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CHAPTER 1

INTRODUCTION

1.1 Introduction

Power electronics is an electrical engineering discipline that involves the efficient conversion and conditioning of electric power using semiconductor devices. The combination of power engineering and electronics enables the implementation of energy conversion techniques in electrical machines [1][2]. Contemporary power electronic circuits employ switching devices including diodes, MOSFETs, IGBTs, and thyristors to perform high-speed switching operations.

Industrial automation, renewable energy, electric vehicles, battery chargers, and switched mode power supplies are among the technologies where power electronics plays a significant role. The efficient power conversion process is important to provide clean power sources in order to operate these technologies in a better manner. Therefore, there is a greater need to design and implement power electronic systems for modern applications [3].

According to the operation mode and type of input/output signals, power electronic converters can be classified into four types namely, AC-DC rectifiers, DC-DC converters, DC-AC inverters, and AC-AC converters[6]. Out of these, DC-DC converters play a very significant role for voltage regulating and power conditioning purpose in low- and medium-power systems. Boost converter is one such DC-DC converter that helps in stepping up the input voltage[4][5].

Modern power electronic circuits often encounter nonlinear electronic loads resulting in major power quality issues like harmonic distortion, poor power factor, and voltage fluctuations in the electrical power system. Power Quality (PQ) issues are minimized by implementing PFC and other intelligent control techniques. ANFIS-based controller is one such technique, which is superior to conventional controllers in terms of its dynamic performance and robustness[7].

In conclusion, power electronics is a vital field that needs to be explored to provide efficient, reliable, and intelligent power conversion systems.

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1.2 Need for Power Factor Correction (PFC)

Today in the world of electronics there is an increase in the usage of switched mode power supplies, battery chargers, speed drives for computers, and industry converters that consume non-sinusoidal current from the source. These devices create harmonic distortions that decrease the power factor of the system. Low power factor is responsible for power loss, poor regulation of voltages, overheating of electric circuits, and inefficiency of power transmission[8][9].

Power factor can be described as a ratio between real power of the load and the apparent power provided by the source. It is desirable that power factor be near unity, but in practice, power factor is poor due to the effect of harmonics. Therefore, higher power demands from the source will occur, along with losses during transmission and increase in the ratings of cables, transformers, and switchgear.

Several methods for power factor correction exist and aim at reducing harmonic distortions. The process of improving the system power factor by changing the input voltage waveform into sinusoidal current waveforms is called Power Factor Correction (PFC)[10]. PFC improves system performance, minimizes harmonics and THD, increases the efficiency of a power distribution network and ensures compliance with international standards such as IEC 61000-3-2.

There are several types of PFC techniques available, but boost converters have advantages such as simplicity, constant input current, high efficiency, and reduction of harmonics. Control schemes including PID and ANFIS algorithms can be employed to increase dynamic performance and stability of PFC converters[11][12].

As a result, Power Factor Correction became necessary in all advanced power electronic systems. As a result, Power Factor Correction became necessary in all advanced power electronic systems.

1.3 Role of DC-DC Converter

A DC-DC converter is an electric circuit that converts a fixed or variable DC input voltage to a controlled DC output voltage. DC-DC converters are useful in modern-day electronic or electrical systems that need various levels of voltages for efficient loading or functioning of a device. The DC-DC converters produce regulated voltage output at high efficiencies with small sizes and fast response.

Based on the specific requirements, a DC-DC converter may increase (boosting converters), decrease (buck converters), and even invert (buck-boost converters) the input DC voltage. Besides, there are other types of converters including Cuk and Flyback converters which offer more options in terms of output voltage. For example, a boost converter produces output voltage higher than the input voltage.

DC-DC converters have diverse applications from solar and fuel cells to electric vehicles and switched mode power supplies. In renewable energy sources like PV solar panel systems and fuel cells, DC-DC converters are applied for maximum power extraction. Furthermore, in the case of electric vehicles, DC-DC converters help manage and distribute the battery power effectively.

Some of the main strengths of DC-DC converters include their efficiencies, which are made possible by the semiconductor switches that operate at very high frequencies. Operating at high frequencies enables DC-DC converters to be smaller in size because of reduced sizes of inductors and capacitors[15]. Moreover, with modern-day controls, these converters become more efficient.

With regard to PFC applications, DC-DC converters ensure that regulated DC output voltage is maintained as well as the input current waveform shaped to have a higher power factor and minimal harmonics. Overall, DC-DC converters play crucial roles in power electronics.

1.4 Boost Converter Fundamentals

A boost converter is a type of DC–DC power electronic converter that increases or “boosts” the input DC voltage to a higher output DC voltage. It is one of the most widely used converter topologies in modern power electronic applications due to its simple structure, high efficiency, and ability to provide regulated output voltage. The basic components of a boost converter include an inductor, power switch, diode, output capacitor, and load resistance [14][16].

The working of a boost converter is based on the principle of energy storage and transfer through the inductor. When the power switch is turned ON, the inductor stores energy from the input source in the form of magnetic energy. During this interval, the diode becomes reverse biased, and the load is supplied by the output capacitor [17][18]. When the switch is turned OFF, the energy stored in the inductor is released

to the load through the diode, resulting in an output voltage greater than the input voltage [19].

The output voltage of the boost converter depends on the duty cycle of the switching signal. The duty cycle is defined as the ratio of ON time of the switch to the total switching period [20]. By controlling the duty cycle, the output voltage can be regulated according to the load requirements. Under ideal conditions, the output voltage relation of a boost converter is given by:

$$V_o = \frac{V_{in}}{1-D} \quad (1.1)$$

where V_o is the output voltage, V_{in} is the input voltage, and D is the duty cycle.

Boost converters operate in different conduction modes such as Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM), and Critical Conduction Mode (CrCM), depending on the inductor current behaviour [21]. As it provides high voltage gain and continuous input current, boost converters are widely used in Power Factor Correction (PFC), renewable energy systems, electric vehicles, and switched-mode power supplies [22].

1.5 Power Quality Issues and Harmonics

Power quality refers to the ability of an electrical power system to provide a stable sinusoidal voltage and current waveform at the rated frequency and magnitude [23]. Good power quality is essential for the reliable and efficient operation of electrical and electronic equipment [24]. However, the rapid growth of nonlinear loads such as switched-mode power supplies, rectifiers, variable speed drives, computers, and power electronic converters has introduced significant power quality problems in modern power systems.

One of the major power quality issues is harmonic distortion. Harmonics are unwanted frequency components present in voltage or current waveforms that are integer multiples of the fundamental frequency. Nonlinear loads draw non-sinusoidal current from the supply, causing distortion in the input current waveform. These harmonics increase power losses in transmission lines, transformers, and electrical machines, leading to overheating and reduced system efficiency.

Harmonic distortion also affects the performance of sensitive electronic equipment by

causing voltage fluctuations, electromagnetic interference, malfunction of protective devices, and inaccurate operation of measuring instruments. In industrial systems, poor power quality can reduce equipment lifespan and increase maintenance costs. Excessive harmonics may also lead to resonance problems in power systems.

The quality of power is commonly evaluated using Total Harmonic Distortion (THD), which measures the amount of harmonic content present in the waveform. Lower THD values indicate better power quality and improved system performance. The THD expression is given by:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2}}{I_1} \times 100\% \quad (1.2)$$

where I_1 is the fundamental current component and $I_2, I_3, \dots, I_n$ are harmonic current components.

To overcome these problems, Power Factor Correction (PFC) techniques and advanced control methods are employed in power electronic converters. These techniques help in reducing harmonic distortion, improving power factor, and maintaining better power quality in electrical systems.

1.6 Importance of PFC Boost Converter

The PFC Boost Converter is a type of power electronics converter that is extensively applied to improve the quality of electricity and increase the value of the power factor of AC - DC converters. The increase in the number of non-linear loads such as computers, chargers, motor drives, and electrical appliances leads to the problem of THD (Total Harmonic Distortion) and poor values of power factors, which is why the development of new technology became necessary. The PFC boost converter is capable of providing near-unity power factor and minimizing the THD by making the input current waveform equal to the input voltage waveform [25][26].

Boost converters are preferable to be used in Power Factor Correction applications due to several reasons. First, a boost converter can provide continuous input current. Second, it is characterized by high efficiency [27][28]. Third, a boost converter has a fairly simple design. Fourth, a boost converter can significantly change the output voltage. Therefore, the PFC boost converter allows shaping the waveform of the current that goes into the input of the boost converter. Thus, the output voltage can be

controlled, while there will also be some regulation of the input current.

As for benefits, a PFC boost converter is able to greatly reduce the total harmonic distortion and comply with all requirements of international standards such as the IEC 61000-3-2. Besides, an increased power factor helps to decrease the consumption of the reactive power and the losses during electricity transmission as well as avoid the problem of voltage drops [29][30]. Moreover, it helps to improve the efficiency of electrical devices.

Applications of PFC boost converters include such spheres as switched-mode power supplies, electric vehicle charging stations, renewable energy systems, LED lights, telecommunication devices, and industrial power supplies. However, PFC boost converter's performance significantly depends on the control algorithm. Although conventional PID controllers can perform adequately, they tend to have slow dynamic response when conditions vary. For this reason, intelligent ANFIS (Adaptive Neuro-Fuzzy Inference System) algorithms work better [31]. Applications of PFC boost converters include such spheres as SMPS, EV charging stations, renewable energy systems, LED lights, telecommunication devices, and industrial power supplies. However, PFC boost converter's performance significantly depends on the control algorithm. Although conventional PID controllers can perform adequately, they tend to have slow dynamic response when conditions vary. For this reason, intelligent ANFIS (Adaptive Neuro-Fuzzy Inference System) algorithms work better [32].

1.7 Literature Review

Several research studies have been carried out on Power Factor Correction (PFC) boost converters to improve power quality, reduce harmonic distortion, and enhance converter efficiency. Conventional PFC boost converters mainly use linear control techniques such as Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers for voltage regulation and current shaping. These controllers provide simple implementation and satisfactory steady-state performance, but their dynamic response may degrade under nonlinear load and parameter variations.

Researchers have proposed different control strategies to improve the performance of PFC converters. Average current control, hysteresis current control, sliding mode control, and predictive control methods have been widely investigated for achieving

low Total Harmonic Distortion (THD) and high power factor. Among these methods, dual-loop control structures consisting of an outer voltage loop and inner current loop are commonly used in PFC applications due to their better stability and regulation capability [33].

Recently, intelligent control techniques such as Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS) have gained significant attention. ANFIS combines the learning capability of neural networks with the reasoning capability of fuzzy systems, resulting in improved dynamic response, robustness, and adaptability. Various studies have reported that ANFIS-controlled PFC boost converters achieve lower THD, faster settling time, and improved power factor compared to conventional PID controllers under varying operating conditions [36].

1.8 Research Gap

Although significant research has been carried out on Power Factor Correction (PFC) boost converters, several limitations still exist in conventional control approaches. Most existing systems employ PI or PID controllers for regulating the output voltage and shaping the input current waveform [34]. These controllers provide acceptable steady-state performance; however, their effectiveness decreases under nonlinear operating conditions, sudden load variations, and parameter uncertainties. Conventional PID controllers require accurate mathematical modelling and careful tuning of controller gains, which may not always ensure optimal dynamic performance [37].

Many research works focus mainly on single-loop control strategies, where either voltage regulation or current control is emphasized individually [35]. Such approaches may not provide sufficient dynamic stability and harmonic suppression under varying operating conditions [38]. In addition, some intelligent control techniques proposed in previous studies involve complex implementation methods and high computational requirements, limiting their practical applicability.

