovoltaic (PV) array into the electrical grid but also performs essential power quality enhancement functions. Unlike conventional inverters, which are limited to active power conversion, MFIs are designed to mitigate harmonic distortion, compensate reactive power, and support load balancing[3]. These extended capabilities make MFIs indispensable in modern power systems with high penetration of nonlinear and distributed loads.

The need for multifunctional inverters arises primarily from the proliferation of nonlinear electronic loads in residential, commercial, and industrial environments. These loads draw distorted current waveforms from the grid, introducing harmonics and degrading power factor. MFIs address these challenges by combining active power injection with compensating current control in a single integrated system, reducing the need for separate active filters or compensators.

The core operation of an MFI revolves around its ability to generate and inject a reference current that meets specific power quality objectives. This reference is derived through techniques such as Instantaneous Reactive Power Theory (IRPT), which decomposes load current into active and non-active components[11]. The inverter is controlled in such a way that it injects a current that supplies the active power from the PV source while simultaneously cancelling the non-active portions drawn by the load. Depending on system availability and load conditions, the inverter can operate in three primary modes: pure active power injection, compensation-only mode, or full multifunctional mode where both tasks are performed concurrently.

The typical architecture of an MFI includes a DC–DC boost converter, which elevates and regulates the PV array voltage while enabling Maximum Power Point Tracking (MPPT). A DC-link capacitor stabilizes the voltage between the converter and the inverter stage. A voltage source inverter (VSI) then converts the regulated DC power into AC power that is synchronized with the utility grid. The control system coordinates the MPPT, reference current generation, and inverter switching logic—often using a current controller such as PI, hysteresis, or intelligent controllers like ANFIS. MFI topologies fall into two categories single and two-stage design. There are advantages and downsides to both single and two-stage MFIs. A single-stage MFI shown in fig 1.1(a) features a DC-AC stage, resulting in fewer electrical components, reduced cost, and improved efficiency[1]. This system connects PV panels directly to the grid-connected inverter's DC bus. Using a voltage-fed (buck-type) inverter, such as the T-type three-level converter, results in a high dc-bus voltage, limiting PV voltage to a high value. For most MFI applications, a two-stage architecture is desirable shown in fig 1.1(b). This allows the front-end dc-dc stage to raise the PV voltage and accommodate the voltage-fed dc-ac stage[19].

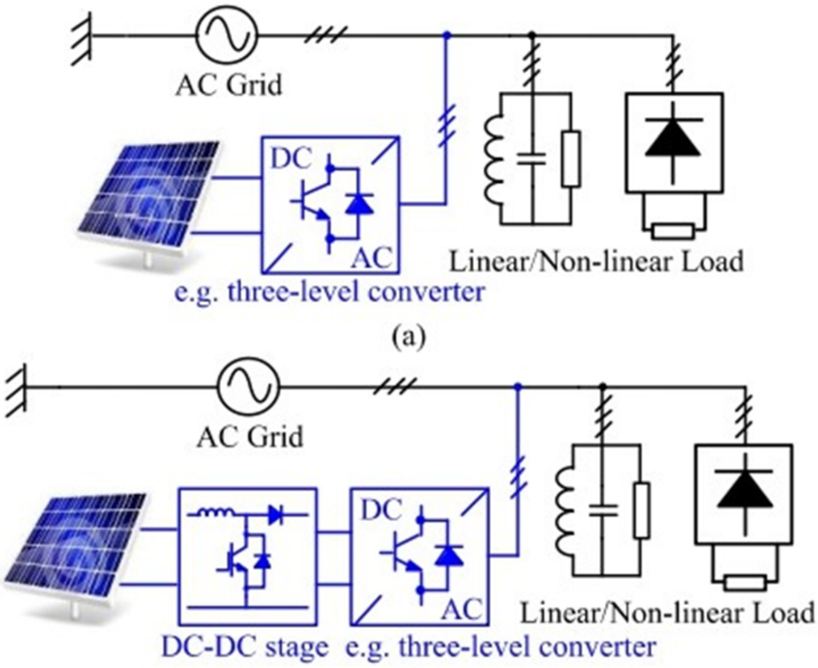


Figure 2.1: Conventional MFI architecture: (a) Single-stage, (b) Dual-stage.

Advanced multifunctional inverters utilize intelligent control techniques to adapt to rapid load changes and grid disturbances. Among them, Adaptive Neuro-Fuzzy Inference Systems (ANFIS) provide a compelling advantage due to their self-learning capability, fast convergence, and robustness against nonlinearity[16]. These controllers can outperform conventional PI controllers, especially under variable load conditions where dynamic compensation is critical.

The multifunctional inverter approach offers numerous advantages. It improves overall energy efficiency, eliminates the need for additional compensation hardware, ensures compliance with IEEE 519 and IEEE 1547 standards, and supports the operation of smart grids and microgrids. However, MFIs also present challenges, including increased control complexity and computational requirements. Research continues in the direction of optimizing control algorithms, reducing hardware costs, and enabling real-time embedded implementation. MFIs are a promising solution for integrating renewable energy sources into the power grid while maintaining high power quality and system reliability.

2.2 Non-Active Current Compensation and Instantaneous Reactive Power Theory (IRPT)

In a typical power system with nonlinear and reactive loads, the current drawn by the load consists of both active and non-active components. The active component is associated with the real power consumed by the load, whereas the non-active component includes harmonic and reactive currents, which do not contribute to useful work but degrade overall power quality. The presence of non-active currents results in increased total harmonic distortion (THD), low power factor, and additional stress on the grid infrastructure[10].

Non-active current compensation refers to the process of injecting compensating currents that cancel out these unwanted components. By doing so, the grid is required to supply only the active portion of the load current, thus improving the power factor and reducing harmonic pollution. In grid-connected PV systems, this compensation can be achieved by utilizing the same inverter that delivers the active power, making the system multifunctional without additional compensating devices.

The generation of compensating current references relies on real-time detection and decomposition of load current. One of the most widely adopted techniques for this purpose is the Instantaneous Reactive Power Theory (IRPT), also known as p–q theory. Developed by Akagi and his colleagues, IRPT operates in the α–β stationary reference frame and allows for instantaneous calculation of active and reactive power components.

To implement IRPT, the three-phase voltages and currents are first transformed into the α–β frame using the Clarke Transformation. The instantaneous active and reactive powers are then calculated as:

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{2.3}$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha \tag{2.4}$$

The resulting p and q powers contain both average (DC) and oscillating (AC) components. The average components correspond to the active power consumed by the load, while the oscillating parts represent the non-active power responsible for power quality issues. A low-pass filter is applied to isolate the oscillating components, which are then used to generate the reference compensating currents. Finally, these reference currents are transformed back to the three-phase domain using inverse Clarke transformation and fed into the inverter current controller. The inverter is then regulated to inject the compensating currents in real time, effectively neutralizing the non-active components drawn by the load.

The IRPT-based compensation strategy is particularly effective in dynamic conditions, including unbalanced and nonlinear loading scenarios. It offers a computationally efficient and real-time solution for multifunctional inverters to enhance power quality and comply with standards such as IEEE 519.

2.3 ANFIS Controller

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is an advanced hybrid control technique that integrates the advantages of both artificial neural networks (ANN) and fuzzy logic systems. Originally introduced by Jang in 1993, ANFIS is particularly effective for modeling and controlling nonlinear and time-varying systems where conventional mathematical modeling proves inadequate[16]. Its capability to learn from data and adaptively modify its internal structure makes it an ideal choice for control applications in power electronics and renewable energy systems.

In the context of a multifunctional inverter (MFI), the ANFIS controller is employed to regulate the output current of the inverter, ensuring accurate compensation of non-active current components and reliable delivery of active power. Unlike classical PI controllers,

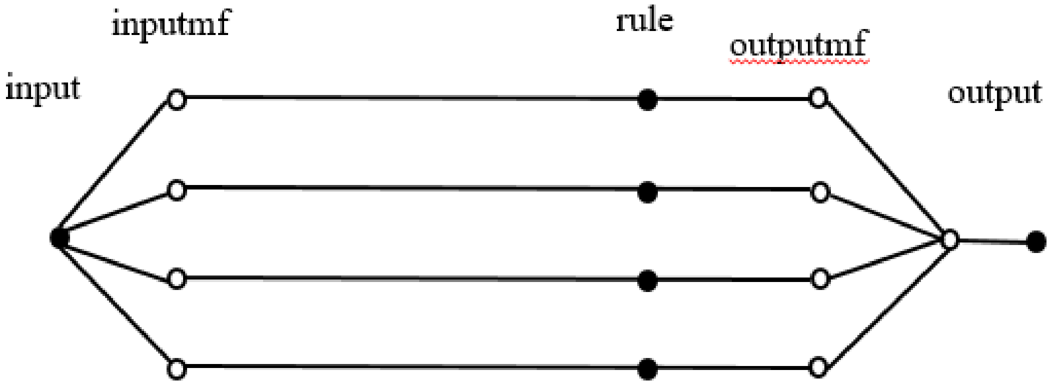


Figure 2.2: Anfis structure

which use fixed gains and often struggle with tuning under dynamic conditions, ANFIS can generalize from training data to generate control actions for previously unseen system states.

The structure of ANFIS consists of five layers as shown in figure 2.2:

- **Layer 1 (Fuzzification)**: Converts crisp input variables, such as error and change of error, into fuzzy membership values using predefined membership functions.

- **Layer 2 (Rule Evaluation)**: Computes the firing strength of fuzzy rules by applying fuzzy logic operations.

- **Layer 3 (Normalization)**: Normalizes the firing strengths of each rule to ensure proper scaling.

- **Layer 4 (Defuzzification)**: Applies a linear function to generate the rule output based on the normalized firing strength.

- **Layer 5 (Summation)**: Aggregates the output of all rules to produce the final control signal.

ANFIS controllers are highly effective in power electronics applications, particularly for non-active current compensation in grid-connected inverters. Their ability to learn and adapt to varying conditions makes them a powerful alternative to traditional controllers. By integrating neural networks and fuzzy logic, ANFIS enhances efficiency, stability, and power quality in modern renewable energy systems[18].

Comparison of ANFIS with Conventional Controllers is shown in table 2.1.

Feature	**PI Controller**	**Fuzzy Logic Controller**	**ANFIS Controller**
Adaptability	Fixed gains with limited flexibility	Adapts to nonlinear behaviors using rule-based logic	Self-learning, adaptive to system variations
Steady-State Error	High under dynamic conditions	Moderate, depends on rule base	Low, due to learning capability
Response Speed	Slow due to fixed parameters	Moderate, reacts based on rules	Fast, dynamically adjusts output
Computational Load	Low, suitable for simple systems	Moderate due to rule evaluation	High, due to training and inference
Power Quality Improvement	Limited to linear loads	Moderate under certain distortions	High, compensates harmonics and reactive power

Table 2.1: Comparison of ANFIS with Traditional Controllers

2.4 Research Gaps:

While significant progress has been made in the design and control of PV inverters, there is a need for further research on the integration of multifunctional inverters with intelligent control techniques. Developing efficient training algorithms and rule bases for ANFIS controllers to improve their performance in non-active current compensation. Exploring hybrid inverter topologies, such as MMC and cascaded H-bridge, to enhance efficiency and scalability.Integrating energy storage systems and advanced grid support functions, such as fault ride-through and voltage regulation, into multifunctional inverters.Validating the proposed systems through real-time implementation and field testing under varying grid and load conditions.

This thesis aims to address these gaps by proposing a dual-stage multifunctional PV inverter with ANFIS-based control for non-active current compensation. The proposed system is expected to enhance power quality by compensating reactive and harmonic current, improve grid stability, and provide a robust solution for the integration of PV systems into the grid.

CHAPTER THREE: METHODOLOGY

3.1 System Design and Modeling

3.1.1 Main Circuit Diagram

The overall circuit for the proposed system is shown in figure 3.1, which consists of PV array, DC-DC converter, AC-DC stage, Non-linear and Reactive load and Grid connection. The methodology adopted in this thesis is designed to achieve dual functionality efficient power injection from a photovoltaic (PV) source and active power quality enhancement through compensation of non-active currents. The complete workflow of the proposed system can be described in sequential steps as follows.

3.1.2 PV Array Modeling

The process begins with the modeling of the photovoltaic array, where the electrical characteristics of the PV system are simulated based on irradiance and temperature conditions. The output of the PV array is inherently variable and nonlinear, and it is therefore processed through a DC–DC boost converter to regulate the voltage and enhance the power transfer capability. The PV array is modeled using the single-diode equivalent circuit,[5] which includes a current source, diode, series resistance (R_s), and shunt resistance (R_{sh}). The output current (I_{pv}) of the PV array is given by:

$$I_{pv} = I_{ph} - I_0 \left(\exp\left(\frac{V_{pv} + I_{pv} R_s}{a V_t} \right) - 1 \right) - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \tag{3.1}$$

where:
I_{ph}: Photocurrent.
I_0: Reverse saturation current.
V_{pv}: PV voltage.
a: Ideality factor.
V_t: Thermal voltage.

The PV array parameters are selected based on paper [5] are given in table**??**

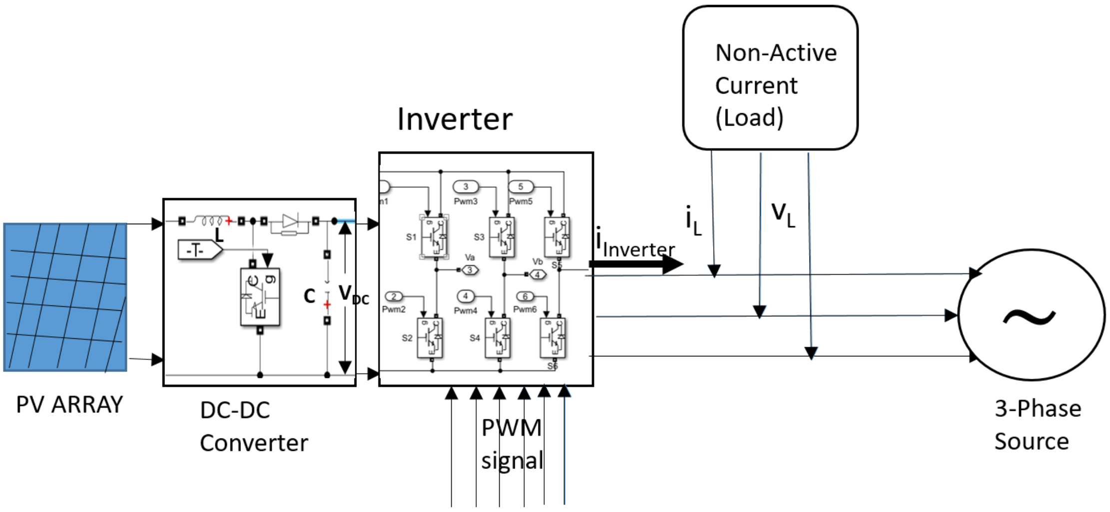


Figure 3.1: Main Circuit Topology for proposed system

Table 3.1: Solar PV Parameters

Parameters	**Values**
P_{mpp} (Maximum PV power)	67.5 kW
V_{mpp} (Voltage at MPPT)	480 V
I_{mpp} (Current at MPPT)	140 A
V_{open} (Open circuit voltage)	570 V
I_{sc} (Short circuit current)	152 A
N_s and N_p (Series and Parallel cells)	40 and 15
Temperature	25°C

3.1.3 Maximum Power Point Tracking using Perturb and Observe (P&O) Method

A Maximum Power Point Tracking (MPPT) algorithm is employed to continuously adjust the duty cycle of the boost converter. Maximum Power Point Tracking (MPPT) is an essential feature in photovoltaic (PV) systems to ensure that the solar array operates at its peak efficiency. Due to the nonlinear nature of the PV module's power–voltage (P–V) characteristic and its dependency on environmental factors such as irradiance and temperature, a dynamic control mechanism is required to extract the maximum possible power from the system.