Adaptive Neuro-Fuzzy Inference System (ANFIS) based controllers have shown promising results in improving converter performance, but limited studies are available on the comparative analysis of dual-loop PID and dual-loop ANFIS

controlled PFC boost converters under both load variation and reference output voltage variation conditions [41] [43]. Furthermore, detailed analysis of parameters such as Total Harmonic Distortion (THD), power factor improvement, settling time, overshoot, and dynamic response is still insufficient in many existing works [39] [40]. Therefore, this research aims to develop and compare dual-loop PID and dual-loop ANFIS control strategies for a PFC boost converter using MATLAB/Simulink in order to achieve improved power quality, reduced THD, enhanced power factor, and superior dynamic performance.

1.9 Objectives of Thesis

The main objective of this thesis is to analyze and compare the performance of dual-loop PID and dual-loop ANFIS controlled PFC boost converters for improved power quality and dynamic response. The study focuses on developing an intelligent control strategy capable of reducing harmonic distortion and enhancing power factor under varying operating conditions.

The specific objectives of the thesis are as follows:

1. To study the operating principle, mathematical modelling, and design of the PFC boost converter.
2. To develop a dual-loop control structure consisting of an outer voltage control loop and an inner current control loop for effective regulation of the converter.
3. To design and implement a conventional PID controller for the dual-loop PFC boost converter using MATLAB/Simulink.
4. To design and implement an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller using the ANFIS Editor Toolbox in MATLAB/Simulink.
5. To generate suitable training data and membership functions for ANFIS controller development.
6. To analyze the performance of PID and ANFIS controllers under different operating conditions such as load variations and reference output voltage variations.
7. To evaluate important performance parameters including output voltage regulation, settling time, overshoot, power factor, and Total Harmonic Distortion (THD).

8. To compare the effectiveness of dual-loop PID and dual-loop ANFIS controllers in terms of dynamic response, harmonic reduction, and overall system performance.
9. To demonstrate that the ANFIS-based intelligent controller provides improved performance over the PID controller for PFC boost converter applications.

1.10 Organization of Thesis

The thesis comprises six chapters on the theoretical background, modelling, control design, simulation and performance analysis of the dual loop PID and ANFIS controlled PFC boost converter.

Chapter 1 discusses introduction to power electronics, necessity for Power Factor Correction (PFC), importance of DC-DC converters and boost converters in general. In addition, power quality, harmonic distortion, literature survey, research gap, aims of the thesis and scope of the thesis have been explained.

Chapter 2 elaborates on operation, mathematical modeling and design of the PFC boost converter. Various operating modes like Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM) and Critical Conduction Mode (CrCM) have been explained. Also, equations for design purposes, state space modeling, harmonics analysis and power factor analysis have been discussed.

Chapter 3 covers dual loop control techniques for the proposed system. It explains about design and principle of operation of PID controller and ANFIS controller respectively. Dual Loop Control concept, Membership Function design and ANFIS structure are also elaborated.

Chapter 4 discusses about development of PFC boost converter in MATLAB Simulink. Open loop, dual loop PID and dual loop ANFIS control systems have been developed. Process of generation of training data, implementation using ANFIS toolbox, FFT analysis and simulation parameters have also been discussed.

Chapter 5 highlights simulation results of dual loop PID and ANFIS controllers along with their performance comparison with the help of output voltage regulation, THD, Power Factor, settling time, overshoot and dynamic response analysis under varying load and input voltage conditions.

Lastly, conclusions drawn through the research process have been discussed in

Chapter 6.

CHAPTER 2

PFC BOOST CONVERTER: OPERATION, MODELLING AND DESIGN

2.1 Introduction

Power Factor Correction (PFC) boost converters have become popular in power electronic circuits due to their ability to improve the quality of energy flow. They allow to reduce THD in order to make sure that the power factor of the circuit is close to unity [42]. Modern power electronics utilize non-linear electronic loads, which distort the current of the circuit by introducing higher-order harmonics. Switched-mode power supplies, battery chargers, motor drives, etc. are such kinds of loads.

Thus, to improve the efficiency and operation of the circuit, it is necessary to install a converter with the ability to reduce THD and correct the power factor of the system. The converter, known as a PFC boost converter, is considered the best way to solve these problems. As its name suggests, it is capable of implementing both processes at once. Its main property consists in forming the shape of the input current waveform so as it resembles the shape of the input voltage waveform.

The choice of the topology for the converter plays a key role in determining its effectiveness. In addition, the right choice of components for the inductor and capacitor also matters greatly since these factors influence the operation of the converter. Mathematical models play an important role in ensuring efficient control of the process.

Therefore, this chapter will describe the operation, modes of operation, design equations, and mathematical modeling of the PFC boost converter. The modes of CCM, DCM, and CrCM will be described. In addition, harmonic analysis and PFC implementation with the help of the boost converter are also presented.

2.2 Basic Boost Converter Topology

Power factor correction boost converter belongs to the category of common converters between AC input and DC output. It can be used for obtaining a stable DC output voltage. The basic topology of PFC boost converter as shown in Figure 2.1 includes an AC source, full-wave bridge rectifier, boost inductor, power switch, diode, output

capacitor, and load resistance. This converter converts AC voltage input into high and stable DC output voltage with unity power factor.

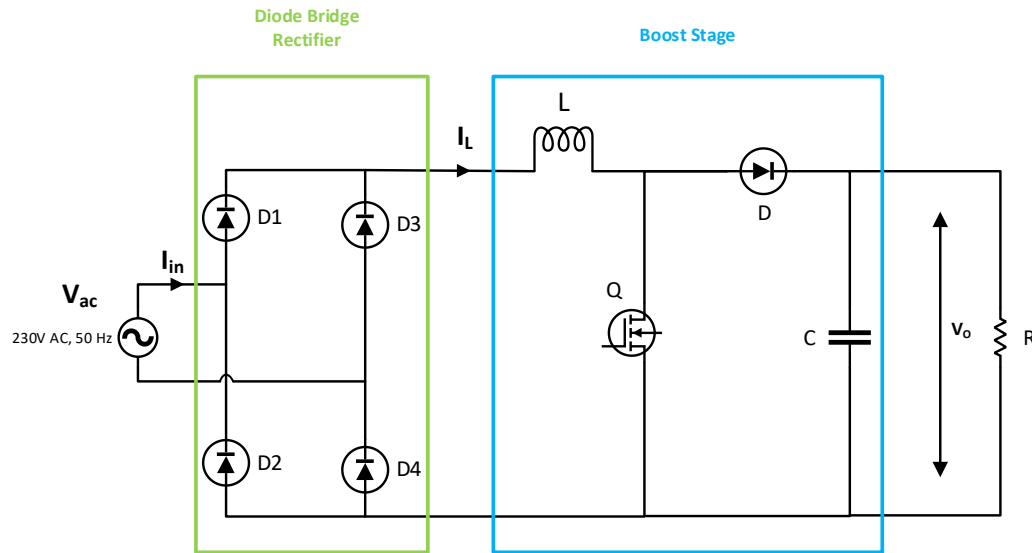


Figure 2.1. Circuit Diagram of PFC Boost Converter

Initially, the AC source feeds the full-wave bridge rectifier that outputs pulsating DC voltage. Then, the DC voltage is fed to the boost converter. Boost inductor accumulates energy when the switch is ON, and gives energy back to the load when the switch is turned OFF. When the switch is turned OFF, diode creates a conducting path from the inductor to the output terminal. Output capacitor reduces the output ripple voltage, smoothing the voltage level and providing stability for the load connected to the converter.

Control system of PFC boost converter implements pulse width modulation of switching frequency. Through the variation of the duty cycle, the output voltage can be regulated according to load. Besides, in order to provide power factor correction and reduce harmonics, the controller makes input current follow the shape of the input voltage waveform.

Boost converter can be chosen among many other types due to several advantages that include continuous input current, low input current ripple, simplicity of the control structure, and high efficiency. Thus, it is used in switched mode power supplies, electric vehicle charging stations, renewable energy, LED drivers, and power supplies for industries.

In conclusion, it is possible to state that basic topology of the PFC boost converter

provides voltage boosting and effective harmonic reduction.

2.3 Principle of Operation of PFC Boost Converter

The operating principle of the PFC boost converter is based on the controlled storage and transfer of energy through an inductor to obtain a regulated DC output voltage with improved power factor. The converter operates by rapidly switching a semiconductor device ON and OFF using Pulse Width Modulation (PWM) control. During this process, the input current is shaped to follow the input voltage waveform, thereby reducing harmonic distortion and improving power quality.

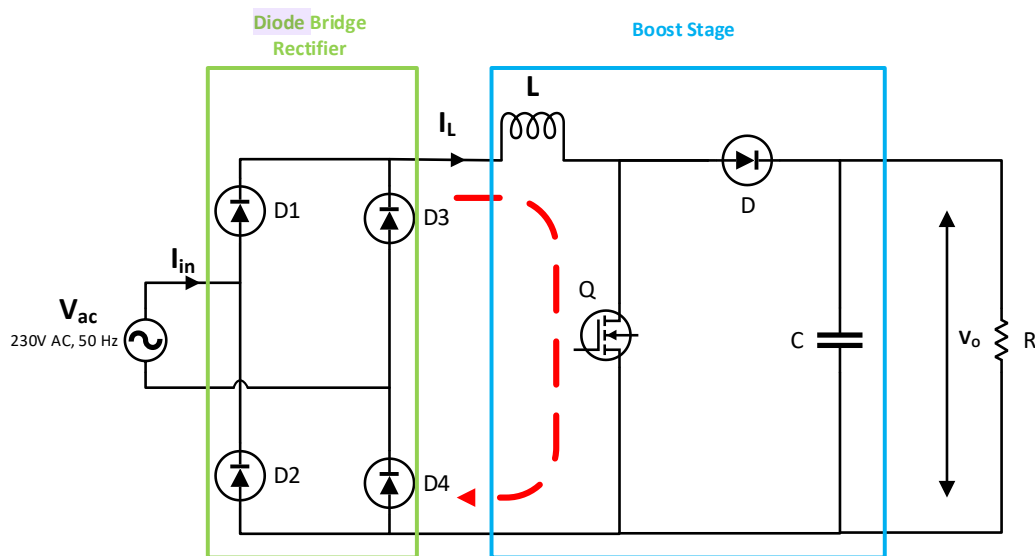


Figure 2.2. Switch ON State PFC Boost Converter

The operation of the boost converter can be explained in two switching intervals. During the ON state of the power switch as shown in Figure 2.2, the switch conducts and the diode gets into reverse bias. The input supply transfers energy to the inductor, causing the inductor current to increase linearly. During this interval, the output capacitor supplies energy to the load. The energy that is stored in the inductor during the ON period is given in equation 2.1.

$$E = \frac{1}{2} L I_L^2 \quad (2.1)$$

where L is the inductance and I_L is the current flowing through inductor.

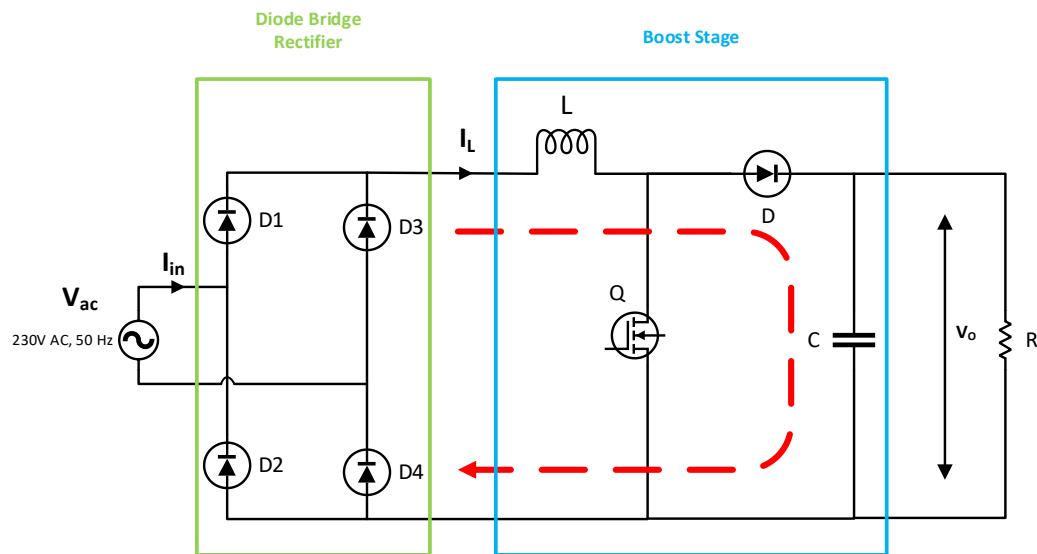


Figure 2.3. Switch OFF State PFC Boost Converter

The output voltage is controlled by regulating the duty cycle of the PWM signal. A higher duty cycle results in higher output voltage. In PFC applications, the controller regulates both the output voltage and input current simultaneously using a dual-loop control structure. The outer voltage loop maintains constant output voltage, while the inner current loop shapes the input current waveform to achieve near-unity power factor and low THD.

Therefore, the PFC boost converter ensures efficient energy conversion, improved power quality, and stable operation under different varying load conditions.

2.4 Modes of Operation

The performance of a PFC boost converter depends greatly on the inductor current profile during the switching period. Based on the inductor current profile, boost converters operate in three main modes namely Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM), and Critical Conduction Mode (CrCM). The selection of mode of operation plays an important role in determining overall converter efficiency, harmonic distortion, losses, etc.

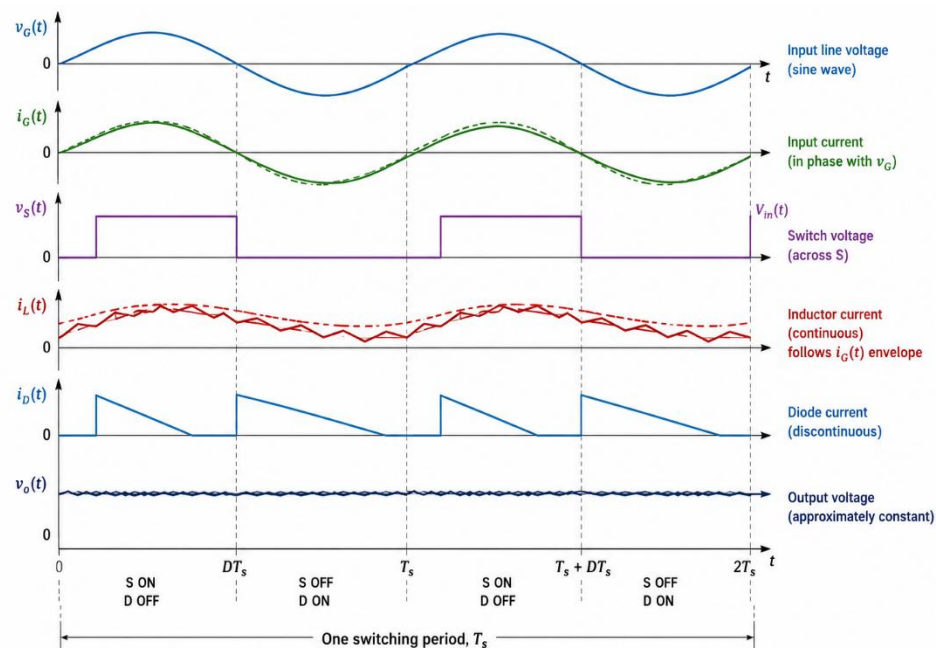


Figure 2.4. Continuous Conduction Operation Waveform Mode (CCM)

In Continuous Conduction Mode (CCM) whose waveform is shown in Figure 2.4, the inductor current does not reach zero point at any instant during the switching period. Since there is continuous conduction of current, the magnitude of current ripple reduces and so does the efficiency of the converter. The operation in CCM is most preferred for medium to high rated power factor correction converters since it gives better results in terms of input shaping, etc. However, it is slightly more complicated than other modes [45].

In Discontinuous Conduction Mode (DCM) whose waveform is shown in Figure 2.5, the inductor current reaches zero before the start of next switching period. The operation in DCM usually takes place under light load conditions. Although DCM gives better dynamic response and simpler control, it suffers from problems like higher current ripple and peak current levels that causes high harmonic distortion. Moreover, it also leads to higher losses and stresses.

Critical Conduction Mode (CrCM) whose waveform is shown in Figure 2.6 occurs where inductor current drops to zero exactly at the end of every switching cycle. In this mode, there are some advantages of both CCM and DCM such as reduced switching losses and efficiency. But due to varying frequency in CrCM mode of operation, it becomes more complicated to control.

The mode of operation for the converters depends upon various factors such as rating, load conditions, control strategies, etc. In this project work, the main consideration has been made for the analysis of the boost converter operated in CCM mode due to superior power quality performance and low harmonic distortion, among others.

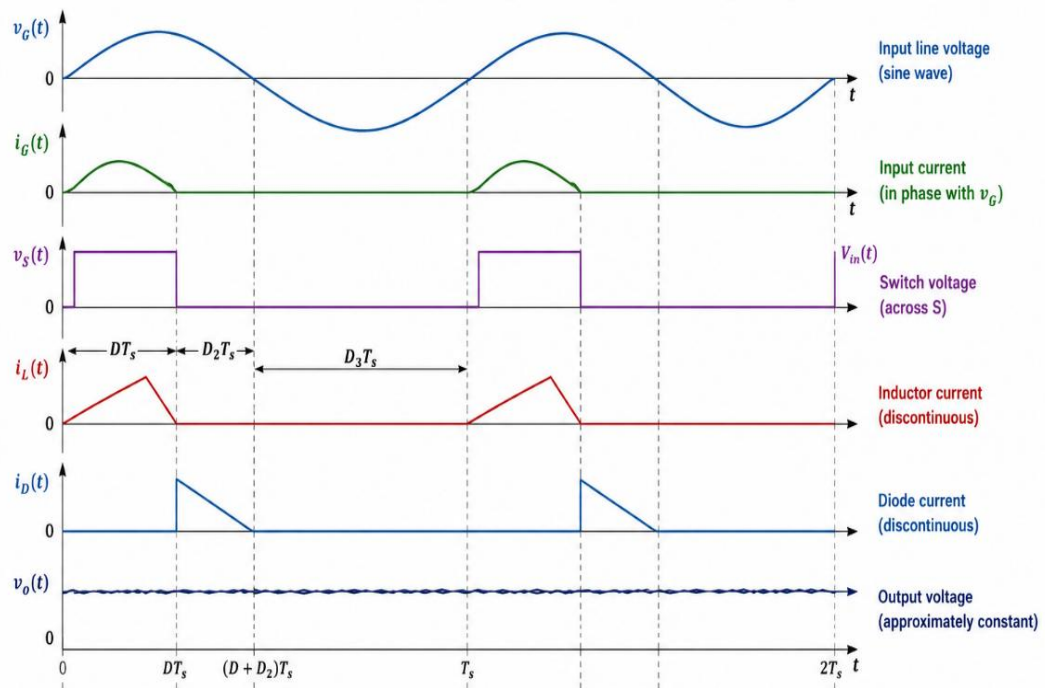


Figure 2.5. Discontinuous Conduction Mode (DCM) Operation Waveform

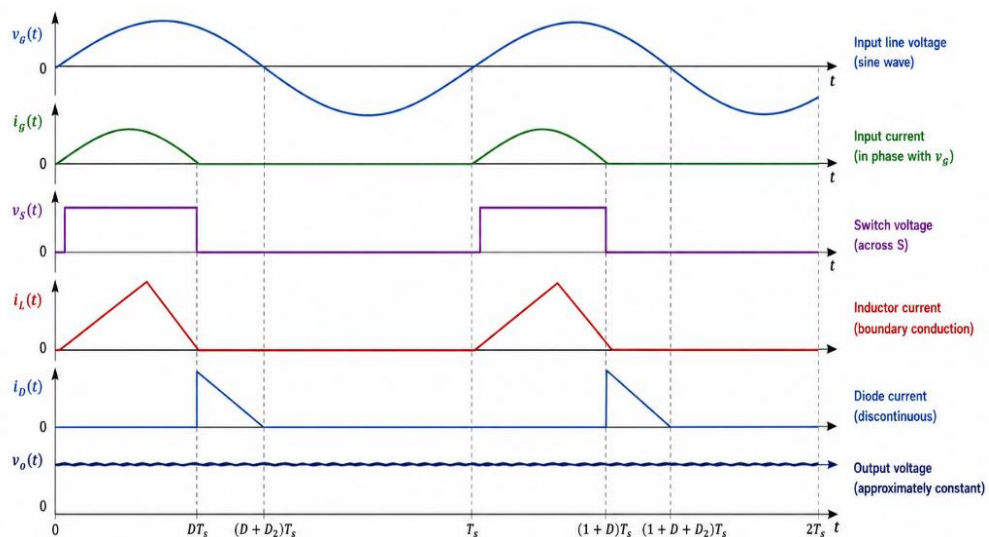


Figure 2.6. Critical Conduction Mode (CrCM) Operation Waveform

2.5 Design Equations of PFC Boost Converter

PFC boost converter design focuses on determining appropriate values of duty cycle, inductor, and output capacitor for the smooth operation of converters, reduction of ripples and improvement of power quality in converters [46] [47].

The duty cycle for the boost converter is the most crucial factor for the determination of boosting ability of the boost converter. Ideally, the equation for calculating the duty cycle for boost converters is given by equation 2.2.

$$D = 1 - \frac{V_{in}}{V_o} \quad (2.2)$$

Here, D stands for duty cycle, V_{in} is the input voltage, and V_o is the output voltage.

Similarly, inductor plays an important role in maintaining continuous flow of current. The equation for calculating the inductance value in CCM is given by equation 2.3 [50].

$$L = \frac{V_{in}D}{f_s \Delta I_L} \quad (2.3)$$

Here, L stands for inductance, f_s denotes the switching frequency, and ΔI_L represents the inductor current ripples.

On the other hand, an output capacitor helps in reducing output voltage ripples and also helps in obtaining a constant DC output voltage. The output capacitor value is calculated using the equation 2.4 [51].

$$C = \frac{I_o D}{f_s \Delta V_o} \quad (2.4)$$

Here, C stands for output capacitor, I_o is the output current, and ΔV_o represents output voltage ripple.

Finally, the output voltage relation for the boost converter is given in equation 2.5.

$$V_o = \frac{V_{in}}{1-D} \quad (2.5)$$

2.6 Harmonic Analysis and THD Calculation

Evaluation of Harmonic Content and THD for PFC Boost Converter is an important parameter while conducting performance analysis of Power Factor Correction boost converters [52]. Harmonic content is generated from nonlinear switching elements

within power electronic circuits, thus distorting the current waveform [53]. Harmonic content has various negative impacts on the power system such as reducing the quality of electricity and efficiency of power usage, increasing power loss, creating electromagnetic interference and reducing efficiency of the system. Thus, minimizing harmonic distortion is among the most crucial aims of Power Factor Correction Boost Converters [54].

Harmonic content of current waveform is often evaluated using Total Harmonic Distortion. THD refers to the total distortion of a waveform caused due to the presence of harmonic currents in the circuit [55]. It is defined by the relationship between root mean square of harmonic contents of current waveform and that of the first current component. Lowering in THD will result to high waveform quality and increased efficiency of power electronic circuits. Expression for THD is given in equation 2.6.