In this work, the Perturb and Observe (P&O) algorithm is adopted for MPPT due to its simple structure, ease of implementation, and fast convergence. The core idea of the P&O method is to perturb the operating voltage or duty cycle of the DC–DC boost converter and observe the corresponding change in output power. If the perturbation results in an increase in power, the algorithm maintains the direction of perturbation. However, if the power decreases, the direction is reversed. This process is repeated continuously, allowing the operating point to converge toward the maximum power point (MPP).

While the P&O method is straightforward and widely used, it can introduce small oscillations around the MPP in steady-state conditions. Additionally, during rapidly changing irradiance, it may temporarily misinterpret the direction of power change, leading to momentary deviations from the true MPP. Despite these limitations, its low computational burden and practical reliability make it a suitable choice for MPPT in PV systems with boost converters.

In the proposed system, the P&O-based MPPT algorithm controls the duty cycle of the boost converter to ensure that the PV array consistently operates near its optimal power point. The regulated DC output is then fed to the voltage source inverter (VSI) for further processing and grid integration.

The algorithm works by perturbing the PV voltage and observing the change in power:

$$\Delta P = P(k) - P(k-1) \tag{3.2}$$

If $\Delta P > 0$, the perturbation is continued in the same direction.
If $\Delta P < 0$, the perturbation direction is reversed.

3.1.4 Boost Converter Design

A DC-DC boost converter is used to step up the voltage from the photovoltaic (PV) array to the required DC-link voltage. This converter operates using maximum power point tracking (MPPT) to ensure optimal power extraction from the PV array.

The design is based on the following given parameters:

- PV maximum power: $P_{\text{mp}} = 67.5$ kW
- PV MPP voltage: $V_{\text{mp}} = 480$ V
- PV MPP current: $I_{\text{mp}} = 147$ A
- Desired DC-link voltage: $V_{\text{dc}} = 600$ V

- Switching frequency: $f_{\text{sw}} = 10$ kHz

Duty Cycle Calculation

The ideal duty cycle for the boost converter is given by:

$$D = 1 - \frac{V_{\text{in}}}{V_{\text{dc}}} \tag{3.3}$$

Inductor Selection

The inductor is chosen to limit ripple in the inductor current. The ripple current is typically $10\% - 20\%$ of the input current:

$$\Delta I_L = 0.20 \times I_{\text{mp}} = 0.20 \times 147 = 28 \text{ A} \tag{3.4}$$

The inductor value is calculated using:

$$L_b = \frac{V_{\text{in}} \cdot D}{\Delta I_L \cdot f_{\text{sw}}} \tag{3.5}$$

Output Capacitor Selection

The output capacitor is chosen to limit the voltage ripple. The output current is given by:

$$I_{\text{out}} = \frac{P}{V_{\text{dc}}} = \frac{67500}{600} \approx 104 \text{ A} \tag{3.6}$$

For a ripple voltage of 5 V, the capacitor value is:

$$C_b = \frac{I_{\text{out}} \cdot D}{\Delta V_{\text{dc}} \cdot f_{\text{sw}}} \tag{3.7}$$

The overall design parameters for DC-DC to converter is given in table 3.2.

Table 3.2: Boost Converter Parameters

Parameters	**Values**
Switching Frequency (f_{sw})	10 kHz
V_{in}	480 V
Duty Cycle (D)	26.153%
Inductance (L)	0.448 mH
Capacitance (C)	540.698 μF
DC Link Voltage	600 V

Switching Devices Selection

The power switches must be rated above the maximum input current and voltage:

- MOSFET/IGBT: Rated at least 800 V and 200 A
- Diode: Rated at least 650 V and 120 A

This design provides a practical boost converter for a 67.5 kW PV system, ensuring stable operation with appropriate ripple limits. Further optimization can be done via simulation to refine component selection.

3.2 Dual-Stage Power Conversion

The output of the boost converter is fed into a DC link capacitor, which stabilizes the intermediate DC voltage. This constant DC voltage is essential for the proper operation of the Voltage Source Inverter (VSI), which forms the second stage of the dual-stage converter system. The inverter is responsible for converting the regulated DC voltage into AC and injecting it into the grid.

3.2.1 DC-Link Capacitor

A DC-link capacitor is used to stabilize the DC bus voltage and reduce ripple. The capacitor value is selected based on the power rating and switching frequency.

3.2.2 Three-Phase Inverter

A three-phase voltage source inverter (VSI) is used to convert DC power to AC for grid integration. The inverter operates at a switching frequency of 10 kHz and uses Sinusoidal

Pulse Width Modulation (SPWM) for generating the gate signals.
MFI and other parameters for the proposed system design is given in table 3.3 .

Table 3.3: MFI, Load, and Other Parameters

Parameters	**Values**
MFI Switching Frequency (f_{sw})	20 kHz
IGBT Rating	>800 V and >200 A
Non-linear Load	10 Ω and 10 mH with diode bridge
Diode Rating	>650 V and 120 A
Reactive Load	1.414 kVA
Grid Voltage	415 V
Frequency	50 Hz
ANFIS Epochs	100

3.3 Non-Active Current Compensation

To ensure that the grid is supplied with only the active component of the load current, a non-active current detection mechanism is integrated. This is achieved using the Instantaneous Reactive Power Theory (IRPT), which decomposes the load current into active and non-active parts in the stationary reference frame. The non-active current component includes reactive and harmonic currents that must be compensated to maintain power quality.

3.3.1 Instantaneous Reactive Power Theory (p-q Theory)

The instantaneous power theory (p-q theory) is used to extract harmonic and reactive components from the grid current[20]. The steps are as follows:

Step 1: Transformation to $\alpha\beta$ Coordinates

The three-phase grid voltages (v_a, v_b, v_c) and currents (i_a, i_b, i_c) are transformed into the $\alpha\beta$ reference frame using the Clarke transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.8}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.9}$$

Step 2: Calculation of Instantaneous Power

The instantaneous real power (p) and imaginary power (q) are calculated as:

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{3.10}$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha \tag{3.11}$$

Step 3: Separation of Harmonic and Fundamental Components

The instantaneous power (p) and imaginary power (q) can be decomposed into their average (DC) and oscillating (AC) components:

$$p = \overline{p} + \tilde{p} \tag{3.12}$$

$$q = \overline{q} + \tilde{q} \tag{3.13}$$

where:

- $\overline{p}$ and $\overline{q}$ are the average (fundamental) components.
- $\tilde{p}$ and $\tilde{q}$ are the oscillating (harmonic) components.

Step 4: Calculation of Harmonic Reference Currents

The harmonic reference currents in the $\alpha\beta$ frame are calculated as:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{3.14}$$

Step 5: Transformation Back to abc Coordinates

The harmonic reference currents in the $\alpha\beta$ frame are transformed back to the abc frame using the inverse Clarke transformation:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \tag{3.15}$$

These reference currents (i_a^*, i_b^*, i_c^*) are used to compensate for the harmonic and reactive components in the grid current. The p-q theory is used to decompose the load current into active (i_p), reactive (i_q), and harmonic (i_h) components. The equations for p-q theory are:

$$p = e_\alpha i_\alpha + e_\beta i_\beta \tag{3.16}$$

$$q = e_\alpha i_\beta - e_\beta i_\alpha \tag{3.17}$$

where e_α, e_β, i_α, and i_β are the grid voltages and load currents in the $\alpha - \beta$ reference frame.

3.3.2 Compensation Strategy

The non-active components (i_q and i_h) are extracted using a low-pass filter (LPF)[21] and compensated by the inverter. The reference currents for compensation are given by:

$$i_\alpha^* = \frac{e_\alpha p}{e_\alpha^2 + e_\beta^2} \tag{3.18}$$

$$i_\beta^* = \frac{e_\beta p}{e_\alpha^2 + e_\beta^2} \tag{3.19}$$

The control diagram for the non-active current compensation using IRPT theory is given in fig:3.2

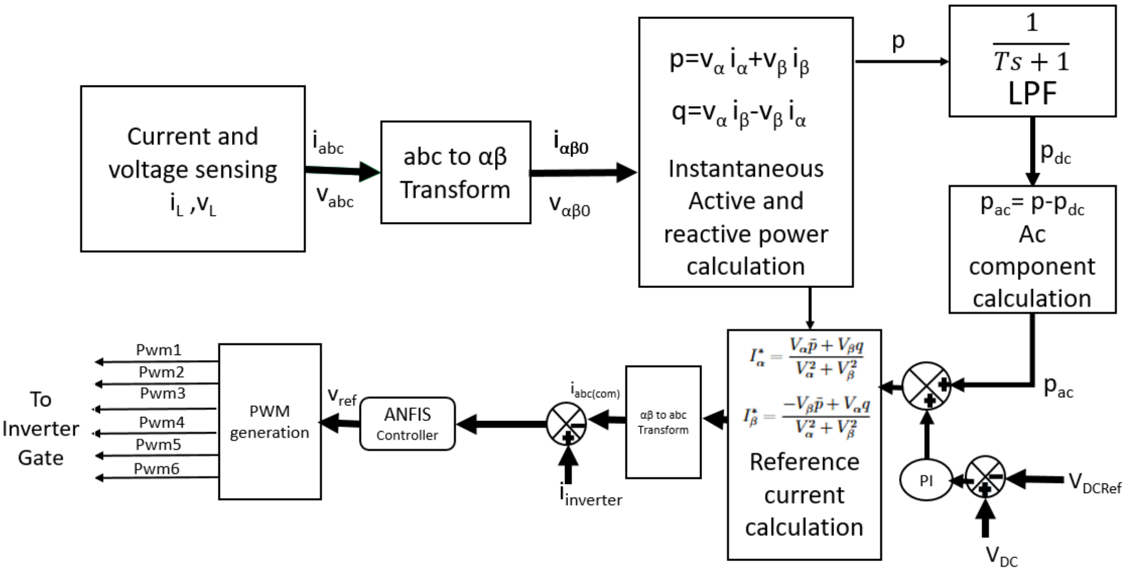


Figure 3.2: Control diagram for IRPT based compensation

3.4 Adaptive Neuro-Fuzzy Inference System (ANFIS)

The extracted non-active current is used to generate a reference compensating current. This reference is then fed to the control loop of the inverter. In this thesis, an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller is trained and implemented to track the reference current accurately. The ANFIS controller receives the error and change of error between the reference and actual current as inputs and outputs the optimal control signal for the inverter.

3.4.1 Overview of ANFIS

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid intelligent control technique that integrates the learning capability of Artificial Neural Networks (ANN) with the knowledge representation and reasoning of Fuzzy Logic. It is particularly effective for nonlinear, time-varying systems where mathematical modeling is complex. In this thesis, ANFIS is utilized within the multifunctional inverter (MFI) to generate compensating reference currents for eliminating non-active current components such as reactive and harmonic currents.

3.4.2 Structure of ANFIS

The ANFIS structure used in this study is based on a first-order Sugeno-type fuzzy inference system, composed of five distinct layers:

- **Layer 1: Fuzzification**
  Each input variable is converted into fuzzy sets using membership functions (MFs). Gaussian or bell-shaped MFs are employed due to their smooth characteristics. The output of this layer is given by:

$$O_{1,i} = \mu_{A_i}(x) \tag{3.20}$$

- **Layer 2: Rule Evaluation**
  The firing strength of each fuzzy rule is computed using the product (T-norm) of the membership values:

$$O_{2,i} = w_i = \mu_{A_i}(x) \cdot \mu_{B_i}(y) \tag{3.21}$$

- **Layer 3: Normalization**
  The firing strengths are normalized as:

$$O_{3,i} = \bar{w}_i = \frac{w_i}{w_1 + w_2} \tag{3.22}$$

- **Layer 4: Rule Output**
  The output of each rule is calculated as a first-order linear function of the inputs:

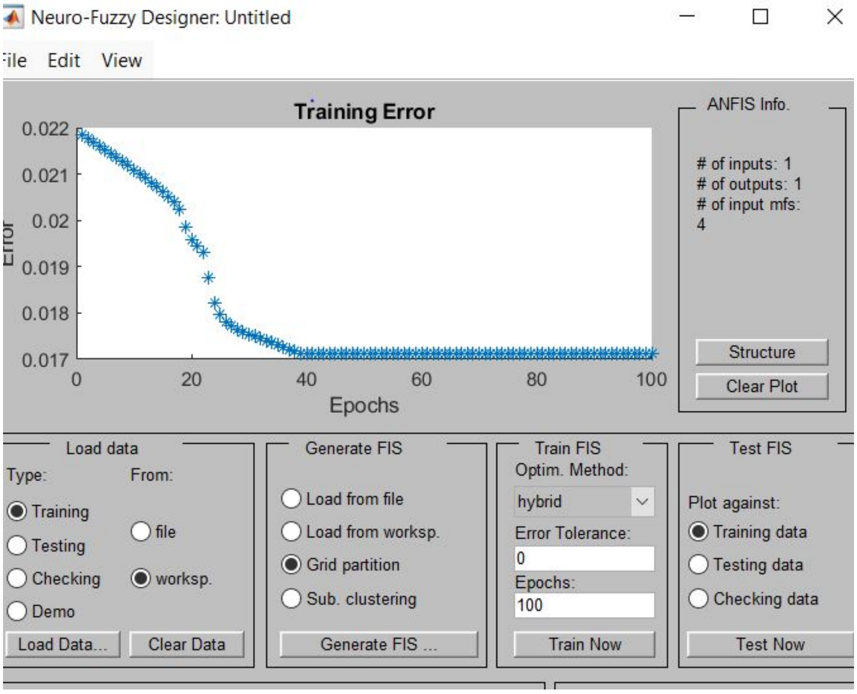
$$O_{4,i} = \bar{w}_i \cdot f_i = \bar{w}_i \cdot (p_i x + q_i y + r_i) \tag{3.23}$$

- **Layer 5: Output Aggregation**
  The final output is the summation of all rule outputs:

$$O_5 = \sum_i \bar{w}_i f_i \tag{3.24}$$

3.4.3 Input-Output Selection

For effective current compensation, the ANFIS system is trained with appropriately selected input and output variables. In this implementation: Inputs to ANFIS Instantaneous grid current, Load current and Output from ANFIS Reference compensating current.



# of inputs: 1
# of outputs: 1
# of input mfs:
4

● Training
○ Testing
○ Checking
○ Demo

○ file
● worksp.

○ Load from file
○ Load from worksp.
● Grid partition
○ Sub. clustering

Optim. Method: hybrid
Error Tolerance: 0
Epochs: 100

Plot against:
● Training data
○ Testing data
○ Checking data

Figure 3.3: Data training using ANFIS

3.4.4 Training Process

The ANFIS model is trained using supervised learning. A training dataset is created by recording the system behavior under various load conditions, where the target output (reference compensating current) is computed using the IRPT theory.

The training is performed over 100 epochs using a hybrid optimization algorithm that combines Least Squares Estimation (LSE) and Gradient Descent to optimize the membership functions and rule parameters. The input and output data of PI controller is taken to workspace and trained using ANFIS Tool Box as shown in figure.3.3

3.4.5 Integration with MFI Control System

Once trained, the ANFIS model is integrated into the control loop of the inverter. The operation involves:

1. measurement of grid and load currents.
2. Feeding the inputs to the trained ANFIS controller.
3. Generating reference compensating current (i_c^{ref}).