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2}}{I_1} \times 100\% \quad (2.6)$$

where I_1 represents the first current component whereas $I_2, I_3, \dots, I_n$ represents other harmonic components.

In case of PFC boost converter, control system manipulates the input current waveform to make sure that it resembles input voltage waveform through shaping of the current waveform [56]. Two-loop control system employing ANFIS and PID controllers can significantly help to shape the input current waveform to have lower harmonic content. Harmonic content and THD in PFC boost converters can be measured by performing Fast Fourier Transform (FFT) analysis of current waveform. FFT analysis tool helps to analyze the different frequency components of current waveform [44] [57].

Therefore, harmonic content and THD measurement is crucial in performance evaluation of PFC Boost converter.

2.7 Power Factor Analysis

The power factor is another crucial parameter that should be considered when evaluating the performance of the electrical power system and the power electronics circuit [58] [59]. The term power factor implies an effective use of electrical power by the load. As a rule, the power factor is defined by means of the ratio of active power

and apparent power. A unit power factor value means a more efficient utilization of electrical power, whereas the lower value of the power factor can cause increased requirements for currents, high losses during power transmission, poor voltage regulation, and lower efficiency of the whole system.

Power factor can be mathematically represented in equation 2.7.

$$PF = \frac{P}{S} = \cos \phi \quad (2.7)$$

Where PF stands for power factor, P for active power, S for apparent power and ϕ is a phase difference between voltage and current waveforms.

As it was already mentioned, conventional rectifier circuits experience the effect of distorted input current due to the nonlinear switching process. Therefore, it is very important to introduce special measures to increase efficiency and decrease harmonic content. For these purposes, PFC techniques can be used, which involve the adjustment of the input current waveform according to the input voltage sinusoid.

Thus, PFC technique can improve performance indicators of the rectifier and reduce harmonic distortion. At that, it is noteworthy to underline the role of intelligent control for the PFC boost converter. In this regard, dual-loop voltage-controlled structure with an outer voltage loop and inner current loop performs better than other structures. Moreover, ANFIS based intelligent controller demonstrates superior performance as compared to PID controller because of improved transient characteristics.

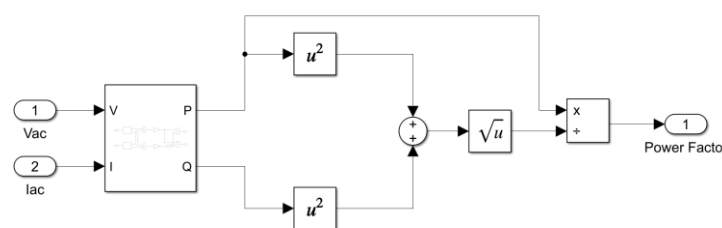


Figure 2.7. Power Factor Measurement

Finally, power factor can be estimated within the MATLAB/Simulink environment on the basis of a phase shift between the input voltage and input current waveforms and harmonic content analysis shown in Figure 2.7.

Consequently, power factor evaluation should be regarded as an integral part of the study.

2.8 Advantages and Applications of PFC Boost Converter

There are multiple benefits provided by the PFC boost converter topology, making it one of the most preferable topologies for implementation in contemporary power electronics applications. These benefits include improved power factor, minimized harmonics and THD, and DC voltage regulation [49].

The first main benefit of the PFC boost converter is its ability to provide near-unity power factor, achieved through the shaping of the input current waveform in accordance with the input voltage waveform. Reactive power is being eliminated, allowing the improvement of power quality and reduction of losses within the power grid. In addition, minimal THD is achieved, ensuring compliance with harmonic standards for example IEC 61000-3-2 [48].

Continuous input current provided by the boost converter allows minimizing input current ripples and decreasing electromagnetic interference between different circuits. High voltage gain and simplicity of control scheme are two other benefits of the boost converter topology. Additionally, the topology is known for increased efficiency, fast transient response, reduced switching losses, and reliable operation under various load conditions.

Enhanced converter performance can be obtained by the employment of intelligent control systems, including PID, fuzzy logic, and ANFIS controllers. Controllers allow obtaining high performance in terms of voltage regulation, fast transient response, and THD reduction capability of the converter.

The benefits provided by the topology explain its widespread usage in many applications, including SMPS, computer power systems, battery charging systems, electric vehicles charging stations, renewable energy systems, LED drivers, telecommunications devices, industrial power supplies, aerospace electronics, and medical devices.

As a result, the application of PFC boost converters proves its importance and benefits in the field of contemporary power electronic systems.

CHAPTER 3

DUAL LOOP CONTROL METHODOLOGIES

3.1 Introduction

The type of control strategies used affects the overall performance, stability, and efficiency of the PFC boost converters. The main aim of the controller is regulating the output voltage and modifying the input current for obtaining high power factor and lower harmonics. For the design of the PFC converters, dual loop control technique is preferred since it provides good response and system stability [69].

In a dual loop control system, there are two loops that are connected together; there is the outer voltage loop with inner current loop. The voltage loop controls the output voltage level, whereas the inner current loop controls the inductor current. Traditional PID controllers are extensively utilized in various applications because they are easy to implement and possess good steady-state performance. Nevertheless, there are some disadvantages associated with conventional PID controller [70].

For instance, these controllers might suffer from slow response time, reduced robustness, and inability to adapt to varying conditions such as nonlinearity and load variations. To address such challenges, intelligent control schemes such as Adaptive Neuro Fuzzy Inference System are utilized in the system. ANFIS integrates the features of both fuzzy logic reasoning and neural network learning. In this work, the concepts of dual-loop control, PID controller, and ANFIS controller are addressed in the chapter [71].

3.2 Open Loop and Closed Loop System

Control systems are employed in power electronic converters in order to control their operation and performance. According to the feedback principle, control systems can be divided into open loop and closed loop systems. These two techniques are both used in power converters; however, they show significant differences regarding their performance characteristics [72].

Unlike a closed loop control system, where feedback signals are used to make corrections and ensure that the output matches the desired value, an open loop control

system does not require any feedback to function properly. In other words, its control actions are based solely on the reference input signal. Despite simplicity, economy, and ease of implementation, such control systems cannot compensate automatically for the influence of changing loads and parameters and possible external disturbances. Thus, their voltage regulation and dynamic performance are unsatisfactory [73].

On the contrary, in the case of closed loop systems, the output and the reference are compared constantly, and the difference between them is processed by the controller in order to obtain the control signal. This feature ensures the high accuracy of the control process and helps increase the system's stability. In addition, closed loop control systems exhibit high disturbance rejection properties and low static errors. For these reasons, closed loop controllers are widely used in PFC boost converters [74].

It should be noted that in the case of dual-loop PFC boost converters, there are two control loops: voltage and current loops. The purpose of the voltage loop is to regulate the output voltage while the current loop aims at shaping the input current.

Thus, closed loop control systems are preferable in power electronics due to their better performance and adaptability than open loop control systems.

3.3 Dual Loop Control Structure of PFC Boost Converter

Dual Loop Control structure is used in PFC Boost Converter for effective and precise regulation of output DC voltage and shaping of input current. Dual Loop control structure has advantages over Single Loop Control such as improved performance, high stability and less harmonic content. It comprises an outer voltage regulation control loop and an inner current regulation loop.

Outer voltage loop maintains DC output voltage at the set reference value. Voltage difference between actual and reference voltages is used to produce the error signal which is then sent to the controller for generation of the reference current of inner loop.

Output voltage regulation is maintained effectively by the Outer Voltage Loop.

Inner Current Loop regulates the inductor current of the boost converter. The Reference current generated by the Voltage Loop is compared with the inductor current, and error signal generated is used to produce switching pulses for regulating the inductor current. The purpose of Inner Current Loop is to improve the input current shape such that its waveform tracks the input voltage waveform in order to provide

near UPF and lower THD.

Switching control signal used in Boost converter for regulating switching process usually uses PWM technique where switching duty ratio of power semiconductor switch is regulated based on the controller's output signal.

In this research study, the implementation of both PID and ANFIS controllers' control structures is done in MATLAB / Simulink for analysis of their effectiveness.

3.4 Conventional PID Controller

One of the widely applied control algorithms in industry and power electronics control devices is known as the Proportional-Integral-Derivative (PID) controller. This type of controllers enjoys great popularity due to its straightforwardness, ease of implementation, and decent performance levels. Moreover, PID controllers can be successfully employed as regulators of voltage and currents in dual-loop PFC boost converters [75].

The basic principle of a PID controller is to produce a control action based on the difference between the reference value and the current output. It should be emphasized that PID controllers comprise three control actions – namely, proportional, integral, and derivative controls. The former implies an output proportionate to the current error, whereas the latter two controls improve the system stability and predict future changes.

The equation that describes the behaviour of a PID controller is given in equation 3.1.

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (3.1)$$

where K_p , K_i , and K_d are proportional, integral, and derivative gains respectively, and $e(t)$ stands for the error signal produced by the controller.

A dual-loop PFC boost converter comprises a PID controller that processes the voltage and current error signals. As a result, the output voltage is regulated and shaped input current waveform is obtained. In addition, the correct tuning of the gains makes it possible to achieve satisfactory transient responses and minimize overshooting.

However, since conventional controllers have poor nonlinear performance and cannot handle abrupt changes of loads properly, new control algorithms, such as ANFIS control, should be applied to obtain improved performance and robustness of

converters.

3.5 Adaptive Neuro-Fuzzy Inference System (ANFIS)

Adaptive Neuro-Fuzzy Inference System (ANFIS) is an intelligent adaptive control technique that combines the learning capability of ANN along with the smart reasoning capability of FLS. ANFIS provides improved adaptability, nonlinear mapping capability, and better dynamic performance compared to conventional controllers. Due to these advantages, ANFIS has become widely popular in power electronic and control applications [61].

In a PFC boost converter, the operating conditions continuously vary because of changes in load and input voltage. Conventional PID controllers may not always provide satisfactory performance under such nonlinear conditions. ANFIS overcomes these limitations by automatically adjusting its control parameters based on the training data and system behaviour.

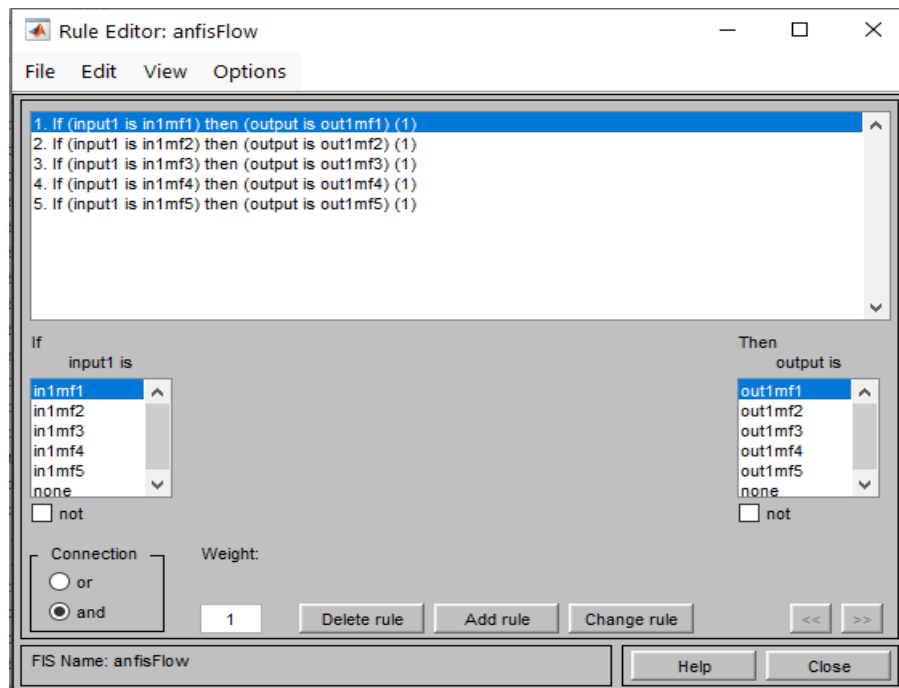


Figure 3.1. ANFIS Rule Editor

The ANFIS controller uses fuzzy IF–THEN rules and membership functions illustrated in Figure 3.1 to model the nonlinear characteristics of the system [67]. The neural network learning algorithm helps in tuning the membership function parameters

to minimize the control error. Thus, ANFIS combines human-like reasoning with adaptive learning capability [62].