4. Controlling the inverter switches using a current controller.

5. Injecting compensating current into the grid to cancel out non-active components.

3.4.6 Advantages of ANFIS in This Work

- Capable of learning nonlinear relationships without explicit mathematical models.
- Adaptive to dynamic changes in load and grid conditions.
- Provides better compensation compared to classical PI controllers.
- Reduces Total Harmonic Distortion (THD) in grid currents.
- Fast response and better steady-state accuracy under varying conditions.

3.4.7 Validation

The effectiveness of the ANFIS controller is validated through simulation by comparing its performance with a conventional PI controller. Parameters such as Total Harmonic Distortion (THD), dynamic response, and steady-state performance are evaluated under different load scenarios. The ANFIS-based approach demonstrates improved power quality and compensation capability.

The inverter uses the control signal generated by ANFIS controller to inject the desired current into the grid, which consists of active power from the PV system and non-active current required for compensation. As a result, the grid only supplies clean sinusoidal current, achieving power factor correction, harmonic compensation, and grid code compliance. Finally, the system performance is evaluated in MATLAB/Simulink under various loading conditions, including nonlinear and unbalanced loads. Comparative analysis between PI and ANFIS controllers is conducted to validate the superiority of the proposed intelligent control scheme in terms of Total Harmonic Distortion (THD), dynamic response, and reactive power compensation.

3.5 Simulation and Performance Analysis

3.5.1 Simulation Setup

The system is simulated in MATLAB/Simulink using the following blocks:
- PV Array.
- Boost Converter.

- Three-Phase Inverter.
- ANFIS Controller.
- Grid and Load.

The proposed simulink model using traditional PI controller is shown in figure3.4

3.5.2 Performance Metrics

The performance of the system is evaluated based on:

Total Harmonic Distortion (THD): Level of harmonic distortion in the grid current.

Power Factor: Quality of power injection into the grid.

Dynamic Response: System response to changes in load and grid conditions.

3.5.3 Comparative Analysis

The performance of the proposed ANFIS-based system is compared with traditional PI controllers to highlight its advantages.

The methodology outlined above provides a comprehensive approach to designing and analyzing a dual-stage multifunctional PV inverter with ANFIS-based control for non-active current compensation. By following these steps, the proposed system is expected to achieve high efficiency, low THD, and improved grid stability, contributing to the advancement of renewable energy systems.

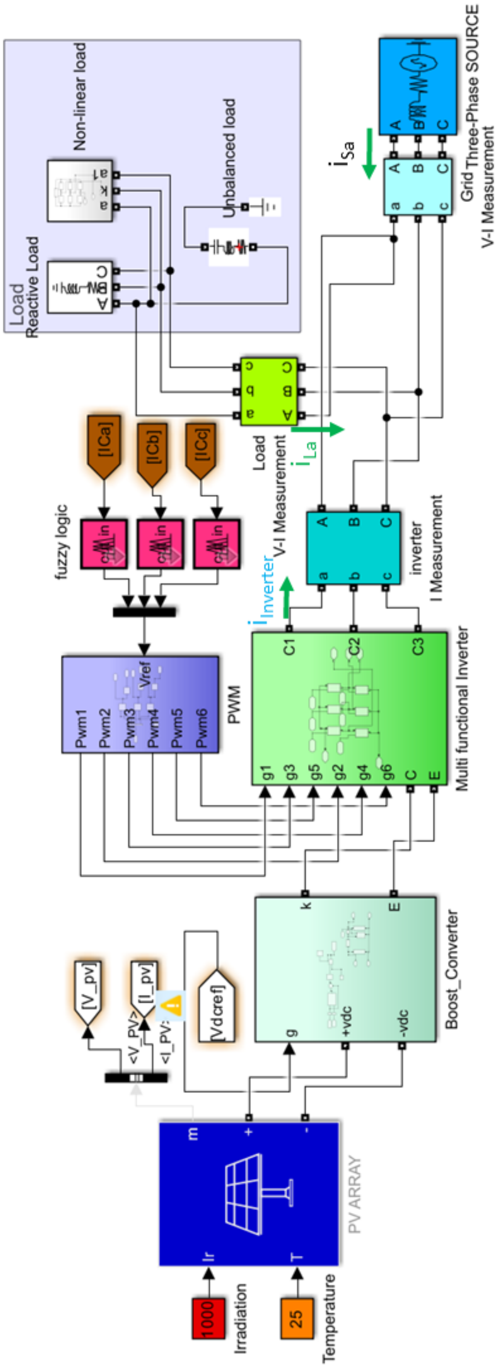


Figure 3.4: Proposed simulink model

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter presents the results obtained using the methodology described in Chapter 3.

4.1 Results

The proposed dual-stage multifunctional PV inverter with ANFIS-based control was simulated in MATLAB/Simulink. The system was tested under various operating conditions, including varying solar irradiance, nonlinear loads, and grid disturbances. The key simulation results are presented below.

PV Array Performance

The PV array was simulated under standard test conditions (STC) with an irradiance of 100,500 and 1000 W/m^2 and a temperature of 25°C. Figure 4.1 shows I-V and P-V characteristics of solar array.

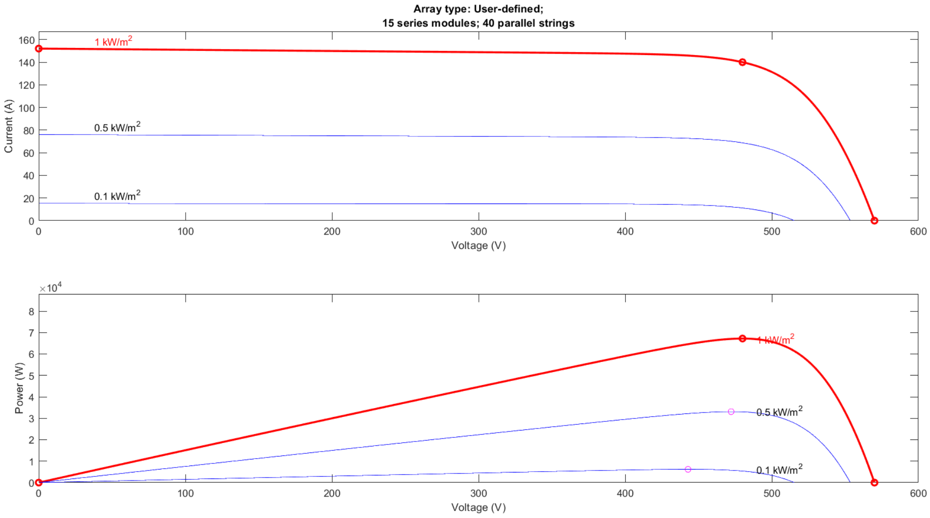


Figure 4.1: I-V and P-V characteristics of the PV array.

Reactive load

A balanced three-phase reactive load (RLC type) with an apparent power of 1.414 kVA was simulated. The active and reactive power components are 1 kW and 1 kVAR respectively. The voltage and current waveforms for this load are illustrated in Figure 4.2.
The current lags behind the voltage, which indicates inductive behavior. Without compensation, the grid must supply both active and reactive components, reducing power factor.

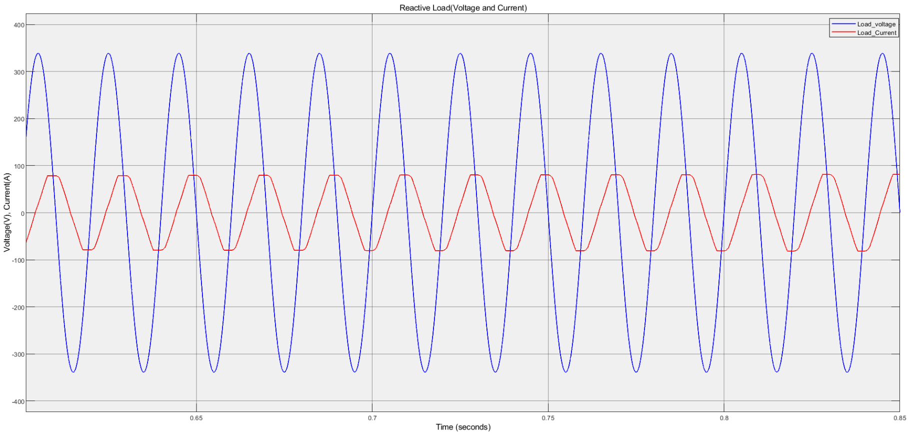


Figure 4.2: voltage and current waveform for reactive load

Non-Linear load

To emulate a typical industrial nonlinear load, a three-phase diode bridge rectifier with an RL load (R = 10ohm, L = 10mH) was modeled and the waveform of the load current is shown in the figure4.3. The harmonic distortion in the load current was analyzed using FFT, as shown in Figure 4.3.

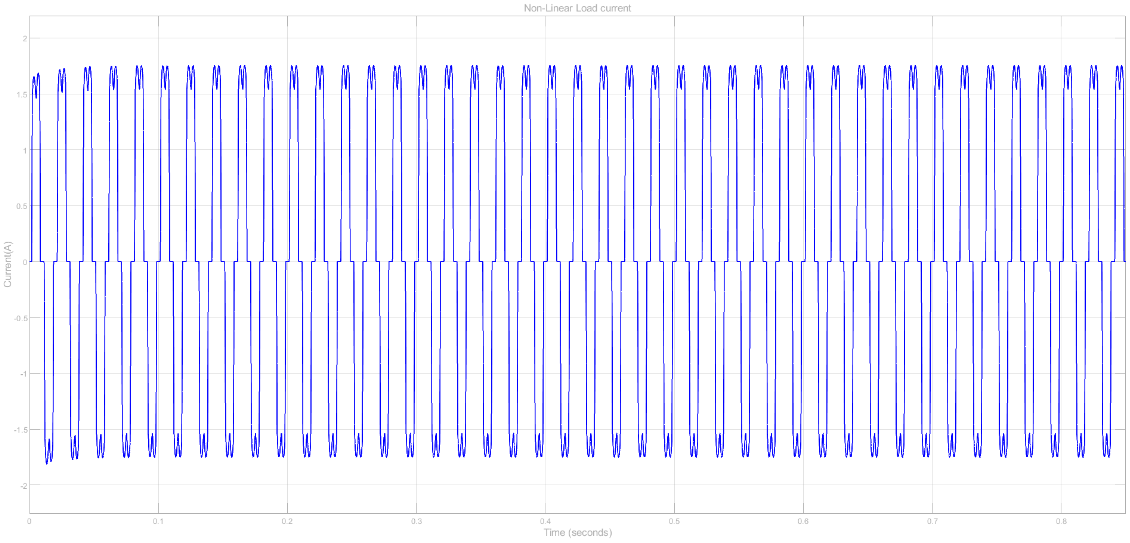


Figure 4.3: waveform for non-linear load current

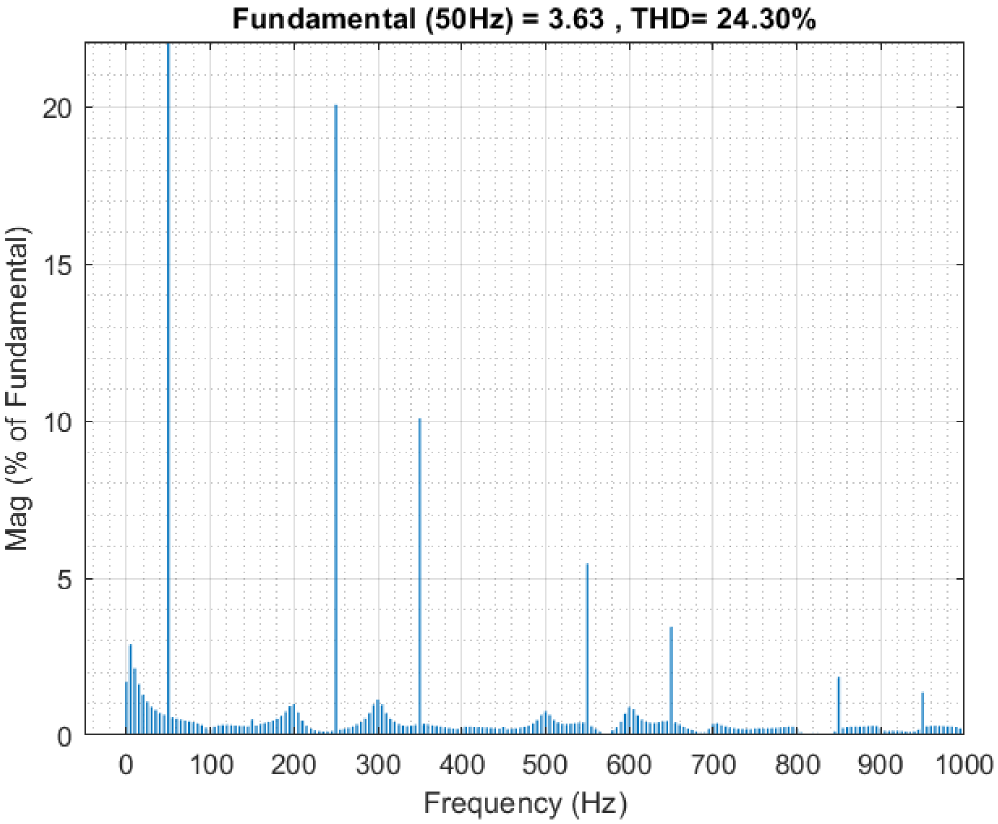


Figure 4.4: FFT waveform for non-linear load

It is evident that the dominant harmonic orders are the 5th, 7th, 11th, and 13th — all odd harmonics commonly associated with nonlinear rectifier loads. The peak magnitudes of these harmonics far exceed the permissible range as defined by IEEE 519. The THD value of 24.3% reaffirms the severity of harmonic pollution caused by the nonlinear load, which can lead to transformer heating, malfunction of sensitive equipment, and increased power losses. The dominant harmonic order is given by:
Dominant harmonic, h= 6n±1
So, dominant harmonics are 5th,7th,11th,13th and so on
5th= 20.08%
7th= 10.10%
11th= 5.45%
13th= 3.45%
17th= 1.85%
These values align with the typical harmonic signature of uncontrolled rectifier loads The details of different harmonics order are given along with the compensated harmonics details.

4.1.1 Inverter Performance

The proposed inverter was programmed to initiate non-active and active current injection at 0.7 seconds during the simulation. The comparative response of the load current, grid current, and inverter current is shown in Figure 4.4.
Before 0.7 s: Grid supplies both active and non-active currents.
After 0.7 s: The inverter compensates for the reactive and harmonic components as well as supply active power.
Grid current is substantially reduced, indicating effective current sharing and power quality improvement.