The structure of ANFIS generally consists of multiple layers responsible for fuzzification, rule evaluation, normalization, defuzzification, and output generation [63]. The controller is trained using the input output data obtained from the converter system. During training, the error between the actual output and desired output is minimized using optimization algorithms.

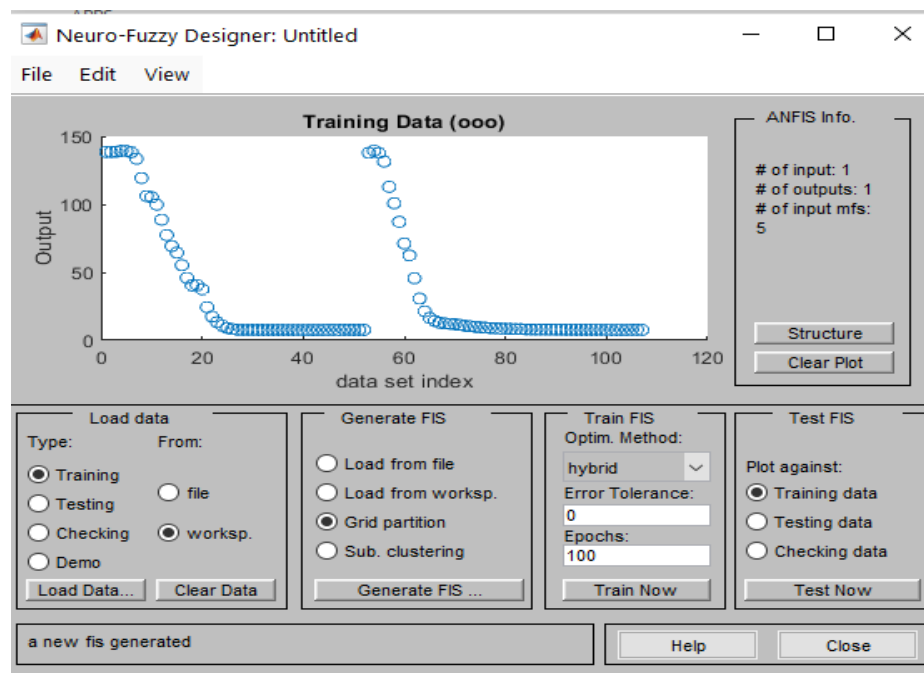


Figure 3.2. ANFIS Editor Toolbox

In this research work, the ANFIS controller is modelled using the ANFIS Editor Toolbox available in MATLAB/Simulink shown in Figure 3.2. The controller is applied in the dual-loop PFC boost converter to improve output voltage regulation, reduce THD, and achieve better power factor and dynamic response compared to the conventional PID controller.

3.6 Comparative Analysis of PID and ANFIS Controllers

The use of PID and ANFIS controllers for regulating converters' operation is common. Nonetheless, these two control strategies have different features and performance. PID is a linear control strategy that ensures simplicity of implementation, small amount of computation, and acceptable steady-state performance. The proportional, integral, and

differential control actions are applied by PID to control system output depending on error signals.

PID is a suitable control strategy for stable linear processes with constant working condition. PID is utilized widely within industry because of simplicity of design and acceptable performance.

Unfortunately, PID fails to provide good performance when it comes to nonlinear processes. Moreover, the proper tuning of controller gains must be done for achieving a stable operation and satisfactory response. The transient operation of PFC boost converter controlled by PID may include large overshoot, long settling time, and harmonic distortion.

ANFIS represents the adaptive neuro-fuzzy inference system. It means that this controller combines the benefits of fuzzy logic and neural network and can be utilized in nonlinear control system. Due to the learning process, ANFIS ensures better performance regarding voltage regulation, transient behaviour, and disturbance rejection.

The expected performance analysis between PID and ANFIS controllers is summarized and illustrated in Table 3.1.

Table 3.1. Expected Performance Comparison Between PID And ANFIS Controllers

S. No.	Parameter	PID Controller	Dual-Loop ANFIS Controller
1.	Dynamic Response	Moderate	Fast
2.	Harmonic Mitigation	Moderate	Excellent
3.	THD Reduction	Higher THD	Lower THD
4.	Power Factor	Improved	Near Unity
5.	Overshoot	Higher	Lower
6.	Settling Time	Longer	Shorter
7.	Adaptability	Limited	High
8.	Stability Under Variations	Moderate	Excellent

The results of research indicate that ANFIS outperforms PID control strategy in terms of THD reduction, power factor improvement, less overshoot, and quick settling time.

Robustness of ANFIS to changes of the load and reference voltage is another advantage compared with PID control.

Thus, ANFIS can be regarded as a preferable solution for advanced PFC boost converters.

CHAPTER 4

MATLAB/SIMULINK MODELLING OF DUAL-LOOP PFC BOOST CONVERTER

4.1 Introduction

MATLAB/Simulink is one of the most widely used software platforms for modelling, simulation, and analysis of power electronic systems and control techniques. It provides a graphical environment for developing converter models, designing controllers, analyzing system performance, and validating control algorithms under different operating conditions. In this research work, MATLAB/Simulink is used to model and analyze the dual-loop PID and ANFIS controlled PFC boost converter.

The modelling of the PFC boost converter includes the implementation of the rectifier stage, boost converter topology, switching device, PWM pulse generation circuit, and control system. The simulation model is designed to regulate the output DC voltage while maintaining high power factor and low harmonic distortion. The converter is mainly operated in CCM to obtain smooth input current and improved power quality performance.

Initially, an open loop PFC boost converter model is developed to study the basic operating characteristics of the converter. Subsequently, a dual-loop PID controlled model is implemented using separate voltage and current control loops. The performance of the PID controller is analyzed in conditions of output voltage regulation, settling time, overshoot, power factor, and THD.

To improve system performance further, an ANFIS controller is developed using the ANFIS Editor Toolbox available in MATLAB. The ANFIS controller is trained using suitable input–output data and integrated into the dual-loop control structure.

This chapter presents the detailed MATLAB/Simulink modelling of the proposed PFC boost converter, controller implementation, simulation setup, FFT analysis, and performance evaluation methods used for comparative analysis of PID and ANFIS controllers.

4.2 MATLAB/Simulink Modelling of Open Loop PFC Boost Converter

Converter

An open loop PFC boost converter system is modeled using MATLAB/Simulink software as shown in Figure 4.1. An open loop system is simulated for studying the basic behavior of the converter system without feedback controls. In addition, the objective of modeling an open loop system is analyzing the converter operations, voltage boosting capabilities, input currents, and output voltages.

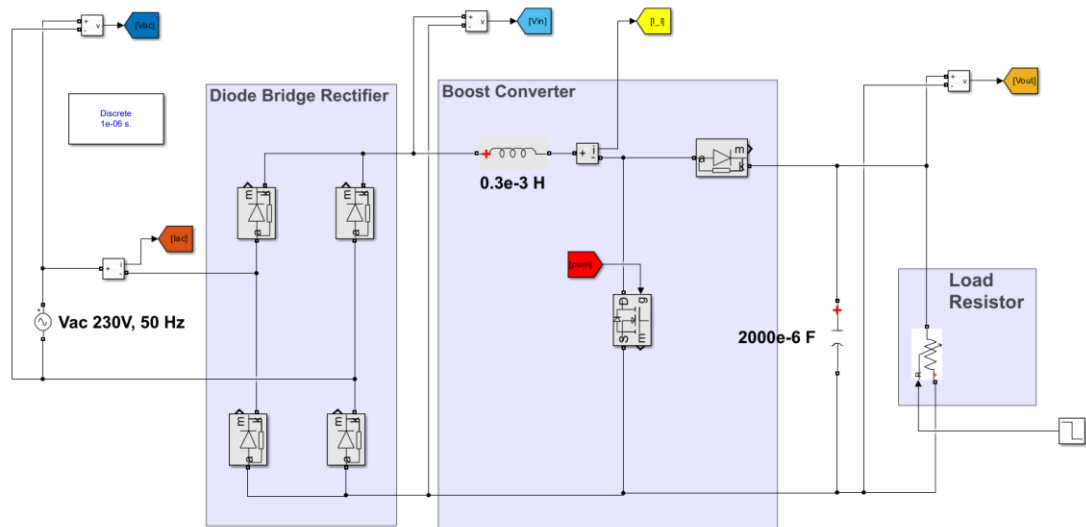


Figure 4.1. Boost Converter Simulink Model

The components used in the open loop system include an AC voltage source fed through bridge rectifier circuit and then to boost stage which consist of boost inductor, MOSFET switch, diode, output capacitor, and resistor as the load. The first step involves rectification of the input sinusoidal voltage signal using the bridge rectifier. After rectifying the voltage signal, the next step involves voltage boosting using a boost converter stage.

A PWM modulation signal for controlling the switch is generated by means of a pulse generator component. When the mosfet switch is ON, energy is stored on the inductor. During the OFF condition, the stored energy is transferred from the inductor to the output via the diode, thus creating a high output voltage that is higher than the input voltage.

An output capacitor is used for filtering the output voltage signal to ensure a low-

voltage ripples. Other measurement blocks used include voltage sensors, current sensors, oscilloscope, and Fourier transform analyzer.

An open loop model will help us understand the dynamic operations of a PFC converter. However, since there is no feedback control, the output voltage will not be constant for varying input voltage or load conditions.

Hence, the simulation results will form the basis for designing other models such as the dual-loop PID and ANFIS control algorithms.

4.3 Dual-Loop PID Controlled PFC Boost Converter

The designed dual-loop PID controller PFC boost converter shown in Figure 4.2 regulates output DC voltage while improving power factor and minimizing the total harmonic distortion. Dual-loop control systems demonstrate higher performance in dynamic response and stability than simple single-loop control systems. In this case, there are two control loops outer voltage control loop and inner current control loop.

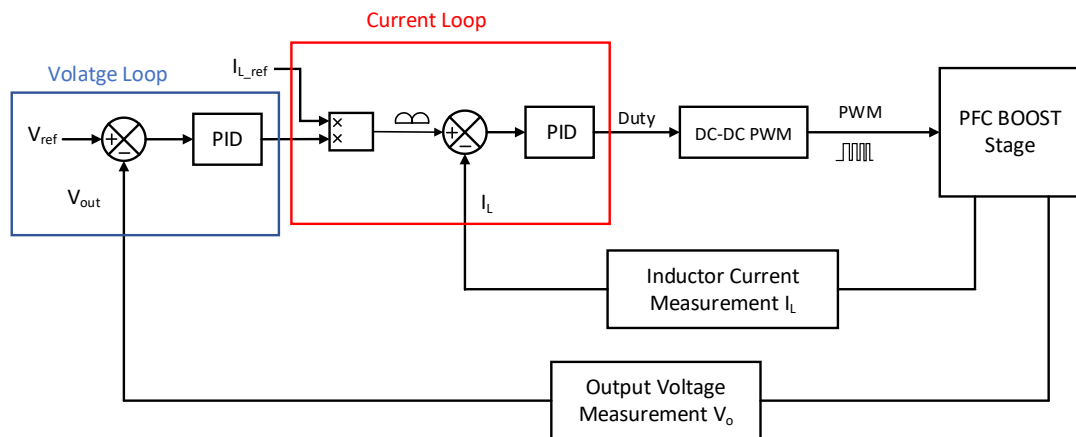


Figure 4.2. Dual Loop PID Control

The current control loop controls the inductor current in the boost converter. In the loop, the difference between the reference current and the measured current is used to process the current error signal with the help of a PID controller to generate a signal to operate the switching duty cycle for PWM generation. As a result, the input current waveform can be shaped close to that of the input voltage, ensuring power factor approaching unity and low THD.

Pulse Width Modulation signals are generated through the comparison of a high frequency carrier signal with the signal from the controller. The duty cycle changes

continuously depending on the PID controller output.

The performance of the dual-loop PID controller based PFC boost converter is evaluated using several parameters, including output voltage control, settling time, overshoot, power factor and THD. Although the PID control gives satisfying results for the steady state performance, its dynamic response is not good enough when there are sudden changes in load or reference value, motivating intelligent ANFIS control techniques application in the system.

4.4 Dual-Loop ANFIS Controlled PFC Boost Converter

The proposed dual-loop ANFIS based control of PFC boost converter shown in Figure 4.3 is designed and simulated in MATLAB/Simulink to obtain improved dynamics, reduction in harmonics distortion, and power factor compared to traditional PID-based control scheme. ANFIS is a powerful combination of ANN and FLC to obtain an intelligent adaptive control of nonlinear electrical systems.

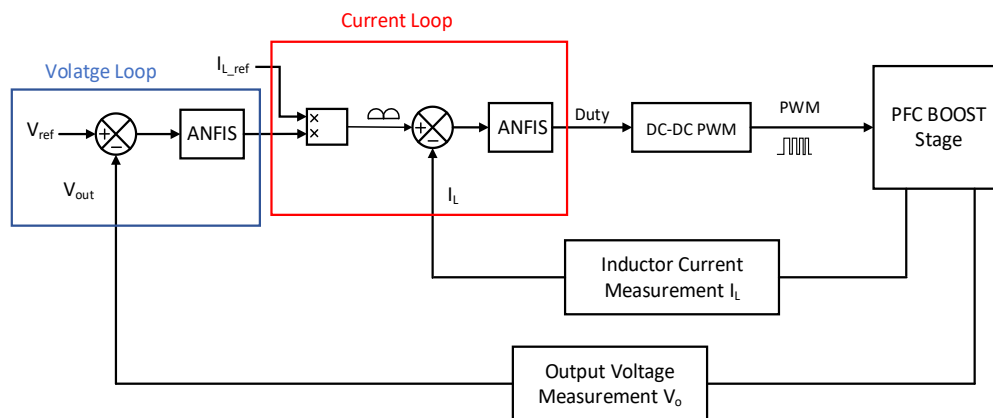


Figure 4.3. Dual Loop ANFIS Control

Like in the case of PID controller based design, the ANFIS based PFC boost converter is also implemented as a dual-loop control strategy. The first outer voltage loop is accountable for regulation of output DC voltage by generating appropriate error signal between actual output and desired DC voltage. The error signal is sent to the ANFIS controller, which produces the reference current signal for controlling the inner current loop.

The second inner current loop regulates the inductor current such that the resulting input current waveform closely follows input voltage. Thus, near unity power factor is obtained along with minimized THD. Control signal generation by the ANFIS

controller relies on a combination of training input-output pairs and fuzzy inference rules.

The ANFIS based controller model can be easily created using the ANFIS Editor toolbox provided by MATLAB using parameters described in Table 4.1. Training data can be prepared from the converter response at different working conditions. Appropriate membership functions and fuzzy rules are to be used to enhance the performance of ANFIS controller. ANFIS controller adapts to the varying system conditions and changes its parameters accordingly.

Table 4.1. ANFIS Editor Toolbox Parameters

S. No.	Parameters	Specifications
1.	ANFIS Type	Sugeno-Type Fuzzy Inference System
2.	Input Variables	(1) Error (e) (2) Change in Error (Δe)
3.	Output Variables	Control Signal / Duty Cycle
4.	Number of Membership Function	5
5.	Input Membership Function Type	Gaussian / Triangular
6.	Output Membership Function Type	Linear
7.	Rule Generation Method	Grid Partitioning
8.	Learning Algorithm	Hybrid Learning Algorithm
9.	Training Method	Least Squares Estimation + Backpropagation
10.	Number of Training Epochs	100

Generation of PWM pulses for turning ON/OFF the MOSFET switch is done by comparison of ANFIS controller output and high frequency carrier signal. Simulation results prove that the proposed design yields superior voltage regulation, fast settling time, lower overshoot, good harmonic elimination, and enhanced power factor

compared to conventional PID-based design.

4.5 Simulation Setup and Performance Measurement

The simulation setup for the designed PFC boost converter is established in the MATLAB/Simulink to analyze the performance comparison of dual-loop PID and ANFIS controllers using system parameters as mentioned in Table 4.2. The entire simulation system consists of an AC input source, a bridge rectifier, boost converter components, blocks for measuring voltage and current signals, pulse width modulation generation block, and a controller block.

Table 4.2. System Parameters

S. No.	Parameter	Symbol	Value
1.	Input AC Voltage	V_{ac}	230 V, 50 Hz
2.	Output DC Voltage	V_{dc}	400 V
3.	Switching Frequency	f_{sw}	65 kHz
4.	Boost Inductor	L	0.3 mH
5.	Output Capacitor	C	2000 μ F
6.	Load Resistance	R	200 Ω - 150 Ω
7.	Sampling Time	T_s	1 μ s
8.	Converter Operating Mode	-	CCM

To get good performance characteristics of the output voltage, the converter is designed to operate in the Continuous Conduction Mode (CCM). Suitable values of inductance, capacitance, switching frequency, and load resistance are chosen according to the design equations of the boost converter. The switching signals required for the MOSFET switch are obtained through the PWM techniques provided in the Simulink environment.

FFT Analyzer

Help

Signal:

Dimension:

Start time (s):

Number of cycles:

Zoom on:

Fundamental frequency (Hz):

Max frequency (Hz):

Max THD frequency:

Display style:

Base value:

Frequency axis:

Harmonic content of the input current signal is analyzed through FFT Analyzer Window shown in Figure 4.4 and Total Harmonic Distortion (THD) calculation is done. Low THD values imply better harmonic suppression performance and higher power quality level. Power factor analysis will be conducted through the phase difference between the input current and input voltage waveforms.

4.6 Conclusion

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converter was created in order to study its characteristics and boosting ability. After which, different methods of implementing a dual-loop control system in order to regulate output voltage and shape input current were performed.

The design of the dual loop PID PFC Boost converter control involves the combination of control of output voltage, control of input current, and PWM pulse generation system. The results show that the PID controller gives satisfactory results in terms of voltage regulation and power factor improvement during normal operation. On the other hand, under nonlinear condition and with load variation, the PID controller fails to deliver better performance.

In order to improve the overall performance of the PFC boost converter, a dual loop ANFIS control system was created through the ANFIS Editor Toolbox in MATLAB. Generation of data, membership function, and ANFIS training procedures were explained in detail. Compared with the PID controller, ANFIS controller is more adaptive and exhibits higher performance when it comes to nonlinear systems.

Lastly, the simulation process and method of analyzing the performance in terms of THD and power factor was discussed. Different scenarios like load variation and reference output voltage variation were included in this analysis.

Therefore, the MATLAB/Simulink models developed in this chapter can be used for the performance evaluation and comparison in the next chapter.

CHAPTER 5

SIMULATION RESULTS AND PERFORMANCE ANALYSIS

5.1 Introduction

This chapter presents the simulation results and performance analysis of proposed dual loop PID and dual loop ANFIS controlled PFC boost converter that was designed using MATLAB Simulink environment. The main aim of performing this performance analysis is to assess the effectiveness of both controllers with respect to output voltage stability, harmonics, power factor, and other performance aspects.

Firstly, the performance of the open loop PFC boost converter is analyzed to understand the basics of PFC boost converter without implementing any controller. Later, the dual loop PID controller is assessed based on its output voltage response, input current wave shape, settling time, overshoots, and so on. Even though PID controller gives reasonable output, some drawbacks such as slow dynamic response and increased THD can be found in case of sudden load and reference voltage changes. To eliminate the above drawbacks, dual loop ANFIS controller is employed and analyzed for PFC boost converter. ANFIS controller makes use of adaptive network and fuzzy logic systems to enhance system performance by making intelligent decisions. The performances of both controllers are analyzed under similar simulation conditions.

FFT analysis is carried out to compute the THD value of input current waveform. Also, power factor analysis is done in order to assess the power quality of the system. Load variation and reference output voltage variation test cases are performed in order to analyze the dynamic nature of the controller.

The simulation results will be presented in the coming chapters and discussed about the comparative performance of both PID and ANFIS controllers.

5.2 Open Loop Converter Performance Analysis

Performance of the open loop PFC boost converter is simulated in MATLAB/Simulink, which helps in studying the fundamental operating principles of

the converter without any form of feedback controller. In an open loop PFC converter, the switching pulses provided to the MOSFET are generated by applying fixed duty cycle Pulse Width Modulation (PWM).

Simulation results demonstrate that the PFC boost converter is capable to boost up the rectified input voltage to produce higher DC output voltage level. However, since there is no feedback controller implemented in the system, the variation in output voltage and input current levels will have considerable impact on performance. In other words, the open loop PFC converter is incapable of regulating constant output voltage under dynamic operating conditions.

It is clear from the Figure 5.1 that the of input current waveform does not appear to be perfectly synchronized with input voltage waveform. Hence, the power factor is low, and consequently, the THD in the current waveform is relatively high.

The open loop PFC boost converter suffers from many shortcomings such as large voltage ripple, slow transient response, and instability in case of sudden load changes, among others. This is mainly due to the fact that the duty cycle remains constant all throughout.

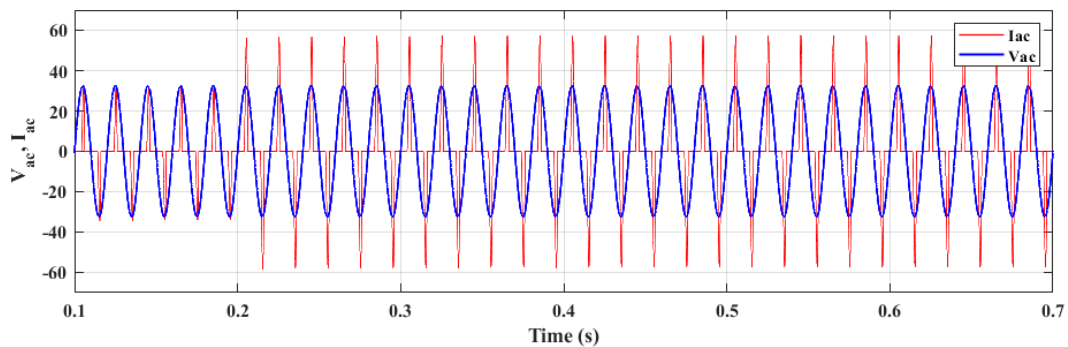


Figure 5.1. Input AC Current without Controller

From the analysis, it is evident that the PFC boost converter operation without a feedback controller causes many problems that need to be addressed. The implementation of sophisticated dual loop feedback controllers including PID and ANFIS controllers becomes absolutely essential.