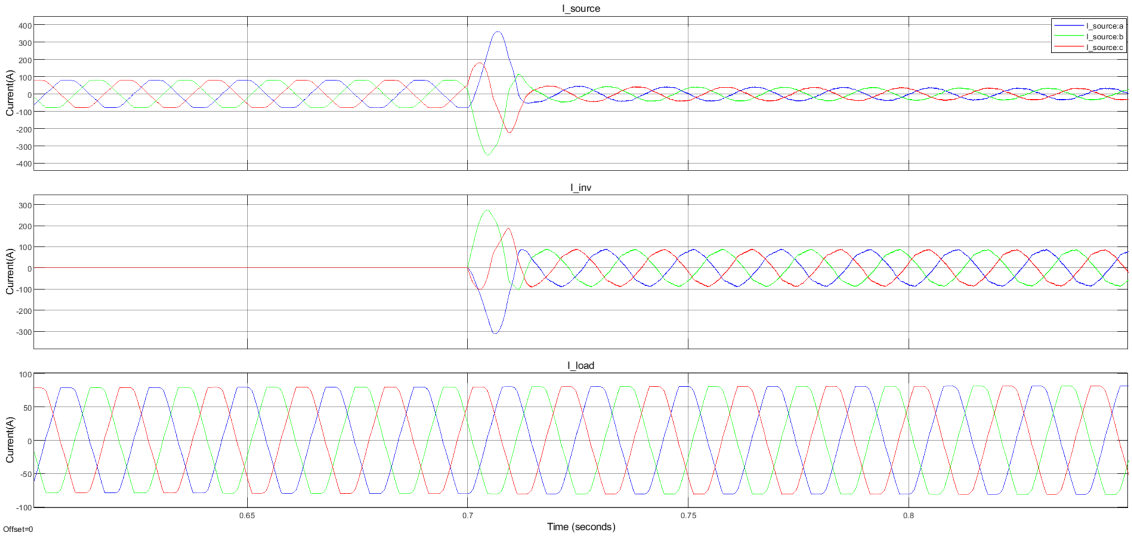


Figure 4.5: Load Source and Inverter current

Harmonic compensation

1.Grid Current Before Compensation

The simulation initially considers the condition where the multifunctional inverter (MFI) is inactive. Figure4.3 shows the grid current waveform under nonlinear load without compensation. The load used is a three-phase diode bridge rectifier with an RL load, which introduces severe harmonic distortion in the grid current. The waveform clearly deviates from a pure sinusoidal shape, exhibiting sharp peaks and notches characteristic of rectifier-induced distortion. The Total Harmonic Distortion (THD) measured using FFT analysis in this case is 24.3%, significantly exceeding the IEEE 519 standard limit of 5%. This condition justifies the need for an active compensation mechanism in grid-connected PV systems.

2.Grid Current After Compensation by MFI

In Figure 4.2, the grid current waveform is shown after activating the MFI at 0.7 seconds.

From this instant onward, the inverter begins injecting the compensating current, derived from the non-active component of the load current. As observed, the grid current transitions to a near-sinusoidal waveform, indicating successful mitigation of harmonic components.The reduction in peak magnitudes and smoothing of the waveform demonstrate the MFI's ability to suppress nonlinearity-induced distortions. The three-phase inverter converted the DC power to AC power with a THD of 4.31%, as shown in Figure 4.6. This result confirms the proper functioning of the reference current generation block based on IRPT and the capability of the inverter to follow the reference accurately.

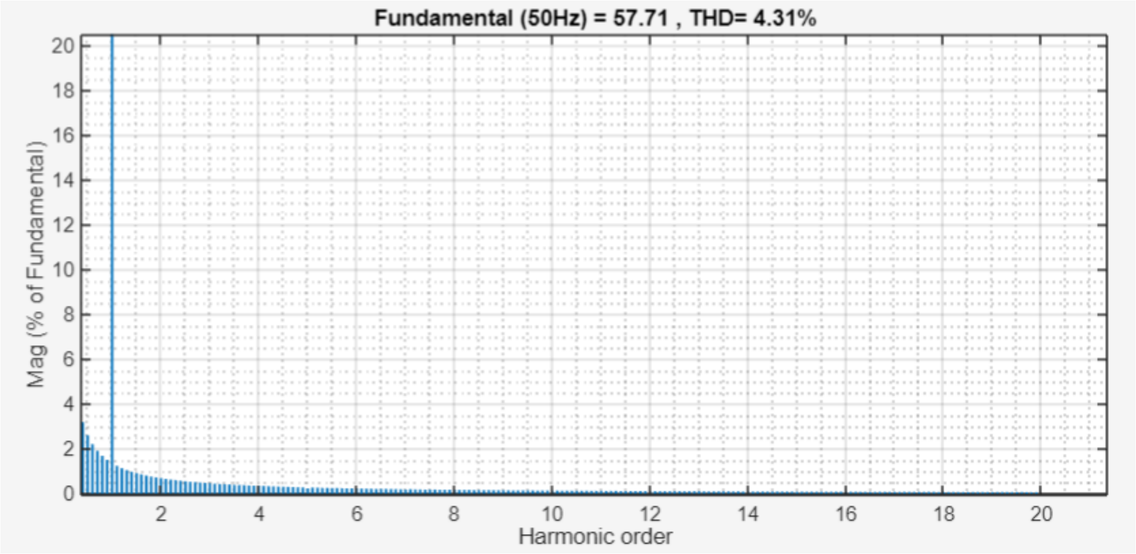


Figure 4.6: Grid current FFT of proposed system.

The non-active current compensation was achieved using the p-q theory. Figure4.7 shows the grid current before and after compensation. The THD was reduced from 24% to 4.31%.

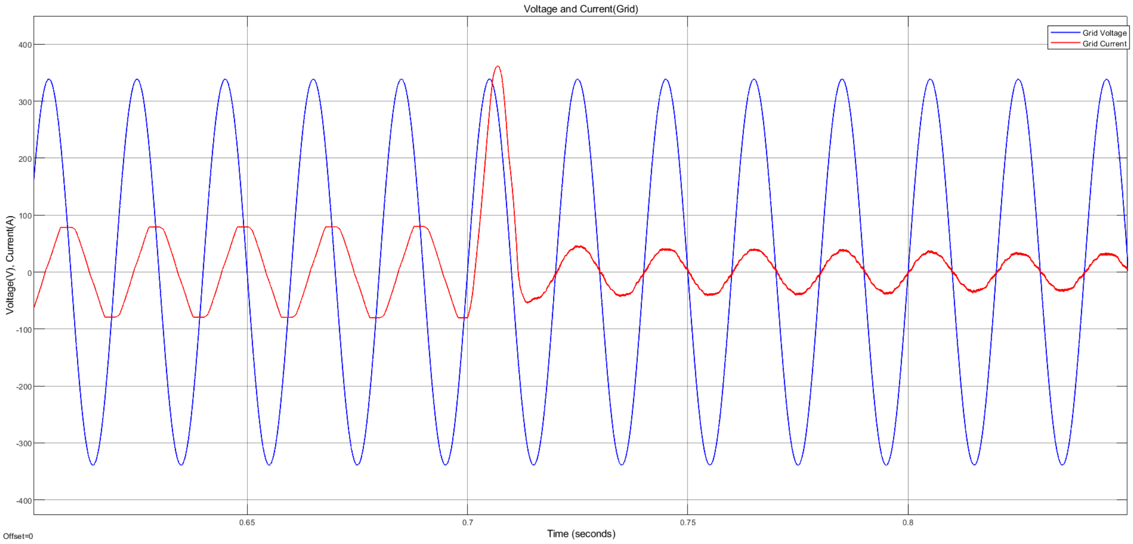


Figure 4.7: Grid current after compensation.

After the activation of the MFI, the FFT analysis in Figure 4.6 illustrates a marked reduction in harmonic content. The 5th and 7th harmonic amplitudes are significantly suppressed, and the overall THD is reduced to 4.31%, now well within IEEE 519 compliance. This validates the harmonic detection accuracy of the IRPT method and the tracking precision of the inverter controller. The waveform spectrum shows a dominant fundamental component and minimal distortion, confirming the effectiveness of the system.

Table 4.1 shows the dominant harmonics orders and their percentage in signal before and after compensation:

Table 4.1: Comparison of Harmonic Amplitudes Before and After Compensation

Harmonic Order	**Without Compensation (%)**	**With Compensation (%)**
5th Harmonic	20.08	0.62
7th Harmonic	10.10	0.42

Reactive Current compensation

Figure 4.7 presents the reactive power waveform of the grid before and after the MFI is activated. Prior to 0.7 seconds, the grid supplies both the active and reactive power components required by the nonlinear reactive load. After 0.7 seconds, the MFI begins to supply the reactive component, as indicated by the sharp decline in the grid current and the power factor is also boost up to unity value as shown in figure 4.8. This transition demonstrates the inverter's role in reactive power support, effectively relieving the grid of the burden. This operation ensures that the grid only supplies active power, thereby improving the power factor towards unity. The MFI's ability to supply reactive power in this way is crucial for maintaining voltage stability and minimizing system losses, particularly during inductive loading.

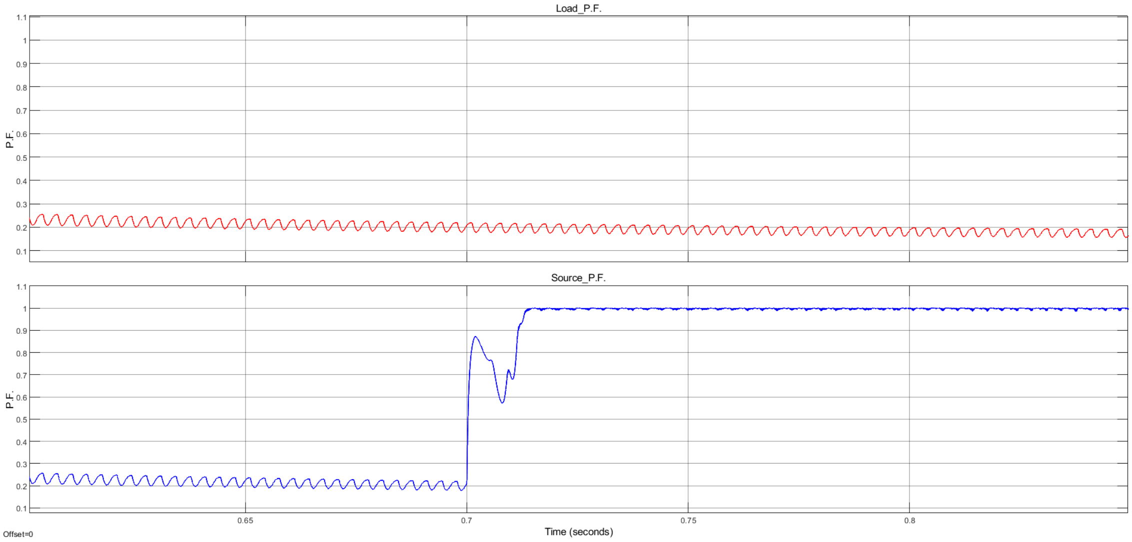


Figure 4.8: P.F. of load and Source current

4.1.2 ANFIS Controller Performance

The ANFIS controller demonstrated superior performance compared to traditional PI controllers. The controller achieved faster tracking time and lower overshoot.

All the results presented for harmonic and reactive current compensation are using ANFIS controller which is trained well and almost track the PI controller behaviour as shown in figure.4.9.

The ANFIS controller designed on the input and output of the PI controller using different irradiation and load values, tracks the PI controller behavior with the following error values:

Mean Square Error(MSE): 0.0001
Root Mean Square Error(RMSE): 0.010025
Mean Absolute Error(MAE): 0.008919

This error values are within the acceptable range, so ANFIS controller was well trained for varying load condition.

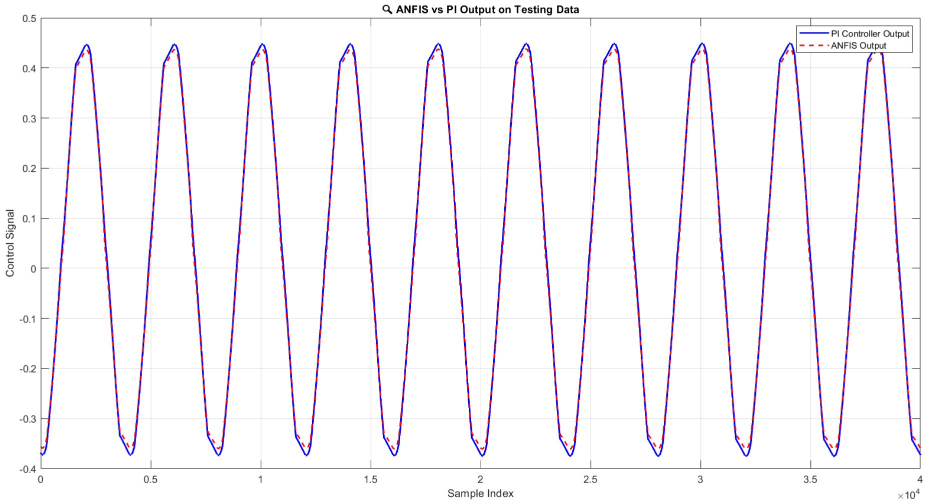


Figure 4.9: ANFIS vs PI plot on test data

4.1.3 Performance Comparison: ANFIS vs PI Controller

PI Controller Performance

The PI controller is designed using trial-and-error method for the given plant dynamics. The proportional gain (Kp = 0.0562) ensures an adequate response to error magnitude, while the integral gain (Ki = 0.141) eliminates steady-state error. However, as shown in Figure 4.11, the PI controller exhibits noticeable overshoot (538 A) in the grid current response. The system takes around 0.06 seconds to settle after a step disturbance at 0.7 seconds, and the current waveform shows visible oscillations before stabilizing. Furthermore, the FFT spectrum in Figure 4.13 reveals that the THD after PI-based compensation remains around 9.00%, which, although improved, does not meet the IEEE limit. This indicates that PI control is suboptimal in dynamic, nonlinear conditions where fixed gain controllers fail to adapt effectively.

ANFIS Controller Performance and Superiority

In contrast, Figure 4.10 shows the grid current waveform controlled by the ANFIS-based controller. The transition at 0.7 seconds is smooth, with low overshoot (338 A) and a very fast settling time of only 0.02 seconds. This improvement is a direct result of ANFIS's adaptive behavior, which learns from input-output patterns and adjusts the control signal dynamically. Unlike the fixed-gain PI controller, ANFIS adapts its rule base based on the system's real-time behavior. The FFT analysis shown in Figure 4.12 demonstrates a THD of 4.31% — the lowest among all cases. This not only meets but exceeds IEEE 519 compliance, making the system more robust under grid-code constraints.

The ANFIS controller receives the error as input and, through its trained fuzzy rule base, generates an optimized control output. The fuzzy rules and membership functions are fine-tuned using a hybrid learning approach (backpropagation + least squares), resulting in minimal steady-state error and fast transient response. The adaptive nature of ANFIS is particularly advantageous during load disturbances or when the non-active current characteristics change suddenly. This leads to higher compensation accuracy and power quality enhancement compared to the PI controller.

To evaluate the superiority of the ANFIS controller, its performance was compared with the conventional Proportional-Integral (PI) controller under identical operating conditions.

Dynamic Response

Figures 4.10 and 4.11 illustrate the grid voltage and current waveforms using the ANFIS and PI controllers, respectively.

Table 4.2: Dynamic Performance Comparison Between ANFIS and PI Controllers

Metric	**PI Controller**	**ANFIS Controller**	**Improvement**
Overshoot (A)	538.1	338.8	37.03% ↓
Settling Time (s)	0.06	0.02	66.67% ↓

As shown in Table 4.2, the ANFIS controller achieves a significantly faster response time and reduced current overshoot compared to the PI controller.

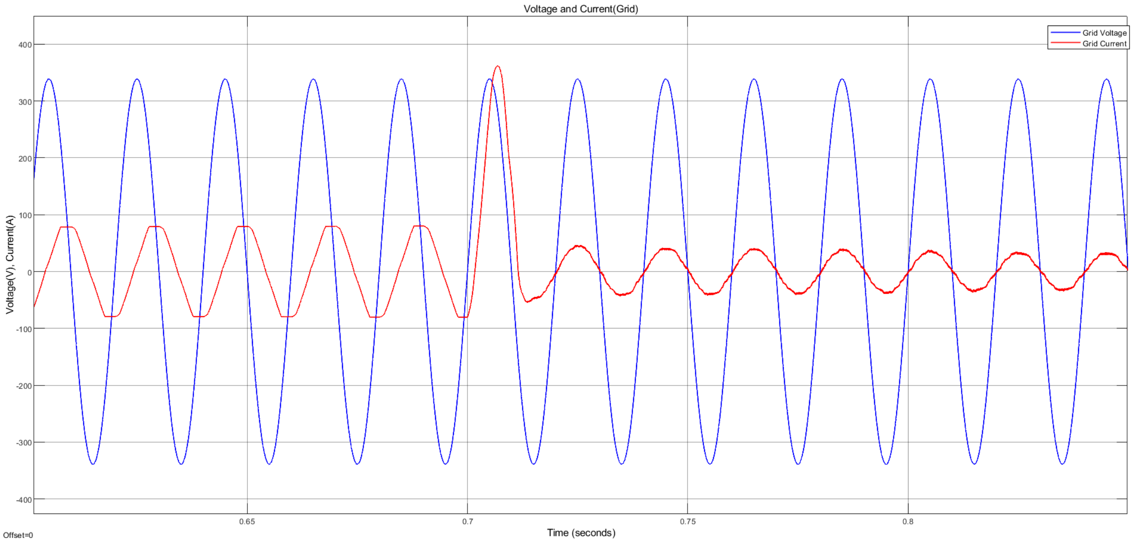


Figure 4.10: Grid voltage and current with ANFIS

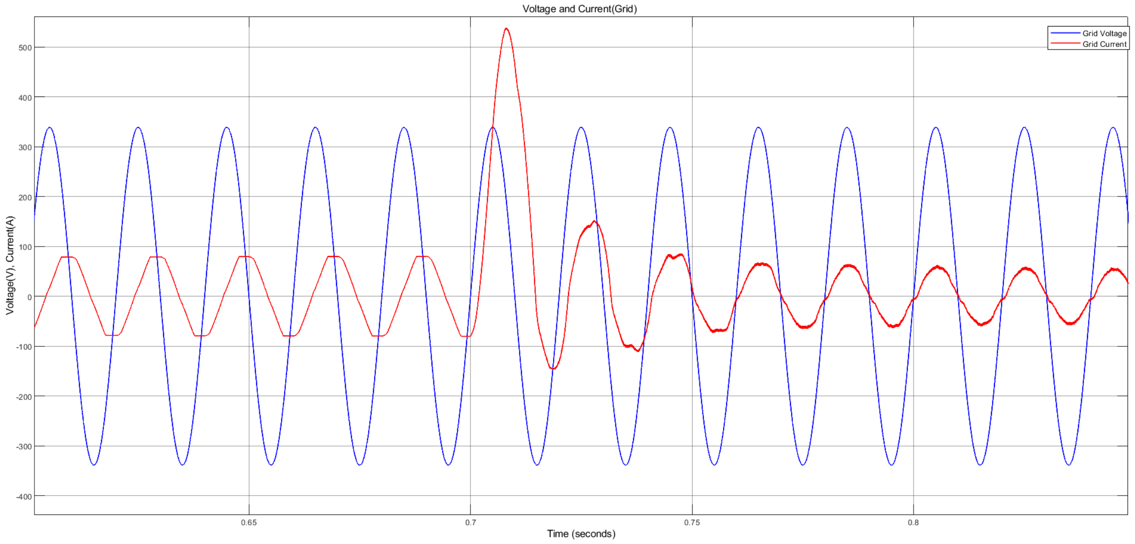


Figure 4.11: Grid voltage and current with PI

Harmonic Distortion Reduction

Figures 4.12 and 4.13 present the FFT spectra of grid current for the ANFIS and PI controllers, respectively. The Total Harmonic Distortion (THD) values are summarized below:

- THD using PI controller: **9.00%**
- THD using ANFIS controller: **4.31%**

The ANFIS controller achieves a **57.7% reduction** in THD compared to the PI controller, thereby significantly improving the harmonic profile of the grid current.

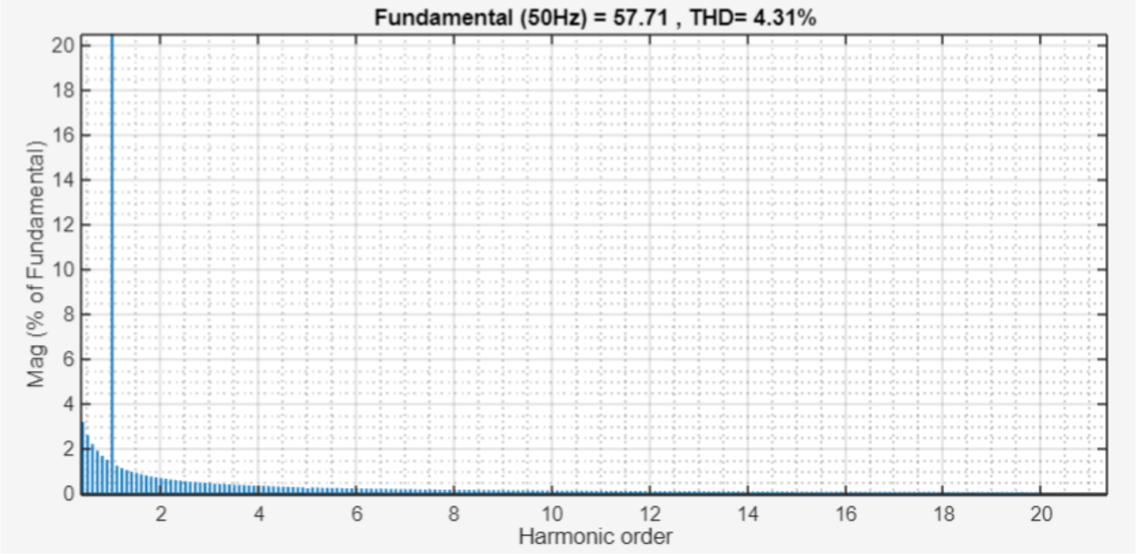


Figure 4.12: Grid FFT using ANFIS

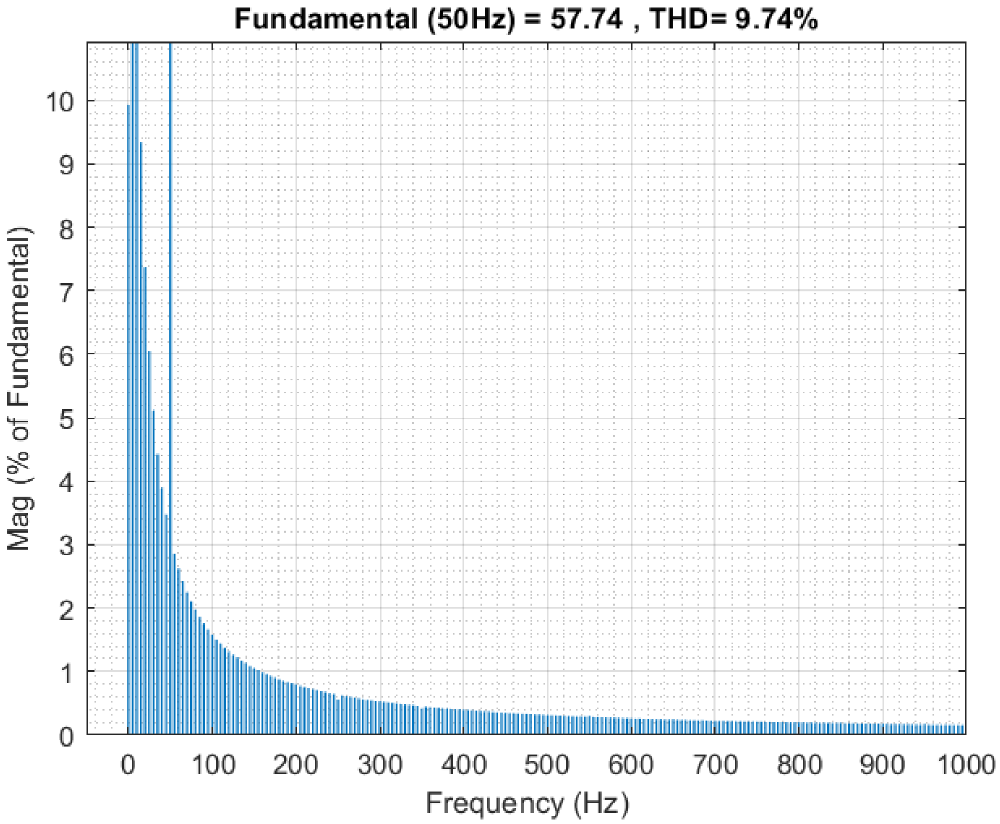


Figure 4.13: Grid FFT using PI

4.1.4 Summary of Results

Table 4.3 provides a concise summary of the system performance under three conditions: without compensation, with a PI controller, and with an ANFIS controller.

Table 4.3: Summary of System Performance Under Different Control Strategies

Parameter	**Without Compensation**	**With PI**	**With ANFIS**
Grid Current THD (%)	24.3	9.00	4.31
Power Factor (PF)	less than 1 (Lagging)	≈ 0.98	1.0 (Unity)
Overshoot (A)	–	538.1	338.8
Response Time (s)	–	0.06	0.02

The results confirm that the proposed ANFIS-based control strategy significantly improves power quality by reducing THD, ensuring unity power factor, and enhancing system dynamic response. These improvements make the proposed controller suitable for grid-connected PV systems operating under variable and nonlinear loading conditions.

4.2 Discussion

The simulation results demonstrate the effectiveness of the proposed dual-stage multifunctional PV inverter with ANFIS-based control. The PV array operated efficiently under standard test conditions. The algorithm demonstrated robustness under varying irradiance conditions. The DC-DC boost converter maintained a stable output voltage, ensuring reliable operation of the inverter. The converter exhibited high efficiency and fast response to load changes. The inverter achieved a THD of 4.31%. The inverter successfully injected active power into the grid while compensating for non-active currents, improving power quality.

The p-q theory-based compensation effectively reduced the THD from 24% to 4.31% and improved the power factor to unity. The compensation algorithm demonstrated high accuracy and robustness under nonlinear load conditions.

The proposed system achieved low THD, and unity power factor, making it suitable for grid-connected PV systems. The ANFIS-based control strategy demonstrated significant improvements in performance compared to traditional methods.

CHAPTER FIVE: CONCLUSIONS

5.1 Conclusions

The proposed dual-stage multifunctional PV inverter, employing ANFIS-based control for non-active current compensation, effectively compensates for non-active current. The system achieved a grid current THD of 4.31%, below IEEE standards. Unity power factor was maintained under nonlinear and reactive load conditions. The ANFIS controller demonstrated superior performance over PI, with 37.03% lower overshoot, 66.67% faster settling time, and 57.7% better harmonic mitigation. In conclusion, the proposed system offers a robust and efficient solution for integrating PV systems into the grid while addressing power quality issues caused by nonlinear and reactive loads. The results validate the effectiveness of the MFI in achieving low THD, unity power factor, and reliable operation.

5.2 Recommendations

Future work can focus on real-time implementation and further optimization of the control strategy for enhanced performance.

Hardware Implementation: Deploy the proposed control strategy in a real-time HIL setup.

Hybrid AI Controllers: Combine ANFIS with evolutionary optimization algorithms.

Scalability Studies: Extend the model to microgrids or hybrid renewable systems.

Fault Ride-Through Enhancement: Investigate grid support under voltage sag and swell.

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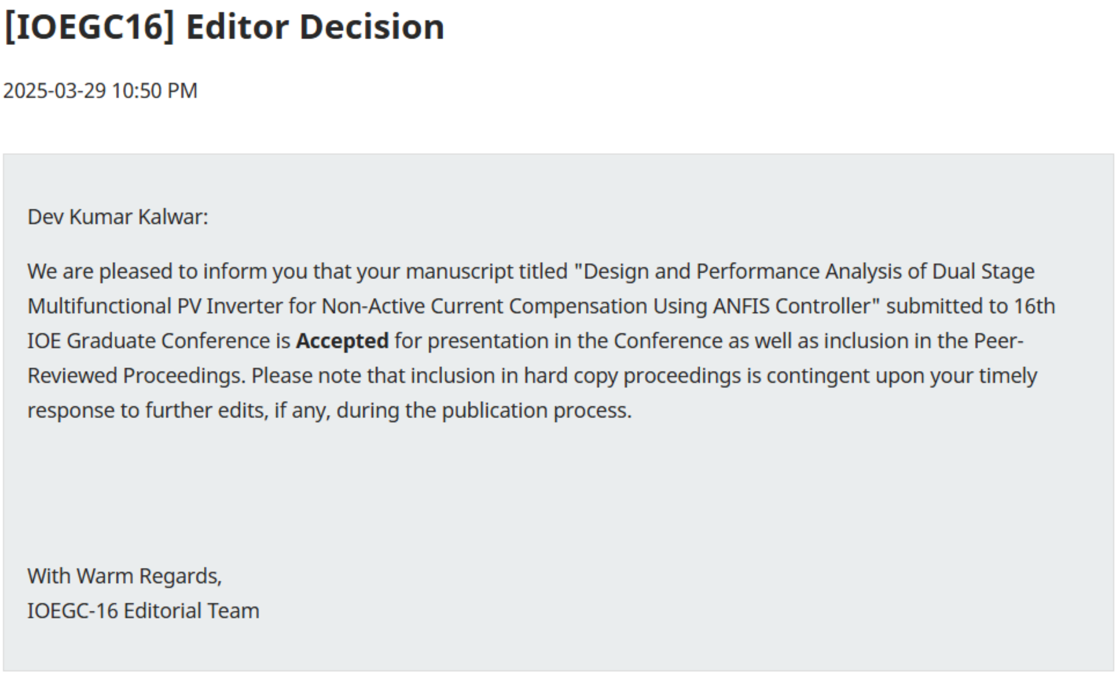
APPENDIX A: PUBLICATION

Conference paper



[IOEGC16] Editor Decision

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Dev Kumar Kalwar:

We are pleased to inform you that your manuscript titled "Design and Performance Analysis of Dual Stage Multifunctional PV Inverter for Non-Active Current Compensation Using ANFIS Controller" submitted to 16th IOE Graduate Conference is **Accepted** for presentation in the Conference as well as inclusion in the Peer-Reviewed Proceedings. Please note that inclusion in hard copy proceedings is contingent upon your timely response to further edits, if any, during the publication process.

With Warm Regards,
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Design and Performance Analysis of Dual Stage Multifunctional PV Inverter for Non-Active Current Compensation Using ANFIS Controller

Dev kumar kalwar [a], *Sujan Adhikari* [b], *Laxman Maharjan* [c], *Jeetendra Chaudhary* [d]

Abstract:

The increasing integration of renewable energy sources, particularly photovoltaic (PV) systems, into the power grid has highlighted the need for advanced inverters capable of not only injecting clean energy but also improving power quality. This thesis presents the design and performance analysis of a dual-stage multifunctional PV inverter that combines maximum power point tracking (MPPT), active power filtering (APF), and non-active current compensation using an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. The proposed system addresses the challenges of harmonic distortion, reactive power, and unbalanced currents caused by nonlinear and unbalanced loads in grid-connected PV systems. The dual-stage topology consists of a boost converter for MPPT and DC-link voltage regulation, followed by a three-phase voltage source inverter (VSI) for grid integration and power quality improvement. The Instantaneous Reactive Power Theory (IRPT) is employed to generate reference currents for non-active current compensation, while the ANFIS controller replaces traditional PI controllers to enhance dynamic performance and robustness. The system is designed to maintain a stable DC-link voltage of 750 V and inject 67.5 kW of PV power into the grid.