Thus, it is concluded that the open loop PFC converter serves as a base model for comparison with the closed loop controllers.

5.3 Performance Analysis of Dual Loop PID Controller

MATLAB/Simulink is used for analyzing the performances of the dual-loop PID controlled PFC boost converter including the voltages regulating ability, input current shaping, dynamic response, etc. The control scheme includes two loops: an outer voltage loop with inner current loop which are both regulated using PID controllers.

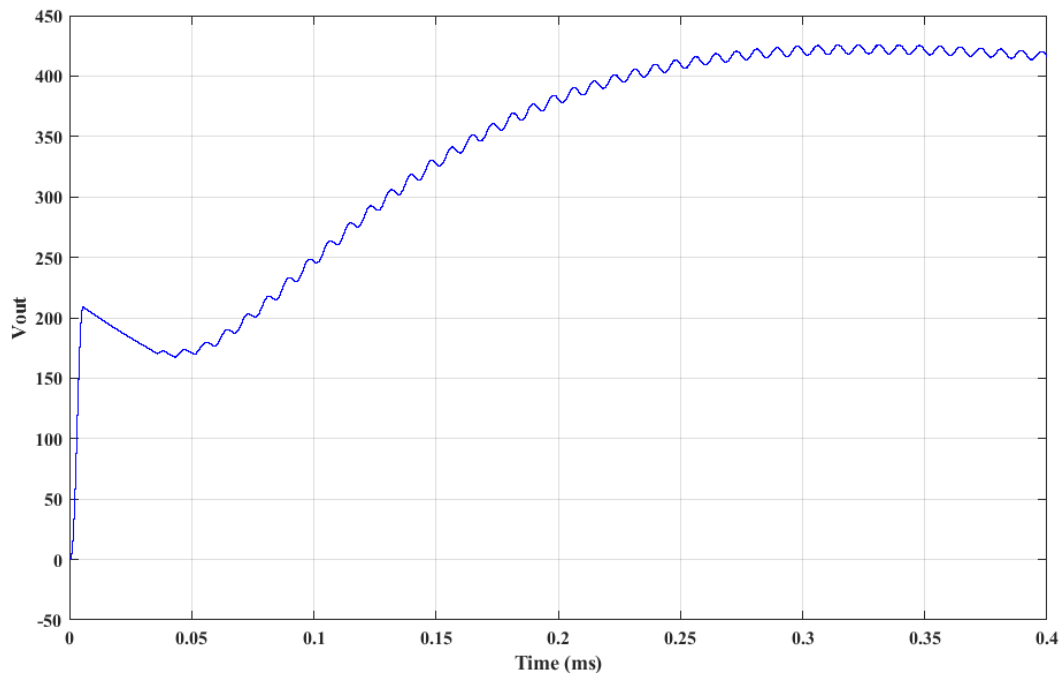


Figure 5.2. Output Voltage Waveform for PID Control

The results of simulations shown in Figure 5.2 reveals that the proposed PID controller regulates the output voltage very well with the voltage tracking the desired reference. The transient performance of the output voltage is also acceptable with moderate settling time and overshoot. But when there is a sudden change in the load or reference voltage, there will be transient oscillation until it reaches the steady state. Thus the response of the PID controller also depends on appropriate tuning of the gains of the controller.

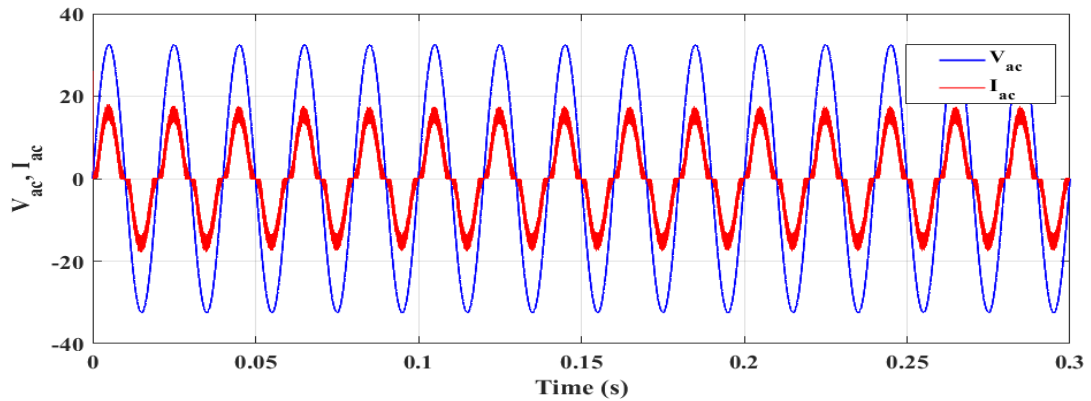


Figure 5.3. Input AC Current for PID Control

From the simulation, the input current waveform shown in Figure 5.3 is found to be smoother and sinusoidal as compared to the input current waveform of the open loop converter. From the Fourier transform shown in Figure 5.4, it is clear that the total harmonic distortion of the input current reduces considerably in the case of dual loop PID controller, thereby improving the power quality.

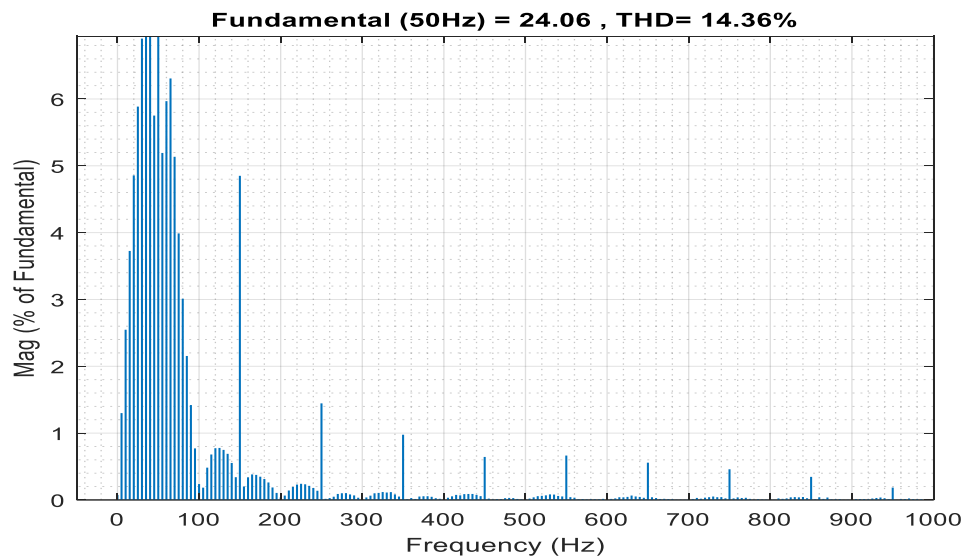


Figure 5.4. Input AC Current THD for PID Control

Despite satisfactory performance of the proposed controller, the capability of the PID controller to regulate the nonlinear operating condition is limited, resulting in slower response and overshoot in such situations.

So, the dual loop PID controller enhances the performance of the converter considerably, but for higher levels of performance, it is advisable to adopt intelligent

ANFIS based control schemes.

5.4 Performance Analysis of Dual Loop ANFIS Controller

To investigate the effects of the developed dual-loop ANFIS controlled PFC boost converter on the improvement of its performance in respect to voltage regulation, dynamic response, power factor, and harmonic suppression, the ANFIS controlled PFC boost converter was simulated using MATLAB/Simulink.

ANFIS controller uses neural network approach for learning, together with fuzzy inference systems to achieve adaptive control of the system based on its changing conditions and parameters.

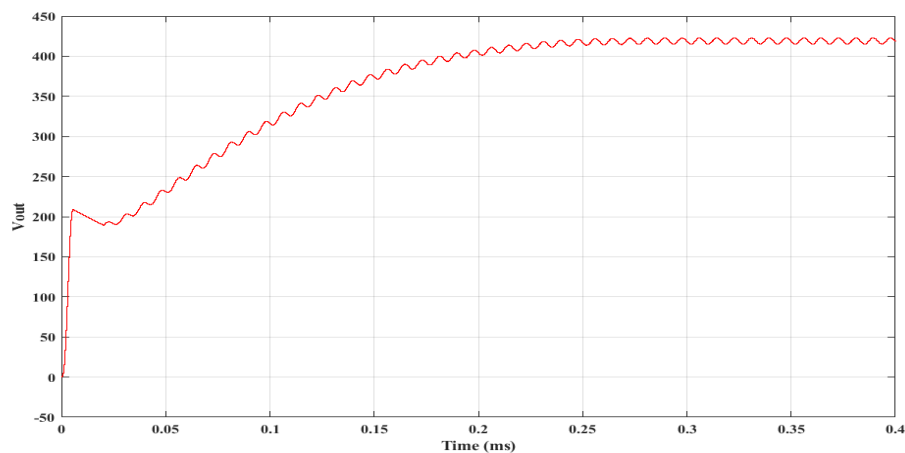


Figure 5.5. Output Voltage Waveform for ANFIS Control

The simulation result in Figure 5.5 reveals that the developed ANFIS controller significantly improved the dynamic behaviour and stability of the control system and was able to regulate the output voltage of the converter at the desired reference level without significant overshoot.

As can be seen from the output voltage signal, the transient response was improved through reduced settling time, decreased overshoot, and decreased steady-state error when compared to conventional PID controller.

Even with sudden changes in the load and/or in the reference voltage signal, ANFIS controller is quickly able to adapt to new conditions of the system and restore stable

operation.

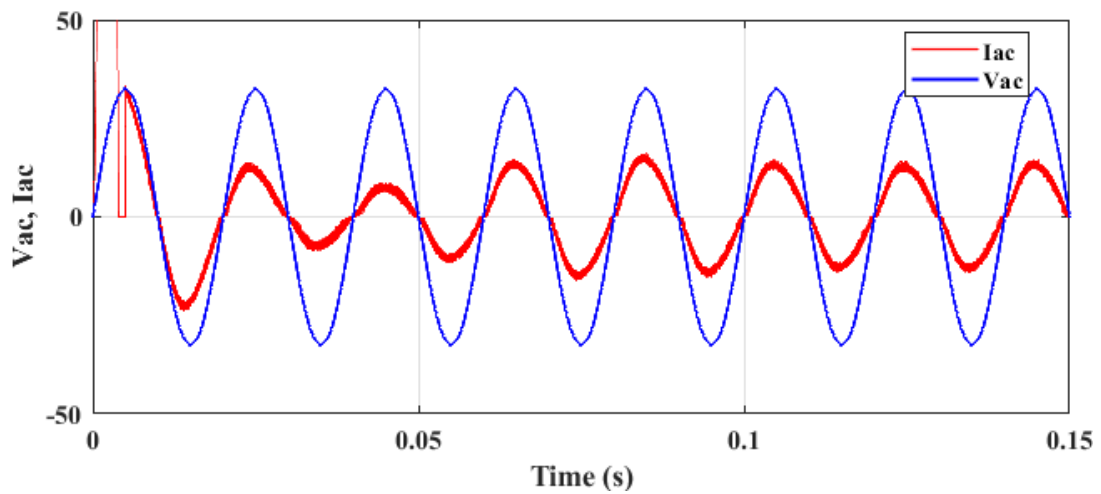


Figure 5.6. Input AC Current for ANFIS Control

Input current signal shown in Figure 5.6 obtained from ANFIS controlled PFC boost converter is less distorted compared to that obtained from PID controlled converter, and FFT analysis shown in Figure 5.7 confirmed low values of THD.