Simulation results demonstrate the effectiveness of the proposed system in compensating for harmonic, reactive, and unbalanced currents, achieving a total harmonic distortion (THD) of less than 5% and a power factor close to unity. The ANFIS controller outperforms conventional controllers in terms of response time and adaptability to varying load and grid conditions.This work contributes to the field of renewable energy integration by providing a comprehensive solution for power quality improvement in grid-connected PV systems. The proposed dual-stage multifunctional inverter, combined with advanced control strategies, offers a cost-effective and efficient approach to enhancing grid stability and power quality in the presence of nonlinear and unbalanced loads.

Keywords:

Multi-Functional Inverter, MPPT, ANFIS Controller,THD

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Design and Performance Analysis of Dual Stage Multifunctional PV Inverter for Non-Active Current Compensation Using ANFIS Controller

Dev kumar kalwar [a], Sujan Adhikari [b] Laxman Maharjan[c] Jeetendra Chaudhary [d]

[a b c d] *Department of Electrical Engineering, Pulchowk Campus*
[a] 079mspde008.dev@pcampus.edu.np

Abstract

The increasing integration of renewable energy sources, particularly photovoltaic (PV) systems, into the power grid has highlighted the need for advanced inverters capable of not only injecting clean energy but also improving power quality. This thesis presents the design and performance analysis of a dual-stage multifunctional PV inverter that combines maximum power point tracking (MPPT), active power filtering (APF), and non-active current compensation using an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. The proposed system addresses the challenges of harmonic distortion, reactive power, and unbalanced currents caused by nonlinear and unbalanced loads in grid-connected PV systems. The dual-stage topology consists of a boost converter for MPPT and DC-link voltage regulation, followed by a three-phase voltage source inverter (VSI) for grid integration and power quality improvement. The Instantaneous Reactive Power Theory (IRPT) is employed to generate reference currents for non-active current compensation, while the ANFIS controller replaces traditional PI controllers to enhance dynamic performance and robustness. The system is designed to maintain a stable DC-link voltage of 750 V and inject 67.5 kW of PV power into the grid.

Simulation results demonstrate the effectiveness of the proposed system in compensating for harmonic, reactive, and unbalanced currents, achieving a total harmonic distortion (THD) of less than 5% and a power factor close to unity. The ANFIS controller outperforms conventional controllers in terms of response time and adaptability to varying load and grid conditions.This work contributes to the field of renewable energy integration by providing a comprehensive solution for power quality improvement in grid-connected PV systems. The proposed dual-stage multifunctional inverter, combined with advanced control strategies, offers a cost-effective and efficient approach to enhancing grid stability and power quality in the presence of nonlinear and unbalanced loads.

Keywords
Multi-Functional Inverter, MPPT, ANFIS Controller,THD

1. Introduction

The increasing demand for energy worldwide and the pressing need to slow down climate change, it is now more important than ever to integrate renewable energy sources into the electrical grid. Photovoltaic (PV) systems have become a popular technology among these sources, providing a sustainable and clean substitute for traditional fossil fuel-based power generation. However, grid stability and power quality are seriously threatened by the sporadic nature of solar energy and the intrinsically non-linear features of PV systems. Significant power quality issues may arise when the number of distributed energy resources (DERs)[1] in the distribution network grows, especially at high penetration levels.

Reactive power fluctuations, harmonic current injection, and possible voltage imbalance are some of the new issues brought about by the extensive use of grid-connected PV inverters. These issues have the potential to impair grid performance and affect the dependability of other grid-connected devices. Advanced control techniques are necessary to resolve these problems and ensure smooth integration of PV systems while maintaining strict requirements of power quality. Multifunctional inverters (MFIs) are an affordable way to meet standard power quality requirements while optimizing the use of distributed energy resources (DERs)[1]. They offer auxiliary services as well as active electricity delivery[2].

There are two types of MFI topologies: single-stage and two-stage designs. Both single-stage and two-stage MFIs have benefits and drawbacks[3]. Figure 1(a) illustrates a single-stage MFI with a DC-AC stage, which reduces the number of electrical components, lowers costs, and increases efficiency. PV panels are connected directly to the DC bus of the grid-connected inverter using this approach. PV voltage is limited to a high value when a voltage-fed (buck-type) inverter, like the T-type three-level converter, is used[3]. This causes a high dc-bus voltage. A two-stage architecture, as seen in fig. 1(b), is preferred for the majority of MFI applications. This enables the voltage-fed dc-ac stage to be accommodated and the PV voltage to be raised by the front-end dc-dc stage. Two separate phases of implementation are possible for the multifunctional control aims. For instance, the active stage and the dc-dc stage both carry out maximum power point tracking (MPPT). Power injection and non-active current correction are provided via the DC-AC stage[4].

In order to compensate for non-active current, this project examine the design and operation of a dual-stage multifunctional PV inverter system using an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller[5]. By combining active power filtering and power generation into a single system, this novel technique improves grid stability and eliminates the need for independent power quality mitigation devices.

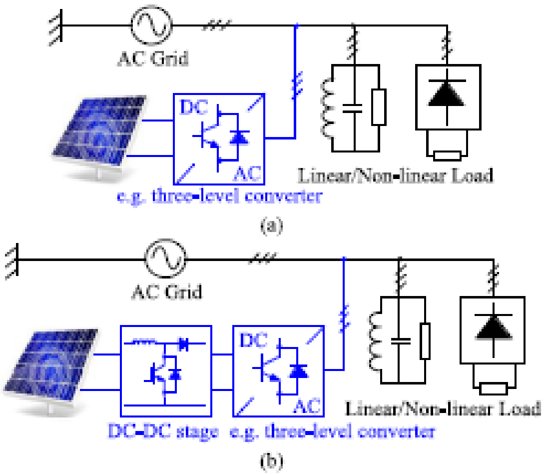


Figure 1: Conventional MFI architecture: (a) Single-stage, (b) Dual-stage.

1.1 ANFIS Controller

The **Adaptive Neuro-Fuzzy Inference System (ANFIS)** is a hybrid intelligent system that combines the learning ability of neural networks with the reasoning capabilities of fuzzy logic[2]. It is widely used in control systems, optimization, and decision-making due to its ability to handle **nonlinearities, uncertainties, and complex system dynamics**.

In power electronics and renewable energy systems, ANFIS-based controllers are increasingly used as an alternative to traditional Proportional-Integral (PI) and Proportional-Resonant (PR) controllers. Specifically, in grid-connected photovoltaic (PV) systems, ANFIS is employed for Maximum Power Point Tracking (MPPT) and non-active current compensation[6], enhancing system efficiency and power quality.

1.1.1 Fundamentals of ANFIS

ANFIS is based on **Takagi-Sugeno fuzzy inference systems** and employs a five-layer neural network structure to approximate complex nonlinear functions[5]. It consists of:

1. **Fuzzification Layer** – Converts crisp inputs into fuzzy values using **membership functions (MFs)**.
2. **Rule Layer** – Implements fuzzy IF-THEN rules, linking input variables to system output.
3. **Normalization Layer** – Normalizes the weight of each rule to ensure stability.
4. **Defuzzification Layer** – Computes the final output based on the weighted sum of fuzzy rules.
5. **Output Layer** – Produces the final crisp output, adjusting system parameters dynamically.

All the above function is shown in figure2

1.1.2 Comparison of ANFIS with Conventional Controllers

ANFIS controllers are highly effective in power electronics applications, particularly for MPPT in PV systems and non-active current compensation in grid-connected inverters. Their ability to learn and adapt to varying conditions makes them a powerful alternative to traditional controllers. By integrating neural networks and fuzzy logic, ANFIS enhances efficiency, stability, and power quality in modern renewable energy systems.

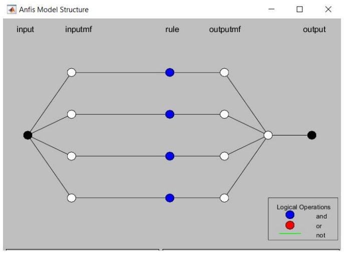


Figure 2: Anfis structure

Feature	PI Controller	Fuzzy Logic Controll
Adaptability	Fixed Gains	Adaptive to Nonlineari
Steady-State Error	High	Medium
Response Speed	Slow	Moderate
Computational Load	Low	Moderate
Power Quality Improvement	Limited	Moderate

Table 1: Comparison of ANFIS with Traditional Controllers

For grid-following operation, proportional-integral (PI) controllers are frequently used in conventional PV inverters. The dynamic and non-linear nature of PV systems and grid interactions, however, may provide challenges for PI controllers. They might react more slowly, manage active and reactive power less accurately, and be less resilient to grid disruptions including voltage swings and imbalanced situations. Furthermore, the usage of separate active power filters is required due to the standard PV inverters' lack of integrated power quality features, which raises the complexity and cost of the system[4].

Advanced control techniques are desperately needed to improve the multipurpose capabilities of PV inverters so they can actively support grid stability and reduce power quality problems in addition to producing clean power. By suggesting a dual-stage multipurpose PV inverter system with an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller, this study tackles this difficulty. ANFIS has several advantages over traditional controllers because of its capacity to manage non-linearity, adjust to shifting operating conditions, and learn from system behavior[5]. The suggested system seeks to address the shortcomings of current PV system architectures by including ANFIS control, which will enable quick and accurate active power supply, efficiently reduce harmonics and reactive power fluctuations, and improve overall grid stability.

2. Literature Review

The integration of photovoltaic (PV) systems into the grid has become a critical area of research due to the global shift toward renewable energy sources. However, the intermittent nature of solar energy and the presence of nonlinear and unbalanced loads in the grid pose significant challenges[6], such as harmonic distortion, reactive power demand, and voltage instability. To address these issues, researchers have proposed various control strategies, topologies, and intelligent techniques for PV inverters. This section provides a comprehensive review of the literature on PV systems, dual-stage inverters, non-active current compensation[7], and intelligent control techniques, with a focus on recent advancements and research gaps.

1.PV Systems and Maximum Power Point Tracking (MPPT) PV systems are the backbone of solar energy harvesting, but their efficiency is highly dependent on the ability to extract maximum power under varying environmental conditions, such as solar irradiance and temperature. Traditional MPPT techniques, such as Perturb and Observe (P&O) and Incremental Conductance (INC), have been widely used due to their simplicity and effectiveness. For instance,[7] provides detailed modeling of a PV array with parameters such as $V_{mp} = 460\,\text{V}$, $P_{mp} = 67.5\,\text{kW}$, and $I_{mp} = 146.7\,\text{A}$. These parameters are essential for designing an efficient PV system.

Recent advancements in MPPT techniques have focused on improving tracking accuracy and dynamic response under partial shading and rapidly changing environmental conditions. Artificial intelligence-based methods, such as fuzzy logic control (FLC) and neural networks, have shown promising results in overcoming the limitations of traditional methods. hybrid MPPT algorithm combining P&O and FLC, demonstrating superior performance in terms of convergence speed and steady-state accuracy proposed in [8].

2. Dual-Stage Power Conversion: Dual-stage power conversion systems, consisting of a DC-DC boost converter and a DC-AC inverter, are commonly used in grid-connected PV systems. The boost converter steps up the PV voltage and performs MPPT, while the inverter converts DC power to AC for grid integration.Paper[8] highlights the importance of a stable DC-link voltage (e.g., 750 V) for efficient inverter operation. The dual-stage topology ensures better voltage regulation, improved power quality, and enhanced system reliability compared to single-stage systems.

Recent studies have explored the use of advanced DC-DC converter topologies, such as interleaved boost converters and cascaded H-bridge converters, to reduce switching losses and improve efficiency. For instance, [3] proposes a dual-stage interleaved boost converter with a high-frequency transformer, achieving higher efficiency and power density compared to conventional designs.

3. Non-Active Current Compensation: Non-active currents, including harmonic, reactive, and unbalanced currents, degrade power quality and increase losses in the grid. The Instantaneous Reactive Power Theory (p-q Theory) is a widely used method for identifying and compensating for these currents.Paper [4] discusses the application of p-q theory in multifunctional inverters to achieve low total harmonic distortion (THD) and unity power factor. The theory decomposes the load current into active and non-active components, enabling precise compensation.

Recent research has focused on improving the accuracy and robustness of non-active current compensation techniques. Paper [4] proposes a modified p-q theory-based algorithm that accounts for grid voltage distortions, achieving better compensation performance under distorted grid conditions. Additionally, advanced filtering techniques, such as adaptive filters and wavelet transforms, have been integrated with p-q theory to enhance harmonic detection and compensation.

4. Multifunctional Inverters: Multifunctional inverters are designed to perform multiple tasks, such as active power injection, reactive power compensation, and harmonic filtering. These inverters enhance grid stability and power quality by addressing the issues caused by nonlinear and unbalanced loads. Paper [6] presents a comprehensive analysis of multifunctional inverters, emphasizing their role in improving the integration of renewable energy systems into the grid.

5.Intelligent Control Techniques: Traditional control methods, such as PI controllers, have limitations in handling the dynamic and nonlinear nature of PV systems and grid disturbances. Intelligent control techniques, such as fuzzy logic, neural networks, and Adaptive Neuro-Fuzzy Inference System (ANFIS), have been proposed to overcome these limitations.Paper [2] demonstrates the effectiveness of ANFIS controllers in non-active current compensation, highlighting their ability to adapt to varying operating conditions and provide superior performance compared to conventional methods.

Recent research has focused on optimizing the design and training of ANFIS controllers for PV systems. Paper [2] proposes a hybrid training algorithm combining particle swarm optimization (PSO) and gradient descent, achieving faster convergence and better accuracy in ANFIS-based MPPT and grid synchronization. Additionally, the integration of ANFIS with other intelligent techniques, such as genetic algorithms and reinforcement learning, has been explored to further enhance system performance.

6.Comparative Analysis: Several studies have compared the performance of traditional and intelligent control techniques in PV systems.Paper [5] compares PI and ANFIS controllers in terms of THD, power factor, and dynamic response. The results indicate that ANFIS controllers outperform PI controllers, especially under varying load and grid conditions.

7.Research Gaps: While significant progress has been made in the design and control of PV inverters, there is a need for further research on the integration of multifunctional inverters with intelligent control techniques. Key research gaps include:

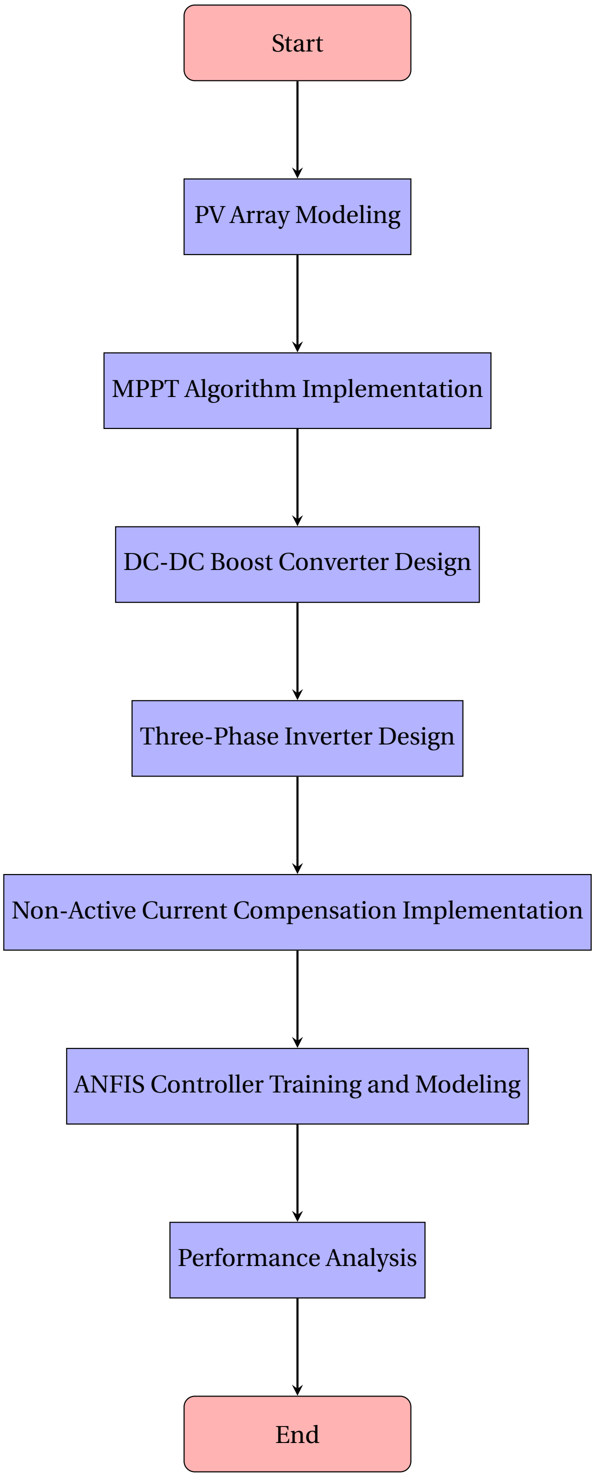
1.Optimization of ANFIS Controllers: Developing efficient training algorithms and rule bases for ANFIS controllers to improve their performance in non-active current compensation.
2.Hybrid Topologies: Exploring hybrid inverter topologies, such as MMC and cascaded H-bridge, to enhance efficiency and scalability.

3. *Grid Support Functions*: Integrating energy storage systems and advanced grid support functions, such as fault ride-through and voltage regulation, into multifunctional inverters.
4. *Real-Time Implementation:* Validating the proposed systems through real-time implementation and field testing under varying grid and load conditions.
This thesis aims to address these gaps by proposing a dual-stage multifunctional PV inverter with ANFIS-based control for non-active current compensation. The proposed system is expected to enhance power quality, improve grid stability, and provide a robust solution for the integration of PV systems into the grid.

The literature review highlights the importance of advanced control strategies, multifunctional inverters, and intelligent techniques in addressing the challenges associated with PV systems and grid integration. The proposed dual-stage multifunctional PV inverter with ANFIS-based control represents a significant contribution to the field, offering improved performance, reliability, and scalability compared to traditional methods. By addressing key research gaps, this thesis aims to advance the state-of-the-art in renewable energy systems and contribute to the global transition toward sustainable energy.

3. Methodology

The thesis will be conducted under the following methodology.



3.1 System Design and Modeling

3.1.1 PV Array Modeling

The PV array is modeled using the single-diode equivalent circuit,[7] which includes a current source, diode, series resistance (R_s), and shunt resistance (R_{sh}). The output current (I_{pv}) of the PV array is given by:

$$I_{pv} = I_{ph} - I_0 \left(\exp\left(\frac{V_{pv} + I_{pv} R_s}{a V_t} \right) - 1 \right) - \frac{V_{pv} + I_{pv} R_s}{R_{sh}}$$

where:
I_{ph}: Photocurrent.
I_0: Reverse saturation current.

V_{pv}: PV voltage.
a: Ideality factor.
V_t: Thermal voltage.

The PV array parameters are selected based on research paper[7]
$V_{mp} = 480\,\text{V}$,
$P_{mp} = 67.5\,\text{kW}$,
$I_{mp} = 146.7\,\text{A}$.
$V_{oc} = 500\,\text{V}$,
$I_{sc} = 150\,\text{A}$.

3.1.2 Load and Grid Modeling

The load is modeled as a combination of linear and nonlinear components to simulate real-world conditions. The grid is modeled as a three-phase voltage source with a nominal frequency of 50 Hz and a voltage of 400 V (line-to-line).

3.2 Maximum Power Point Tracking (MPPT)

3.2.1 MPPT Algorithm

The Perturb and Observe (P&O) algorithm is implemented for MPPT due to its simplicity and effectiveness.[7] The algorithm works by perturbing the PV voltage and observing the change in power:

$$\Delta P = P(k) - P(k-1)$$

If $\Delta P > 0$, the perturbation is continued in the same direction. If $\Delta P < 0$, the perturbation direction is reversed.

3.2.2 Boost Converter Design

A DC-DC boost converter is used to step up the voltage from the photovoltaic (PV) array to the required DC-link voltage. This converter operates using maximum power point tracking (MPPT) to ensure optimal power extraction from the PV array.

The design is based on the following given parameters:

- PV maximum power: $P_{\text{mp}} = 67.5$ kW
- PV MPP voltage: $V_{\text{mp}} = 480$ V
- PV MPP current: $I_{\text{mp}} = 147$ A
- Desired DC-link voltage: $V_{\text{dc}} = 650$ V
- Switching frequency: $f_{\text{sw}} = 10$ kHz

Duty Cycle Calculation The ideal duty cycle for the boost converter is given by:

$$D = 1 - \frac{V_{\text{in}}}{V_{\text{dc}}} \tag{1}$$

Inductor Selection The inductor is chosen to limit ripple in the inductor current. The ripple current is typically $10\% - 20\%$ of the input current:

$$\Delta I_L = 0.20 \times I_{\text{mp}} = 0.20 \times 147 = 28\text{ A} \tag{2}$$

The inductor value is calculated using:

$$L_b = \frac{V_{\text{in}} \cdot D}{\Delta I_L \cdot f_{\text{sw}}} \tag{3}$$

Output Capacitor Selection The output capacitor is chosen to limit the voltage ripple. For a ripple voltage of 5 V, the capacitor value is:

$$C_b = \frac{I_{\text{out}} \cdot D}{\Delta V_{\text{dc}} \cdot f_{\text{sw}}} \tag{4}$$

Switching Devices Selection The power switches must be rated above the maximum input current and voltage:

- MOSFET/IGBT: Rated at least 800 V and 200 A
- Diode: Rated at least 650 V and 120 A

This design provides a practical boost converter for a 67.5 kW PV system, ensuring stable operation with appropriate ripple limits. Further optimization can be done via simulation to refine component selection.

3.3 Dual-Stage Power Conversion

3.3.1 DC-Link Capacitor

A DC-link capacitor is used to stabilize the DC bus voltage and reduce ripple.[7]

The capacitor value is selected based on the power rating and switching frequency.

3.3.2 Three-Phase Inverter

A three-phase voltage source inverter (VSI) is used to convert DC power to AC for grid integration. The inverter operates at a switching frequency of 10 kHz and uses Sinusoidal Pulse Width Modulation (SPWM) for generating the gate signals.

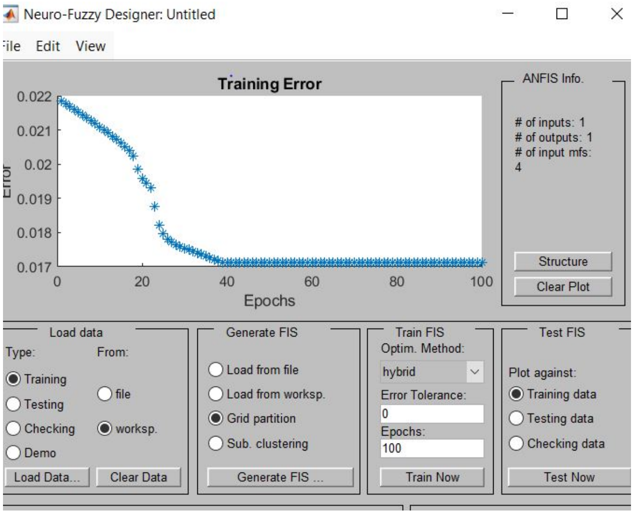
3.3.3 Development of the ANFIS Controller

The ANFIS controller at the heart of the control scheme learns from simulation data to adjust to the behavior of the system. Important actions consist of:

Data Collection: To replicate real-world situations, simulation data is collected under a variety of circumstances, including varying irradiance levels, load variations, and grid disruptions.

Training Procedure: The ANFIS model is trained to optimize its fuzzy rules and membership functions using a hybrid learning approach that combines gradient descent and least-squares estimation[5].

Integration of the Controller: After training, the ANFIS controller is integrated into the control loop of the inverter. It offers a strong reaction to shifting grid conditions by actively modifying its outputs to accommodate for reactive currents and harmonics. The input and output data from PI was exported to workspace and using ANFIS Tool Box data is trained as shown in figure 3.



\# of inputs: 1
\# of outputs: 1
\# of input mfs: 4

Type: ● Training ○ Testing ○ Checking ○ Demo

From: ○ file ● worksp.

○ Load from file
○ Load from worksp.
● Grid partition
○ Sub. clustering

Optim. Method: hybrid
Error Tolerance: 0
Epochs: 100

Plot against: ● Training data ○ Testing data ○ Checking data

Figure 3: Data training in ANFIS

3.4 Harmonic Detection and Compensation

The efficient isolation and correction of harmonic components is a crucial component of the design:

Signal Transformation: Park's transformation is used to turn measured three-phase voltage and current data into a d–q reference frame[8]. This makes it easier to accurately extract the harmonic and fundamental components. **Compensation Strategy**: To offset the observed harmonics, the system subsequently produces correcting signals. For practical use at the inverter output, these signals are transformed back into the three-phase domain via an inverse transformation[1].

Non-active currents are extracted using **Instantaneous Power Theory (p-q)** method[4]. The harmonic reference currents (i_h^*) are computed as:

$$i_h^* = i_{\text{load}} - i_{\text{fundamental}} \tag{5}$$

where $i_{\text{fundamental}}$ is derived from low-pass filtered grid currents.

Harmonic Reference Current Extraction Using Instantaneous Power Theory

The instantaneous power theory (p-q theory) is used to extract harmonic and reactive components from the grid current[4]. The steps are as follows:

Step 1: Transformation to $\alpha\beta$ Coordinates

The three-phase grid voltages (v_a, v_b, v_c) and currents (i_a, i_b, i_c) are transformed into the $\alpha\beta$ reference frame using the Clarke transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Step 2: Calculation of Instantaneous Power

The instantaneous real power (p) and imaginary power (q) are calculated as:

$$p = v_\alpha i_\alpha + v_\beta i_\beta$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha$$

Step 3: Separation of Harmonic and Fundamental Components

The instantaneous power (p) and imaginary power (q) can be decomposed into their average (DC) and oscillating (AC) components:

$$p = \overline{p} + \tilde{p}$$

$$q = \overline{q} + \tilde{q}$$

where:

- $\overline{p}$ and $\overline{q}$ are the average (fundamental) components.
- $\tilde{p}$ and $\tilde{q}$ are the oscillating (harmonic) components.

Step 4: Calculation of Harmonic Reference Currents

The harmonic reference currents in the $\alpha\beta$ frame are calculated as:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix}$$

Step 5: Transformation Back to abc Coordinates

The harmonic reference currents in the $\alpha\beta$ frame are transformed back to the abc frame using the inverse Clarke transformation:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix}$$

These reference currents (i_a^*, i_b^*, i_c^*) are used to compensate for the harmonic and reactive components in the grid current.

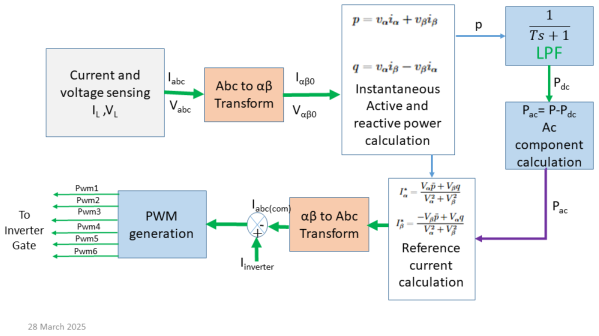


Figure 4: Non-Active current compensation using IRPT Method

3.5 Simulation Setup

The system is simulated in MATLAB/Simulink using the following blocks:

- PV Array.
- Boost Converter.
- Three-Phase Inverter.
- ANFIS Controller.
- Grid and Load.

The proposed simulink model using ANFIS controller is shown in figure5

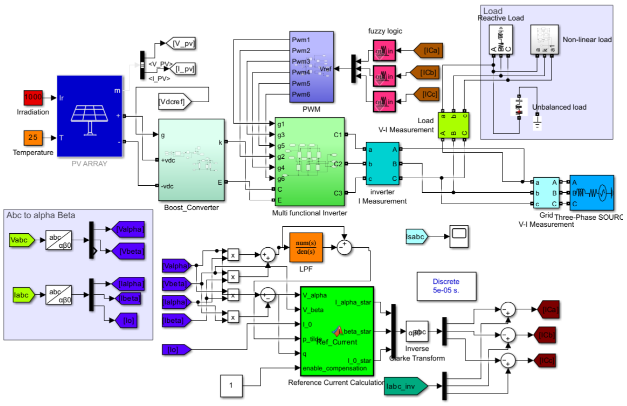


Figure 5: Simulink model of proposed ANFIS based MFII.

MATLAB/Simulink is used to model the complete system, including accurate models for: PV Array: 67.5 kW, 40 series × 15 parallel modules.

Control Parameters: Switching frequency: 10 kHz (DC-DC converter), 20 kHz (inverter).

ANFIS membership functions: 4 Gaussian functions per input. SPWM is used in a dual-stage inverter to provide accurate control.

4. Results & Discussion

4.1 Results

4.1.1 Simulation Results

The proposed dual-stage multifunctional PV inverter with ANFIS-based control was simulated in MATLAB/Simulink. The system was tested under various operating conditions, including varying solar irradiance, nonlinear loads, and grid disturbances. The key simulation results are presented below.

4.1.2 PV Array Performance

The PV array was simulated under standard test conditions (STC) with an irradiance of 1000 W/m^2 and a temperature of 25°C. Figure 6 shows I-V and P-V characteristics of solar array.

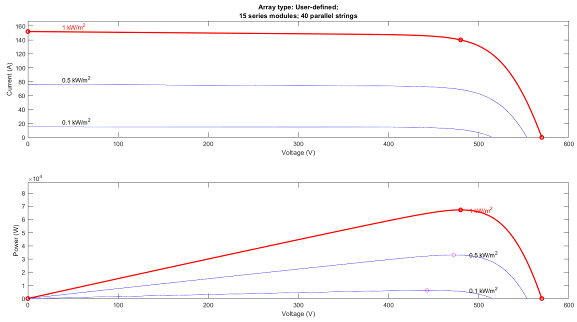


Figure 6: I-V and P-V characteristics of the PV array.

4.1.3 Reactive load

Three phase series RLC load is taken with 1.414kVA apparent power[7]. 1kW active and 1kVar reactive power. The current taken by the load is shown in figure. from the figure we can see that the reactive current is drawn by the laod.