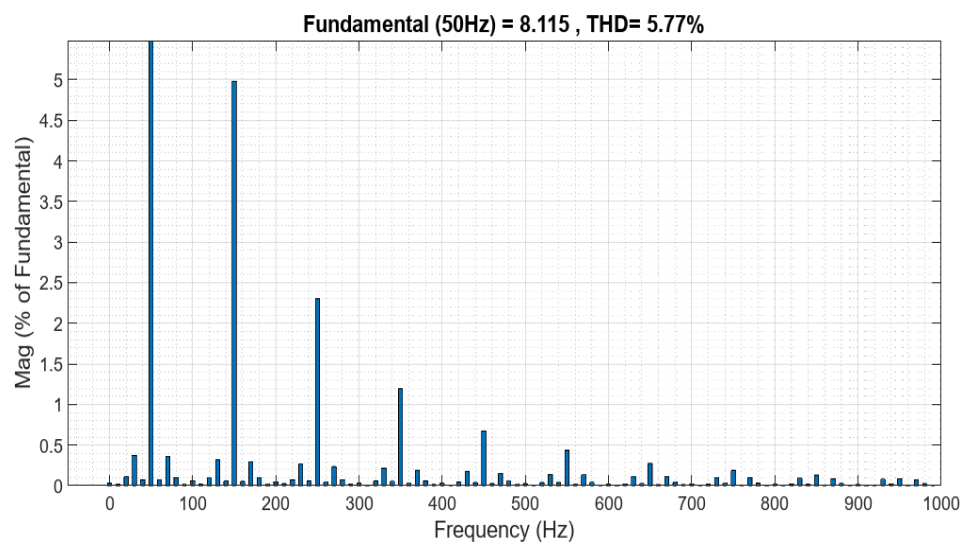


Figure 5.7. Input AC Current THD for ANFIS Control

Therefore, simulation results proved superior performance of ANFIS controller in comparison with the conventional PID controller due to intelligent and adaptive nature of ANFIS algorithm.

5.5 Comparative Performance Analysis

Performance comparison analysis between the proposed dual-loop PID and ANFIS controlled PFC boost converters shown in Table 5.1 is performed to examine the performance of both controllers under identical working conditions. Important parameters like output voltage regulation, input current waveform quality, THD, power factor, settling time, overshoot, and dynamic response under varying conditions are used for performance comparison.

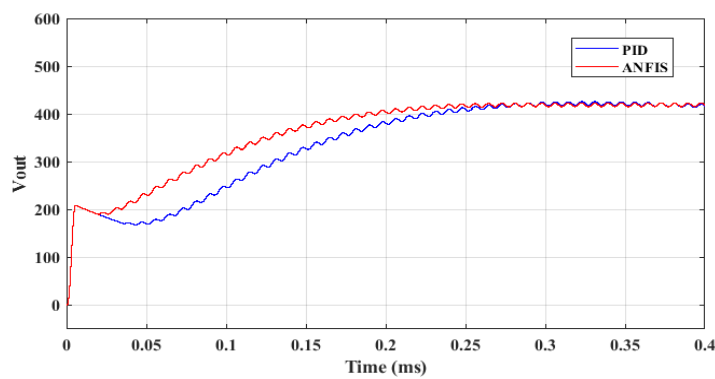


Figure 5.8. Output Voltage Comparison for PID and ANFIS Control

Both ANFIS and PID controllers perform well in improving the overall performance of the PFC boost converter system compared to the open loop case. Nevertheless, ANFIS control exhibits better performance compared to the conventional control technique due to its adaptive intelligent control features.

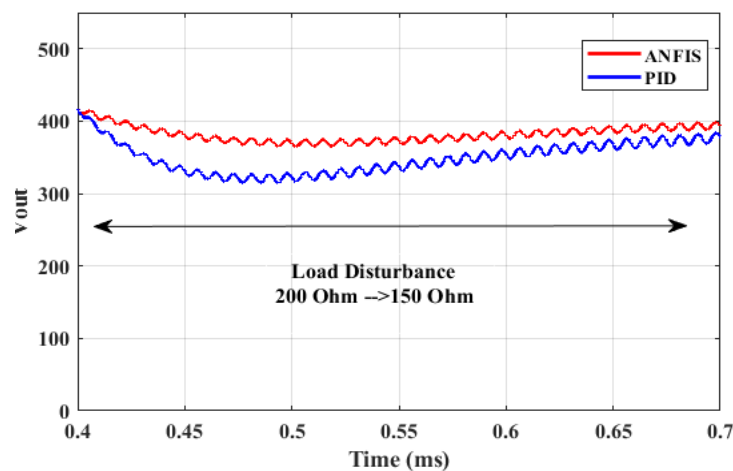


Figure 5.9. Output Voltage Under Load Variation for PID and ANFIS Control

Table 5.1. Performance Comparison Table

S. No.	Performance Parameters	Dual-Loop PID Controller	Dual-Loop ANFIS Controller
1.	Total Harmonic Distortion (THD)	14.33%	5.77%
2.	Power Factor	0.9654	0.9994
3.	Percentage Overshoot	7%	3%
4.	Settling Time	0.35 ms	0.2 ms
5.	Input Current Waveform	Distorted	Near Sinusoidal
6.	Harmonic Mitigation Capability	Moderate	High
7.	Dynamic Response	Slower	Faster
8.	Robustness under Load Variation	Moderate	Improved
9.	Voltage Recovery under Disturbance	Slower	Faster
10.	Current Tracking Capability	Moderate	Superior

ANFIS controller gives a much faster settling time, small overshoot, and low steady-state error in output voltage regulation than PID control shown in Figure 5.8. When sudden load disturbances occur or there are abrupt variations in output voltage, ANFIS quickly responds to the disturbance and restores a stable output with minimal oscillation shown in Figure 5.9.

ANFIS controller generates much smoother and sinusoidal input current waveform compared to that from PID controller. Hence, the total harmonic distortion of the input current is reduced considerably for the ANFIS controller. As a result, ANFIS gives an output with high power quality. ANFIS controller ensures that the power factor is close to unity by properly shaping the input current.

The PID controller is characterized by simplicity and satisfactory steady state response. Nevertheless, it exhibits slow response during dynamic operations due to nonlinear system dynamics.

Thus, ANFIS control has been proven to have better voltage regulation, dynamic response, reduced harmonic distortion, and improved power quality compared to the

PID control.

5.6 Discussion of Results

The simulation outputs generated using the developed MATLAB/Simulink models reveal high effectiveness of the designed dual-loop control techniques for the PFC boost converter. In particular, the comparison between the performance of PID and ANFIS based control demonstrates the significant advantage of utilizing intelligent ANFIS control strategy for the converter.

In the case of open loop control, poor performance in terms of output voltage regulation, input current distortion, and increased THD was observed due to lack of feedback control. With the development of dual-loop PID controller, there was a remarkable improvement in performance in all the three mentioned respects, since PID controller could stabilize the operation of the converter under normal conditions.

Despite satisfactory behaviour of the PID controller for steady-state operation, the controller demonstrated relatively large transient response with respect to rapid changes in load and reference voltages. The slow transient response and increased overshoot are typical features of the PID controller due to its constant gain and relatively low adaptability for non-linear operations.

The developed ANFIS dual-loop controller demonstrated outstanding results in terms of converter performance. Thanks to intelligent learning ability, ANFIS controller could rapidly adjust the response in the face of various disturbances and non-linearities within the control range. ANFIS controller was able to provide smooth output voltage with reduced overshoot and fast convergence time.

Furthermore, thanks to the adaptation of input current to sinusoidal shape, the controller demonstrated low THD and improved power factor. As shown by FFT analysis, the controller provided better harmonic suppression compared to PID controller. Therefore, the obtained simulation results prove the superiority of the dual-loop ANFIS controller with respect to traditional PID control technique.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusions

This thesis presented the modelling, simulation, and comparative performance analysis of dual-loop PID and ANFIS controlled Power Factor Correction (PFC) boost converters using the MATLAB/Simulink platform. The primary objective of the work was to improve power quality, reduce Total Harmonic Distortion (THD), and achieve near-unity power factor under varying operating conditions.

Initially, the open loop PFC boost converter was analyzed to study the basic converter characteristics and limitations without feedback control. Subsequently, a dual-loop PID controlled PFC boost converter was implemented using separate voltage and current control loops. The PID controller provided acceptable output voltage regulation and improved power factor compared to the open loop system. However, its dynamic response was comparatively slower under sudden load and reference voltage variations.

To overcome these limitations, an Adaptive Neuro-Fuzzy Inference System (ANFIS) based intelligent controller was developed using the ANFIS Editor Toolbox in MATLAB. The ANFIS controller demonstrated superior adaptability and nonlinear control capability due to the combined advantages of fuzzy logic and neural network learning. Simulation results confirmed that the ANFIS controller significantly improved converter performance compared to the conventional PID controller.

The comparative analysis showed that the ANFIS controller reduced Total Harmonic Distortion (THD) from approximately 15% to below 6%, while improving the power factor from 0.9654 to 0.9994. In addition, the ANFIS controller achieved reduced overshoot, shorter settling time, smoother input current waveform, and better dynamic response under load variation and output voltage disturbance conditions. FFT analysis also verified superior harmonic mitigation capability of the ANFIS controller.

Therefore, the proposed dual-loop ANFIS controlled PFC boost converter provides improved power quality, enhanced transient response, and better overall performance compared to the conventional dual-loop PID controlled system, making it highly suitable for modern power electronic applications.

6.2 Contributions of the Thesis

The main contributions of this thesis are mentioned as follows:

1. A detailed mathematical modelling and simulation of the Power Factor Correction (PFC) boost converter operating in Continuous Conduction Mode (CCM) has been carried out using MATLAB/Simulink.
2. A dual-loop control structure consisting of an outer voltage loop and an inner current loop has been developed for effective output voltage regulation and input current shaping.
3. A conventional dual-loop PID controller has been designed and implemented for the PFC boost converter to improve power factor and reduce harmonic distortion.
4. An intelligent Adaptive Neuro-Fuzzy Inference System (ANFIS) controller has been developed using the ANFIS Editor Toolbox in MATLAB to enhance converter performance under nonlinear operating conditions.
5. Suitable ANFIS training data, membership functions, fuzzy rules, and hybrid learning algorithms have been implemented to achieve improved adaptive control performance.
6. A comparative analysis between PID and ANFIS controllers has been performed under identical operating conditions including load variation and reference output voltage variation.
7. FFT based harmonic analysis has been carried out to evaluate Total Harmonic Distortion (THD) performance of the proposed controllers.

8. Simulation results demonstrated that the ANFIS controller reduced THD from approximately 15% to below 6% while improving the power factor from 0.9654 to 0.9994.
9. The ANFIS controller achieved reduced overshoot, faster settling time, improved current tracking capability, and better dynamic response compared to the conventional PID controller.
10. The proposed dual-loop ANFIS controlled PFC boost converter demonstrated enhanced power quality, improved harmonic mitigation capability, and superior robustness, making it suitable for modern power electronic applications such as switched-mode power supplies, renewable energy systems, and electric vehicle charging systems.

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LIST OF PUBLICATIONS

1. A. Mishra and B. Bhushan, “PSO Optimised Sliding Mode Dual Band Hysteresis Control for Grid-Tied LCL Inverter,” in Proc. International Conference on Next Generation Adaptive Research and Innovation (ICNARI), Mar. 2026. [Presented]
2. A. Mishra and B. Bhushan, “Enhanced Harmonic Mitigation in PFC Boost Converter Using Dual-Loop ANFIS Control: A Comparative Study with Conventional PID,” in Proc. 5th International Conference on Emerging Frontiers Electrical and Electronic Technologies (ICEFEET), Jul. 2026. [Accepted]





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ICEFEET-2026: Decision regarding Submission ID: 556

1 message

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