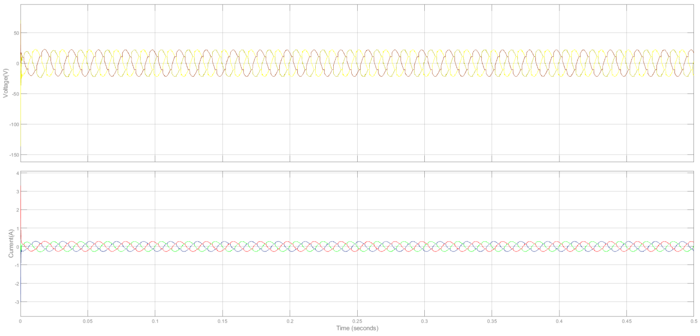


Figure 7: voltage and current waveform for reactive load

4.1.4 Harmonic load

three phase diode rectifier with RL load is connected to the Point of common coupling. the resistance and inductance values are 10 ohm and 10mH respectively. The non-linear load current waveform is shown in figure. the figure shows that before the compensation there are different oreder of harmonics present in current drawn by load.

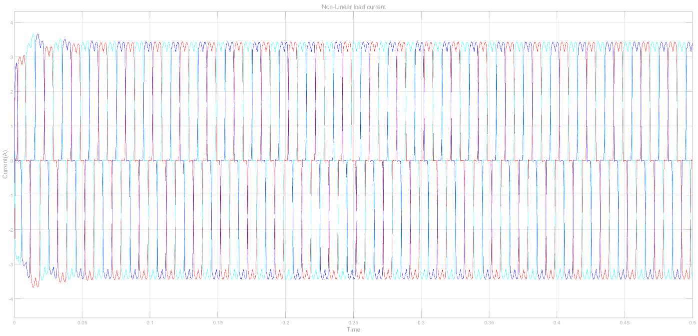


Figure 8: voltage and current waveform for non-linear load

Also the FFT analysis of non-linear load is done and waveform is shown in figure.

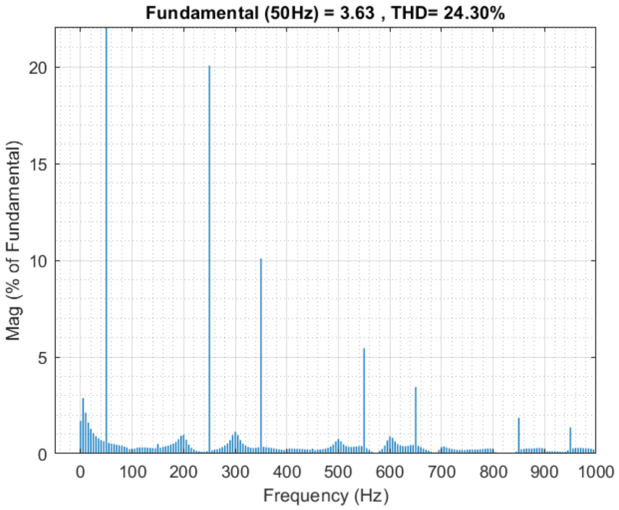


Figure 9: FFT waveform for non-linear load

from the FFT analyis before the compensation we can see that total harmonica distortion(THD) was 24.3% also the different harmonics orders were analysed and the dominant harmonic order is given by:
Dominant harmonic, h= 6n±1
So, dominant harmonics are 5th,7th,11th,13th and so on
5th=> 20.08%
7th=> 10.10%
11th=> 5.45%
13th=> 3.45%
17th=> 1.85%
The details of different harmonics order are given along with the compensated harmonics details.

4.1.5 Unbalance load

For the unbalance laod current injection into the grid from three phases of grid different power load were added to draw unbalanced load current as shown in figure below.

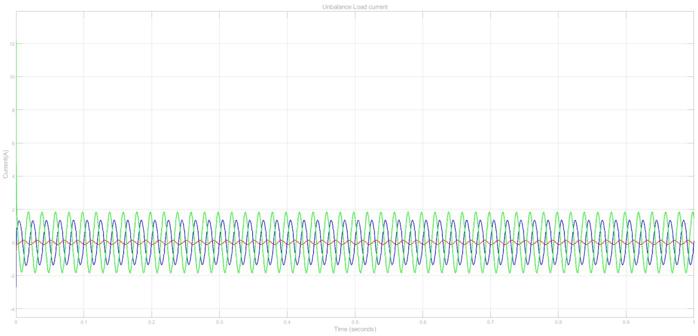


Figure 10: Unbalance load current

4.1.6 Inverter Performance

The three-phase inverter converted the DC power to AC power with a THD of 4.31%, as shown in Figure 12. The inverter successfully injected active power into the grid while compensating for non-active currents as shown in figure.

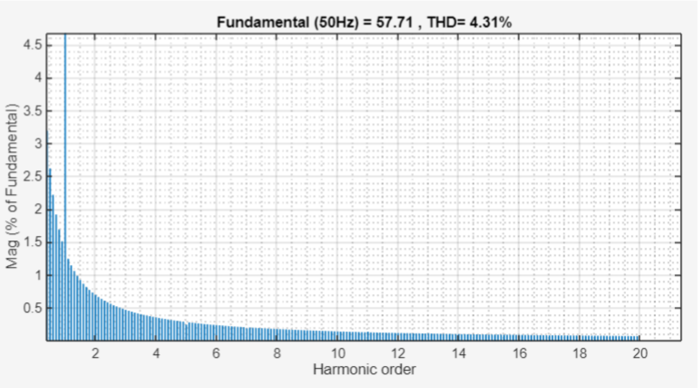


Figure 11: Grid current FFT after compensation(harmonic order).

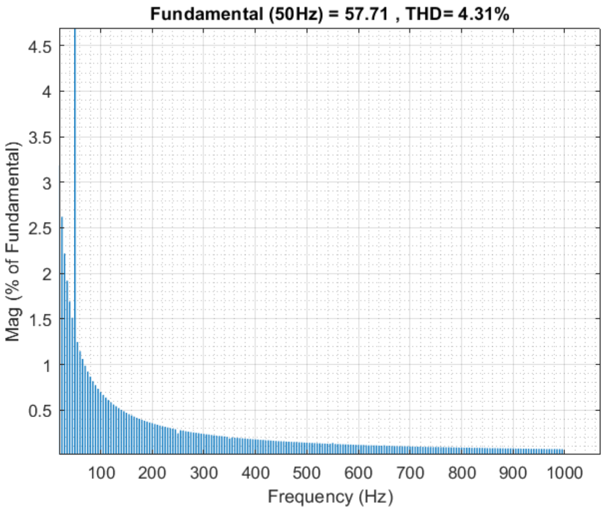


Figure 12: Grid current FFT after compensation(frequency).

4.1.7 Non-Active Current Compensation

The non-active current compensation was achieved using the p-q theory. Figure 13 shows the grid current before and after compensation. The THD was reduced from 25% to 4.31%.

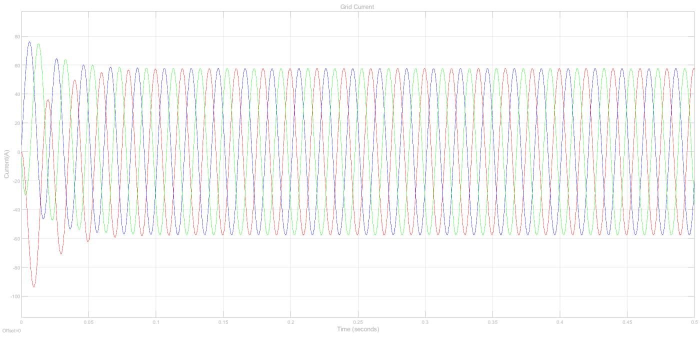
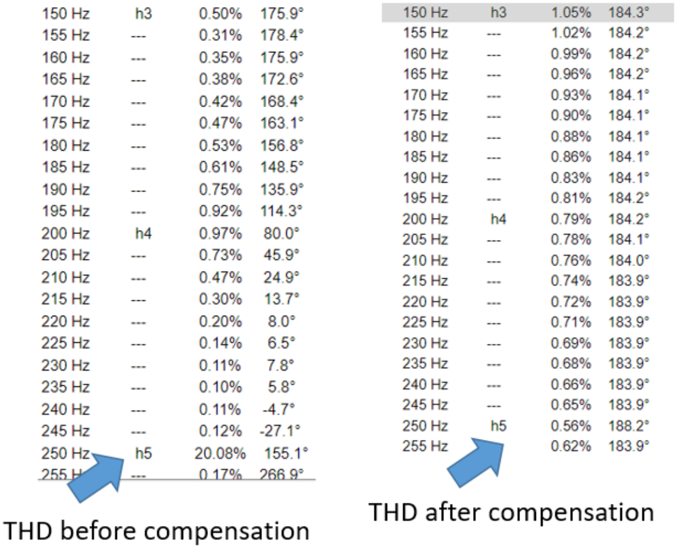


Figure 13: Grid current after compensation.

Figures14 & 15 shows the harmonics orders and their contribution before and after compensation:



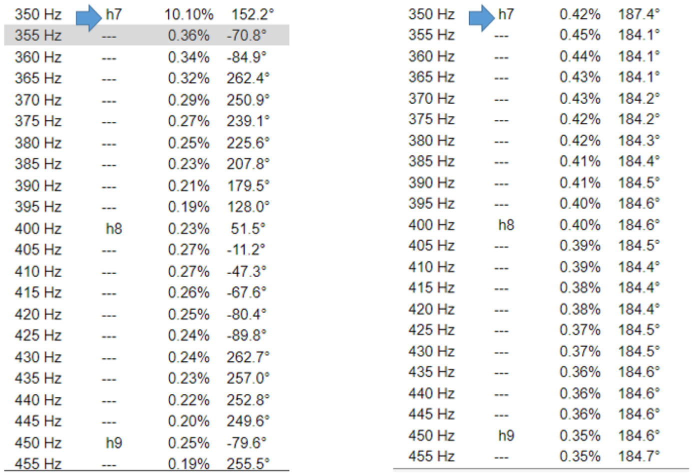
150 Hz	h3	0.50%	175.9°
155 Hz	---	0.31%	178.4°
160 Hz	---	0.35%	175.9°
165 Hz	---	0.38%	172.6°
170 Hz	---	0.42%	168.4°
175 Hz	---	0.47%	163.1°
180 Hz	---	0.53%	156.8°
185 Hz	---	0.61%	148.5°
190 Hz	---	0.75%	135.9°
195 Hz	---	0.92%	114.3°
200 Hz	h4	0.97%	80.0°
205 Hz	---	0.73%	45.9°
210 Hz	---	0.47%	24.9°
215 Hz	---	0.30%	13.7°
220 Hz	---	0.20%	8.0°
225 Hz	---	0.14%	6.5°
230 Hz	---	0.11%	7.8°
235 Hz	---	0.10%	5.8°
240 Hz	---	0.11%	-4.7°
245 Hz	---	0.12%	-27.1°
250 Hz	h5	20.08%	155.1°
255 H	---	0.17%	266.9°

THD before compensation

150 Hz	h3	1.05%	184.3°
155 Hz	---	1.02%	184.2°
160 Hz	---	0.99%	184.2°
165 Hz	---	0.96%	184.2°
170 Hz	---	0.93%	184.1°
175 Hz	---	0.90%	184.1°
180 Hz	---	0.88%	184.1°
185 Hz	---	0.86%	184.1°
190 Hz	---	0.83%	184.1°
195 Hz	---	0.81%	184.2°
200 Hz	h4	0.79%	184.2°
205 Hz	---	0.78%	184.1°
210 Hz	---	0.76%	184.0°
215 Hz	---	0.74%	183.9°
220 Hz	---	0.72%	183.9°
225 Hz	---	0.71%	183.9°
230 Hz	---	0.69%	183.9°
235 Hz	---	0.68%	183.9°
240 Hz	---	0.66%	183.9°
245 Hz	---	0.65%	183.9°
250 Hz	h5	0.56%	188.2°
255 Hz		0.62%	183.9°

THD after compensation

Figure 14: FFT before and after compensation.



350 Hz	h7	10.10%	152.2°
355 Hz	---	0.36%	-70.8°
360 Hz	---	0.34%	-84.9°
365 Hz	---	0.32%	262.4°
370 Hz	---	0.29%	250.9°
375 Hz	---	0.27%	239.1°
380 Hz	---	0.25%	225.6°
385 Hz	---	0.23%	207.8°
390 Hz	---	0.21%	179.5°
395 Hz	---	0.19%	128.0°
400 Hz	h8	0.23%	51.5°
405 Hz	---	0.27%	-11.2°
410 Hz	---	0.27%	-47.3°
415 Hz	---	0.26%	-67.6°
420 Hz	---	0.25%	-80.4°
425 Hz	---	0.24%	-89.8°
430 Hz	---	0.24%	262.7°
435 Hz	---	0.23%	257.0°
440 Hz	---	0.22%	252.8°
445 Hz	---	0.20%	249.6°
450 Hz	h9	0.25%	-79.6°
455 Hz	---	0.19%	255.5°

350 Hz	h7	0.42%	187.4°
355 Hz	---	0.45%	184.1°
360 Hz	---	0.44%	184.1°
365 Hz	---	0.43%	184.1°
370 Hz	---	0.43%	184.2°
375 Hz	---	0.42%	184.2°
380 Hz	---	0.42%	184.3°
385 Hz	---	0.41%	184.4°
390 Hz	---	0.41%	184.5°
395 Hz	---	0.40%	184.6°
400 Hz	h8	0.40%	184.6°
405 Hz	---	0.39%	184.5°
410 Hz	---	0.39%	184.4°
415 Hz	---	0.38%	184.4°
420 Hz	---	0.38%	184.4°
425 Hz	---	0.37%	184.5°
430 Hz	---	0.37%	184.5°
435 Hz	---	0.36%	184.6°
440 Hz	---	0.36%	184.6°
445 Hz	---	0.36%	184.6°
450 Hz	h9	0.35%	184.6°
455 Hz	---	0.35%	184.7°

Figure 15: FFT before and after compensation.

4.1.8 ANFIS Controller Performance

The ANFIS controller demonstrated superior performance compared to traditional PI controllers. The controller achieved faster settling time and lower overshoot.

4.2 Discussion

The simulation results demonstrate the effectiveness of the proposed dual-stage multifunctional PV inverter with ANFIS-based control. The inverter achieved a THD of 4.31%. The inverter successfully injected active power into the grid while compensating for non-active currents, improving power quality. The compensation algorithm demonstrated high accuracy and robustness under nonlinear load conditions. The proposed system achieved high efficiency, low THD, and better power factor, making it suitable for grid-connected PV systems. The ANFIS-based control strategy demonstrated significant improvements in performance compared to traditional methods.

5. Conclusions & Recommendations

The design and performance analysis of a dual-stage multifunctional PV inverter with ANFIS-based control for non-active current compensation have been successfully demonstrated. The key findings of this study are summarized as follows:

- The proposed system achieved a Total Harmonic Distortion (THD) of 4.31% under normal operating conditions, which is within acceptable limits for grid-connected systems as per IEEE standard.
- Under nonlinear load conditions, the THD was significantly higher at 24.4%, highlighting the adverse effects of nonlinear loads on power quality.
- The Multifunctional Inverter (MFI) effectively compensated for non-active currents, as evidenced by the sinusoidal waveform of the grid current after compensation. This demonstrates the capability of the MFI to improve power quality and ensure compliance with grid standards.

In conclusion, the proposed system offers a robust and efficient solution for integrating PV systems into the grid while addressing power quality issues caused by nonlinear and unbalanced loads. The results validate the effectiveness of the MFI in achieving low THD, good power factor, and reliable operation. Future work can focus on real-time implementation and further optimization of the control strategy for enhanced performance.

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